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Klodian Gradeci

Doctoral thesis

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NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
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Department of Structural Engineering

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The performance to withstand biodeterioration

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Preface

This doctoral thesis is submitted to Norwegian University of Science and Technology (NTNU) in partial fulfilment of the requirements for the degree of Philosophiae Doctor (PhD).

The research was carried out at the Department of Structural Engineering at Norwegian University of Science and Technology, Trondheim, Norway and partially at Department of Architectural Science, Ryerson University, Toronto, Canada. The project was financed by TallFaçades project that is funded by the Research Council of Norway under the fourth joint call of the European WoodWisdomNet research programme. The project started on August 18, 2014, and the thesis was submitted on December 1, 2017, including a half year of teaching duties at the Department of Structural Engineering. The main supervisor was Professor Dr Jochen Köhler at Norwegian University of Science and Technology, Norway. The co-supervisor was Dr Berit Time, Chief Scientist at SINTEF Building and Infrastructure, Norway.

Klodian Gradeci

Trondheim, December 1, 2017.

Abstract

Mould and decay are biodeterioration phenomena that jeopardize the integrity, functionality and durability of timber façade constructions. Accounting for them during the design stage is crucial for the prevention of social problems and financial loss, and to ensure a healthy, safe and comfortable interior environment. The design of façade constructions is replete with uncertainties. They are mainly related to the representation of the outdoor and indoor climate, physical parameters of the materials properties and geometries, and modelling of complex physical phenomena. Current design approaches fail to account for these uncertainties, especially in representing the outdoor climate and microbial growth. The aim of this work is to develop and apply a probabilistic-based methodology, which evaluates the performance of timber façade constructions to withstand biodeterioration and accounts for the involved uncertainties. The time series analysis according to autoregressive-moving-average models is applied to develop the stochastic model representing the outdoor climate. This technique identifies mathematical expressions that can generate probable patterns of the weather data in a time series containing plausible sequences, frequencies and correlations, future trends of the climate and can be long enough to resemble the expected service life. The temperature-dependent thermal conductivity of the insulation material is investigated by carrying out lab measurements, and subsequently, a stochastic model is developed to represent this property. Deficiencies, considering penetration of wind-driven rain, are accounted for and represented by different moisture sources. Moreover, the development of criteria and models representing mould growth in wood-based materials are investigated by carrying out a systematic literature review. Subsequently, three mould models are selected to derive the mould growth outcome as a mixture of their distribution to account for their competencies and diminishing their limitations in representing mould. This outline derives the likelihoods of potential levels of mould growth; hence, facilitates their association to the corresponding consequences adapted from the case study at hand. Uncertainty and sensitivity analysis methods are performed to quantify the ranges of the output, the likelihood of each outcome and to evaluate the significance of key contributors to output uncertainty. The methodology is applied to evaluate traditional and modern façade constructions. The results prove that the probabilistic-based methodology enables a more systematic approach to the evaluation of façade constructions. It accounts for the involved uncertainties, provides a clear association of microbial growth and its likelihood, and enables the identification and significance of the dominant parameters; hence, it delivers a more comprehensive representation to evaluate construction performance. The methodology can facilitate the development of cost-optimisation and risk-based inspection planning methodologies, and enable the upgrading of current codes and standards.

Keywords: mould; decay; façade; probabilistic; uncertainty; sensitivity analysis.

Acknowledgements

I would like to express my gratitude to all those who supported, supervised, encouraged and helped me to complete this thesis. I would like to thank my main supervisor, *Jochen Kohler*, for making me part of this dynamic experience, introducing me to this interesting field, supporting my initiatives and internationalization. The shared responsibilities and autonomy grew me professionally and helped me become an independent researcher. I am very grateful to my co-supervisor, *Berit Time*, who continuously supported me academically and professionally, even before accepting to be my supervisor. I have learned a lot from your constructive attitude and practical approach. I would also like to thank *Umberto Berardi* for our fruitful collaboration and for the warm welcome in a friendly working environment at RU. Furthermore, I am very grateful for my 'PhD coach', *Nathalie Labonnote* – without listing all your incisive pieces of advice, my skills as a researcher were definitely refined from you. I would like to express my appreciation also to my friends and colleagues from NTNU, SINTEF and RU, that have enriched this experience. In particular, I would like to thank *Michele* for his assistance, interesting discussions on reliability and friendship.

I would particularly show gratitude to my dearest family and friends for their encouragement, support and ensuring my happy and fun life- especially to my parents, *Vera and Fatri*, to whom this work is dedicated to.

Mirza - buku, we're half way there!

List of Papers

The thesis consists of four parts. The first three parts provide an overview that interconnects the publications together in a logical structure, provide the wider context of the thesis, summarize reasons regarding the decision, emphasize the main findings and propose ideas for further research. The fourth part provides the appended papers. They consist of two peer-reviewed international conference papers, one review article and three original research articles.

List of appended papers

Paper I. Gradeci, K., N. Labonnote, B. Time, and J. Köhler. *A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades*. in World Conference on Timber Engineering. 2016. Vienna.

Paper II. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review*. Construction and Building Materials, 2017. 150: p. 77-88.

https://doi.org/10.1016/j.conbuildmat.2017.05.204

Paper III. Gradeci, K., N. Labonnote, J. Köhler, and B. Time, *Mould Models Applicable to Wood-Based Materials – A Generic Framework*. Energy Procedia, 2017. 132: p. 177-182.

https://doi.org/10.1016/j.egypro.2017.09.751

Paper IV. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *A probabilistic-based methodology for predicting mould growth in façade constructions.* Building and Environment, 2018. 128: p. 33-45.

https://doi.org/10.1016/j.egypro.2017.09.641

Paper V. Gradeci, K., U. Berardi, B. Time, and J. Köhler, *Uncertainty and sensitivity analysis for evaluating highly insulated walls to withstand rot decay and mould growth* (under review in an international journal). 2017.

Paper VI. Gradeci, K., M. Baravalle, B. Time, and J. Köhler. *Cost-Optimisation for Timber Façades Exposed to Rot Decay*. in 12th International Conference on Structural Safety & Reliability 2017. Vienna.

Other publications from the author

Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *A probabilistic-based approach for predicting mould growth in timber building envelopes: Comparison of three mould models*. Energy Procedia, 2017. 132: p. 393-398.

https://doi.org/10.1016/j.egypro.2017.09.641

Fufa, S., C. Skaar, K. Gradeci, N. Labonnote, B. Time, and J. Köhler, *Parametric LCA of a ventilated timber wall constructions* (under review in an international journal). 2017.

Andrea Tietze, S.O., Sylvain Boulet, Klodian Gradeci, Nathalie Labonnote, Steinar Grynning, Joakim Noreen, Anna Pousette *Tall Timber Facades – Identification of Cost-effective and Resilient Envelopes for Wood Constructions*. 2017.

Fufa, S., C. Skaar, K. Gradeci, N. Labonnote, B. Time, and J. Köhler. *Parametric LCA of a ventilated timber wall construction in tall timber buildings*. in 14th International Conference on Durability of Building Materials and Components. 2017. Ghent.

Declaration of authorship

Klodian Gradeci developed the ideas, carried out the reviews, performed the simulations, analysed the results, wrote the manuscript in Papers I-VI. In Paper I, Nathalie Labonnote and Klodian Gradeci jointly prototyped the interface, Jochen Köhler proposed the idea to convert the relative humidity into absolute humidity and Berit Time proposed the façade constructions for the parametric studies. In Paper V, Umberto Berardi and Klodian Gradeci jointly designed and carried out the experiments, while the results were analysed by Klodian Gradeci. In Paper VI, Michele Baravalle and Klodian Gradeci jointly developed the methodology and analysed the results. All respective authors revised, edited or proofread each of the manuscripts.

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PART I - CONTEXT

1. Introduction to the context

1.1 Motivation

1.1.1 Consequences of biodeterioration

The façade construction is one of the most crucial elements that concerns the aesthetic and technical performance of a building. Therefore, well-functioning and cost-effective solutions of façade constructions have long been a societal requirement. Nevertheless, moisture-related damages are still persistent both in private and public buildings. A recent study concludes that 31% out of 10112 inspected dwellings in Norway had moisture damage [1]. Similarly, 75 % of damages and defects in the Norwegian building stock could be related to moisture damages, where 66 % related to the façade construction [2, 3]. The total annual costs related to repairs of buildings was estimated approximately 10 % (1.65 billion Euros) in Norway in 2013 [4] and 3-5 % specifically for façade constructions in Europe [5]. One of the main causes is biodeterioration.

Mould and decay are biodeterioration phenomena that jeopardize the integrity, functionality and durability of timber façade constructions. Several conditions are required for them to occur, where the most important is the presence of humidity or dampness. The share of the population in EU countries living in an indoor environment affected by dampness equals approximately 15-16 % [6]. The substantial fraction of the time that populations spend in buildings [7] underlines the importance of preventing microbial growth occurrence in order to avoid adverse consequences.

The most severe consequences related to microbial growth are the adverse health and indoor air quality (IAQ) effects. When conditions are met, microbial growth occurs on building materials which subsequently emit spores, cells, fragments and volatile organic compounds into the indoor air [7]. The latter may cause a mouldy odour and microbial pollution, which are key constituents of indoor air pollution [8]. Thus, the indoor air quality is reduced, which leads to discomfort of the occupants. Exposure to diverse species of microbial growth may also lead to adverse health effects including increased prevalence of respiratory symptoms, allergies and asthma, bronchitis as well as perturbation of the immunological system [7-13].

During the microbiological attack, biodeterioration occurs and subsequently transform the wood-based material. Biodeterioration can be classified into: biophysical, which disrupts and distorts the material; biochemical, which modifies the properties of the material; and aesthetic, which creates a presence of a surface layer of microorganisms [14]. Their effects cause discolouration of the material and significant weakening and softening of wooden structure. Their consequences can vary from shortening of the aesthetic service life, reduced structural performance (stiffness and strength) up to complete destruction of façade constructions. As a result, undesirable societal and economic costs are derived from health interventions, mitigation actions such as repair and replacement and the reduction of the asset or reputation of the building. In light of this, decay and mould occurrence should be prevented.

1.1.2 Uncertainties related to the performance evaluation of façade constructions

The building environment is characterised by a stochastic nature. The performance evaluation of façade constructions is replete with uncertainties. They can be distinguished between 'aleatory' uncertainty, which refers to random inherent uncertainties, and 'epistemic' uncertainty, which is dependent on human knowledge and can be reduced with additional information, better modelling and better parameter estimation [15]. This distinction affects the way these uncertainties are handled.

The uncertainties that a practitioner encounters during the design of façade constructions come from a variety of sources. A more detailed breakdown of these uncertainties categorises them into physical, modelling, statistical and those due to human factor. Physical uncertainties are those identified with the inherent natural variability [15] and may be associated to the meteorological phenomena i.e. wind, clouds, rainfall, heat wave, or to the physical properties of the materials i.e. thickness, thermal conductivity, density, permeability. The latter may result due to the material's inhomogeneity, manufacturing, production and measurement process. Modelling uncertainties are associated with the mathematical representation or modelling of the variables that constitute of the façade construction, its boundary conditions and their interrelationship. They may be subcategorised into uncertainties related to the modelling of the; a) meteorological phenomena, b) material property functions, c) indoor climate, and d) transfer of the physical phenomena into differential equations. Statistical uncertainties arise from the suggested probability functions and associated parameters. Uncertainties due to human factor can be considered as the ones originating due to the effect of human error or human intervention [15] related to design, construction and operation stage.

Uncertainties are generally very interconnected to each other. An example can be the representation of a weather event. The uncertainties due to inherent natural variability would be the uncertainties associated with the extreme values or continuous time series of this phenomenon over time. The mathematical representation of this phenomenon in time would introduce model uncertainties. The estimated parameters of the model would introduce statistical uncertainties since it is based on a finite number of experiments. Moreover, the prediction of this phenomenon from the model would also introduce additional model uncertainties. The decision considered in any of the previous steps would also introduce uncertainties due to the human factor.

Because of all uncertainties, the performance of façade construction to withstand biodeterioration will vary. In order to develop robust designs of façade constructions by making balanced and sound decisions, all these factors should be considered during the design stage. In light of this, a methodology that accounts for uncertainties involved should be approached.

1.2 Background

1.2.1 Conventional approach in performance evaluation to withstand biodeterioration

The codes or standards are mainly performance-based and give limited directions regarding the composition of the façade construction and limited suggestions regarding the selection of different layer properties [16, 17]. Consequently, the façade constructions are often designed based on experience and opinions of practitioners rather than well-established methodologies [18]. In general, the design of the façade composition is based upon the choice of the materials that deliver the best performing construction exposed to a one-year deterministic severe reference climate [19]. Furthermore, the codes provide guidelines on how to avoid microbial growth [17, 20]; however, suggestions are limited and expressed in terms of maximum threshold values in terms of moisture content, relative humidity or temperature. Independent of the choice of standard or code, the conventional approaches are characterized by a deterministic nature; hence, not accounting for the uncertainties involved. Consequently, by only following these terms might lead to underestimation of the performance, which causes premature failure of the construction, or overestimation of the performance, which leads to over-designed façades and hence undesirable societal costs.

1.2.2 Probabilistic approach in performance evaluation to withstand biodeterioration: State-of-the-art

A probabilistic-based approach can account for the involved uncertainties. Hence, it delivers a more comprehensive overview of the probable state. Due to these capabilities, it is established in the field of structural engineering [15], where consequences of the failure of the structures are associated with casualties. As an approach, it has also found increasing application in the field of building physics during the last two decades [21-33] in evaluating the performance of constructions to withstand mould growth. A state-of-the-art review explaining the development in more details can be found in [34] (*Paper I*). The application of this approach for constructions subjected to decay can be found only in structural engineering applications such as timber trusses or in forestry application [35, 36]. Table 1 present the results in a tabular form. This thesis concerns application on timber façades; however, other construction are selected in this review considering the similarities in the general approach. The criteria for comparison consist of the way the uncertainties involved are accounted for. They can be categorised into the followings:

a) *System representation*, constituting of probabilistic modelling of outdoor and indoor climate, material properties and geometry including deficiencies.
b) *Performance evaluation* of mould growth, constituting of the model representing mould growth and design criteria.
c) *Methods*, constituting of the methods/techniques applied to sample the random variables and perform uncertainty (*UA*) and sensitivity analysis (*SA*).

The results can be grouped according to the selected criteria into the followings:

a) *System representation.*

- *Outdoor climate*. The outdoor climate is either represented as a single deterministic year (severe, MDRY or reference year) or a random sampling of one year out of several historical measured years. The initiation time is always specified and considered as a deterministic parameter. The simulation durations include either six months or maximum one year.
- *Indoor Climate*. The temperature is represented either by a constant value, or by function of the outdoor climate, or as normally distributed. The humidity or moisture conditions are represented by either a constant value, or by a deterministic daily scenario, or by a function of the outdoor climate, or as a normal distribution of moisture sources, or a stochastic model derived from measurements. Other important derivations of stochastic models representing the indoor climate can be found in [37-40].
- *Material*. The material properties are represented either by a deterministic value or as normally distributed. Other relevant literature investigating uncertainties of material properties in the hygrothermal simulation of wall constructions can be found in [41-44].
- *Deficiencies*. When accounted for, the airtightness's of the attic floor is considered as either tight or leaky.
- *Other parameters*. Uncertainties related to other parameters include the surface coefficients or design parameters (i.e. the height of the building, inclination, orientation).

b) *Performance evaluation.*

The mould growth is represented either by threshold values, or isopleths, or periods of favourable condition of mould growth, or more advanced models that incorporate mould governing factors and transient conditions during the calculation procedure. The design criteria used to evaluate the performance of the construction constitute of either the onset (germination) of mould growth per hour/year or critical hours/cycles of threshold values.

c) *Methods.*

The techniques used in uncertainty analysis include Crude or Latin Hypercube Sampling Monte Carlo [45] or first-order reliability method (*FORM*) [15]. Sensitivity analyses methods include both local, such as one-at-a-time (*OAT*) or Morris, and global analysis, such as regression-based, correlation-based, variance-based or scatterplots [46]. Application of several sensitivity analysis techniques in different fields of building physics can be found in [32].

Table 1. Comparison of probabilistic approaches in the evaluation against biodeterioration, where: '-' denotes not accounted for, '✓' denotes accounted for, 'CST' denotes constant value, 'f(outdoor)' denotes function of the outdoor climate, 'DS' denotes deterministic daily scenario, 'N(μ,σ2)' denotes normally distributed, 'T' denotes temperature, 'RH' denotes relative humidity/moisture.

Literature (year)	**Appl.**	**System representation**							**Performance Evaluation**		**Method**	
		Outdoor Climate		Indoor Climate		Material	Deficiency	Other	Model	Criteria	UA	SA
		Method	Duration	T	RH							
[21] (1997)	Facade	Severe year	One year	CST	$N(\mu,\sigma^2)$	$N(\mu,\sigma^2)$	-	-	Threshold relative humidity	Onset of mould (VTT Index 1) over 2,4,12 weeks	MC	Spearman
[22] (1999)	Facade/ building	MDRY	One year	f(outdoor)	f(outdoor)	-	-	-	Daily temperature ratio	Onset of mould	-	-
[23] (2005)	Facade/ building	Reference year	One year	$N(\mu,\sigma^2)$	$N(\mu,\sigma^2)$	$N(\mu,\sigma^2)$	-	✓	Isopleth/IEA	Onset of mould/ growth risky days	MC LHS	Morris
[24] (2011)	Attic	Random sample	One year	CST	$N(\mu,\sigma^2)$	-	air leakage	✓	Mould growth potential m	Onset of mould (VTT Index 1) per hour	MC	-
[25] (2011)	Facade	Random sample	One year	-	-	-	-	-	MRD Model	Onset of mould (VTT Index 1)	-	-
[26] (2012)	Facade	Reference year	One year	$N(\mu,\sigma^2)$	$N(\mu,\sigma^2)$	-	-	✓	Isopleths of IBP model	Total hours of mould onset	MC LHS	Scatterplots
[27] (2013)	Facade	Random sample	One year	CST	Stochastic model	-	-	-	VTT Model and mould growth potential m	Critical hourly humidities and onset of mould per year	MC LHS	OAT
[28] (2014)	Attic	Random sample	One year	CST	$N(\mu,\sigma^2)$	-	air leakage	✓	VTT Model	Onset of mould (VTT Index 1) per year	MC	-
[29, 30] (2014)	Facade	Random sample	Half year	f(outdoor)	Daily scenario	$N(\mu,\sigma^2)$	-	-	TOW (Time of wetness)	Cycles with TOW ≥ 0,5	MC LHS	-
[31] (2015)	Attic	Reference	Half year	CST	CST	-	-	-	Threshold relative humidity	Onset of mould per hour	FORM	-
[32, 33] (2015, 2017)	Attic	Random sample	One year	$N(\mu,\sigma^2)$	$N(\mu,\sigma^2)$	$N(\mu,\sigma^2)$	air leakage	✓	VTT Model	Onset of mould (VTT Index 1) per year	MC	Diverse

1.2.3 Opportunities for further advancements

The advancements in this field are clear. The representation of the indoor and outdoor climate has progressed from single time series to stochastic models. Moreover, the representation of mould growth has advanced from being considered as a threshold value, as suggested from norms, up to more advanced models. Nevertheless, challenging subjects remain to be addressed. A methodology including an accurate stochastic representation of the system together with a comprehensive representation and evaluation of biodeterioration is necessary to fully exploit the capabilities of a probabilistic approach.

The outdoor climate is a very important variable affecting the design of building envelopes; hence, assumptions regarding its representation should be reliable. Its representation should consider the temporal and spatial variability of weather phenomena, the future trends such as the implication of climate change, and also resemble the expected service life of the constructions. Moreover, material properties are better represented when the probabilistic models are based on measurements or experimental investigations and account for several interrelationships of parameters and exposures. The estimation of the significance that each material property has on the uncertainty of the results is crucial to the decision-making process. Furthermore, in real life conditions, the impacts of deficiencies of water leakages and workmanship quality increase moisture problems. Therefore, the impact of such deficiencies should be accounted for during the design stage, as they are most likely to occur during the service life [47]. Once the aforementioned issues are accounted for in the design methodology, the representation of hygrothermal results, derived from reliable HAM tool, can be reliable to be used as input in the models representing mould growth, and subsequently evaluate constructions performance.

The evaluation of microbial growth, as calculated from mould and decay models, against design criteria establishes the performance to withstand biodeterioration. Models representing microbial growth have been developed in the last two decades and currently, there are several available that can be applicable to wood-based materials [48-50]. Distinct features, including extensiveness and limitations, characterise these models; hence, their applicability should be distinguished. In addition, issues concerning their capabilities have been raised [51-53]. Consequently, researchers and practitioners are facing the challenge to identify the adequate model to the case at hand. Moreover, decay is a biological phenomenon that requires more extreme conditions to occur compared to mould growth [49, 50, 53]. Previous studies mostly concern only of mould growth. However, the models representing these two phenomena assume different behaviour during unfavourable 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. On the other hand, design criteria are not elaborated in standards, which poses difficulties in relating the results to the performance. Therefore, previous research has generally considered the failure event as the onset of mould growth. However, the level of acceptability depends on several characteristics of the case study at hand since its consequences can vary from marginal to substantial, even for the same rating scale. Considering the current status, an overview of the probable situation that associates the occurrence of the possible levels of biodeterioration to their respective likelihoods can deliver a more comprehensive representation. The latter would provide a more overarching outline to evaluate the performance of façade constructions and simultaneously flexible enough to associate it to the characteristics of the case study at hand.

The main incentive of this thesis is that the problem of biodeterioration on timber façade constructions persists despite its prevention has already been a requirement during the design stage. Statistics based on inspections and measurements in Trondheim [54] show that 50 % of the inspected houses had one or more indicators of a mould problem. Similarly, another study concludes that 615 000 buildings are situated in areas with a high potential risk of rot-decay in Norway, in 2011 [4]. Other reported mould growth problems in buildings industry [55-61] suggest that the conventional design approaches need revision and consequently, it is a necessity to explore and study new approaches. Probabilistic approaches are an alternative. Finally, the main research question is raised: 'How can the probabilistic approach be effectively implemented in the performance evaluation of timber façades?'.

1.3 Outline of the thesis

The schematic overview of the thesis is presented in Figure 1. It consists of four parts. The first, second and third part provide an overview that interconnects the publications together in a logical structure, provide the wider context of the thesis, summarize reasons regarding the decision and emphasize the main findings. Part I presents the motivation, background and establishes the aim and scope of this work. The second part presents the methods and the reasons for their selection, provides an overview of the developed probabilistic-based methodology and delivers a short summary of the content of each paper. The third part is constituted by the final remarks of this work by drawing the conclusions, the main contributions of this work and further research. Special attention is given to the latter where current challenges are discussed and potential methods on how to approach them are proposed. The fourth part provides the appended papers, where the research is presented and discussed in details, and completes the contribution of this work.

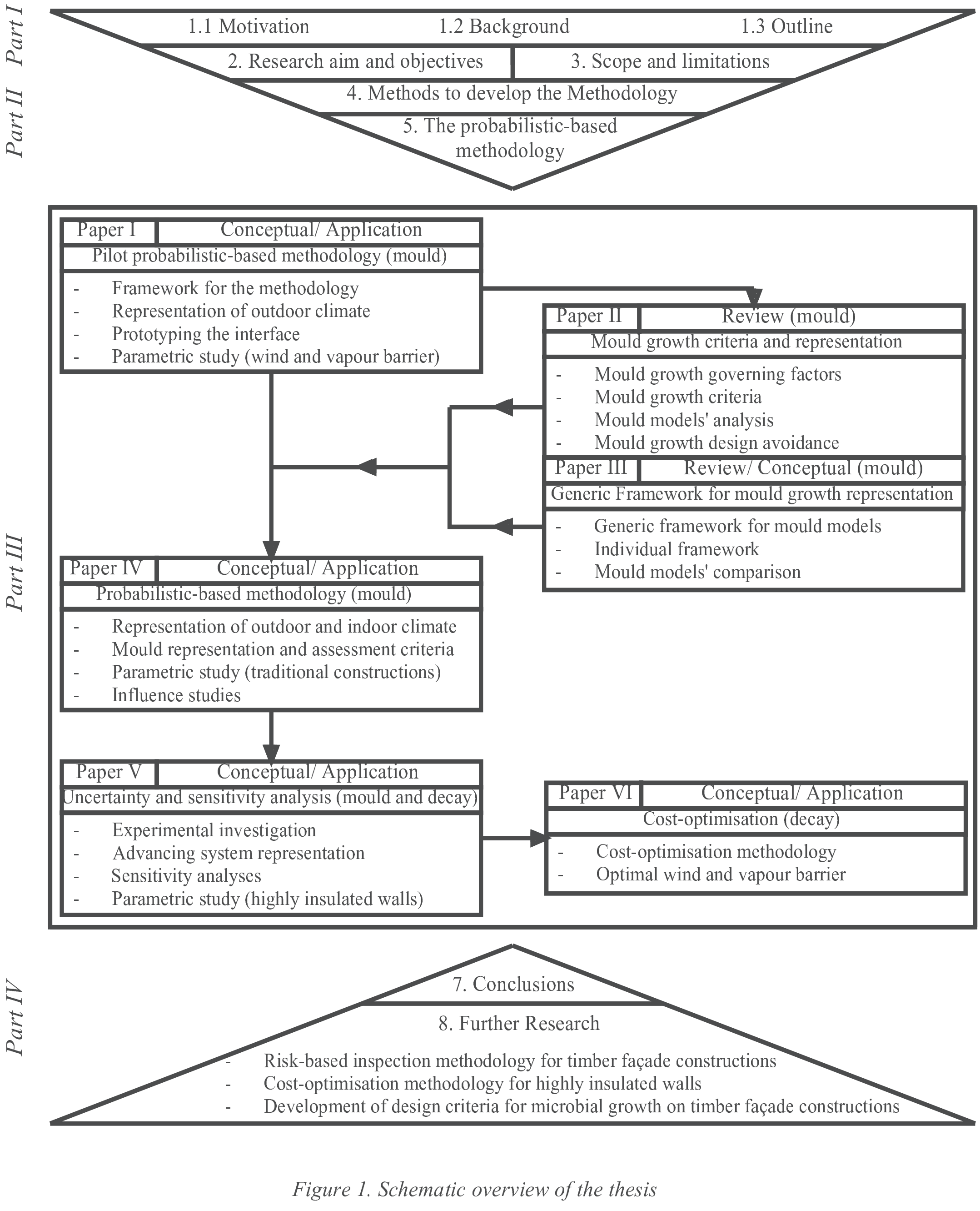

Figure 1. Schematic overview of the thesis

2. Research Aim and Objectives

The aim of this work is to develop and apply a probabilistic-based methodology for evaluating the performance of timber façade constructions to withstand biodeterioration. This aim is achieved by addressing the following objectives:

1- Development of a comprehensive approach representing the microbial growth and its assessment criteria, by:
   a. Identifying and studying the factors governing mould and decay.
   b. Providing a state-of-the-art of current models representing mould on wood-based materials.
   c. Analysing these models in relation to the synthesised results drawn from experimental and field studies.
   d. Discussing current design avoidance approaches against biodeterioration.
   e. Identifying and discussing current assessment criteria.
   f. Representing mould growth and decay rating with assessment criteria.

2- Development of the stochastic representation of the system, by:
   a. Identifying the involved uncertainties.
   b. Representing the input variables and the output.
   c. Investigating the significance of key contributors to the output uncertainty.

3- Development of a conceptual probabilistic-based methodology, by:
   a. Providing a state-of-the-art of probabilistic-based approaches in the field of building physics focusing on biodeterioration.
   b. Discussing the gaps and possibilities for further advancement in this field by identifying the limitations of both current conventional and probabilistic-based design approaches.
   c. Mapping the necessary steps and considerations to produce a conceivable methodology.
   d. Prototyping the interface that incorporates the proposed methodology.
   e. Validating, implementing and exploiting the application of this methodology.

3. Scope and Limitation of the Study

This thesis develops a probabilistic-based methodology that evaluates the performance of façade constructions to withstand biodeterioration. Biodeterioration concerns mould and decay. Modelling of the random variables in this work are derived from lab measurements, literature studies, numerical simulations, codes/standards and when necessary, qualified assumptions based on engineering judgements. It falls out of the scope of this work to account for uncertainties related to modelling and representing the mathematical equations incorporated into the HAM tools. Moreover, the simulations are performed using a one-dimensional HAM tool; hence, aspects that require a two- or three-dimensional simulation, such as geometrical changes in the façade, height or inclination, fall outside this study's scope. Other limitations are further discussed throughout the papers.

PART II - RESEARCH

4. Methods to develop *The Methodology*

This section discusses the overall methodology, the decisions, and reasons that have guided the main research activities of this work. To address the aim and objectives, this research has mainly focused on quantitative research methods. The research methodology applied in this work is illustrated in Figure 2.

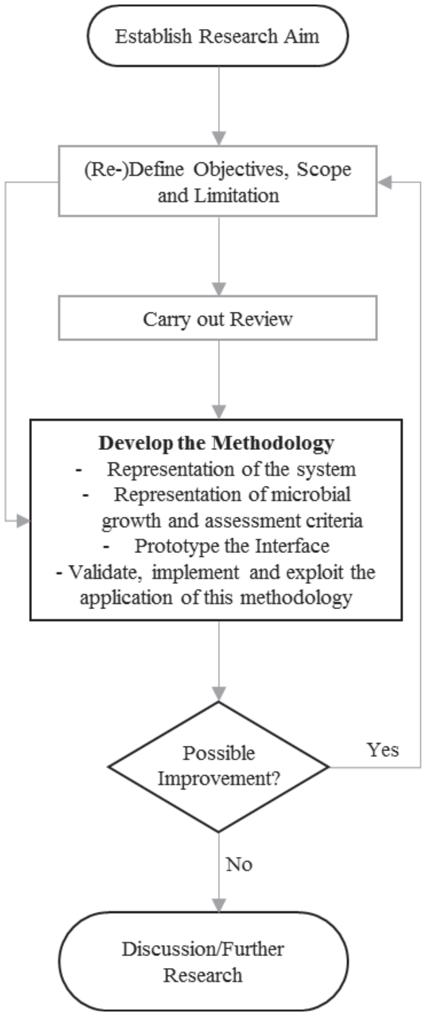

Figure 2. Workflow of the research methodology

4.1 Review

A literature review is defined as a '*systematic, explicit, and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work produced by researchers, scholars, and practitioners*' [62]. Different types of review are available and can be carried out; however, all literature reviews should be systematic [63]. They mainly differ in the degree to which they are systematic and how explicitly their methods are reported; however, each type should help to reveal what exactly has and has not been done.

This work has carried out different types of review, as identified in [63], to address part of the objectives according to each review's role and function. More precisely, a systematic literature review was carried out to review the development of criteria and models representing mould growth in wood-based materials (Objective 1 a) - c)). Due to the complexity and inconsistent findings across literature in this field, it was reasoned this topic requires a comprehensive search process and systematic review of the relevant literature. This part of study concerns only mould since a comprehensive review regarding decay was already available in [50].

A systematised review was carried out to discuss current methodologies to evaluate the performance to withstand mould and decay occurrence in building engineering field (Objective 1 d), 1 e), and 3 b)). The main reason was to provide an overview of how mould and decay are considered in building engineering field and identify their limitations considering the results from the previous review.

A critical review has been carried out to provide the state-of-the-art of the probabilistic approach in the field of building physics focusing on microbial growth (Objective 3 a) and b)). The choice stems from the need to aggregate the existing literature of the probabilistic approach, critically evaluate its quality, and subsequently, identify the robust ideas of existing methodology and gaps that require further research.

4.2 Development of the methodology

A methodology based on probabilistic approaches has been proposed and developed (Objective 3 c)) in this work to address the requirement for better design methodologies that evaluate the performance of façade constructions to withstand biodeterioration. Development of this methodology has been carried out in a systematic and structured looped process. The proposed methodology has undergone four main stages: the stochastic representation of the system (Objective 2 a) - c)); the representation of microbial growth and its evaluation (Objective 3 f)); prototyping the interface (Objective 3 d)); and the validation, implementation and application of this methodology (Objective 1 f) and 3 e)).

4.2.1 System representation

The representation of the system consists of the description, analysis and modelling of the inputs, outputs and their interrelationships. Experimental analysis and specified rapid review have been conducted to retrieve data for developing stochastic models representing the input. Statistical analysis has been used to analyze the results of the two previous methods and process the input-output relationship. These stochastic models concern the representation of the outdoor and indoor climate and material properties and geometries.

The time series analysis according to autoregressive-moving-average models [64] has been applied to develop the stochastic model representing the outdoor climate, consisting of temperature and relative humidity. This technique identifies mathematical expressions that can generate probable patterns of the weather data in a time series containing plausible sequences, frequencies, correlations, and accounting for future trends. Another technique developed in this study to represent the outdoor climate (temperature, relative humidity, rain, wind and radiation) is the five-year climate series combination of one-year historical data. The initiation date is also selected randomly between the first of each month.

The temperature-dependent thermal conductivity is represented by an auto-regressive stochastic model, which is derived by results of laboratory measurements. The modelling of other material properties is elaborated by performing a rapid review of the literature, which concerns the specific topic to retrieve data, and subsequently applying probabilistic techniques to represent them. Assumptions based on engineering judgment were applied when necessary.

Uncertainty and sensitivity analyses have been performed to quantify the ranges of the output, the likelihood of each outcome and to evaluate the significance of key contributors to output uncertainty. Both local and global sensitivity analysis methods are selected among the numerous available. The methods applied to this work include Morris, regression-based and correlation-based techniques [46]. Crude and Latin Hypercube Monte Carlo are used as techniques to sample the variables.

4.2.2 Representation of microbial growth and its evaluation

Due to the various limitations and strengths of models representing mould growth [8-12], the representation of mould growth is derived by integrating three established mould models, the VTT [65-68], MRD [69-71] and IBP biohygrothermal model [72, 73]. The latter delivers a more comprehensive overview of the probable situations, provides the possibility to account for and control identified limitations or capabilities of each model extends, and consequently, it provides more confidence in the decision-making process. 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 [74, 75]. The contribution of each model to 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, as defined by the strengths or limitations of the model to the case study, establishes the weight of these coefficients. The decay degree is calculated according to Logistic

Dose-Response model (LDR) [76] and VTT decay model [77]. It is not possible to use the same integration as done for mould since the units to express decay are not compatible with each other. Due to the lack of established design criteria, the results are expressed as a density function associating levels of microbial growth to their respective likelihood. Nevertheless, acceptable levels of consequences are proposed by considering the aesthetic, IAQ/health and structural aspects.

4.2.3 Prototyping the interface

The interface prototype is developed as an automated and integrated workflow by combining Matlab [44], Python [46] and XML codes. The heat and moisture simulations are performed using the hygrothermal building simulation software WUFI 6.1 ® [78]. WUFI provides a detailed moisture transfer analysis in multi-layered walls and the surrounding environment. It also enables penetration of wind-driven rain by applying moisture sources. The software SimLab [79] and Matlab [44] have been used to generate the samples of the input variables and to elaborate the results of uncertainty and sensitivity analyses.

4.2.4 Validating, implementing and exploiting the application of this methodology

The developed methodology has been implemented in different fields in order to exploit its capabilities. Current façade constructions have been selected to assess it and afterwards to compare their results with common engineering judgment derived from practice. The results from the selected mould models have been validated with official tools/add-ins [78].

Finally, the limitations of the proposed methodology are identified and discussed. Possible improvements that fall within the scope of this thesis are carried out and subsequently, the methodology is upgraded. In addition, other advancements in the field are discussed in the further research section.

5. The probabilistic-based methodology

The probabilistic-based methodology developed according to the methods discussed in the previous chapter is presented in a schematic form in Figure 3. The proposed methodology can effectively and practically perform probabilistic and sensitivity analyses, which account for uncertainties related to outdoor climate, indoor climate, material properties, and potential deficiencies. The performance evaluation to withstand biodeterioration is presented as a distribution by associating continuous microbial growth levels with their corresponding likelihoods (and subsequently their associated consequences depending on the case study at hand), assessed by several criteria.

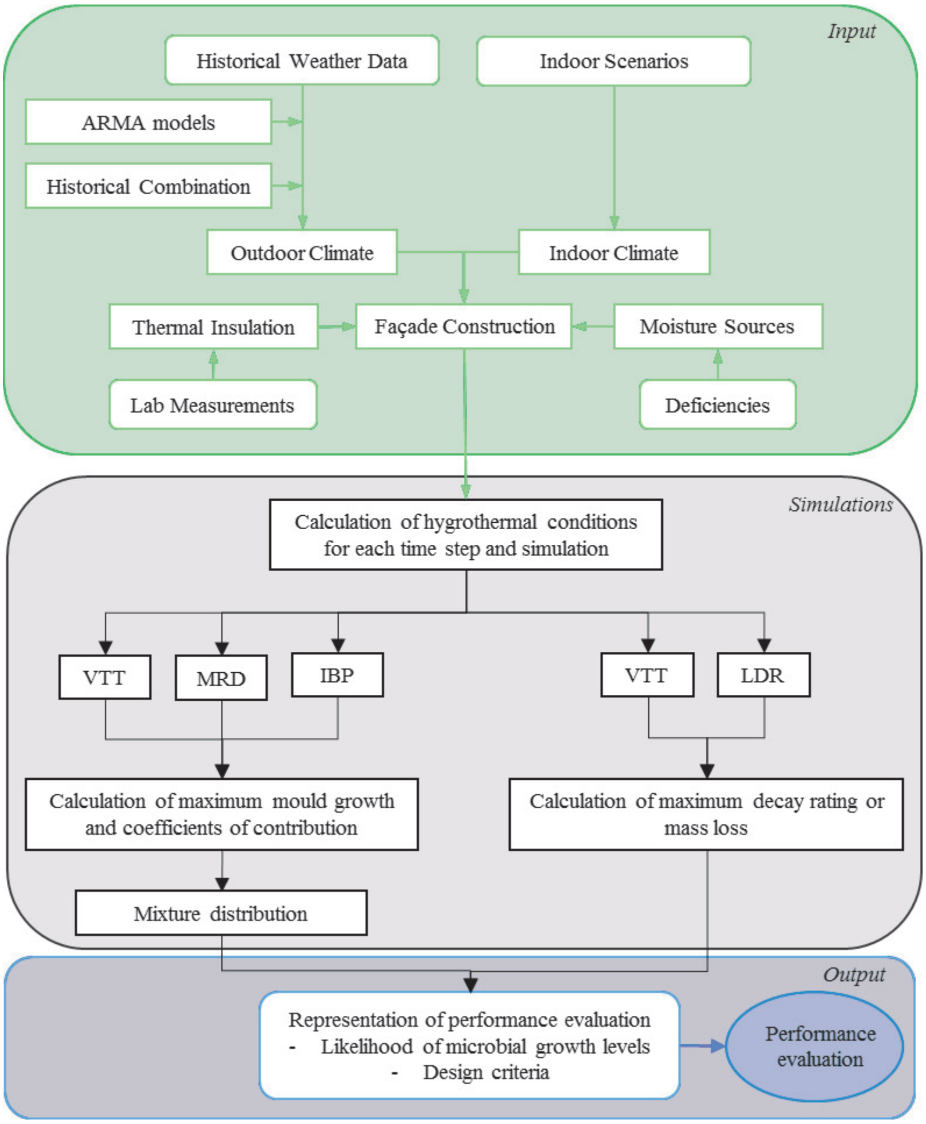

Figure 3. The probabilistic-based methodology

This methodology has been implemented in the followings studies:

1) The performance evaluation and comparison of different façade constructions.

The evaluation of construction performance is more comprehensive since it delivers a range of the output instead of a single value, accounts for uncertainties involved, resembles the expected service life, and provides flexibility of adapting the design criteria to the case study at hand. Similarly, the cross-comparison between different constructions is more thorough since it delivers an overview of the construction that has the most uncertain performance and can rank the construction depending on the selected degree of microbial growth. The latter is important since different rankings are obtained for different levels of microbial growth as shown in *Papers I, IV, V* [34, 80, 81] and in [5].

2) Comparison of mould models and analysis of most critical parameters regarding mould models

When applying the probabilistic approach, the comparison between mould models represented by a density distribution delivers a more truthful overview of the similarities and differences. This approach diminishes bias related to different methodologies used to establish mould models, different parameters of mould models, and those related to specific user-defined decisions, such as for example the climatic conditions. A comparison between three mould models derived from the same experiments but with different methodologies is presented in [82]. Moreover, similar capabilities are also provided when performing analysis to investigate the decision to select the parameters of mould models when applying them, such as in *Paper IV* [80] which investigates the influence of chosen substrate class and decline effect, time duration, time step and initiation time of the simulation.

3) Uncertainty and sensitivity analysis

The probabilistic methodology can be incorporated in uncertainty and sensitivity analyses, such as in *Paper V* [81], and deliver useful information during the decision-making process.

4) Cost-optimal design methodology for façade construction

The methodology can enable the development of a methodology for the cost-optimal design of façades, such as in *Paper VI* [83] applied to constructions exposed to rot decay.

5) Parametric life cycle assessment (LCA)

The methodology can enable a more thoughtful overview of the parametric life cycle assessment (LCA) for evaluating the risk of greenhouse gas emissions, such as in [84, 85].

The methodology can also facilitate reliability-based design, risk-based inspection planning and be integrated into the formulation a semi-probabilistic design concept as part of future building codes such as in the field of structural engineering [86, 87]. The methodology can also be implemented in other fields of building physics. These issues are further discussed later in section 8.

6. Summary of the appended papers: Long story short

Paper I: A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades

Paper I introduces the pilot probabilistic-based methodology for predicting mould occurrence in timber façades. Firstly, a literature review regarding the probabilistic approach applications in building physics is presented. Limitations of current approaches are identified, especially with regard to the representation of outdoor climate and mould occurrence. Therefore, the study develops the stochastic model representing the outdoor climate based on time series analysis according to autoregressive-moving-average models. Moreover, mould growth is evaluated according to the biohygrothermal model instead of threshold values as approached conventionally. The interface employing the system with the previous characteristics is prototyped. The application of the pilot methodology is performed through a parametric study that investigates three different building envelopes in which the materials representing the wind and vapour barrier constitute the variables. The paper underlines the importance of representing the outdoor climate since it significantly affects the output uncertainty, and of representing mould growth.

Paper II: Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review

Paper III: Mould Models Applicable to Wood-Based Materials – A Generic Framework

The development of criteria and models representing mould growth in wood-based materials are investigated in *Paper II* and its complementary *Paper III* by carrying out a systematic literature review. First, results from experimental research that investigate mould growth on wood-based materials are synthesised and studied. The governing factors when opting mould growth representation are identified and compared across the literature. The review shows substantial discrepancies between criteria reported for onset and growth of mould across different studies, even with similar settings. Afterwards, the state-of-the-art of current mould models is delivered in order to exploit the current possibilities for representing mathematically this phenomenon. Several models are identified and are compared with respect to their applied methodology, how they account for the governing factors and their interrelation, experimental set-ups and nutrients, and how they express mould. Their comprehensiveness is analysed with the experimental results derived before in order to establish their limitations and capabilities. A generic framework, representing the general computation procedure of all models, is developed considering the factors that govern mould behaviour. This framework, adapted to each model, is used to structure, evaluate and compare current models. This framework supplemented with a comparison table, revealing the models' extensiveness and differences, establishes an outline that ensures an adequate application of the selected mould model for the case at hand. Lastly, the papers highlight the limitations of current standards and challenge in selecting the appropriate mould model bearing in mind potential limitations. Considering the current ambiguity in representing mould growth, it has been concluded that some of the limitations of conventional approaches can be reduced by applying a probabilistic-based approach.

Paper IV: A probabilistic-based methodology for predicting mould growth in timber façade constructions

Paper IV develops further the methodology presented in *Paper I* by incorporating the findings regarding mould growth representation in *Paper II* and *III*. Due to the various limitations and strengths of models presented in the previous papers, three models are selected due to their most extended capabilities to consider mould-governing factors. The final mould growth is represented as a mixture of density distributions from each mould model, where their contribution in the outcome is decided based on the relevance that each model has with characteristics of the case study at hand. Different levels of mould growth are associated with their respective likelihoods and integrated into the same plot with current assessment criteria. This outline facilitates the association between the likelihood of an event and its respective consequences. The uncertainties related to indoor climate and few material properties are accounted for. A parametric study varying different traditional constructions exploits the use and prevails the application of this methodology compared to the conventional methods. This methodology is generic and can accommodate other failure modes or other updates regarding mould models or the stochastic representation of the system. The influence of several parameters of the mould models is also investigated and corresponding assumptions are discussed. The paper discusses the influence of the assumptions and accuracy of the input in the uncertainty of the output.

Paper V: Uncertainty and sensitivity analysis for evaluating highly insulated walls to withstand biodeterioration

The methodology presented in *Paper IV* is further developed in *Paper V* by adding decay occurrence as a failure mode, which is represented by two models with different features. An uncertainty and sensitivity analysis is performed to investigate the relationship between the variables constituting the system representation and the performance to withstand biodeterioration. A systematic identification of uncertainties involved in the design of building envelopes is discussed to facilitate the requirements for representing the system. The latter is thus further developed by considering uncertainty in material properties and potential deficiencies represented by moisture sources. The temperature-dependent thermal conductivity of the insulation material is investigated by carrying out lab measurements, and subsequently, an autoregressive model is developed to represent this property. Three versions of representing the outdoor climate are discussed and investigated. Different sensitivity analysis techniques are performed and recommendations regarding their application on this topic are drawn. The methodology is applied to evaluate the performance of three highly insulated walls, which are constructions developed to meet new energy requirements in European countries during the last years. The paper discusses subjects for further improvements of the probabilistic approach applied in this field in terms of probabilistic modelling of the input data and design criteria.

Paper VI: Cost-Optimisation for Timber Façades Exposed to Rot Decay

The probabilistic-based methodology has been implemented in a cost-optimisation methodology for the design of façade constructions subjected to rot decay in *Paper VI*. The design parameters, which are objective of optimisation, constitute of the wind and vapour barrier materials. The cost regarding the initial investment and potential intervention schemes during the service life of the façade construction are accounted for in the methodology. The optimal solution is identified as the one with the maximised expected benefit over time. The cost-optimal design methodology can accommodate other failure modes and potential life-cycle measures.

PART III – FINAL REMARKS

7. Conclusions

Predicting microbial growth during the design stage is crucial for the prevention of social problems and financial loss, and to ensure a healthy, safe and comfortable interior environment. Current standards and codes offer limited guidance with simplistic assumptions of the design approach; hence, relying on them can lead to incorrect design solutions followed by overestimation or underestimation of constructions performance. As a result, large undesirable societal and economic consequences can be attributed. This work develops a probabilistic-based methodology for evaluation of the performance of timber façade constructions to withstand biodeterioration, constituting of decay and mould. Current design approaches are upgraded in the representation of the system, the failure mode and assessment criteria.

The performance evaluation of façade constructions is replete with uncertainties. They are related to the representation of the outdoor and indoor climate, physical parameters of the materials properties and geometries, and the representation of complex physical phenomena. Current design approaches fail to account for these uncertainties, especially regarding the representation of the variability and duration of the climate exposure and representation of microbial growth. This work demonstrated that the uncertainty of the microbial growth outcome is highly influenced by the uncertainty of input variables. The study showed that a more accurate evaluation of the performance to withstand biodeterioration is achieved only when these uncertainties and potential deficiencies are accounted for in the system representation, in settings that resemble the expected service life of the construction. The developed methodology accounts for the uncertainties of most critical variables; hence, it delivers a better representation of the expected system's hygrothermal conditions, which are further, used to calculate the expected microbial growth.

Mould growth was found to be highly dependent of the interrelation between humidity, temperature, material parameters and time; including fluctuating conditions, the level and duration of favourable and unfavourable conditions together with their sequence, the absorption, desorption and condensation processes. Disagreements across several experimental studies suggest that the representation of this biological phenomenon is very complex and associated with uncertainties. Disagreements and discrepancies were also found when comparing the numerous mould models within each other or analysing them with the previous experimental results. Mould models were found to differ with respect to governing factors and their interrelations, applied methodology, experimental set-ups and nutrients, and how they express mould. Results also showed that they are characterized by different limitations and competencies in regard to various features. Current mould models may require validation or specific improvements to ensure their applications; however, they are a better representative of mould growth compared to the simplistic guidelines suggested in current codes.

This study proposed to integrate three most established mould models to represent the mould growth outcome as a mixture distribution in order to account for their competencies and simultaneously diminishing their limitations. The outcome, as calculated from a probabilistic analysis, has the advantage to be expressed as a density distribution instead of a deterministic value. The assessment criteria, derived by different literature, are further assembled in this distribution creating a more comprehensive overview of the evaluation. This outline associates potential levels of mould growth to their respective likelihoods; hence, facilitating the association to the corresponding consequences adapted from the case study at hand. Therefore, the performance evaluation is succinctly more overarching and, subsequently can provide better support for the design of façade constructions.

The methodology is developed as a generic framework with specific compounds. Hence, it can accommodate future improvements such as a validated representation of microbial growth or inclusion of other failure modes, more accurate stochastic models representing the system, and design criteria. The generic part can also be transferred to other applications in building physics related to other types of performances of façade constructions or other types of building constructions. It can also be integrated into the formulation of a simplified semi-probabilistic design concept as part of future building codes, where partial safety factors can be introduced into the limit state functions.

It is expected that this methodology will become a valuable tool in the investigation of construction performance and the overall influence of façade construction properties, geometry, details, and additional boundary conditions. The results from applying this probabilistic-based methodology can support more reliably the decision-making processes during the evaluation of the performance or optimisation of timber façade constructions. This methodology can enable the upgrade of current codes and standards dealing with microbial growth avoidance design.

8. Discussion and Further Research

8.1 Discussion regarding the accuracy of results and future perspectives

The probabilistic-based methodology is a very reliable methodology for evaluating the performance of facade constructions while accounting for the involved uncertainties. However, the accuracy of the results depends on the assumptions and accuracy of representation of the capabilities of mould and decay models and assumptions regarding their implementation, the accuracy of the HAM tools and modelling of the deficiencies and stochastic models representing the system (outdoor climate, indoor climate and material properties). The latter are further elaborated in the discussion sections of Paper II, IV and V. It is noteworthy to highlight a challenge that needs to and can be addressed: the lack of a stochastic database representing the relevant material properties. Cooperation and communication between specialists of different fields can enable the development of a database containing such probabilistic models, which subsequently facilitates and improves the probabilistic-based applications. Considering the increased interest in the application of probabilistic-approach in building physics, it is of the material production companies' interest to provide models of their material properties. The development of such database containing the distributions of the properties of different materials is proposed in [44]. This database together with a model representing microbial growth can be incorporated into HAM tools and develop a user-friendly environment. This will overcome the current challenges related to the complexity of using probabilistic approaches and microbial models when evaluating façade constructions, which has impeded the implementation and establishment of both the former and latter. On the other hand, the proposed methodology can improve 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 [86, 87], where partial safety factors can be introduced into the limit state function. The latter can introduce implicitly the probabilistic approach in the design and simultaneously provide a user friendly performance evaluation computation. Considering the wider implementation of the probabilistic approach in other engineering fields, it can be concluded that the implementation of this approach in the field of building physics is merely in progress. Therefore, different methodologies that further exploit and prevail the application of this approach are proposed in the next sections.

8.2 Risk-based inspection methodology for timber façade construction

8.2.1 Background

The design against microbial growth occurrence can be improved by applying the probabilistic methodology developed in this study. However, as discussed, the accuracy of the results depends on the assumptions related to the representation of the input variables, predicting capabilities of mould models and computation accuracy of the HAM analysis tools. Many of these variables are uncertain and very difficult to model. The outdoor climate is unpredictable. The indoor climate is also difficult to represent since it is based upon behaviour patterns, which may also change through the years and innovations. In addition, discrepancies are found in the literature regarding the models representing the microbial growth [49]. The predicting capabilities can be improved when features of these models are integrated together as presented in this study; especially, when integrating the experimental results from which they are derived from. The latter, established by one of the methodologies using a probabilistic approach, can extend the capabilities of each model and integrate all the data into one model. However, they would still need further validation to get wider acceptance in the design methodologies and to accurately predict the microbial growth on different materials. Lastly, timber façades are very sensitive to the quality of workmanship, especially in parts of the structure that are considered risk spots. Therefore, such constructions might need regular monitoring/inspection in order to verify their anticipated performance.

Façade inspection using traditional techniques is considered expensive, causes disruption and thus inconvenience on transportation systems. In addition, the interfaces inside the façade construction cannot be easily inspected. Due to different risk spots located on the entire façade, many inspections are needed both in its outer part and inside. A different methodology is therefore needed to optimise the related cost while ensuring the expected performance of the façade. Systematic decisions that minimise the total expected cost are achievable through risk-based decision making. Risk-based inspection planning provides the means to identify cost-optimal inspection strategies and it has been developed during the last decades in the field of structural engineering [88]. In light of this, this paper proposes the development of a generic risk-based inspection planning technique that can overcome the aforementioned challenges.

8.2.2 Proposed risk-based inspection methodology

The workflow of the proposed methodology is presented in Figure 4.

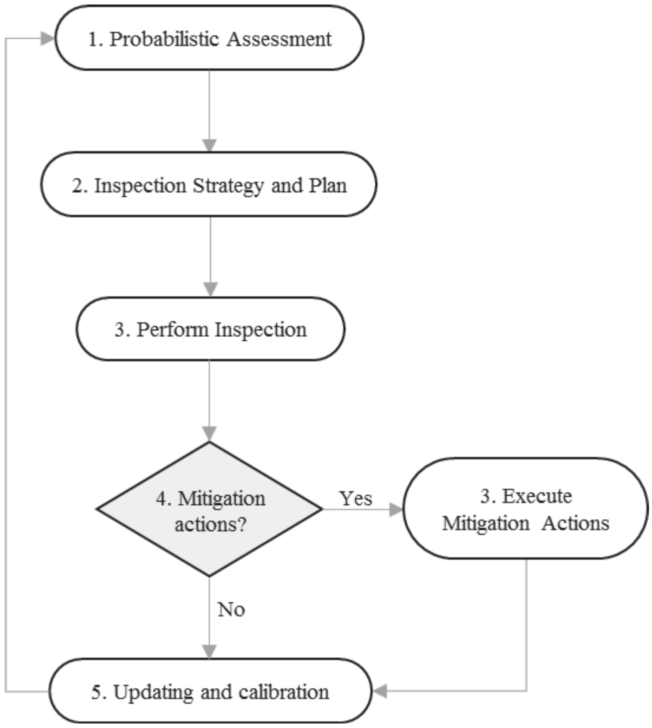

Figure 4. *Workflow of risk-based inspection risk-based inspection methodology*

The followings steps are identified:

1. Probabilistic analysis

a. Calculation of the likelihood of microbial growth

The probabilistic-based methodology developed in this work is applied to calculate the likelihood of microbial occurrence in different parts of the façade. Since the microbial models may not be reliable in calculating the exact mould growth, it is decided to firstly start with a similar contribution of each model and afterwards calibrate the individual contribution coefficients. A similar strategy is approached for decay occurrence. The assessment time is firstly computed for five years, again by accounting for the fact that these models might not be reliable. The human error is considered in terms of moisture leakages.

The cumulative probability density of diverse microbial growth is presented for each interface of the façade construction. In general, the cladding is the one most exposed; however, the interface between insulation and wind barrier might pose problems, especially for highly insulated wall constructions. Therefore, a model is developed to infer the conditional probability of microbial occurrence of each interface of the façade construction given the probability of microbial occurrence on the outer surface.

b. Assessment criteria and intervention decision tree

Different degrees of mould growth (MG) and decay rating (DR) are related to three possible interventions depending on the rating scales of the microbial model used:

- no intervention (when MG < 1 and DR < 1)
- repair (when either 1 < MG < 3 or 1 < DR < 2)
- replacement (when either 3 > MG or 2 > DR).

Failure is considered the stage when either the façade is no longer functional due to microbial growth or it is not beneficial to perform a mitigation action.

2. Optimal inspection strategy and plan

The workflow of the optimal inspection strategy is inspired from [88], as used in structural engineering, and adapted to the application of timber façade constructions. Risk-based inspection planning is an application analysis from the Bayesian decision analysis and utility theory based on the inspection decisions e, the inspection outcomes z, the intervention action a (or decision rule d), the condition of the structure Θ and the utility (cost or benefit) associated with each set of these variables [88]. The latter components are all expressed in monetary costs. The problem is best represented in the form of a decision tree (see Figure 5), where possible strategies and inspection plan are considered and their expected costs are calculated and compared. The optimal strategy is defined as the strategy associated with lowest expected costs during the planned lifetime of the façade constructions. The following are considered:

- the buildings and spots to inspect (i.e. amount of buildings, locations, geometrical changes)
- the flight path itinerary of the mini drones (see next step)
- the inspection technique (image inspection by drones or also human inspection)
- the time(s) of inspection.

3. Perform inspection

Drone with high-quality image analysis is selected as the inspection technology. It can reduce the time and disturbances to adjacent areas while providing a high-quality image of the current state. ASTM [89] is developing a guide, WK52572, for the visual inspection of building façades using drones. An accurate association should transfer the information produced by the image into an indication of microbial growth.

4. Decision regarding mitigation actions

Depending on the detected microbial growth, it is first decided whether to perform a mitigation. Both potential defects of detection and the current state of the inside part of the façade should be accounted for.

5. Execute mitigation actions

The mitigation actions include:

- Additional inspection, by traditional methods, when the results of drone inspection are unclear
- Intervention technique including the repair or replacement.

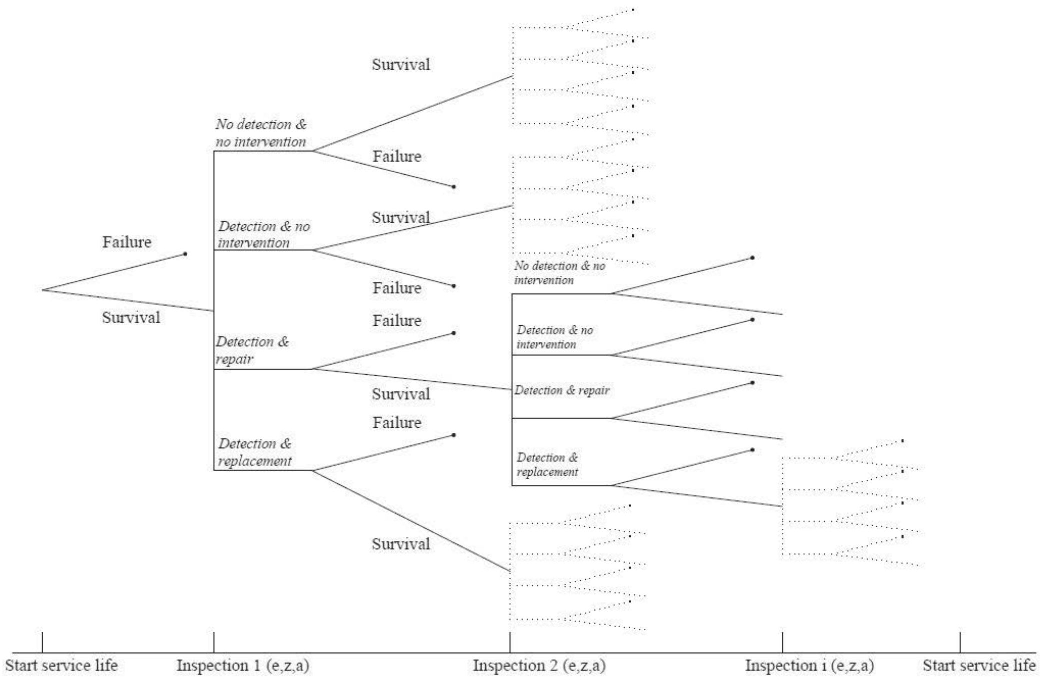

Figure 5. Classical decision tree based on the possible even outcome

6. Updating/ Calibration of the whole system

During the service life, it is possible to retrieve crucial information that can increase the accuracy of the numerical simulation, by updating the followings:

- the stochastic variables constituting the exposure (measured outdoor and better interior climate)
- the material properties and configuration
- calibration of the microbial models
- the path strategy when new building(s) and/or location(s) are added
- the inspections are updated according to the updated information and re-calculation processes.

Lastly, the interface with the necessary steps and calculations employed by this methodology can be implemented in Matlab [44] and Simulink® [90]. The former can be used to perform the necessary calculations of the probabilistic-based methodology and integrate with Simulink Support Package for PARROT® Minidrones, which enables to design and deploy flight controllers for a palm-sized quadcopter [90]. Three-dimensional visualisations are possible to represent the expected path itinerary and the spots to be inspected.

8.2.3 Expected Outcome: Advantages of risk-based inspection application in avoiding microbial growth

This work suggests the development of a risk-based inspection methodology for timber façade constructions that can verify and subsequently ensure their anticipated performance. Performing real-life full-scale measurements on a substantial amount of building via the proposed methodology would enable:

- the calibration of microbial predicting models
- the identification and hence the representation of the risky spots which might be the most sensitive to workmanship
- the regular monitoring of the performance of the façades and the possibility to control the anticipated performance during the expected service life
- the integration of a cost-optimisation scheme during the design stage of the façade construction, where the cost related to inspection together with the increased certainty of the anticipated performance might outperform the cost related to investments, and
- the quantification and identification of cost-optimal inspection strategies.

8.3 Cost-optimisation methodology for highly insulated building envelopes

8.3.1 Background: Necessity of cost-optimisation in today's society

Energy consumption in buildings contributes significantly to the worldwide energy consumption. The energy for space heating is 78 % of EU15 household delivered energy consumption, corresponding to approximately a significant of 21 % of the EU15 total delivered energy [91]. Consequently, the passive house concept has been developed to reduce energy demand. By promoting low energy building technology, the passive house's aim is to provide an acceptable and even improved thermal comfort and well-being in the indoor environment in terms of IAQ and thermal comfort at minimum energy demand [92]. Therefore, the cost related to heating is reduced. However, the cost reduction should compensate for the increased cost related to the investment in the envelope configuration. The thermal performance of the building envelope is generally improved by increasing the insulation layer. However, the thickness of this layer is decided by a deterministic approach to meet the requirements for the minimum R-value; thus, evaluated through general threshold values and independent of any variable of the system representation.

The results from *Paper V* indicated that the thermal performance of highly insulated building envelopes is highly affected by the uncertainty involved in the system representation (outdoor climate, indoor climate, material properties). On the other hand, the associated costs are subject to uncertainties in the economic parameters, such as future electricity prices, interest and inflation rates. Therefore, an optimal solution of the highly insulated walls can be achieved only by approaching a systematic cost-optimisation methodology that accounts for the aforementioned uncertainties.

8.3.2 Proposed cost-optimisation methodology

The system representation consisting of the material properties and outdoor climate is similar to the one presented in *Paper V*. However, additional variables including the solar radiation and indoor heating, which affect the thermal performance of the envelopes, should be accounted for. The temperature and solar radiation can be represented by stochastic models derived from time series analysis according to autoregressive–moving-average model [64] as presented in *Paper IV* or any of its derivatives. The latter offers the capability to account for potential future trends of climate change. In addition, the heating, ventilation, and air conditioning (HVAC) system should be incorporated into the system.

Firstly, the performance criterion that represents the design requirements should be selected. Afterwards, an uncertainty and sensitivity analysis should be performed to identify which are the most dominant parameters that affect the thermal performance of the envelope. The results are most likely to be similar to the ones drawn from *Paper V*, where the thermal conductivity of the insulation is the most dominant parameter affecting the heat fluxes. This variable may constitute the design parameter. The methodology can accommodate the optimization of other parameters as well; however, the computation efficiency may be decreased. Since the cost-optimisation analysis is driven by this design parameter, it is suggested to carry out experimental analysis to improve its stochastic model. Afterwards, the cost-effective solution can be derived by performing a cost-benefit analysis that delivers the solution with the maximised expected benefit. This is equivalent to minimising the total expected cost since the benefits (given by the existence of the building) are independent of the façade design. The proposed methodology addressing this scope is presented schematically in Figure 6. The methodology can be carried out using genetic algorithms by coupling the building performance simulation program, such as for example EnergyPlus [93], which incorporates the HVAC systems in the calculation, with Simulink® environment [90].

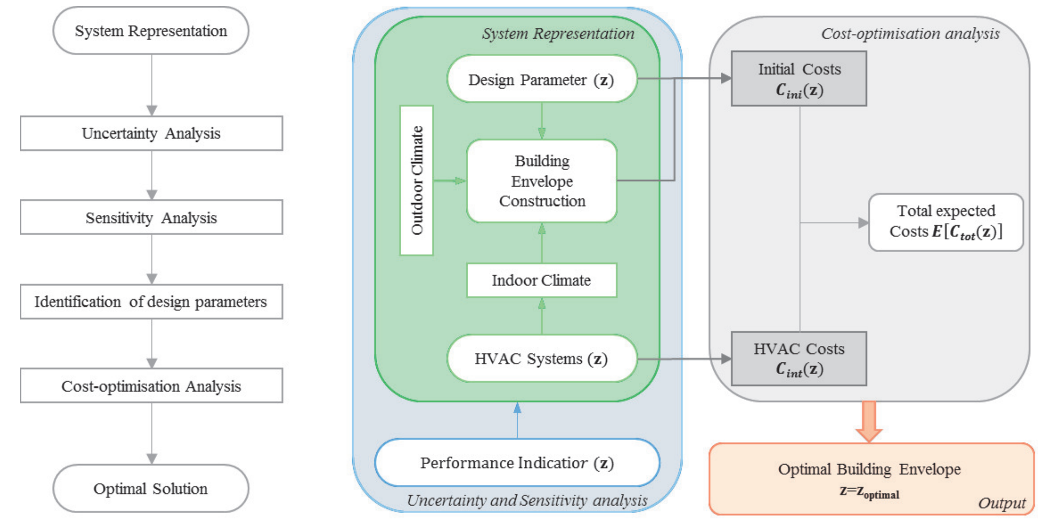

Figure 6. Proposed cost-optimisation methodology

The total cost of a façade unit C_{tot} is the sum of the following costs:

$$C_{tot}(\mathbf{z}) = C_{ini}(\mathbf{z}) + C_{HVAC}(\mathbf{z}) \tag{1}$$

where:

$\mathbf{z}$ is the design parameter(s) influencing implicitly the future costs by controlling the envelope's thermal performance, and therefore subjected to optimisation.

C_{ini} is the initial cost of the building envelope considering the costs of all its layers. Expressing explicitly the fixed cost (C_0) and cost $C_1(\mathbf{z})$ depending on $\mathbf{z}$, it follows:

$$C_{ini}(\mathbf{z}) = C_0 + C_1(\mathbf{z}) \tag{2}$$

- $C_{HVAC}(\mathbf{z})$ is the cost related to the use of HVAC systems to compensate for the reduced thermal performance.

The decision considering the solution for the building envelope is taken at the time $t = 0$ (the construction stage). Therefore, the cost of heating, that occurs in the future, should take into account the electricity price escalation, the interest and inflation rates. Consequently, the decision is taken on the present value of total expected cost. A cash flow C at the future point in time τ is transformed to a present value using the following equation:

$$PV(C) = \sum_{\tau=1}^{n} \frac{C_\tau}{\left(\frac{1+\gamma}{1+\Pi}\right)_\tau} \tag{3}$$

where γ is the nominal interest rate, Π is the inflation rate and τ the time expressed in n units.

The forecasting of the inflation rates and the electricity price can be modelled by time series analysis according to autoregressive integrated moving-average (ARIMA) model or its derivatives [64, 94]. The Maximum Likelihood Method [15] can be applied to estimate the most accurate parameters of the stochastic model. A review of current main methods used in electricity price forecasting can be found in [94, 95]. This approach has been already carried out in research about electricity price forecasting [96-98] and inflation rates forecasting [99, 100].

The present value of the total cost is therefore given by the following:

$$PV(C_{tot}(\mathbf{z})) = PV(C_{ini}(\mathbf{z})) + \sum_{\tau=1}^{n} PV\big(C_{HVAC,\tau}(\mathbf{z})\big) = C_{ini}(\mathbf{z}) + \sum_{\tau=1}^{n} C_{HVAC,\tau}(\mathbf{z}) \frac{1}{\left(\frac{1+\gamma}{1+\Pi_\tau}\right)} \tag{4}$$

The optimal solution is defined as $\mathbf{z} = \mathbf{z}_{\boldsymbol{optimal}}$, which minimises the total cost (balancing the investments at the time of construction and the future cost related to heating).

8.3.3 Expected outcome: Advantages of a systematic cost-optimisation methodology

The proposed methodology provides a systematic approach to perform a cost-optimisation analysis of highly insulated building envelopes. The capabilities of this methodology include:

- It accounts for uncertainties related to the system representation.
- It accounts for future trends of dominant variable affected by climate change or economic parameters.
- It identifies the dominant variable(s) affecting the performance of the building envelope; hence, provides directions for the selected design parameter(s) to be optimized.
- It derives the most cost-effective building envelope by performing a cost-benefit analysis that delivers the solution with the maximised expected benefit.

8.4 Development of design criteria for microbial growth on timber façade constructions

8.4.1 Background: The lack of design criteria

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 are available. However, this value should depend on the case study. For example, the same threshold may not be acceptable in a hospital or other environments with higher exposure. Integrating the VTT model in the codes is clearly an advancement compared to the criteria set beforehand, which were too simplistic; yet, acceptable limits or targets need to be defined for improving the design against microbial growth or enabling reliability-based design.

A qualitative approach was applied in *Paper V* to associate different levels of microbial growth to acceptable levels. However, the selection of the design criteria depends on several characteristics of the project since its consequences can vary from marginal to substantial, even for the same rating scale. Furthermore, different construction's performance might be ranked differently based on the selected degree of mould growth or decay rating. In light of this, it is suggested the development of design criteria relating target reliabilities (or probabilities of failure) with a different classification of consequences, as already developed in the field of structural engineering [101].

8.4.2 Proposed methodology to establish design criteria for microbial growth

The review shows that there exists an association between health consequences and occurrence of mould growth; however, there is no clear evidence that relates the microbial growth and mortality. Until the association between health issues and mould growth are further elaborated and established, a safety cost-benefit approach can be used to develop the risk acceptance criteria. Otherwise, the concept of marginal life-saving costs principle [102] should be integrated into the methodology and develop risk acceptance criteria. The reported microbial growth problems in building industry should also be accounted for to establish what is already acceptable from a safety point of view from the societal perspective.

The design criteria should be expressed as target reliabilities over a specified reference time. The development of design criteria can be approached by categorising the direct and indirect consequences of microbial growth. The workflow is presented in Figure 7 and the proposed categorisation in Table 2 to Table 4. The followings are considered:

1. *Hazards.* The direct consequences of the hazards, mould and decay rot, are related to three different perspectives:

- IAQ. The proposed index in [103] can be adopted for compounds related to biodeterioration.

- Aesthetics. The acceptability of the aesthetic performance can be subjective; however, the limit state concept proposed in [104] based on colour changes can be adapted to establish the aesthetic requirement.
- Structural. The limit state principles as applied in the field of structural engineering can be adopted in this context.

2. *Rating scales*. There are different models that may express the occurrence and growth of microbial growth with different rating scales. A standard and defined rating scale should be selected and approached.
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 followings:
   - the depth of the wall (outer part of the wall, inside the façade construction and inner part or contact with the indoor environment)
   - the height of the building (i.e. underground, first floor, 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.

8.4.3 Expected outcome: Advantages of the availability of design criteria

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 [86, 87], where partial safety factors can be introduced into the limit stated function. On this basis, the selected solution for the façade construction and its optimisation can be based on established criteria. On the other hand, it will also be possible to accurately estimate the influence of the assessment time in the probability of failure. This may provide useful information regarding the time that failure probability converges, inferring the time when it is representative of the service life. Subsequently, the computation efficiency for a specific design project may be increased, which is crucial when it comes to computationally demanding calculations.

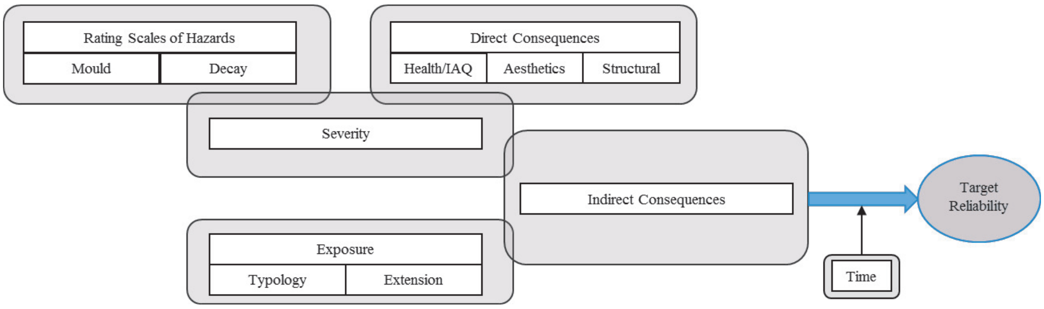

Figure 7. Workflow to set up the target reliability levels

Table 2. Proposed severity categories based on the rating scales of decay and mould growth

		Decay Rating (DR)				
		0	1	2	3	4
Mould Growth (VTT Index)	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

Table 3. Proposed levels of indirect consequences based on categories for exposure and severity

		Severity			
	Category	1	2	3	4
Exposure	1	Low	Moderate	High	Very high
	2	Low	Moderate	High	Very high
	3	Moderate	High	High	Very high
	4	Very high	Very high	Very high	Very high

Table 4. Target reliability indices based on the level of consequences for a reference period.

Consequences	Low	Moderate	High	Very High
Target Reliability	β_{low}	$\beta_{moderate}$	β_{high}	$\beta_{very\ high}$

9. Main contributions

The aim of the present work was to develop a probabilistic-based methodology for evaluating the performance of timber façade constructions to withstand biodeterioration. The content advances the existing knowledge of probabilistic approaches in the field of building physics by addressing three main objectives: i) representing the microbial growth and assessment criteria, ii) advancing the stochastic representation of the system, and iii) exploiting the application of this methodology.

The first objective was addressed by conducting a systematic review of the development of criteria and models representing mould growth in wood-based materials. The new developments include the followings:

- The current knowledge about mould governing factors, as identified by experimental results, has been synthesised and brought together in a wider context.
- Current mould models applicable to wood-based materials have been identified and their capabilities have been analysed based on the previous results.
- A comparison table has been developed to demonstrate and compare the characteristics of the identified models based on mould governing factors, establishing methodology, and computational characteristics.
- A generic framework, representing the general computation procedure of all models, has been developed considering the factors that govern mould behaviour. This framework, adapted to each model, has been used to structure the models' computation procedure and compare them. This outline supplemented with the comparison table establishes a basis to ensure an adequate application of the selected mould model for the case at hand.
- The representation of mould growth has been derived by integrating three established mould models into a mixture of density distributions where each model's contribution is assigned to a user-defined coefficient. Different levels of mould growth are associated with their respective likelihoods and integrated into the same plot with current assessment criteria. The latter delivers a more comprehensive overview of the probable situations, provides the flexibility to account for and control identified limitations or capabilities of each model extends based on the case study at hand, associated the likelihood of an event with its respective consequences, and therefore, it provides more confidence in the decision-making process.
- The occurrence of both mould and rot decay have been accounted for. The lack of design criteria has been discussed and a methodology how to develop the latter has been proposed.

The second objective is addressed by various methods and contributions. The new developments included the followings:

- The uncertainties involved in the design of façade constructions has been systematically identified and grouped.

- The stochastic representation of the outdoor climate has been developed either by time series analysis according to autoregressive-moving-average models or by random combination of one-year historical data, whose initiation date is also selected randomly, into a five-year model.
- The representation of the indoor climate has been developed by uniformly distributing the moisture categories according to EN 15026 and accounting for model uncertainties.
- The temperature-dependent thermal conductivity has been represented by an auto-regressive model derived by results of several laboratory measurements.
- The impact of deficiencies has been accounted for in a parametric way by applying moisture sources with different penetration amounts of wind-driven rain.

The new developments related to the third objective include the followings:

- The probabilistic-based methodology has been developed by integrating the previous findings and prototyped into an interface.
- The performance of several constructions has been evaluated and their performance ranking has been delivered in a more dynamic and comprehensive perspective.
- The methodology has been integrated into several applications including uncertainty, sensitivity and influence studies; cost-optimisation methodology; parametric life cycle assessment; and proposed for risk-based inspection, reliability-based design and integration into the formulation of a semi-probabilistic design concept.

10. References

1. Becher, R., A.H. Høie, J.V. Bakke, S.B. Holøs, and J. Øvrevik, *Dampness and Moisture Problems in Norwegian Homes.* International journal of environmental research and public health, 2017. **14**(10): p. 1241.

2. Lisø, K.R., *Building envelope performance assessments in harsh climates: Methods for geographically dependent design*. 2006, Fakultet for ingeniørvitenskap og teknologi.

3. Lisø, K., T. Kvande, and J. Thue, *Learning from experience–an analysis of process induced building defects in Norway.* 2006.

4. Almås, A.-J., K.R. Lisø, H.O. Hygen, C.F. Øyen, and J.V. Thue, *An approach to impact assessments of buildings in a changing climate.* Building Research & Information, 2011. **39**(3): p. 227-238.

5. Andrea Tietze, S.O., Sylvain Boulet, Klodian Gradeci, Nathalie Labonnote, Steinar Grynning, Joakim Noreen, Anna Pousette *Tall Timber Facades – Identification of Cost-effective and Resilient Envelopes for Wood Constructions*. 2017.

6. Eurostat, *Income and living conditions* 2017, European Commission.

7. Heseltine, E. and J. Rosen, *WHO guidelines for indoor air quality: dampness and mould*. 2009: WHO Regional Office Europe.

8. Organization, W.H., *Development of WHO guidelines for indoor air quality: Dampness and mould.* Germany: WHO, 2007.

9. Jaakkola, M.S., R. Quansah, T.T. Hugg, S.A.M. Heikkinen, and J.J.K. Jaakkola, *Association of indoor dampness and molds with rhinitis risk: A systematic review and meta-analysis.* Journal of Allergy and Clinical Immunology, 2013. **132**(5): p. 1099-1110.e18.

10. Méheust, D., P. Le Cann, G. Reboux, L. Millon, and J.-P. Gangneux, *Indoor fungal contamination: Health risks and measurement methods in hospitals, homes and workplaces.* Critical Reviews in Microbiology, 2014. **40**(3): p. 248-260.

11. Quansah, R., M.S. Jaakkola, T.T. Hugg, S.A.M. Heikkinen, and J.J. Jaakkola, *Residential dampness and molds and the risk of developing asthma: a systematic review and meta-analysis.* PloS one, 2012. **7**(11): p. e47526.

12. Sharpe, R.A., N. Bearman, C.R. Thornton, K. Husk, and N.J. Osborne, *Indoor fungal diversity and asthma: A meta-analysis and systematic review of risk factors.* Journal of Allergy and Clinical Immunology, 2015. **135**(1): p. 110-122.

13. Urlaub, S. and G. Grün, *Mould and dampness in European homes and their impact on health.* IBP-Report EER-058/2016/950, 2016.

14. Allsopp, D., K.J. Seal, and C.C. Gaylarde, *Introduction to biodeterioration*. 2004: Cambridge University Press.

15. Melchers, R.E., *Structural reliability*. 1987: Horwood.

16. Byggforsk, *Byggforskserien 421.132*, in *Fukt i bygninger. Teorigrunnlag - 13 Kritisk fukttilstand*. 2005.

17. DIN-4108, *Thermal insulation and energy economy in buildings, Part 4: Hygrothermal design values*. 2013.

18. Ojanen, T. and J. Ahonen, *Moisture performance properties of exterior sheathing products made of spruce plywood or OSB*. 2005.

19. EN-15026, *Hygrothermal performance of building components and building elements*, in *Assessment of moisture transfer by numerical simulation*. 2004.

20. EN-13788, *Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods.* 2012.

21. Geving, S. *A systematic method for hygrothermal analysis of building constructions using computer models*. in *Proceedings of the building simulation*. 1997.

22. Hens, H.L.S.C., *Fungal Defacement in Buildings: A Performance Related Approach.* HVAC&R Research, 1999. **5**(3): p. 265-280.

23. Moon, H.J. and G. Augenbroe. *A mixed simulation approach to analyze mold growth under uncertainty*. in *Building Simulation 2005 - 9th International IBPSA Conference, BS 2005*. 2005. Montreal.

24. Hagentoft, C.-E. *Probabilistic Analysis of Hygrothermal Conditions and Mould Growth Potential in Cold Attics. Impact of Weather, Building System and Construction Design Characteristics*. in *International Conference on Durability of Building Materials and Components*. 2011.

25. Thelandersson, S., T. Isaksson, M. Häglund, and E. Frühwald. *Probabilistic methods for performance based service life evaluation of wooden components*. in *Applications of Statistics and Probability in Civil Engineering*. 2011.

26. Van Gelder, L., H. Janssen, and S. Roels. *Retrofitting cavity walls–probabilistic study of energy savings and moisture risks*. in *Proceedings of the 5th International Building Physics Conference (IBPC)*. 2012.

27. Pallin, S., *Risk Assessment of Hygrothermal Performance-Building Envelope Retrofit*. 2013: Chalmers University of Technology.

28. Hagentoft, C.-E. and A. Sasic Kalagasidis. *Moisture safe cold attics-Assessment based on risk analyses of performance and cost*. in *Proceedings of 10th Nordic Symposium on Building Physics*. 2014.

29. Sadovsky, Z., O.G. Koronthalyova, P. Matiaovsky, and K. Mikulova, *Probabilistic modelling of mould growth in buildings.* Journal of Building Physics, 2014. **37**(4): p. 348-366.

30. Sadovský, Z. and O. Koronthályová, *Exploration of probabilistic mould growth assessment.* Applied Mathematical Modelling, 2017. **42**(Supplement C): p. 566-575.

31. Pietrzyk, K., *A systemic approach to moisture problems in buildings for mould safety modelling.* Building and Environment, 2015. **86**: p. 50-60.

32. Hagentoft, C.E., A.S. Kalagasidis, and C. Rode, *55, Reliability of Energy Efficient Building Retrofitting-Probability Assessment of Performance & Cost (RAP-RETRO)*, in *Framework for probabilistic assessment of performance of retrofitted building envelopes*. 2015.

33. Hagentoft, C.-E., *Reliability of energy efficient building retrofitting-probability assessment of performance and cost (Annex 55, RAP-RETRO).* Energy and Buildings, 2017. **155**: p. 166-171.

34. Gradeci, K., N. Labonnote, B. Time, and J. Köhler. *A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades*. in *WCTE 2016 - World Conference on Timber Engineering*. 2016.

35. Wang, C.h., R.H. Leicester, and M. Nguyen, *Probabilistic procedure for design of untreated timber poles in-ground under attack of decay fungi.* Reliability Engineering and System Safety, 2008. **93**(3): p. 476-481.

36. Brites, R.D., L.C. Neves, J. Saporiti Machado, P.B. Lourenço, and H.S. Sousa, *Reliability analysis of a timber truss system subjected to decay.* Engineering Structures, 2013. **46**: p. 184-192.

37. Johansson, P., S. Pallin, and M. Shahriari. *Development of a Risk Assessment Procedure Applied on Building Physics: Part One; Model Development*. in *International Conference on Building Materials and Components*. 2011. Porto.

38. Pallin, S., P. Johansson, and M. Shahriari. *Development of a Risk Assessment Procedure Applied on Building Physics: Part Two; an Applicability Study*. in *International Conference on Building Materials and Components*. 2011. Porto.

39. Haldi, F., *Predicting the Risk of Moisture Induced Damages on the Building Envelope Using Stochastic Models of Building Occupants' Behaviour.* Energy Procedia, 2015. **78**(Supplement C): p. 1377-1382.

40. Haldi, F. *A probabilistic model to predict building occupants' diversity towards their interactions with the building envelope.* in *Proceedings of the international IBPSA conference, Chambery, France*. 2013.

41. Salonvaara, M., A. Karagiozis, and A. Holm, *Stochastic building envelope modeling—the influence of material properties.* Thermal Performance of Exterior Envelopes of Whole Buildings VIII, 2001: p. 2-8.

42. Zhao, J., R. Plagge, A. Nicolai, J. Grunewald, and J.S. Zhang, *Stochastic study of hygrothermal performance of a wall assembly—The influence of material properties and boundary coefficients.* HVAC&R Research, 2011. **17**(4): p. 591-601.

43. Holm, A.H. and H.M. Kuenzel, *Practical application of an uncertainty approach for hygrothermal building simulations—drying of an AAC flat roof.* Building and Environment, 2002. **37**(8): p. 883-889.

44. Zhao, J., R. Plagge, N.M. Ramos, M.L. Simões, and J. Grunewald, *Concept for development of stochastic databases for building performance simulation–A material database pilot project.* Building and Environment, 2015. **84**: p. 189-203.

45. Metropolis, N. and S. Ulam, *The monte carlo method.* Journal of the American statistical association, 1949. **44**(247): p. 335-341.

46. Saltelli, A., M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola, *Global sensitivity analysis: the primer*. 2008: John Wiley & Sons.

47. Tietze, A., S. Boulet, S. Ott, and S. Winter. *Consideration of disturbances and deficiencies in the moisture safety design of tall timber facades*. in *World Conference on Timber Engineering*. 2016. Vienna.

48. Gradeci, K., N. Labonnote, J. Köhler, and B. Time, *Mould Models Applicable to Wood-Based Materials – A Generic Framework.* Energy Procedia, 2017. **132**: p. 177-182.

49. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review.* Construction and Building Materials, 2017. **150**(Supplement C): p. 77-88.

50. Brischke, C. and S. Thelandersson, *Modelling the outdoor performance of wood products–A review on existing approaches.* Construction and Building Materials, 2014. **66**: p. 384-397.

51. Vereecken, E. and S. Roels, *Review of mould prediction models and their influence on mould risk evaluation.* Building and Environment, 2012. **51**: p. 296-310.

52. Flink, C., *Utvärdering av m-modellen i jämförelse med andra mögelriskmodeller.* Rapport TVBM (5000-serie), 2012.

53. Vereecken, E., K. Vanoirbeek, and S. Roels, *Towards a more thoughtful use of mould prediction models: A critical view on experimental mould growth research.* Journal of Building Physics, 2015. **39**(2): p. 102-123.

54. Holme, J., S. Geving, and J.A. Jenssen. *Moisture and mould damage in Norwegian houses*. in *Danish Society of Engineers*. 2008.

55. Gunnbjörnsdóttir, M.I., K.A. Franklin, D. Norbäck, E. Björnsson, D. Gislason, E. Lindberg, C. Svanes, E. Omenaas, E. Norrman, and R. Jogi, *Prevalence and incidence of respiratory symptoms in relation to indoor dampness: the RHINE study.* Thorax, 2006. **61**(3): p. 221-225.

56. Howden-Chapman, P., K. Saville-Smith, J. Crane, and N. Wilson, *Risk factors for mold in housing: a national survey.* Indoor Air, 2005. **15**(6): p. 469-476.

57. Mudarri, D. and W.J. Fisk, *Public health and economic impact of dampness and mold.* Indoor air, 2007. **17**(3): p. 226-235.

58. Haverinen-Shaughnessy, U., A. Borras-Santos, M. Turunen, J.P. Zock, J. Jacobs, E. Krop, L. Casas, R. Shaughnessy, M. Täubel, and D. Heederik, *Occurrence of moisture problems in schools in three countries from different climatic regions of Europe based on questionnaires and building inspections–the HITEA study.* Indoor Air, 2012. **22**(6): p. 457-466.

59. Dekker, C., R. Dales, S. Bartlett, B. Brunekreef, and H. Zwanenburg, *Childhood asthma and the indoor environment.* Chest, 1991. **100**(4): p. 922-926.

60. Norbäck, D., E. Björnsson, C. Janson, U. Palmgren, and G. Boman, *Current asthma and biochemical signs of inflammation in relation to building dampness in dwellings.* The International Journal of Tuberculosis and Lung Disease, 1999. **3**(5): p. 368-376.

61. Butler, S., M. Williams, C. Tukuitonga, and J. Paterson, *Problems with damp and cold housing among Pacific families in New Zealand.* The New Zealand Medical Journal 2003. **116**(1177).

62. Fink, A., *Conducting research literature reviews: From the internet to paper*. 2005: Sage.

63. Booth, A., D. Papaioannou, and A. Sutton, *Systematic approaches to a successful literature review*. 2011: Sage.

64. Box, G.E., G.M. Jenkins, G.C. Reinsel, and G.M. Ljung, *Time series analysis: forecasting and control*. 2015: John Wiley & Sons.

65. Hukka, A. and H. Viitanen, *A mathematical model of mould growth on wooden material.* Wood Science and Technology, 1999. **33**(6): p. 475-485.

66. Viitanen, H. and T. Ojanen, *Improved Model to Predict Mold Growth in Building Materials.* 2007.

67. Ojanen, T., H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, and K. Salminen. *Mold growth modeling of building structures using sensitivity classes of materials*. in *Thermal performance of the exterior envelopes of whole buildings XI international conference.* 2010.

68. Ojanen, T., R. Peuhkuri, H. Viitanen, K. Lähdesmäki, J. Vinha, and K. Salminen. *Classification of material sensitivity–new approach for mould growth modeling*. in *9th Nordic symposium on building physics*. 2011.

69. Thelandersson, S., T. Isaksson, A. Ekstrand-Tobin, and P. Johansson, *Modelling of onset of mould growth for wood exposed to varying climate conditions*, T.I.R.G.O.W. PROTECTION, Editor. 2009: Beijing, China.

70. Isaksson, T., S. Thelandersson, A. Ekstrand-Tobin, and P. Johansson, *Critical conditions for onset of mould growth under varying climate conditions.* Building and Environment, 2010. **45**(7): p. 1712-1721.

71. Thelandersson, S. and T. Isaksson, *Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions.* Building and Environment, 2013. **65**: p. 18-25.

72. Sedlbauer, K., *Prediction of Mould Growth by Hygrothermal Calculation.* Journal of Building Physics, 2002. **25**(4): p. 321-336.

73. Sedlbauer, K., *Prediction of mould fungus formation on the surface of and inside building components*, in *Fraunhofer Institute*. 2001.

74. Guide, M.U.s., *The MathWorks Inc.* Natick, MA, 1998. **4**: p. 382.

75. Martinez, W.L. and A.R. Martinez, *Computational statistics handbook with MATLAB*. Vol. 22. 2007: CRC press.

76. Brischke, C. and L. Meyer-Veltrup, *Modelling timber decay caused by brown rot fungi.* Materials and Structures, 2016. **49**: p. 3281-3291.

77. Viitanen, H., T. Toratti, L. Makkonen, R. Peuhkuri, T. Ojanen, L. Ruokolainen, and J. Räisänen, *Towards modelling of decay risk of wooden materials.* European Journal of Wood and Wood Products, 2010. **68**(3): p. 303-313.

78. Hartwig Michael Künzel, *Simultaneous heat and moisture transport in building components, One-and two-dimensional calculation using simple parameters. IRB-Verlag Stuttgart* 1995.

79. Giglioli, N. and A. Saltelli, *SimLab 1.1, Software for Sensitivity and Uncertainty Analysis, tool for sound modelling*. 2000.

80. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *A probabilistic-based methodology for predicting mould growth in façade constructions.* Building and Environment, 2018. **128**: p. 33-45.

81. Gradeci, K., U. Berardi, B. Time, and J. Köhler, *Uncertainty and sensitivity analysis for evaluating highly insulated walls to withstand rot decay and mould growth (under review).* 2017.

82. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *A probabilistic-based approach for predicting mould growth in timber building envelopes: Comparison of three mould models.* Energy Procedia, 2017. **132**: p. 393-398.

83. Gradeci, K., M. Baravalle, B. Time, and J. Köhler. *Cost-Optimisation for Timber Façades Exposed to Rot Decay*. in *12th International Conference on Structural Safety & Reliability* 2017. Vienna.

84. Fufa, S., C. Skaar, K. Gradeci, N. Labonnote, B. Time, and J. Köhler. *Parametric LCA of a ventilated timber wall construction in tall timber buildings*. in *14th International Conference on Durability of Building Materials and Components*. 2017. Ghent.

85. Fufa, S., C. Skaar, K. Gradeci, N. Labonnote, B. Time, and J. Köhler, *Parametric LCA of a ventilated timber wall constructions (under review).* 2017.

86. (CEN), E.C.f.S., *Eurocode 0-Basis of structural design*. 1990.

87. JCSS, *Part 1–Basis of Design:-Joint Committee of Structural Safety*. 2000.

88. Straub, D., *Generic approaches to risk based inspection planning for steel structures*. Vol. 284. 2004: vdf Hochschulverlag AG.

89. ASTM. *WK58243 - New Guide for Visual Inspection of Building Facade using Drone*. 2017 [cited 2017.

90. Simulink, M. and M. Natick, *The mathworks*. 1993, Inc.

91. Eurostat, *Energy consumption in households*, in *1995 survey*. 1999, European Commission.

92. Feist, W., J. Schnieders, V. Dorer, and A. Haas, *Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept.* Energy and Buildings, 2005. **37**(11): p. 1186-1203.

93. Crawley, D.B., L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, and M.J. Witte, *EnergyPlus: creating a new-generation building energy simulation program.* Energy and buildings, 2001. **33**(4): p. 319-331.

94. Aggarwal, S.K., L.M. Saini, and A. Kumar, *Electricity price forecasting in deregulated markets: A review and evaluation.* International Journal of Electrical Power & Energy Systems, 2009. **31**(1): p. 13-22.

95. Nowotarski, J. and R. Weron, *Recent advances in electricity price forecasting: A review of probabilistic forecasting.* Renewable and Sustainable Energy Reviews, 2017. **81**(Part 1): p. 1548-1568.

96. Bunn, D.W. and N. Karakatsani, *Forecasting electricity prices.* London Business School, 2003. **1**.

97. Zhou, M., Z. Yan, Y. Ni, G. Li, and Y. Nie, *Electricity price forecasting with confidence-interval estimation through an extended ARIMA approach.* IEE Proceedings-Generation, Transmission and Distribution, 2006. **153**(2): p. 187-195.

98. Weron, R., *Modeling and forecasting electricity loads and prices: A statistical approach*. Vol. 403. 2007: John Wiley & Sons.

99. Meyler, A., G. Kenny, and T. Quinn, *Forecasting Irish inflation using ARIMA models.* 1998.

100. Ang, A., G. Bekaert, and M. Wei, *Do macro variables, asset markets, or surveys forecast inflation better?* Journal of monetary Economics, 2007. **54**(4): p. 1163-1212.

101. Faber, M., *Risk Assessment in Engineering–Principles, System Representation Risk Criteria.* JCSS Joint Committee of Structural Safety, 2008.

102. Nathwani, J.S., M.D. Pandey, and N.C. Lind, *Engineering decisions for life quality: How safe is safe enough?* 2009: Springer Science & Business Media.

103. Cony Renaud Salis, L., M. Abadie, P. Wargocki, and C. Rode, *Towards the definition of indicators for assessment of indoor air quality and energy performance in low-energy residential buildings.* Energy and Buildings, 2017. **152**(Supplement C): p. 492-502.

104. Rüther, P., *Wood weathering from a service life perspective*. 2011.

PART IV – APPENDED PAPERS

Paper I

A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades.

WCTE 2016
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A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades

Klodian Gradeci[1], Nathalie Labonnote[2], Berit Time[3], Jochen Köhler[4]

ABSTRACT: Predicting mould occurrence in timber buildings during early-stage design is important for the prevention of social problems and financial loss, and to ensure a healthy and comfortable interior environment. Uncertainties in predicting mould occurrence are two-fold; a) those related to representation of the biological activity involved, and b) those related to representations of climate exposure. This paper proposes a probability-based design methodology for predicting mould occurrence, supported by an application study. The outdoor climate exposure is represented by simulated time series. Mould germination criteria are not considered as threshold values as in traditional approaches. Instead, the biohygrothermal model is considered to provide a more reliable assessment of the conditions under which mould occurs. This paper proposes an innovative method to facilitate the optimisation of façade construction design by integrating the variability of parameters.

KEYWORDS: Mould, Wufi-Bio, Probability, Monte Carlo, Time Series

1 INTRODUCTION

1.1 STATE-OF-THE-ART

Mould is one of the problems associated with excessive moisture accumulation in timber façades construction, which can result in financial loss and unfavourable social problems such as discomfort and health risks [1, 2]. Probabilistic-based design approaches have the potential to support decision-making processes and to improve timber constructions by reliably preventing damage caused by moisture.

During the last two decades, there have been advances in the development of probabilistic-based design approaches to assess mould growth risk. Among the first to use this approach was Geving [3] who evaluated the mould growth risk of a wooden frame wall without a vapour barrier using critical relative humidity for mould growth measured as a function of simulated weekly average relative humidity and the corresponding temperature as performance criteria. Weather scenarios representative for severe moisture loads were used for moisture design calculations, while the indoor air temperatures were kept constant. The Monte-Carlo simulation method was applied to find the distribution of the environmental load, while the hygrothermal conditions of the wall were calculated using the coupled heat, air and moisture transport program 1D-HAM. Hagentoft [4] presented a probabilistic model for the attic mould risk using mould growth potential, estimated as the ratio of the relative humidity and the critical relative humidity (RH) according to a so-called VTT-model [5]. The probability density function for mould growth potential was modelled using the Monte Carlo method (up to 500 simulations), while simplified deterministic models were used for heat and moisture transfer based on hourly-based weather data accumulated over 30 years. Subsequently, the same methodology was applied for the mould risk assessment of attic design solutions [6]. In [7] the mould growth of an old retrofitted cavity wall was assessed using the isopleths from the biohygrothermal model [8]. Monte Carlo and Latin Hypercube technique were used to model the stochastic variables (105 samples). Heat and moisture transfer were calculated using the finite element code HAMFEM on the basis of weather data from a specified reference year. Pallin [9] evaluated mould germination risk for a retrofitted external wall. Three variable input parameters were sampled using the Monte Carlo method (500 simulations). Outdoor climate data consisted of hourly-based data acquired over a period of 44 years, and indoor moisture production and ventilation rates were based on plausible scenarios and measurements. Performance was evaluated using the VTT mould index while the failure criterion at the threshold value RH=80%. The one dimensional simulation model for heat and mass transport was created in HAM-tools and developed in Simulink. In [10] a time-dependent probabilistic approach was applied to assess the mould growth potential of a concrete external wall evaluated by the TOW concept [11]. Monte Carlo and Latin Hypercube technique were used to sample the stochastic variables. The outdoor climate data consisted of hourly records accumulated over 13 years, while the interior climate was calculated based on indoor air temperatures and RH values resulting from the coupled effect of inhabitant's behaviour, the

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hygroscopic properties of indoor surfaces and outdoor climate conditions. The probability of mould germination on the internal surfaces of different types of attic floor constructions was assessed in [12]. A first-order reliability method (FORM) was used as a tool to provide a probabilistic approximation. Hourly values of climatic data measured over a six-month period were used, while internal parameters were kept constant. Mould occurrence was defined based on the surface relative humidity normally distributed for three temperature intervals exceeding the VTT Mould Index 1 [5]. The hygrothermal performance was simulated using HAM tools.

1.2 AIMS OF THE STUDY

Challenging research issues that remain when assessing the performance of wooden façades in relation to mould occurrence include the representation of temporal and spatial variability in weather conditions, and a realistic representation of mould development. Performance criteria represented by a single threshold value underestimate the complexity and uncertainty of mould phenomena. More realistic representations, in the form of mathematical models that consider crucial factors in mould germination such as relative humidity, temperature, time and nutrients should be used instead.

Outdoor climate is an important parameter influencing façade performance and is stochastic in nature. In order to consider the uncertainties related to a given façade's outdoor exposure, probabilistic models are calibrated using historical data. Moreover, several simulations are required to represent multiple parameter variability. This process may be considered impractical, cumbersome and time-consuming, especially when traditional HAM tools are used to run manual simulations.

This paper proposes a new probabilistic-based design approach that overcomes the aforementioned issues and identifies mould as a potential failure mode of timber façades. The approach is applied here to evaluate mould growth in a timber façade construction. The following challenges are addressed:

- Simulation of realisations of weather data (temperature and relative humidity) as a basis for adequate Monte Carlo analysis that provides realistic results
- Development of an accurate approach to mould occurrence prediction. A mould model that considers the crucial factors that affect germination and growth is chosen to evaluate construction performance.
- Integration of all necessary steps within a user-friendly process that enables efficient and practical probabilistic analyses.

2 MATERIALS AND METHODS

2.1 MATERIALS AND CONSTRUCTION

In general, the construction of timber façades includes a vapour barrier located towards the warm side of the construction and a wind barrier towards the cold side. During recent years, there has been increasing interest in the use of OSB (Oriented Strand Board) vapour retarders instead of traditional PE foils, even though issues concerning water vapour resistance and air-tightness remain the subject of some discussion [13]. For this reason, this paper uses parametric studies to investigate three different configurations in which the materials representing the wind and vapour barrier constitute the variables. The reference cross-section of the timber façade construction is presented in Figure 1 and the material properties in Table 1. The first façade cross-section uses a PE foil as vapour barrier, while the second and third use an OSB board. These studies are referred as CS-1, CS-2 and CS-3 respectively.

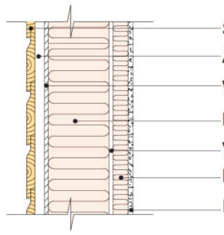

***Figure 1**: Timber façade cross-section*

***Table 1:** Material properties of the façade cross-section*

Material	d	λ	μ	ρ	c	Φ
	mm	W/mK	-	kg/m³	J/kgK	m³/m³
Spruce cladding	22	0.09	130	455	1500	0.73
Air Cavity	25					
Wind barrier	$s_{d1} = 0.1$; $s_{d2} = 0{,}015$; $s_{d3} = 0{,}2$ [-m]					
Wood stud	25	0.09	130	455	1500	0.73
Insulation	160	0.035	1.0	21	840	0.95
Vapour barrier	$s_{d1} = 23$; $s_{d2} = 2{,}5$; $s_{d3} = 2{,}5$ [-m]					
Battens	40					
Insulation	40	0.035	1	21	840	0.95
Gypsum board	13	0.2	8.3	850	850	0.65

2.2 PROPOSED PROBABILISTIC-BASED DESIGN METHODOLOGY

2.2.1 Probabilistic analysis

The performance assessment process employed as part of this probabilistic-based design approach consists of the following steps:

- *Selection of the failure performance criterion*

The first step is the identification of a façade construction damage mechanism based on our economic, social and structural criteria. In this study, mould growth is selected as the failure criterion.

- *Identification of influencing parameters*

Following identification of the damage mechanism, a fault tree analysis and a clear and concise cause-and-effect investigation can be developed from which all influencing factors are selected. In the case of mould germination, these factors include relative humidity, temperature, time and nutrients. In turn, the input parameters affecting these factors include exterior weather conditions, indoor climate, as well as the material properties and geometry of the façade construction.

- *Development of probabilistic models for input parameters supported by sensitivity analysis*

The Monte Carlo method is an alternative to sample the varying influential parameters input to the simulation model. In order to rationalise computational resources, a metamodel may be incorporated.

- *Evaluation of output and the decision-making process*
The results support the decision-making process. If, the probability of failure is higher than expected, based on the results from the sensitivity analysis, it may be possible to determine which construction parameters can be changed to effectively reduce failure occurrence.

2.2.2 Model representation of weather phenomena

One of the most important factors for the façade constructions performance is its exposure; the outdoor weather and the indoor climate, with the latter affected from the former and the use of inner space. The conventional method (deterministic method) of assessing the façade performance make use of historical time series of weather data for a specific or several climate exposures. The deterministic approach may give a rough comparison of the façade performance under different climate locations. Generally, the MDRY (Moisture Design Reference Year) may be applied. However, such comparisons are constructed based on a single overall combination of different parameters (including temperature and humidity) from this specific design reference year. As a result, it fails fully to identify the influence of one or several parameters related to a specific climate exposure. A further serious drawback of specifying an MDRY for a certain location is that different constructions exhibit different levels of performance in response to different types of climates [14], consequently using a MDRY might be limited to some types of constructions. On the other hand, use of average weather values may lead to incorrect moisture data for the construction in question [14]. When assessing a façade construction in relation to mould occurrence, it is demonstrated that uncertainties originating from climate variability from year to year and from location to location is significant [15].
The type of failure mode that might occur in a façade construction are based on the time duration and interval of several parameters. Most bio-deterioration failure events result from complex biological phenomena and occur only when certain conditions are met. These conditions are rarely based only on one parameter, rather on the realisation of the combined influence of several parameters in combination that define the limit between "safe" and "unsafe" region. For example, mould growth is influenced by both temperature and relative humidity, combined with these factors' respective temporal sequences and interrelations. A given year, such as an MDRY, may include worst case scenario conditions for humidity, but may lack mould growth scenarios that are mostly dependent on temperature. Thus, the use of a specific year as a basis for façade construction assessment might not provide all plausible scenarios favourable for mould growth. Additionally, the use of a single year's climate exposure data is considered too short to provide realistic results, especially when the failure mode is modelled as non-declining biological activity as is the case for mould growth in the biohygrothermal model [16]. The use of single-year weather data as input for construction assessment will make the results highly sensitive to the initial time of the climate series, which is also a stochastic variable. Moreover, if several additive MDRYs are used in such cases, results are likely to be conservative and not suited to support a risk-based decision process.
The aforementioned reasons confirm the need to use a different approach when assessing façade construction performance, which is highly influenced by outdoor weather exposure. The methodology presented in this paper proposes the simulation of weather conditions using a time series analysis according to the so-called autoregressive–moving-average models as presented in [17]. Several authors have used this approach, such as in global warming forecasting [18] and weather pricing derivative applications [19]. The use of the autoregressive–moving-average time series provides the opportunity to identify a mathematical expression that generates possible historical patterns in a time series containing plausible sequences, frequencies and correlations. In order to improve probabilistic modelling, a large number of simulations are preferred. This ensures that varying climatic influences are taken fully into account. The innovative use of time series in this study is also motivated by their ability to accommodate a large number of simulations that help exploiting the influence of each parameter during sensitivity analyses.
Long-term measurements of exposed exterior wall assemblies were performed by Vihna [20], who concluded that solar radiation and driving rain do not increase the average humidity (by volume) of the ventilation gap in relation to outdoor air. Sudiyani [21] arrived at similar results. Since mould growth is mainly influenced by the latter, this paper uses only hourly-based temperature and relative humidity as input parameters representing outdoor exposure conditions. In worst-case scenarios, this methodology can be applied to sheltered constructions or in climates where solar radiation and wind-driven rain (WDR) do not have a significant influence on results.
The influence of wind-driven rain and solar radiation was studied for the ventilated façade construction presented in this paper. The relative humidity of the insulation layer is computed for two scenarios, the first considering only relative humidity and solar radiation, and the other in which all weather parameters are considered. Based on such data from the Blindern station in Oslo, the influence of wind-driven rain and solar radiation was found to be insignificant. In the case of Oslo climate conditions, it was found that this influence is insignificant even when a moisture source with 1% of WDR is mounted on the exterior part of the insulation [22].

2.2.3 Failure criterion

In this paper, the biohygrothermal model is used to predict the occurrence and growth of mould on a façade (Figure 1). This model predicts mould fungi activity based on temperature, relative humidity, substrate, and exposure time [8, 16]. It combines two predictive models; an isopleth model that determines germination time for spores and mycelium growth rate, and a transient biohygrothermal model that considers the influence of varying conditions. To account for the influence of the substrate, four substrate categories were identified and

biodegradable building materials are assigned substrate group I.
The generalised isopleth systems for spore germination and mycelium growth for all relevant mould species that may occur in buildings are presented in Figure 2. In order to prevent mould formation, the basic principle of this model assumes a possible worst-case scenario. The Lowest Isopleth Model (LIM) curves for each substrate group were used to represent possible minimum requirements for mould germination. Each isopleth takes into account different building materials as a function of optimal culture media [16].

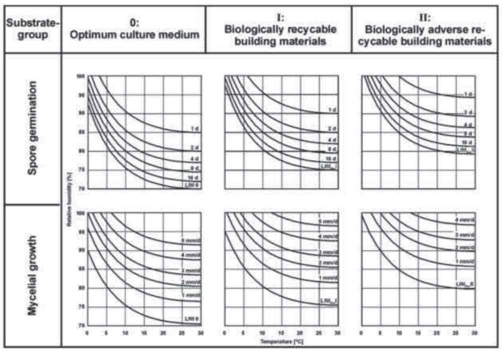

Figure 2: Generalised isopleth systems for spore germination (top) and mycelium growth (bottom) [16]

Mycelial growth for each of the isopleths is given in mm/d, which is also the unit of measurement used in this model. The biohygrothermal model is based on the principle that fungal spores use osmotic potential to absorb water vapour from their immediate environment, thus making it possible to calculate humidity within a spore under transient boundary conditions and enabling any interim drying out to be considered [16]. The latter is described mathematically by moisture retention curves derived with slight modification from the moisture retention curves of bacteria spores. When the critical water content value taken from the LIM and moisture retention curve values are achieved within the spore, spore germination is considered to be completed and the mould will start growing. By adjusting the vapour permeability of the spore septum so that germination time coincides with the biohygrothermal model, and by slightly raising the retention curve in the upper humidity range, it is possible to achieve a material property representation of a model spore. This concept and the relationships between the aforementioned parameters are shown in Figure 3.

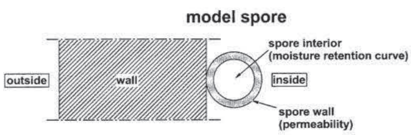

Figure 3: Development of the biohygrothermal model [16]

The computational procedure is based on comparing the water content of the spores under transient climatic conditions with current critical water content. The entire procedure is presented schematically in Figure 4. The biohygrothermal model ignores the difference between germination and growth critical water content and uses the latter parameter as a general criterion for the onset of germination as well as growth. Total growth is expressed in mm (the radius of a mould blotch).

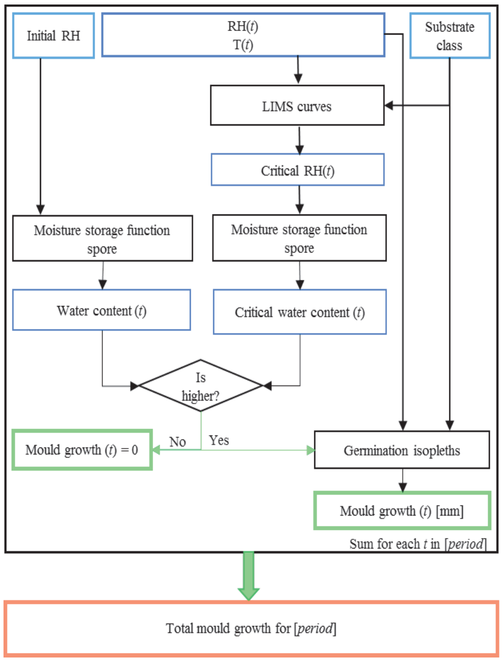

Figure 4: A schematic of the biohygrothermal model

The standard process of façade performance assessment results in three categories or "states" depending on the amount of mould growth (see Table 2).

Table 2: Assessment of mould growth risk and the severity of infestation (if any) according to [23]

Mould growth (MG) [mm/year]	State
MG < 50	Usually acceptable
50 ≤ MG < 200	Additional criteria or investigations required to assess acceptability
200 ≤ MG	Usually not acceptable

2.2.4 Probability of failure

In structural reliability applications, failure is defined when the difference between the capacity and demand for a given limit state is negative, according to the following condition:

$$F = C - D < 0 \quad (1)$$

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 2. The demand term is sampled using the Monte Carlo method. After N simulations have been conducted, the approximate probability of failure is given by the following equation:

$$P_f = \frac{N_F}{N} \quad (2)$$

where N_F is the number of trials during which $F < 0$.

2.2.5 Integrated process

The entire probabilistic-based design approach is implemented in the form of a seamless and integrated parametric workflow by means of efficiently combining the Matlab [24], Python [25] and xml codes. A schematic workflow is presented in Figure 5. Seamless workflow enables us efficiently to convert the variability of the input parameters into a probabilistic representation of the output.

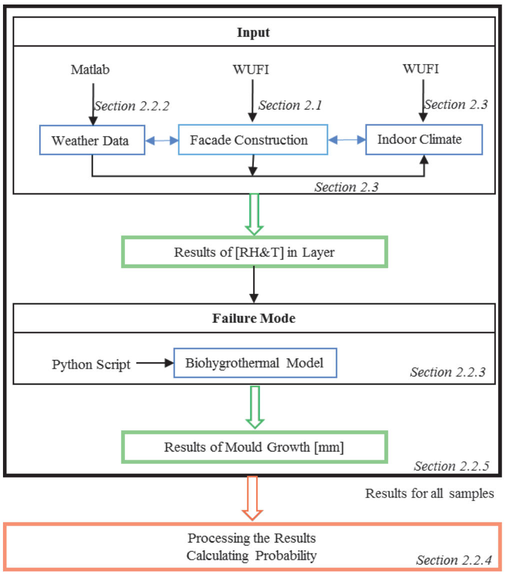

Figure 5: Schematic seamless and integrated workflow

2.3 SIMULATION SET-UP

The heat and moisture simulations are performed using the hygrothermal building simulation software WUFI® [26]. This model calculates the temperature and relative humidity in the building components, as developed by Fraunhofer IBP and validated by numerous research studies. The initial conditions are set at RH=80% and T=20°C. The indoor climate used in this study is represented by a sine wave derived from a single year period representing medium moisture load according to WUFI. The mean air temperature is 21°C with an amplitude of 1°C, while the mean air relative humidity is 50% with an amplitude of 10%. The initial biohygrothermal model conditions are set to LIM I for the isopleth representing the building materials, and an initial relative humidity of 70%. Since a relative humidity of 80% immediately provides favourable conditions for mould growth, the initial value selected for this study is 70%. Three-year hourly-based records of simulated outdoor weather data (300 simulations).

3 RESULTS AND DISCUSSION

3.1 MATHEMATICAL REPRESENTATION OF WEATHER DATA

Input to the model consisted of a set of hourly-based temperature and absolute humidity data measured over a period of 10 consecutive years (01.10.2004 to 30.09.2014) at the Blindern Station in Oslo (eKlima, 2014). Absolute humidity data were later converted to relative humidity values. The time series are firstly computed for temperature. Since relative humidity does not exhibit clear seasonality, absolute humidity simulations (which do exhibit seasonality) are computed. They are then transformed into relative humidity taking into account the coupled effect of the simulated temperatures. Three-year climate series are considered sufficiently long to provide a realistic analytical basis for mould growth and a representation of the variability that may cause the initial simulation date/period.

Several steps are required to compute weather data simulations. Firstly, a mean temperature for 10 consecutive years (6.963°C) is calculated and then removed from the time series. A double sine model is fitted to the remaining data as directed by the physical nature of the weather data and seasonality as follows:

$$seasonal(t) = x_1 \cdot \sin(y_1 \cdot t + z_1) + x_2 \cdot \sin(y_2 \cdot t + z_2) \quad (3)$$

where t is the time [in hours], and x, y, z are the calculated parameters shown in Table 3.

Table 3: *Parameters included in the double sine model*

Parameters	Value	Bounds	
x_1	10.48	10.44	10.51
y_1	0.01723	0.01723	0.01724
z_1	-23.50	-25.64	-21.37
x_2	2.27	2.24	2.306
y_2	6.28	6.28	6.283
z_2	-1107.00	-1116.00	-1097

The seasonality expressed using the double sine model is removed from the times series and the residuals are studied. The autocorrelation and partial autocorrelation factors of the residuals are examined to check the randomness of the residuals. An auto-regressive model involving the first 94 seasonal lags, representing a correlation for the first four days, is used to model the residuals which are then retrieved from the series. Some of the most influencing lag coefficients are presented in Table 4. The second residuals series are calculated and their autocorrelation function is computed (Figure 6). The results show that the second residuals are uncorrelated, meaning that they can be modelled independently using a t-location-scale distribution.

Table 4: Lag coefficients and confidence intervals

Lag no.	Coefficient	Confidence interval	
1	1.2051	1.1988	1.2114
2	-0.1442	-0.1541	-0.1343
3	-0.073	-0.083	-0.0631
4	-0.0306	-0.0405	-0.0206
5	-0.0072	-0.0172	0.0027
22	0.0186	0.0087	0.0286
23	0.0219	0.0119	0.0318
24	0.0526	0.0427	0.0626
25	-0.0746	-0.0845	-0.0647
26	-0.0221	-0.032	-0.0121

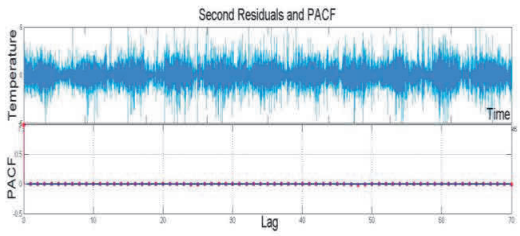

Figure 6: *Second residuals and their partial autocorrelation factor*

Finally, the time series model is constructed by assembling the following quantities; a) a constant value (the mean hourly data), b) the seasonal component (a second order sine model), c) the regression parameters and autocorrelation lags (to simulate the relationship between subsequent and preceding data) and d) the residuals probability distribution (represented by residual data which are identically independent and randomly distributed – *iid* data).

$$T(t) = Const(t) + Seas(t) + f(autoc, regres) + iid \qquad (4)$$

The Pearson correlation coefficient is computed for each simulation with the historical measurement, and the results vary from 0.76 to 0.84. This shows good agreement with the measured data and opens the possibility of accommodating the variability of the climate exposure data. A random simulation has been selected and is presented in Figure 7.

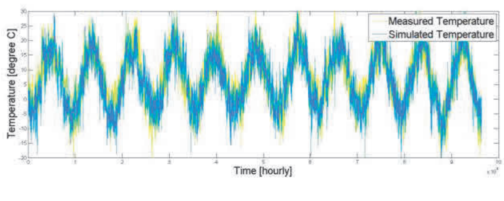

Figure 7: *Simulated and measured temperature data*

3.2 FAILURE CRITERION

The mould growth assessment criteria presented in 2.2.3 are based on WUFI-Bio recommendations [23]. WUFI-Bio is a plug-in supplementary software to WUFI and is based on the biohygrothermal model. It has been validated in many applications [27]. However, the model makes some conservative assumptions that result in over-prediction of the extent of mould growth [23]. The biohygrothermal model allows continuous mould growth in favourable conditions and exhibits zero growth in unfavourable conditions. Consequently, mould blotch diameter continues to increase when conditions are favourable. The evaluation period in WUFI is set to one year, corresponding to a severe outdoor climate. The acceptable mould growth criterion of 50mm/year may be based on the same traditional principles used to analyse façade performance under unfortunate climate conditions. If this limiting value is converted to a three-year assessment period, it corresponds to growth of 150 mm/3years. However, the acceptability of this value might be considered questionable, especially when the evaluation period is increased even further, implying the addition of 50 mm of acceptable mould growth for any additional year.

3.3 ADVANTAGES OF THE INTEGRATED APPROACH

The integrated approach is an efficient and practical tool for performing uncertainty and sensitivity analyses. Although the combination of WUFI software with the biohygrothermal model can be achieved using the commercially available add-on WUFI-Bio, there are constraints regarding both the extent of the calculation and the calculation process itself. Among other things, this means that sensitivity analyses that require a large number of calculations would also require the same large number of manual operations for the following steps:

- implementation of a given climate file
- authorisation of WUFI software to perform the calculation
- opening the results into WUFI-Bio
- copying the results of WUFI-Bio into another independent file for further post-processing.

This procedure becomes increasingly impractical when the variation of material properties and geometry are considered in the probabilistic assessment. Moreover, the evaluation period is only one year and the model assesses mould growth only for interior surfaces. In the façade configurations used in this study, the most favourable conditions for mould growth are met within the façade construction.

In contrast, the integrated approach presented in this study enables efficient parametrisation and systematic changes to the input variables. The key benefits include:

- an ability to assess mould growth for each specific layer, and not just the configuration's inner layer
- practical usability and an opportunity to reduce large volumes of manual work
- an ability automatically to produce a vast amount of simulations as a basis for accurate probabilistic analysis
- an ability to change the input parameters (façade construction properties and geometries, inner climate and outdoor weather conditions) and performance criteria as a basis for performing influence studies.

3.4 MOULD OCCURRENCE IN THE REFERENCE CASE STUDY CS-1

Since the temperature and relative humidity conditions in the insulation layer offer favourable conditions for mould germination and growth, mould occurrence in this layer has been investigated for the reference case study. Good agreement is observed when the results from the integrated process are compared with manually-derived WUFI-Bio results. Calculations for 300 different weather data series, generated by the time series analysis as described in section 3.1, are performed automatically as part of the integrated approach. The results showing the probability of an event involving mould growth exceeding 50, 100 or 150 mm during the three years are given in Table 5. The mould growth results are shown when the number of samples progressively increases from 50 to 300. Convergence is achieved when the number of samples equals 200.

Table 5: *The probability of not exceeding a given mould growth level during three years for CS-1. The number of samples increases progressively from 50 to 300.*

		Mould Growth [mm]		
		50	100	150
Number of Samples	50	0,0678	0,7582	0,9763
	100	0,0476	0,7679	0,9837
	150	0,0369	0,7381	0,9801
	200	0,0865	0,7200	0,9574
	250	0,0863	0,7158	0,9556
	300	0,0755	0,7149	0,9591

The probability plot and cumulative probability distribution plot of mould growth potential for the façade reference case (CS-1) are presented in Figure 8 and Figure 9 respectively. A log-normal distribution is fitted to the 300 samples taken from the three-year data simulations. As expected, the results reveal that based on mould growth results, the weather data (outside air temperature and air relative humidity – which are regarded as the stochastic variables in this study), have a strong influence on the mould growth potential of the building façade.

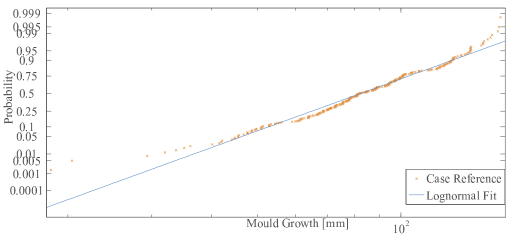

Figure 8: *Probability plot of mould growth potential. Log-normal distribution fitted to 300 samples.*

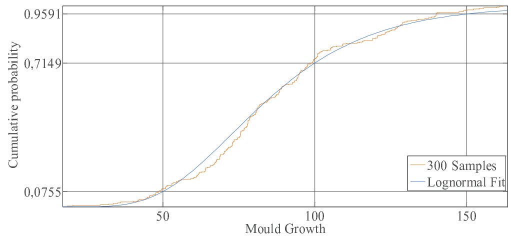

Figure 9: *Cumulative probability distribution of mould growth potential for CS-1. Log-normal distribution fitted to 300 samples.*

3.5 PARAMETRIC ANALYSIS OF THE FAÇADE CROSS- SECTIONS

Table 6 displays the values and Figure 10 the cumulative probability plot for mould growth taken from the three case studies discussed in section 2.2. In each case, a log-normal distribution curve is fitted to 200 samples. Results show that the reference construction, using a PE foil (CS-1) displays the lowest probability of failure, while the construction CS-3 displays the highest. This result is much as expected since the ratio of the "s_d- value" between the vapour and wind barriers decreases progressively from the first to the last case. As the results indicate, the differences between the probabilities for the event 'mould growth is less than 100mm' between the three types of construction are high. However, the difference between the probabilities is diminished for the event 'mould growth is less than 150 mm' for the first two cases. Therefore, when the mould growth limiting value is set at 150 mm, it can be stated that the CS-1 and CS-2 cases deliver the same performance, with CS-1 slightly better.

Table 6: *The probability of not exceeding a given mould growth level. Comparison of the three case studies.*

MG [mm]	CS 1- PE Foil	CS 2- OSB 1	CS 3- OSB 2
50	0.086	0.038	0.037
100	0.720	0.640	0.443
150	0.957	0.945	0.794

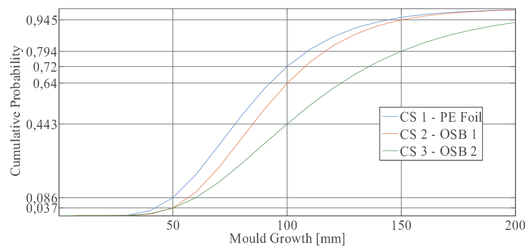

Figure 10: *Cumulative probability distribution of mould growth potential for three case studies. Log-normal distribution fitted to 200 samples.*

4 CONCLUSIONS

Uncertainties in predicting mould occurrence are two-fold; a) those related to representation of the biological activity involved, and b) those related to representations of climate exposure. The development of a probabilistic-based design approach offers the potential to treat these uncertainties when predicting mould occurrence as a failure mechanism. This paper proposes a probabilistic-based methodology that treats the uncertainties of the significant parameters involved in façade design.

The scope of this paper was designed to demonstrate the methodology and the benefits of its application. Mould was selected as a failure criterion in this case. However, other failure modes may also be the subject of further study. It is expected that this new approach will become an important tool in the investigation of construction performance and the overall influence of façade construction properties, geometry, details and the climate exposure. This new approach will be further developed in order to support decision-making processes during the evaluation or optimisation of innovative timber façade constructions.

ACKNOWLEDGEMENT

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REFERENCES

[1] W. Europe, "WHO Guidelines for indoor air quality," *Selected pollutants. WHO Regional Office for Europe Regional Publications, Copenhagen,* 2010.

[2] R. Arthur, "Damp Indoor Spaces and Health. Institute of Medicine: Committee on Damp Indoor Spaces and Health. The National Academy Press. ISBN 0-309-09193-4. Washington, DC 2004, pp. 355," *Journal of Public Health,* vol. 27, pp. 234-234, 2005.

[3] S. Geving, "A systematic method for hygrothermal analysis of building constructions using computer models," in *Proceedings of the building simulation*, 1997, pp. 355-61.

[4] C.-E. Hagentoft, "Probabilistic Analysis of Hygrothermal Conditions and Mould Growth Potential in Cold Attics. Impact of Weather, Building System and Construction Design Characteristics," in *Proceedings of International Conference on Durability of Building Materials and Components*, 2011.

[5] H. A. Viitanen, "Modelling the time factor in the development of brown rot decay in pine and spruce sapwood-the effect of critical humidity and temperature conditions," *Holzforschung-International Journal of the Biology, Chemistry, Physics and Technology of Wood,* vol. 51, pp. 99-106, 1997.

[6] C.-E. Hagentoft and A. Sasic Kalagasidis, "Moisture safe cold attics-Assessment based on risk analyses of performance and cost," in *Proceedings of 10th Nordic Symposium on Building Physics*, 2014, pp. 1366-1373.

[7] L. Van Gelder, H. Janssen, and S. Roels, "Retrofitting cavity walls–probabilistic study of energy savings and moisture risks," in *Proceedings of the 5th International Building Physics Conference (IBPC)*, 2012, pp. 112-112.

[8] K. Sedlbauer, "Prediction of mould fungus formation on the surface of and inside building components," *Fraunhofer Institute for Building Physics,* 2001.

[9] S. Pallin, *Risk Assessment of Hygrothermal Performance-Building Envelope Retrofit*: Chalmers University of Technology, 2013.

[10] Z. Sadovsky, O. G. Koronthalyova, P. Matiaovsky, and K. Mikulova, "Probabilistic modelling of mould growth in buildings," *Journal of Building Physics,* vol. 37, pp. 348-366, 2014.

[11] O. C. Adan and R. A. Samson, *Fundamentals of mold growth in indoor environments and strategies for healthy living*: Wageningen Academic Publishers Wageningen, The Netherlands, 2011.

[12] K. Pietrzyk, "A systemic approach to moisture problems in buildings for mould safety modelling," *Building and Environment,* vol. 86, pp. 50-60, 2015.

[13] S. Korsnes, B. Time, M. Vågen, H. Halstedt, S. Geving, and J. Holme, "Moisture risk in prefabricated wooden wall elements (TES-elements) with a vapour retarder of OSB/3," *Passivhus Norden,* pp. 336-348, 2013.

[14] S. Geving, "Moisture design of building constructions. Hygrothermal analysis using simulation models," *Department of Building and Construction Engineering, The Norwegian University of Science and Technology,* 1997.

[15] S. Thelandersson, T. Isaksson, M. Häglund, and E. Frühwald, "Probabilistic methods for performance based service life evaluation of wooden components," *Applications of Statistics and Probability in Civil Engineering,* p. 401, 2011.

[16] K. Sedlbauer, "Prediction of Mould Growth by Hygrothermal Calculation," *Journal of Building Physics,* vol. 25, pp. 321-336, 2002.

[17] G. E. Box, G. M. Jenkins, and G. C. Reinsel, "Time series analysis: Forecastingand control," *San Francisco: Holdenday,* 1976.

[18] W. A. Woodward and H. L. Gray, "Global warming and the problem of testing for trend in time series data," *Journal of Climate,* vol. 6, pp. 953-962, 1993.

[19] S. D. Campbell and F. X. Diebold, "Weather forecasting for weather derivatives," *Journal of the American Statistical Association,* 2011.

[20] J. Vihna, "Hygrothermal performance of timber-framed external walls in Finnish climatic conditions," PhD, Tampere University of Technology, Tampere, 2007.

[21] Y. Sudiyani, S. Horisawa, K. Chen, S. Doi, and Y. Imamura, "Changes in surface properties of tropical wood species exposed to the Indonesian climate in relation to mold colonies," *Journal of Wood Science,* vol. 48, pp. 542-547, 2002.

[22] A. Tietze, S. Boulet, S. Ott, and S. Winter, "Consideration of disturbances and deficiencies in the moisture safety design of tall timber facades," presented at the World Conference on Timber Engineering, Vienna, 2016.
[23] WUFI®Bio, "WUFI®Bio," ed: Fraunhofer IBP.
[24] M. U. s. Guide, "The MathWorks Inc," *Natick, MA,* vol. 4, p. 382, 1998.
[25] G. Van Rossum and F. L. Drake, "PYTHON 2.6 Reference Manual," 2009.
[26] H. M. Künzel, "Simultaneous heat and moisture transport in building components," *One-and two-dimensional calculation using simple parameters. IRB-Verlag Stuttgart,* 1995.
[27] H. Viitanen, M. Krus, T. Ojanen, V. Eitner, and D. Zirkelbach, "Mold Risk Classification Based on Comparative Evaluation of Two Established Growth Models," *Energy Procedia,* vol. 78, pp. 1425-1430, 11// 2015.

Paper II

Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review.

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Review

Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review

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HIGHLIGHTS

- Approaches to indicate and represent mould growth are reviewed.
- Experimental results show discrepancies about mould governing factors and growth criteria.
- Mould models account for and represent differently the mould growth.
- Current standards and approaches provide unreliable representation of mould growth.

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ABSTRACT

This paper presents a systematic literature review about the development of criteria and models representing mould growth in wood-based materials. First, results from experimental research regarding factors governing mould growth are discussed; afterwards, they are used to analyse the comprehensiveness of current mould models. The review shows substantial discrepancies between criteria reported for mould growth. Moreover, mould models differ with respect to governing factors and their interrelations, applied methodology, experimental set-ups and nutrients, and how they express mould. Lastly, this paper proposes solutions that account for or reduce uncertainties related to the representation and design against mould occurrence.

Contents

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1. Introduction

Mould is one of the problems associated with excessive humidity in wooden constructions, which can result in financial loss and unfavourable social problems such as discomfort and health risks [1–4]. Mould prevention is a conventional part of the timber constructions design; however, the repeated mould growth problems in buildings industry [5–8] suggest that the representation and prediction of this biological phenomenon are associated with large uncertainties. Additionally, the criteria used during the design stage need improvements.

Extensive research has been carried out during the last decades to understand and represent mould growth. Many studies have developed mould models opting for the mathematical representation of the mould growth and corresponding mould performance criteria. These performance criteria have improved by setting a threshold value to one governing factor [9–15], up to mathematical models dependent on several governing factors [16–19]. Despite a general agreement on the factors influencing mould activity, less consensus is found on their significance and how they are incorporated into the models. In order to evaluate the extensiveness and comprehensiveness of these models accurately, the mould phenomenon requires a thorough analysis, especially concerning what factors influence the growth and how. Therefore, in order to provide more clarity in this field and its application in building engineering, this paper proposes to:

A) Conduct a systematic literature review to thoroughly:
  - Identify the mould governing factors and their influence in wood-based materials.
  - Provide a state-of-the-art of current mould models applicable to wood-based materials.
  - Analyse how the models incorporate governing factors in relation to the results as drawn from experimental and field studies.
  - Discuss the research gaps where advancement or development may improve the representation of mould.

B) Discuss current design approaches in order to give an overview of how mould is considered in building engineering field.

2. Systematic literature review methodology

The literature review presented in this study is built upon an established research methodology [20] that ensures a comprehensive search process and systematic review of the relevant literature. This methodology originates from health and social sciences; however, its principles are applicable to other fields of study. This approach provides the tool for a transparent and reproducible research synthesis, thus offering greater clarity, internal validity and audibility [20].

The first step in the literature review process is to define the scope of the research, which allows focusing the research question [20]. In the present study, the research question opts to identify the criteria and representation for mould growth in wood-based materials as derived from the experimental analysis. The PICOC framework [21] is used to define the key concepts of the research (see Table 1). Three electronic databases of peer-reviewed literature are used. Scopus, Web of Science and Engineering Village are relevant sources of information in this research area [22–24]. The keywords, operators and nesting combinations are presented in Table 2. The last search was performed in March 2016. The keyword "mould" is related to other fields, and it is necessary to insert several exclusion key terms. The searching scheme and exclusion criteria are shown in Fig. 1 and Table 3.

While screening the literature based on full content, cross-referencing methodology and author searching are used to check for additional literature. The final number of selected publications is 101. Subsequently, a data extraction process [20] is developed to identify common elements among individual publications. Table 4 shows the subgroups of the data extraction that structure the literature review results of the following two sections.

3. Literature review results: mould governing factors

The knowledge of the environmental requirements for mould growth is focused on its governing factors: humidity and temperature conditions at the material surface, exposure time and substrate [16,25–30]. Mould growth also depends both on pH-level of the material surface, which is directly related to the material, and the oxygen, which is always available [31–34].

3.1. The influence of humidity and temperature

Relative humidity (RH) is the most investigated criterion, considered the most decisive for mould growth and research mostly investigates the critical range 75–95% RH [31,35–38]. Table 5 chronologically presents the summarized results of minimum relative humidity at which mould can grow. The reader is referred to the respective literature for further understanding of the experimental set-ups. It goes beyond the scope of this paper to compare how these results are obtained from different experiments since to achieve the latter many factors should be controlled and the same test method should have been used [39].

Several experimental set-ups, opting to identify the critical relative humidity, are conducted at optimal constant temperature. However, a dependence on temperature should be expected since biochemical processes affect the metabolic activity of mould growth [16,30,44,51]. These values shall be further used to evaluate the models' comprehensiveness. Table 6 presents a summary of the experimental results regarding the outermost values of temperature affecting mould growth, including low and high temperatures. The results show that low (up to – 20 °C) and high (up to 60 °C) may influence mould growth.

Table 1
The PICOC framework.

Population	Mould
Intervention or **E**xposure	Experimental, laboratory, field studies, theoretical studies
Comparison	Comparison between different results, analyses and models
Outcome(s)	Mould growth criteria, Mould models
Context	Wood-based materials

Table 2
Keywords and Boolean operators.

What?		Where?		How?		Exclude	
mould	and	wood*	and	criteria	and not	cast*	injection
mould		sapwood		model*		electro*	alloy
moulds		building		prediction		polymer	moulding
moulds		house		level		food	moulding
		roof		growth		steel	fabrication
		cladding		risk		toxic	symptom
		facade				glass	animal
						pathog*	simulator

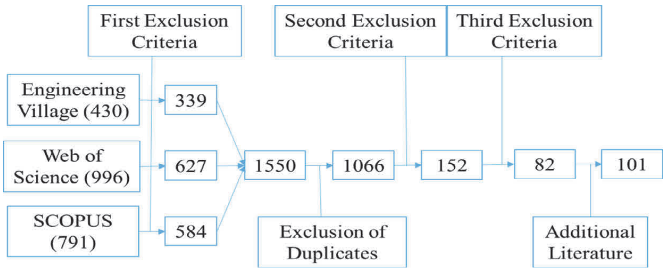

Fig. 1. Screening of the literature based on exclusion criteria.

Table 3
Exclusion criteria.

Exclusion	1st Exclusion Criteria	2nd Exclusion Criteria	3rd Exclusion Criteria
Reason	Qualitative based on the type of literature	Scientific based on keywords, titles	Scientific based on abstract
What	Article Conference (Chapter) Books English	Fungi other than mould; Other than building materials; Investigation and remediation; Moulding as technological process; Pollution, health, disease; Use of pesticides and antibodies	

Table 4
Data extraction.

Factors	Relative Humidity Temperature	Time-Factor Nutrients/Substrate
Models	Description	Comparison

Table 5
Minimum RH requirements for onset of mould growth.

Literature	(Non) Critical Relative Humidity
[31]	Growth starts at RH = 85%
[40–45]	Growth starts at RH = 80–85%
[46]	Growth starts at RH = 76%
[47]	Growth starts at RH > 72%
[16]	Growth starts at RH > 70%
[48]	No growth at RH = 75%, yes at RH = 80%
[49]	No growth at RH = 74.5%, yes at RH = 78.5%
[50]	No growth RH = 69%, yes at RH = 78%
[39]	No growth at RH = 80%, yes at RH = 75%

Many studies provide the critical moisture level of a specific material to show the requirements for mould growth. However, most of the mould models subgroup wide-ranging materials into one single category (see Section 6) in order to achieve more application in the field of building engineering. Therefore, the scope of Tables 5 and 6 is to demonstrate the outermost values where mould can grow unrelated to specific materials, in response to the broad categorization that many of the mould models incorporate. These values shall be further used to evaluate the models' comprehensiveness.

3.2. The influence of the time-factor

The exposure time is a significant factor for mould growth. The same exposure conditions under short constant conditions may not lead to mould growth, while longer exposures offer more favourable conditions [16,39,48,55]. Temperature and humidity are subject to fluctuations; consequently, mould successively encounters favourable and unfavourable conditions. Several authors have investigated mould growth subjected to fluctuating conditions [19,29,55,62]. A general agreeing result is that during fluctuating conditions, mould growth is delayed. Mould is also affected by the duration of these favourable/unfavourable conditions and their sequence. Mould growth reacts slowly to fast changes of humidity conditions [29,30]. According to Viitanen [48], the growth rate is a function of the sum of repeated favourable periods under fluctuating conditions. When the period at high RH is longer than 24 h, the effect of cumulative time at high humidity is linear, but if the dry periods are long, then very low or negligible growth can be expected. Contrary, according to Johansson et al. [62], mould growth is more affected when the fluctuating duration is longer (1 week) rather than shorter (12 h). It is also suggested that using the sum of favourable periods for growth or mean relative humidity provides unrealistic results; instead, the

Table 6
Outermost values of temperature (low and high values) and how mould growth is affected.

Literature	Temperature Influence	Comments
[47,48,50,52–56]	Low Temperatures	Mould grows below 10 °C
[57]		Temperature affecting mould growth varies 5–7 °C as minimum
[48,50]		Mould growth is found at 5 °C
[58]		Mould grows at around −5 to −7 °C
[47]		Mould grows at −4 °C
[56]		Temperature of −20 °C has more influence than −5 °C
[48]	High Temperatures	Mould grows up to 40 °C
[47,48,50,52–56]		Mould grows above 35 °C
[57,59]		When the temperature exceeds 40 °C problems could be observed with mould growing continuation
[57]		Temperature limits affecting mould growth varied up to 37–53 °C
[60]		High temperatures (>60 °C) have a negative impact
[61]		High temperatures (>50 °C) have a negative impact

duration and alteration of both conditions should be considered. Similarly, Pasanen et al. [29] suggests that the previous history of humidity and temperature conditions affects growth rates. An exposure period at low relative humidity prevents growth and has a direct effect on the time until onset of mould [30].

Additional important variables affecting mould growth are absorption/desorption processes and condensation. The condensation causes significant restraint to mould growth and is not necessary for fungal defacement [29,63]. Contrary, it is suggested that very high RH (97.0 ± 6.1%) offers optimal conditions [64]. A fall in temperature during fluctuating temperature conditions at a high relative humidity will add or condense moisture on the surface and drastically enhance the conditions for microbial growth [65]. Capillary absorption of water in wood-based materials with moisture content (MC) above 20% results in rapid mould contamination [29]. Fast drying (RH 30%) decreases the viability of fungal spores adapted to high humidity, while drying at RH 50% has only a slight effect [29]. Another study [66] concludes that mould growth activities during desorption process are higher than during wetting adsorption processes under the same relative humidity due to higher moisture levels. This implies that mould growth is not only a function of water activity, but also of moisture ratio.

The importance of which factor is fluctuating has also been studied. An alternation of the temperature within the optimal values (5–22 °C) has less significant effect as alternating relative humidity [62]. The results do not differ much between these temperature-fluctuating conditions and when the temperature is kept constant at 10 °C. However, it is lower when the temperature is held constant at 22 °C [62]. Similarly, an increase of 1% RH has a greater influence on the mould growth than an increase of temperature of 8 °C for RH higher than 85% [67].

3.3. The influence of type of material, surface and mould fungi

Besides humidity and temperature, the nutrient content of the substrate is the most influencing factor for mould growth [16,30,68]. A general conclusion [34,39,69] reveals that different materials experience a different time and critical conditions for the onset of mould growth. The minimum humidity for mould growth is related to the moisture content of each different material [31]. Moreover, nutrients are a crucial factor to mould and their influence depend on specific wood-material properties including amount and quality of heartwood and sapwood, surface quality and finish system, surface treatment and drying schedule.

Sapwood is found to be more susceptible to mould growth than heartwood [32,70–73]. One reason might be the higher nutrients in the sapwood and/or higher amounts of toxic extractives in the heartwood [74]. This is however not true in the areas of light-coloured wood [73] or for heat-treated wood [74]. Humidity conditions on the materials' surface are the critical ones since mould grows on the surface and cannot use the moisture accumulated inside the material [75,76]. This influence is highly dependent on surface quality and treatment. Additionally, mould fungi are dependent of nitrogen and low-molecular hydrocarbon compounds [77], which are influenced by the way the wood is treated. During kiln drying, the content and distribution of the compounds can be changed [78,79]. Mould growth is found to be higher on the original-kiln dried wood surface than on a resawn surface since sugar and other nutrients are transported to the surface during the drying process [32,80–85]. For the same reason, mould growth is higher at surfaces of winter-processed than at spring-processed material [86]. Moreover, wood dried with faster schedules [32,70,87] and low-temperature-dried wood [74,88,89] are found to be more susceptible to mould growth. In the case of kiln drying, boards dried at 110 °C are less susceptible to mould than at 70 °C [84,90]. Thermal modification increases mould resistance [90,91] since the material becomes less hygroscopic due to the chemical changes in the wood components. The resistance of sapwood subjected to heat treatment (180, 220 °C) is slightly increased in most of the cases [92].

Another mould-governing factor is the quality and type of surface. The relationship between mould growth and time can be characteristic for a specific combination of wood substrate and surface coating system [72]. The wood substrate is found to be less significant compared to coating [71]. However, when sawn spruce and pine are treated at 225 °C, no decrease in surface growth of coated wood is detected, even though it lowered the moisture content level [93]. Opaque coating, soft model paint, paints without fungicide and triple treatment system offer better performance against mould compared to transparent or semi-transparent coating, harder model paints and paint with fungicide respectively [80,94,95]. Other wood properties such as origin, annual ring, density, knot properties or manufacturing characteristics have no significant effect, due to the use of a high-performance coating system [96] compared to small differences in surface roughness on newly treated fresh wood [97].

Different mould growth requirements are also observed depending on the way the experimental set-up is conducted. Experimental set-ups conducted in culture medium provide optimal conditions for mould growth [46,57]. In buildings, fewer amounts of nutrients are found, however dust, air pollution or contagions/organic additives can increase the mould susceptibility [16]. Research categorizing and identifying common fungi available in buildings can be found at [16,98,99].

4. Literature review results – mould models

The results from the experimental research reveal discrepancies in defining the critical conditions for mould growth since mould is a very complex phenomenon. In order to represent the complex interaction between many factors influencing mould, much effort has been spent to develop mould models. Several literature reviews on mould models have been conducted for years, for example [16,65,100–103]. The present paper, due to the chosen methodology (systematic literature review – see Section 2), offers the advantage of a broader coverage of existing mould models applicable to wood-based materials. The results show that:

- There are several mould models developed to predict the mould growth (see Table 7). Due to space requirements, this paper investigates models that may represent mathematically mould growth as a time variant quantity. Other models representing mould growth can be found at [26–28,47,57,104,105]; however, they are no further investigated in this paper due to the previous reason or the models have been advanced by other authors in a more detailed version.
- Many models incorporate the governing factors defined in Section 3; however, differences are observed in the extension and importance of each factor.
- Same experimental data are used to develop several models; however, different methodologies and hypothesis are applied.
- Models implement several characteristics into a similar framework; however, the interrelations between the factors and their contribution to the result is different.
- Models share the same scope of predicting mould growth, but they differ in the way they communicate it.
- Several comparative studies show both agreements and disagreements between the predicted mould growths calculated from different mould models.

In light of this, this section's scope is to provide a clearer overview of the current models and their characteristics. This offers the end-user a basis and the background for the selection of most applicable model to the specific case study at hand. To achieve these, the followings are developed:

- A generic framework integrating the most important factors of mould growth (as revealed from Section 3) and how they are approached from different models. It also describes the calculation process, divided into three main parts (input, calculation and output) as shown in Fig. 2. This framework can be used as a basis to develop new models or to compare current ones. It is adapted and further developed for each mould model and the results can be found in [106].
- A comparison mould growth requirements, expressed by borderlines or doses of relative humidity and temperature.
- A table showing and comparing the characteristic of mould models. These include: the extensiveness of the governing factors, relative humidity, temperature and whether the models consider material dependence (specific or as a group) or mould species dependence; the experimental data from which these models were established including the methodology used to establish the representation of mould growth; characteristics of how mould is assessed and computation procedure; whether is incorporate into a software and the relevant literature (see Table 7).

4.1. Summary of comparative studies investigating mould models

Several models have been compared in terms of the critical borderline as a relation between temperature and relative humidity [65,103,126]. It is observed that in some condition the criteria coincide, while in other conditions clear differences can be spotted. Agreements are observed between VTT and MRD model despite the different consideration regarding the unfavourable conditions [121]. Good agreements are also observed between VTT model without decrease and biohygrothermal model [30] or their minimum requirements for growth [120]. However, this type of comparison may be considered simplified since the models include several parameters that have effects in various directions [65]. Nevertheless, it was possible to develop a conversion function that approximately transforms the biohygrothermal model results presented in [mm] into VTT mould index [127,128].

Disagreements are observed when the comparison is based upon different constant or cyclic conditions [103]. Disagreements are also observed in [102] and [129,130] when comparing the results of experimental analysis from [39] and [50] and the respectively calculated mould growth from several models. It should be noted a difference of interpretation of mould assessment: in [130] the VTT mould index 1 is converted to Johansson scale 1 [39], while this may be also interpretative whether is scale 1 or 2 [102].

4.2. Comparison of minimum requirement for mould growth

Fig. 3 shows the minimum growth requirements in terms of isopleths (Mould Germination Graph Method, LIM I and LIM II of the biohygrothermal model, Johansson model and ESP-r categories A and B) or equations (VTT model-spruce resawn and m-model). Good agreement is observed between LIM I and ESP-r A isopleths or between VTT model, m-model, ESP-r B, LIM II. Johansson model agrees with the latter models when the temperature ranges in [10–30 °C]. Despite some similarities across the borderlines, discrepancies remain substantial. It should be noted that these models, sharing the same scope, are established based on different methodologies and datasets that are retrieved by experiments with different settings and/or assumptions.

Fig. 4 compares the minimum growth requirement when the duration time is one day and eight days (for the m-model the seven days curve is selected). The two graphs show large differences between all mould models, both in ranges of applicability, shape and bounds.

Fig. 5 compares the respective temperature and relative humidity doses of MRD (12 h and 24 h-average), Johansson (monthly average) and Max-days model (weekly average). The product of the relative humidity and temperature doses (unitless quantities) expresses the degree of mould growth. Once more, the domains of applicability are different especially when the relative humidity is lower than 75% or higher than 95%, and for temperature higher than 25 °C. Johansson et al. and Max-days model agree on the relative humidity dose; however, the opposite is found for the temperature. The graph shows a significant difference when the MRD model reduces the time step from 24 to 12 h, even though their product may be comparable. It should be noted that Johansson and Max-days have the maximum dose set to one, while MRD accommodates higher values.

5. Design avoidance of mould growth and conventional approaches

Mould was found to be a very complex phenomenon for which temperature and relative humidity on the material surface are crucial. These microclimate data may be calculated by traditional analysis methods such as Glaser diagram, the Dew Point Method or Kieper diagram [131] or by computer programs such as WUFI® [132]. However, the main issue is to interpret these continuous time series of microclimate data in terms of mould growth risk [121]. Many of the aforementioned models are incorporated to computer programs (see Table 7). This facilitates the instant mould growth after calculating the microclimate data on the surface of the material. In addition, many guidelines concerning the preven-

Table 7
Overview of different characteristics related to mould models (symbol '✓' stands for 'accounted or covered in the model', symbol '–' stands for 'not accounted or not covered', symbol 'Y/N' stands for Yes/No).

Factor		Model								
		ESP-r(1996)	Max days – Model (1997)	VTT Model (1999)	Biohygro-thermal (2001)	Mould Germinati-on Graph (2004)	Johansson et al. Indices (2001)	MRD Model (2010)	Gobakken et al. model (2010)	m – model (2011)
RH	<75%	–	–	–	✓	✓	–	–	–	–
	75–80%	✓	✓	–	✓	✓	–	✓	–	–
	>80%	✓	✓	✓	✓	✓	✓	✓	✓	✓
T	<0 °C	–	–	–	✓	–	✓	✓	–	✓
	0–5 °C	–	✓	✓	✓	–	✓	✓	–	✓
	5–30 °C	✓	✓	✓	✓	✓	✓	✓	✓	✓
	>30 °C	✓	✓	✓	–	✓	✓	–	✓	✓
Experiments	Agar	✓	–	–	✓	✓	✓	–	–	–
	Laboratory	✓	✓	✓	✓	–	–	✓	–	✓
	Exposed	✓	–	–	–	–	✓	–	✓	–
Inspection	Visual	✓	✓	✓	✓	–	✓	✓	–	✓
	Microscope	✓	–	✓	✓	✓	✓	✓	✓	–
Assessment	Onset	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Additional Growth	–	✓	–	✓	–	✓	–	✓	–
	Unit	Y/N	Y/N	VTT Index	mm, Index	Time	Mould Indices	Time, Index	Logit ratio	Time, Index
Computation	Delay	–	–	✓	✓	✓	✓	✓	Implicit	✓
	Steps	Hourly	Weekly	Hourly	Hourly	Daily	Hourly	12 h	Daily	Hourly
	Decrease	–	–	✓	–	–	–	✓	Implicit	✓
	Ass. Period	No limit	One year	No limit	No limit	No limit	No limit	No limit	12 years	4 years
Mould-based		Six mould categories	–	–	–	*A. Versicolor*	*Cladosporium spp.*	–	–	–
Material-based		–	Wooden materials	Four classes	Four classes	–	Wooden materials	Variation of wooden materials	Wooden materials & properties	Four classes
Software		ESP-r	–	Latenite, TCCC2D, Delphin	WUFI-Bio	–	–	WUFI	–	–
Methodology		Equation & isopleths	Equation	Equation	Isopleths and biohygrothermal model	Isopleths & equation	Indices & isopleth	Dose & isopleths	Logit model	Equation
Literature		[107,108]	[48,109–111]	[55,86,111–115]	[16,116,117]	[57,100,104,118]	[119]	[17,62,111,112,120-124]	[38,71,72,95]	[18,33,55,111,125]

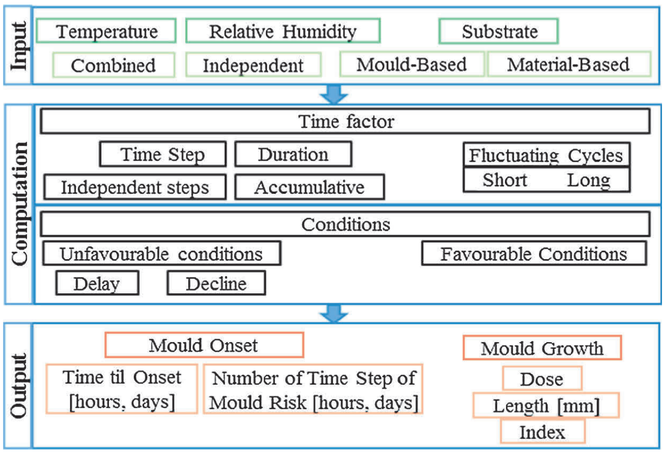

Fig. 2. General scheme of mould models.

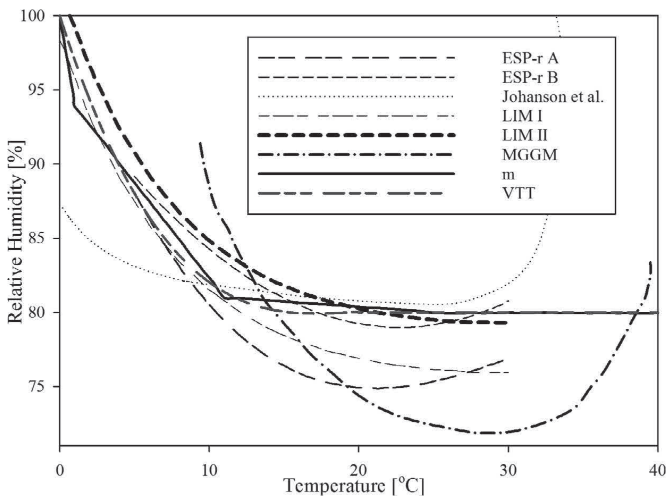

Fig. 3. Comparison of the minimum requirement for the onset of mould growth for different mould models.

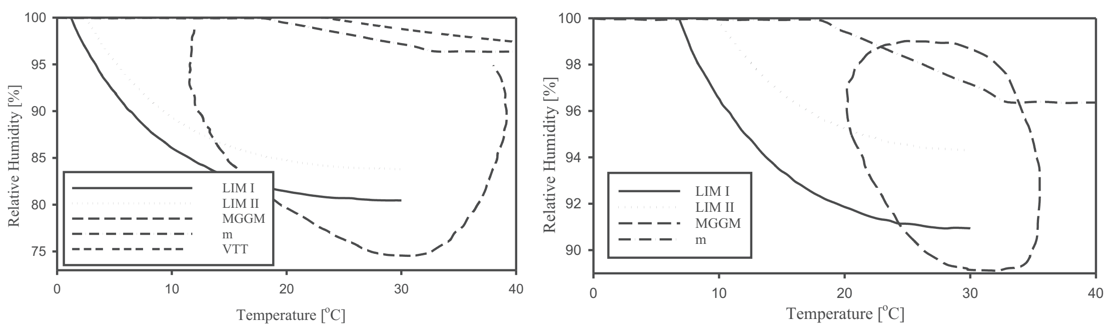

Fig. 4. Comparison of the minimum requirement for the onset of mould growth in the duration of 8 days (left) and 1 day (right).

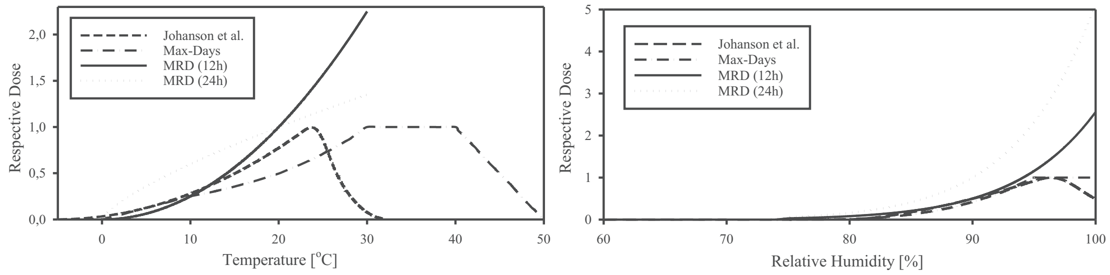

Fig. 5. Respective dose based on the relative humidity (left) and temperature (right) level for MRD (12 h and 24 h), Johansson and Max-days model.

Table 8
Overview of the widely used standards regarding mould growth.

Country & Standard/Code	Criteria	Guidelines
CEB member countries *ISO 13788:2012* [9]	80% ≤ RH	The monthly mean RH should not exceed a critical RH, which should be taken as 80% unless information that is more specific is available.
USA *BSR/ASHRAE Standard 160P* [10]	80% ≤ RH and 5 °C ≤ T ≤ 40 °C	This condition shall be met: a 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5 °C and 40 °C.
Norway *Byggforskserien 421.132* [11]	80% ≤ RH and T ≤ 0 °C	When the RH is over 80% and the temperature over 0 °C over time, mould growth can occur.
Sweden *BFS 2011:6, BB* [12]	75% ≤ RH	If the critical moisture level for a material is not well researched and documented, a RH = 75% shall be used.
United Kingdom *BS 5250:2002* [13]	70% ≤ RH	If the average RH within a room stays at 70% for a long period, the RH at the external wall surfaces will be high enough to support the growth of moulds.
Australia *Condensation in Buildings 2014* [14]	70% ≤ RH and 4 °C ≤ T ≤ 40 °C	Moulds can develop when spores are present with a sufficient nutrient supply, temperatures stay between 4 °C and 40 °C and RH rises above 70%.
Germany *DIN 4108:2014* [15]	8 0% ≤ RH	The moisture is stated as the essential prerequisite for mould fungus formation.

Table 9
Overview of software that predict mould growth.

Software	Model	Comments
ESP-r [133,134]	ESP-r Model	The predictive capability has been evaluated and calibrated against monitored data collected from mould-infected houses [108,135]. It predicts the mould condition and plots it in the mould growth curves.
WUFI-Bio [136]	Biohygrothermal IBP Model	The evaluation period is one year. The assessment are divided in three categories, where less than 50 mm/year is acceptable and more than 200 mm/year as unacceptable. The result can also be expressed in terms of VTT index.
TCCC2D [65,137]	VTT model	Boundary conditions may consists of hourly climate data (ambient temperature and relative humidity, solar radiation intensities, and wind velocity and direction) or user-defined measured data. Assessment criteria are based on VTT Index.
Condensation Targeter II [138]	Specific algorithm	This model allows the impact variables associated with mould growth (fabric type, ventilation, heating system, occupant fuel affordability and occupant density) to be assessed [138]. It is based on monthly steady-state solutions. Another version of the tool measures the risk of mould on the coldest surfaces within the dwelling each month of the year [139].
WUFI [132]	MRD	The results from WUFI are used as input for the calculation of onset of mould growth according to MRD.
Delphin [140]	VTT Model	The VTT model is used for the evaluation of mould growth, which is implemented in the DELPHIN-Postprocessor hourly values of temperature and relative humidity, are necessary. This model only is valid for surfaces.
Mold Simulator Pro [141]	ISO 13788 standard	This 2D/3D finite elements modeller assesses the mould length [mm] on internal surfaces.

tion of mould inside and on building components exist (see Table 8 as extracted and then synthesised from the specific codes); however, generally simplified suggestions are provided [16].

Generally, the guidelines state that the critical conditions that are liable to increase the occurrence of mould growth should not be met. These critical conditions are generally suggested as threshold values if the latter information is not well researched and documented. Different values are provided from different countries, with a relative humidity ranging from 70% to 80% and temperature from 0 to 40 °C. Moreover, several software products or tools attempt to evaluate the mould growth (see Table 9).

Despite the advancement of the design against mould occurrence during the last decades, including the advancement of mould representation and computation of the hygrothermal conditions, there are continuous reports on mould growth problems in the building industry [128], suggesting that the criteria and approaches used during the design stage may need improvements.

6. Summary and discussion

6.1. Disagreements regarding mould governing factors

The present review showed that mould is a very complex biological phenomenon, which is highly dependent of the interrelation between humidity, temperature and time; including fluctuating conditions, the level and duration of favourable/unfavourable conditions together with their sequence, absorption, desorption and condensation processes. Several material characteristics may also affect mould including the amount of quantity and quality of sapwood and/or heartwood, surface quality and finish system, wood treatment and drying schedule. Generally, supporting results regarding the governing factors and their influence were found; however, less agreement was found in the absolute values. Reasons for these discrepancies may include methodologies used and assessment criteria, type of materials and mould species, experimental set-ups and climate conditions, and different assumptions.

6.2. Mould models – validity and comprehensiveness

The applicability, validity and comprehensiveness of the current mould models are discussed based on the results from Section 3.

6.2.1. The consideration of relative humidity, temperature and substrate

Different models, developed from different datasets, consider different ranges of temperature and relative humidity that affect the mould growth. The result from this review revealed the possibility of mould growth even for conditions when RH < 80%, T < 0 °C and T > 30 °C. Therefore, the estimated mould growth in these domains calculated from different models should be carefully assessed because the prediction of mould growth for the case study at hand may be limited.

Different models are developed for different types of materials and/or mould species (see Table 7). Besides the categorization of the substrate, the rating scale of the categories is another observed difference. Regardless of the same prescriptive characteristics, these rating scales may differ from model to model, especially when considering that the results were interpreted visually by different researchers based on different standards. The review revealed that mould growth is highly sensitive to the material selection. Overestimation or underestimation of the mould growth prediction may result due to the wrong assumed substrate class or broad categorization of the substrate classes. A convertible common rating scale and technique how to assess them is required.

Large differences are found between several mould models when comparing the isopleths or the doses, and therefore the outcome depending on the duration time may differ. Since discrepancies were found when comparing the experimental results, it is expected that the mould models established from the latter data do not agree with each other. Nevertheless, prediction of mould growth should not be thought of as an attempt to predict the exact growth, but the likelihood of mould occurrence. Therefore, it is advised that the results should be carefully interpreted [30,65,120]. However, it is prudent to assume that these mould models provide a good basis and may go beyond their application in comparative and sensitivity analysis.

6.2.2. The consideration of the time-factor

The largest differences between mould models are found in the time component including time step, assessment duration and fluctuating conditions. The applied time step is a parameter that affects the calculated mould growth and differs in current models (see Table 7). Using averages of long periods may not consider the strong variations in temperature and relative humidity [17]. For example, two hours of RH = 95% if followed by a decrease of RH (for example 75%) may not be hazardous [65]. Therefore, a particular daily sequence of high and low relative humidity values might not be favourable for mould growth due to these abrupt changes; however, the daily average might fall within the minimum growth requirements. Consequently, considering long time steps may underestimate or overestimate the result.

Another time-related characteristic of the models is the *assessment duration*. Many models assess the mould growth for a certain duration based on the cumulative approach. Consequently, it is questionable whether assessing the mould growth for a short time such as one year is realistic, especially for models that do not consider negative growth during unfavourable conditions. Moreover, extrapolation of the results from short exposure data, as assumed in the logit model, may be risky and uncertain [72].

The *fluctuating conditions* are the time dimension developed differently in all mould models. The ESP-r isopleths do not indicate the time duration of the conditions required to sustain mould growth. Therefore, the superimposed simulation results can at best indicate only a worst-case scenario [135]. Johansson et al. third index has a recovery function delaying the growth exposed to unfavourable conditions. However, no suggestion is given regarding this recovery duration (which is not known and most probably be different for different exposures [119]), and consequently whether the characteristics of the unfavourable condition are related to their time exposure. The logit model predicts mould based on results of outdoor exposed materials, thus implicitly considering the fluctuating conditions. However, in the last model threshold values are used, thus considering them independently and without any influence on the previous time steps as considered in the case of Mould Germination Graph model. Similarly to the latter, the biohygrothermal model assumes delay, but no decrease, during unfavourable conditions. Contrarily, the MRD, VTT and m- model assume that mould growth decreases during unfavourable conditions. Nevertheless, these models represent differently this process. The VTT model considers decrease only during relatively short-term cycles, while the m-model uses the reduction factor up to four weeks. Different lower values of relative humidity and temperature are used to initiate the negative growth. The review revealed that fluctuating conditions are crucial to consider when representing the mould growth. Moreover, both short and long fluctuating conditions affect the mould growth.

6.2.3. The effect of the chosen methodology and experimental set-ups to establish mould models

Different models have used different approaches and/or different experimental set-ups, and subsequently datasets, to develop the critical borderline and the mathematical representation of mould growth (see Table 7). The lowest isopleth approach establishes this borderline as the lowest growth requirements for one or several mould species. Contrary, models that represent this borderline as an equation are developed through regression analysis technique as the best fit to the data. For example, the VTT model is based on average values, because using maximum index values would have led to a model with more intensive growth [142]. This implies that the predicted growth may be overestimated or underestimated in specific cases, depending on the chosen methodology, even when using the same datasets. The aforementioned differences including the methodologies and the specific experimental settings may have given rise to models with different characteristics and features.

The way the results are expressed differs correspondingly (see Table 7). Models express the mould growth in different quantities. Nevertheless, the VTT mould index 1 is the most widely used criterion to indicate the onset of mould growth. Only three models can assess the mould growth after its onset. The VTT model uses the VTT index (6 rating scale), while the Logit model uses the five rating scales as in EN 927-3 [143]. Both models offer a limiting growth value. Alternatively, the biohygrothermal model's unit of measure is [mm] and has no limit. This may be a questionable unit when the length becomes too large. A common rating scale is advised to achieve more clarity across different research studies.

6.3. Research gaps in the literature

Research gaps that can contribute to a more accurate representation of mould growth and calibration of mould models are:

- The mould growth when subjected to low and high temperatures (lower than 0 °C and higher than 35 °C)

- The mould growth when subjected to the unclear relative humidity ranging in 70–80%.
- The mould growth when subjected to fluctuating condition including the influence of short and long cycles.
- The mould growth considering the materials dependency and the applicability on wood-based constructions.

This knowledge will help improve and/or validate current mould models. The development of a new model can be an alternative. This requires excessive time and costs and again the results may disagree with current ones. Another more cost- and time-effective solution can be the integration of different models into one, where strong points of each model are combined together.

6.4. Limitations of current models and conventional approaches. Opportunities associated to probabilistic approach

Current standards and codes offer limited guidance with simplistic representation of the mould phenomenon. Considering the results from this review, using threshold values can lead to incorrect guidance followed by overestimation or underestimation of the result with large undesirable societal and economic consequences. Furthermore, mould occurrence in building materials is usually assessed through deterministic approach, most of the cases considering the worst-case scenario. However, mould as a phenomenon has a stochastic nature and should be considered as such. In addition, mould-governing factors are stochastic too, adding more complexity and uncertainty to the design solutions. Therefore, during the last years, probabilistic-based approaches have been developed to assess the design solutions against mould occurrence [144] since they account for the uncertainties related to the design, thus providing more reliable results.

While many models are available, it becomes overwhelming the choice of the most appropriate one due to their individual limitations as showed in this review. Consequently, a sound comparison between the models is required to provide directions and guidelines of the models' applicability. In order to compare the results from different models two important matters must be considered. First, different methodologies and datasets (retrieved from experiments with different settings) are used to develop the models. Since the review shows that many factors affect the mould growth in different directions, it is expected the outcome of the calculated mould growth may be also different. However, many studies (see Section 4.2) have found inconsistencies between the outputs of models that have used the same datasets but different methodologies (the reader is referred to Table 7 under row 'Literature' to find models that use the same experimental results). There is a possibility that a specific climate exposure falls in 'intermitted' domain, which is a specific climate exposure that may offer limited conditions for mould growth and is treated differently based on the methodology used. When using isopleths, such exposure is always treated as favourable, while when using a regression technique, it might fall outside the valid domain of the regression equation. Second, due to the different rating scales used in the models, the results must be carefully evaluated and interpreted when comparing different models. These may be an explanation of the large discrepancies found in studies when comparing different models under specific climate exposure. A more plausible comparison can be developed through a probabilistic approach since it offers the possibility to account the uncertainties related to model predictions and additionally [144], reduce the possibility of providing results that might fall outside of the 'intermitted' domain. Therefore, it is expected that this approach will reveal more accurately the differences and similarities when comparing mould models. Moreover, by running sensitivity analysis the influence of different parameters associated to the models can be investigated, which forms a more overarching comparison basis of the models.

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References

[1] WHO, WHO Guidelines for indoor air quality, Selected pollutants, 2010.
[2] R. Arthur, Damp indoor spaces and health, J. Public Health 27 (2) (2005). 234 234.
[3] M.S. Jaakkola, J.J. Jaakkola, Indoor molds and asthma in adults, Adv. Appl. Microbiol. 55 (2004) 309–338.
[4] IOM, Damp Indoor Spaces and Health, in: N.A. Press (Ed.) Washington DC, 2004.
[5] M.I. Gunnbjörnsdóttir, K.A. Franklin, D. Norbäck, E. Björnsson, D. Gislason, E. Lindberg, C. Svanes, E. Omenaas, E. Norrman, R. Jogi, Prevalence and incidence of respiratory symptoms in relation to indoor dampness: the RHINE study, Thorax 61 (3) (2006) 221–225.
[6] P. Howden-Chapman, K. Saville-Smith, J. Crane, N. Wilson, Risk factors for mold in housing: a national survey, Indoor Air 15 (6) (2005) 469–476.
[7] D. Mudarri, W.J. Fisk, Public health and economic impact of dampness and mold, Indoor air 17 (3) (2007) 226–235.
[8] U. Haverinen-Shaughnessy, A. Borras-Santos, M. Turunen, J.P. Zock, J. Jacobs, E. Krop, L. Casas, R. Shaughnessy, M. Täubel, D. Heederik, Occurrence of moisture problems in schools in three countries from different climatic regions of Europe based on questionnaires and building inspections–the HITEA study, Indoor Air 22 (6) (2012) 457–466.
[9] EN-13788, Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods, 2012.
[10] A. Standard, Standard 160-2009: Criteria for Moisture Control Design Analysis in Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta (2009).
[11] Byggforsk, Byggforskserien 421.132, Fukt i bygninger. Teorigrunnlag – 13 Kritisk fukttilstand, 2005.
[12] BSF, BFS 2011:26, Boverkets föreskrifter om ändring i verkets byggregler (2011: 6)–föreskrifter och allmänna råd, 2011.
[13] B. Standard, 5250: 2002: Code of practice for control of condensation in buildings, BSI, 2002.
[14] ABCB, Condensation in buildings – Handbook, Problems with Relative Humidity, Australian Building Codes Board, Australia, 2014.
[15] DIN-4108, Thermal insulation and energy economy in buildings, Part 4: Hygrothermal design values, 2013.
[16] K. Sedlbauer, Prediction of Mould Fungus Formation on the Surface of and Inside Building Components, Fraunhofer Institute, 2001.
[17] S. Thelandersson, T. Isaksson, Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions, Build. Environ. 65 (2013) 18–25.
[18] Togerö, Åse, Tengberg, The m-model: a method to assess the risk for mould growth in wood structures with fluctuating hygrothermal conditions, in: NSB 2011 – 9th Nordic Symposium on Building Physics, Tampere, Finland, 2011.
[19] H. Viitanen, T. Ojanen, Improved model to predict mold growth in building materials, in: Proceedings of the X International Conference on the Performance of the Exterior Envelopes of Whole Buildings, Clearwater, FL, 2007.
[20] A. Booth, D. Papaioannou, A. Sutton, Systematic approaches to a successful literature review, Sage (2011).
[21] M. Petticrew, H. Roberts, Systematic Reviews in the Social Sciences: A Practical Guide, John Wiley & Sons, 2008.
[22] M.E. Falagas, E.I. Pitsouni, G.A. Malietzis, G. Pappas, Comparison of PubMed Scopus, web of science, and Google scholar: strengths and weaknesses, FASEB J. 22 (2) (2008) 338–342.
[23] A. Aghaei Chadegani, H. Salehi, M.M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, N. Ale Ebrahim, A comparison between two main academic literature collections: web of Science and Scopus databases, Asian Social Sci. 9 (5) (2013) 18–26.
[24] P. Jacso, As we may search-comparison of major features of the Web of Science, Scopus, and Google Scholar citation-based and citation-enhanced databases, Curr. Sci.-Bangalore 89 (9) (2005) 1537.
[25] O. Adan, R. Samson, Fundamentals of mold growth in indoor environmens and strategies for a healthy living, Wageningen, The Netherlands, 2011.
[26] H. Hens, Fungal defacement in buildings: a performance related approach, HVAC&R Res. 5 (3) (1999) 265–280.
[27] IEA, Guideline & Practice, ANNEX XIV: Condensation and Energy, 1990.
[28] P. Johansson, T. Svensson, A. Ekstrand-Tobin, Validation of critical moisture conditions for mould growth on building materials, Build. Environ. 62 (2013) 201–209.

[29] A.L. Pasanen, J.P. Kasanen, S. Rautiala, M. Ikäheimo, J. Rantamäki, H. Kääriäinen, P. Kalliokoski, Fungal growth and survival in building materials under fluctuating moisture and temperature conditions, Int. Biodeterior. Biodegrad. 46 (2) (2000) 117–127.

[30] H. Viitanen, J. Vinha, K. Salminen, T. Ojanen, R. Peuhkuri, L. Paajanen, K. Lähdesmäki, Moisture and bio-deterioration risk of building materials and structures, J. Build. Phys. 33 (3) (2010) 201–224.

[31] S. Block, Humidity requirements for mold growth, Appl. Microbiol. 1 (6) (1953) 287.

[32] O. Theander, J. Bjurman, J. Boutelje, Increase in the content of low-molecular carbohydrates at lumber surfaces during drying and correlations with nitrogen content, yellowing and mould growth, Wood Sci. Technol. 27 (5) (1993) 381–389.

[33] H. Viitanen, Factors affecting the development of mould and brown rot decay in wooden material and wooden structures, (1996).

[34] A. Ritschkoff, H. Viitanen, K. Koskela, The response of building materials to the mould exposure at different humidity and temperature conditions, Proceedings of healthy buildings, Espoo, Finland, 2000, pp. 317–322.

[35] J.B.M. Coppock, E.D. Cookson, The effect of humidity on mould growth on constructional materials, J. Sci. Food Agric. 2 (12) (1951) 534–537.

[36] A.L. Pasanen, T. Juutinen, M.J. Jantunen, P. Kalliokoski, Occurrence and moisture requirements of microbial growth in building materials, Int. Biodeterior. Biodegrad. 30 (4) (1992) 273–283.

[37] P. Johansson, I. Samuelson, A. Ekstrand-Tobin, K. Mjörnell, P. Sandberg, E. Sikander, Microbiological growth on building materials – critical moisture levels. State of the art, in: S.S.N.T.a.R. Institute (Ed.) 2005.

[38] L.R. Gobakken, O.A. Høibø, H. Solheim, Factors influencing surface mould growth on wooden claddings exposed outdoors, Wood Mater. Sci. Eng. 5 (1) (2010) 1–12.

[39] P. Johansson, A. Ekstrand-Tobin, T. Svensson, G. Bok, Laboratory study to determine the critical moisture level for mould growth on building materials, Int. Biodeterior. Biodegrad. 73 (2012) 23–32.

[40] J. Bjurman, Influence of storage on mould susceptibility of wood at RH values lower than 100%. The International Research Group On Wood Preservation. Doc, IRG/WP/1413, 1989.

[41] D. Park, Phylloplane fungi: tolerance of hyphal tips to drying, Trans. Br. Mycol. Soc. 79 (1) (1982) 174–178.

[42] Q. Wang, Wood-based boards-Response to attack by mould and stain fungi, Sveriges Lantbruksuniv.1992.

[43] A. Hocking, B. Miscamble, J. Pitt, Water relations of Alternaria alternata Cladosporium sphaeospermum, Curvularia lunata and Curvularia pallescens, Mycol. Res. 98 (1) (1994) 91–94.

[44] Q. Wang, Growth of mold and stain fungi on wood-based boards in relation to temperature and relative-humidity, Mater.Org. 28 (2) (1994) 81–103.

[45] C. Black, Mould Resistance of Full Scale Wood Frame Wall Assemblies, University of Waterloo, Waterloo, 2006.

[46] C. Grant, C. Hunter, B. Flannigan, A. Bravery, The moisture requirements of moulds isolated from domestic dwellings, Int. Biodeterior. 25 (4) (1989) 259–284.

[47] N. Magan, J. Lacey, Effect of water activity, temperature and substrate on interactions between field and storage fungi, Br. Mycol. Soc. 82 (1) (1984) 83–93.

[48] H. Viitanen, Factors affecting the development of biodeterioration in wooden constructions, Mater. Struct. 27 (8) (1994) 483–493.

[49] J. Clarke, C. Johnstone, N. Kelly, R. McLean, N. Rowan, J. Smith, A technique for the prediction of the conditions leading to mould growth in buildings, Build. Environ. 34 (4) (1999) 515–521.

[50] K.F. Nielsen, G. Holm, L.P. Uttrup, P.A. Nielsen, Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism, Int. Biodeterior. Biodegrad. 54 (4) (2004) 325–336.

[51] N. Magan, Fungi in extreme environments, in: D.T. Wicklow, B. Soderstrom (Eds.), The Mycota IV, Environmental and Microbial Relationships, Springer-Verlag, Berlin, 1997.

[52] A. Nevalainen, A.-L. Pasanen, M. Niininen, T. Reponen, P. Kalliokoski, M. Jantunen, The indoor air quality in Finnish homes with mold problems, Environ. Int. 17 (4) (1991) 299–302.

[53] A.-L. Pasanen, P. Kalliokoski, P. Pasanen, M. Jantunen, A. Nevalainen, Laboratory studies on the relationship between fungal growth and atmospheric temperature and humidity, Environ. Int. 17 (4) (1991) 225–228.

[54] H.A. Viitanen, Modelling the time factor in the development of mould fungi – the effect of critical humidity and temperature conditions on pine and spruce sapwood, Holzforschung 51 (1) (1997) 6–14.

[55] H. Viitanen, J. Bjurman, Mould growth on wood under fluctuating humidity conditions, Mater. Org. 29 (1) (1995) 27–46.

[56] K. Salminen, R. Peuhkuri, K. Lähdesmäki, H. Viitanen, J. Vinha, L. Paajanen, H. Iitti, T. Ojanen, T. Strander, Mould growth on building materials in laboratory and field experiments, Rakennusfysiikka Symposium Proceedings 2009 (2009) 219–228.

[57] G. Ayerst, The effects of moisture and temperature on growth and spore germination in some fungi, J. Stored Prod. Res. 5 (2) (1969) 127–141.

[58] C. Land, Z. Banhidi, A.C. Albertsson, Surface discoloring and blue staining by cold-tolerant filamentous fungi on outdoor softwood in Sweden, Mat. Organismen (Germany, FR) (1985).

[59] C. Nunes, J. Usall, T. Manso, R. Torres, M. Olmo, J. García, Effect of high temperature treatments on growth of Penicillium spp. and their development on 'Valencia'oranges, Food Sci. Technol. Int. 13 (1) (2007) 63–68.

[60] J. Holme, K. Noreng, T. Kvande, Moisture and Mould Growth in Compact Roofs–Results from a Three-Stage Field Survey, 8th Symposium on Building Physics in the Nordic Countries., Dept. of Civil Engineering, Technical, 2008, pp. 1221-1228.

[61] S. Geving, J. Holme, The drying potential and risk for mold growth in compact wood frame roofs with built-in moisture, J. Build. Phys. 33 (3) (2010) 249–269.

[62] P. Johansson, G. Bok, A. Ekstrand-Tobin, The effect of cyclic moisture and temperature on mould growth on wood compared to steady state conditions, Build. Environ. 65 (2013) 178–184.

[63] H.L.S.C. Hens, Mold in dwellings – a building physics related approach, Moisture, Microbes and Health Effects: Indoor Air Quality and Moisture in Buildings Conference, IAQ 2001, November 4, 2001 – November 7, 2001, Amer. Soc. Heating, Ref. Air-Conditoning Eng. Inc., San Francisco, CA, United states, 2001.

[64] S. Boutin-Forzano, C. Charpin-Kadouch, S. Chabbi, N. Bennedjai, H. Dumon, D. Charpin, Wall relative humidity: a simple and reliable index for predicting Stachybotrys chartarum infestation in dwellings, Indoor Air 14 (3) (2004) 196–199.

[65] T. Ojanen, H. Viitanen, R. Peuhkuri, Modelling of Mould Growth in Building Envelopes, IEA-Annex Meeting Porto, 2007.

[66] Y. Li, L. Wadsö, Fungal activities of indoor moulds on wood as a function of relative humidity during desorption and adsorption processes, Eng. Life Sci. 13 (6) (2013) 528–535.

[67] J. Holme, Mould Growth in Buildings, Norwegian University of Science and Technology, 2010.

[68] K. Sedlbauer, Prediction of Mould Fungus Formation on the Surface of and Inside Building Components, Fraunhofer Institute for Building Physics, 2001.

[69] Y. Sudiyani, S. Horisawa, K. Chen, S. Doi, Y. Imamura, Changes in surface properties of tropical wood species exposed to the Indonesian climate in relation to mold colonies, J. Wood Sci. 48 (6) (2002) 542–547.

[70] H. Viitanen, Factors affecting mould growth on kiln dried wood, in: Proceedings of COST E15 Conference, Helsinki, 2001.

[71] L.R. Gobakken, M. Westin, Surface mould growth on five modified wood substrates coated with three different coating systems when exposed outdoors, Int. Biodeterior. Biodegrad. 62 (4) (2008) 397–402.

[72] L.R. Gobakken, P.K. Lebow, Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors, Wood Sci. Technol. 44 (2) (2010) 315–333.

[73] C. Kose, A.M. Taylor, Evaluation of mold and termite resistance of included sapwood in eastern redcedar, Wood Fiber Sci. 44 (3) (2012) 319–324.

[74] E. Frühwald, Y. Li, L. Wadso, Image analysis study of mould susceptibility of spruce and larch wood dried or heat-treated at different temperatures, Wood Mater. Sci. Eng. 3 (1–2) (2008) 55–61.

[75] O.C.G. Adan, On the Fungal Defacement of Interior Finishes, Technische Universiteit Eindhoven, 1994.

[76] B. Flannigan, Approaches to assessment of the microbial flora of buildings, Environments for People: IAQ'92 (1993).

[77] J.M. Dinwoodie, Timber, its nature and behaviour, E & FN Spon; with the support of the Centre for Timber Technology and Construction at BRE2000.

[78] J. Boutelje, Increase in the content of nitrogenous compounds at lumber surfaces during drying and possible biological effects, Wood Sci. Technol. 24 (2) (1990) 191–200.

[79] N. Terziev, J. Bjurman, J. Boutelje, Effect of planing on mould susceptibility of kiln-and air-dried Scots pine (Pinus sylvestris L.) lumber, Mater. Org. 30 (2) (1996) 95–104.

[80] H. Viitanen, Mould growth on painted wood, Proceedings of Special Seminar COST E, 2002, pp. 4–5.

[81] N. Terziev, J. Bjurman, J. Boutelje, Mould growth at lumber surfaces of pine after kiln and air drying, Document-the International Research Group on Wood Preservation (Sweden) (1994).

[82] N. Terziev, J. Boutelje, Effect of felling time and kiln-drying on color and susceptibility of wood to mold and fungal stain during an above-ground field test, Wood Fiber Sci. 30 (1998) 360–367.

[83] H. Viitanen, J. Bjurman, Mould growth on wood under fluctuating humidity conditions, Mater. Org. 29 (1) (1994) 27–46.

[84] M. Sehlstedt-Persson, O. Karisson, T. Wamming, T. Moren, Mold growth on sapwood boards exposed outdoors: the impact of wood drying, Forest Prod. J. 61 (2) (2011) 170–179.

[85] P. Johansson, T. Wamming, G. Bok, M.L. Edlund, Mould growth on kiln-dried and air-dried timber, Eur. J. Wood Wood Prod. 71 (4) (2013) 473–481.

[86] A. Hukka, H.A. Viitanen, A mathematical model of mould growth on wooden material, Wood Sci. Technol. 33 (6) (1999) 475–485.

[87] N. Terziev, J. Boutelje, O. Söderström, The influence of drying schedules on the redistribution of low-molecular sugars in Pinus sylvestris L, Holzforschung-Int. J. Biol. Chem. Phys. Technol. Wood 47 (1) (1993) 3–8.

[88] S. Sehlstedt-Persson, High-temperature drying of Scots pine A comparison between HT- and LT-drying, Holz als Roh-und Werkstoff 53 (2) (1995) 95–99.

[89] J. Jermer, S.P.-O. Forskningsinstitut, Heat-treated Wood–durability and Technical Properties: Swedish Wood Association Project 2001-025, SP Swedish National Testing and Research Institute 2003.

[90] S.A. Ahmed, M. Sehlstedt-Persson, T. Morén, Mould susceptibility of Scots pine (Pinus sylvestris L.) sapwood: Impact of drying, thermal modification, and copper-based preservative, Int. Biodeterior. Biodegrad. 85 (2013) 284–288.

[91] D. Kocaefe, J.L. Shi, D.Q. Yang, J. Zhang, Preliminary study of thermal treatment effects on mold growth of selected Quebec wood species, For. Prod. J. 57 (12) (2007) 30–33.

[92] N. Yilgor, S. Nami Kartal, Heat modification of wood: Chemical properties and resistance to mold and decay fungi, For. Prod. J. 60 (4) (2010) 357–361.

[93] P. Ahola, S. Jämsä, H. Viitanen, P. Viitaniemi, Mould and blue stain on heat treated wood, Seminar on Bio-deterioration of Coated Wood–Coating and Substrate. COST E, 2002.

[94] S.L. Bardage, Susceptibility of painted wood to Aureobasidium pulluians: fungal stain and growth patterns, Holz als Roh-und Werkstoff 56 (5) (1998) 359–364.

[95] L.R. Gobakken, O.A. Høibø, H. Solheim, Mould growth on paints with different surface structures when applied on wooden claddings exposed outdoors, Int. Biodeterior. Biodegrad. 64 (5) (2010) 339–345.

[96] L.R. Gobakken, G.I. Vestøl, Surface mould and blue stain fungi on coated Norway spruce cladding, Int. Biodeterior. Biodegrad. 75 (2012) 181–186.

[97] P. Johansson, A. Ekstrand-Tobin, The effect of surface roughness on mould growth on wood, 10th Nordic Symposium on Building Physics, Lund, 2014.

[98] B. Andersen, J.C. Frisvad, I. Søndergaard, I.S. Rasmussen, L.S. Larsen, Associations between fungal species and water-damaged building materials, Appl. Environ. Microbiol. 77 (12) (2011) 4180–4188.

[99] B. Flannigan, J. Miller, Microbial growth in indoor environments, in: B. Flannigan, R.A. Samson, J.D. Miller (Eds.), Microorganisms in Home and Indoor Work Environments, New York: Taylor & Francis, 36, 2001, 67.

[100] H.J. Moon, Assessing Mold Risks in Buildings under Uncertainty, College of Architecture Georgia Institute of Technology, USA, 2005.

[101] Z. Abidin, A. Murad, Minimising energy use and mould growth risk in tropical hospitals, © Abdul Murad Zainal Abidin, 2012.

[102] C. Flink, Utvärdering av m-modellen i jämförelse med andra mögelriskmodeller, Rapport TVBM (5000-serie) (2012).

[103] E. Vereecken, S. Roels, Review of mould prediction models and their influence on mould risk evaluation, Build. Environ. 51 (2012) 296–310.

[104] S.L. Smith, S.T. Hill, Influence of temperature and water activity on germination and growth of Aspergillus restrictus and A. versicolor, Trans. Br. Mycol. Soc. 79 (3) (1982) 558–560.

[105] H. Hens, Mold in dwellings: field studies in a moderate climate, BETEC Conference (2003) 12–14.

[106] K. Gradeci, N. Labonnote, B. Time, J. Köhler, Mould Models Applicable to Wood-Based Materials – A Generic Framework (Accepted manuscript), Energy Procedia (2017).

[107] J. Anderson, J. Clarke, N. Kelly, R. McLean, N. Rowan, J. Smith, Development of a technique for the prediction/alleviation of conditions leading to mould growth in houses' Final Report for Contract Number 68017 Scottish Homes, Edinburgh, 1996.

[108] J.A. Clarke, C.M. Johnstone, N.J. Kelly, R.C. McLean, J.A. Anderson, N.J. Rowan, J. E. Smith, A technique for the prediction of the conditions leading to mould growth in buildings, Build. Environ. 34 (4) (1999) 515–521.

[109] S. Geving, Moisture Design of Building Constructions, Norwegian University of Science and Technology, Trondheim, 1997.

[110] S. Geving, Hygrothermal conditions in wooden claddings: test house measurements: report from Climate 2000, Byggforsk (2006).

[111] H. Viitanen, A. Ritschkoff, Mould growth in pine and spruce sapwood in relation to air humidity and temperature, Uppsala, 1991.

[112] H.A. Viitanen, Modelling the time factor in the development of mould fungi – the effect of critical humidity and temperature conditions on pine and spruce sapwood, Holzforschung-Int. J. Biol. Chem. Phys. Technol. Wood 51 (1) (1997) 6–14.

[113] H. Viitanen, T. Ojanen, Improved Model to Predict Mold Growth in Building Materials, (2007).

[114] T. Ojanen, H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, K. Salminen, Mold growth modeling of building structures using sensitivity classes of materials, in: Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference, 2010, pp. 1–10.

[115] T. Ojanen, R. Peuhkuri, H. Viitanen, K. Lähdesmäki, J. Vinha, K. Salminen, Classification of material sensitivity–new approach for mould growth modeling, in: 9th Nordic Symposium on Building Physics, 2011, pp. 867–874.

[116] M. Krus, K. Sedlbauer, W. Zillig, H.M. Künzel, A New Model for Mould Prediction and its Application on a Test Roof, The current problems of building-physics in the rural building, Cracow, 1999.

[117] K. Sedlbauer, Prediction of mould growth by hygrothermal calculation, J. Build. Phys. 25 (4) (2002) 321–336.

[118] H.J. Moon, G.L.M. Augenbroe, Towards a practical mould growth risk indicator, Build. Serv. Eng. Res. Technol. 25 (4) (2004) 317–326.

[119] S. Johansson, L. Wadsö, K. Sandin, Estimation of mould growth levels on rendered façades based on surface relative humidity and surface temperature measurements, Build. Environ. 45 (5) (2010) 1153–1160.

[120] S. Thelandersson, T. Isaksson, A. Ekstrand-Tobin, P. Johansson, Modelling of onset of mould growth for wood exposed to varying climate conditions, in: T. I.R.G.O.W. PROTECTION (Ed.) Beijing, China, 2009.

[121] T. Isaksson, S. Thelandersson, A. Ekstrand-Tobin, P. Johansson, Critical conditions for onset of mould growth under varying climate conditions, Build. Environ. 45 (7) (2010) 1712–1721.

[122] H.A. Viitanen, Modelling the time factor in the development of brown rot decay in pine and spruce sapwood-the effect of critical humidity and temperature conditions, Holzforschung-Int. J. Biol. Chem. Phys. Technol. Wood (1997) 99–106.

[123] H. Viitanen, Critical conditions for mould and decay resistance of wood, VTT Symp (263) (2010) 114–118.

[124] S. Thelandersson, T. Isaksson, J. Niklewski, Fuktsäker utformning av klimatskiljande byggnadsdelar med fuktkänsliga material, Lund, 2014.

[125] B. Berggren, M. Wall, Hygrothermal conditions in exterior walls for passive houses in cold climate considering future climate scenario, PassivhusNorden 2012 (2012).

[126] M. Nofal, K. Kumaran, Biological damage function models for durability assessments of wood and wood-based products in building envelopes, Eur. J. Wood Wood Prod. 69 (4) (2011) 619–631.

[127] M. Krus, M. Seidler, K. Sedlbauer, Comparative evaluation of the predictions of two established mold growth models, Thermal Performance of the Exterior Envelopes of Whole Buildings XI 2010, Florida, 2010.

[128] H. Viitanen, M. Krus, T. Ojanen, V. Eitner, D. Zirkelbach, Mold risk classification based on comparative evaluation of two established growth models, Energy Procedia 78 (2015) 1425–1430.

[129] E. Vereecken, K. Vanoirbeek, S. Roels, A preliminary evaluation of mould prediction models based on laboratory experiments, Energy Procedia 78 (2015) 1407–1412.

[130] E. Vereecken, K. Vanoirbeek, S. Roels, Towards a more thoughtful use of mould prediction models: a critical view on experimental mould growth research, J. Build. Phys. 39 (2) (2015) 102–123.

[131] H.R. Trechsel, M. Bomberg, Moisture control in buildings: the key factor in mold prevention, ASTM International, 2009.

[132] H.M. Künzel, Simultaneous heat and moisture transport in building components, One-and two-dimensional calculation using simple parameters. IRB-Verlag Stuttgart (1995).

[133] J. Clarke, Energy Systems Research Unit in collaboration with Department of Bioscience/Biotechnology, Energy Systems Unit, Dept of Bioscience and Biotechnology, University of Stracthclyde (1996).

[134] J.A. Clarke, Energy simulation in building design, Routledge2001.

[135] J. Clarke, Moisture flow modelling within the ESP-r integrated building performance simulation system, J. Build. Perform. Simul. 6 (5) (2013) 385–399.

[136] WUFI®Bio, WUFI®Bio, Fraunhofer IBP.

[137] T. Ojanen, R. Kohonen, M.K. Kumaran, Modeling heat, air, and moisture transport through building materials and components, Moisture Control Build (1994) 18–34.

[138] T. Oreszczyn, S. Pretlove, Condensation Targeter II: modelling surface relative humidity to predict mould growth in dwellings, Build. Serv. Eng. Res. Technol. 20 (3) (1999) 143–153.

[139] T. Oreszczyn, S. Pretlove, Mould index, (2000).

[140] B.B. Dresden, Simulation program for the calculation of coupled heat, moisture, air, pollutant, and salt transport.

[141] Dartwin, Mold Simulator, Italy.

[142] T. Ojanen, H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, K. Salminen, Mold growth modeling of building structures using sensitivity classes of materials, Proceedings Building XI, 2010.

[143] E. 927-3, Paints and varnishes. Coating materials and coating systems for exterior wood. Natural weathering test, 2000.

[144] K. Gradeci, N. Labonnote, B. Time, J. Köhler, A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades, World Conference on Timber Engineering, Vienna, 2016.

Paper III

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Mould Models Applicable to Wood-Based Materials – A Generic Framework

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Abstract

This paper systematically reviews mould models that are applicable to wood-based materials. Both similarities and differences are observed with respect to governing factors and their interrelations, methodology, experimental set-ups, substrate and extensiveness, and how the result is communicated. Therefore, a generic framework, representing the general computation procedure of all models, is developed considering the factors that govern mould behaviour. This framework, adapted to each model, is used to structure, evaluate and compare current models. This outline supplemented with a comparison table, revealing the models' extensiveness and differences, establishes a basis to ensure better adequate application of the selected mould model for the case at hand.

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Keywords: Mould, Wood, Timber, Mould Models, Generic Framework, Systematic Review

1. Introduction

Mould can result in financial loss and unfavourable social problems such as discomfort and health risks [1]. Mould prevention is a conventional design stage part; however, the repeated problems in buildings suggest that the representation of this biological phenomenon need clarification [2]. Models have been developed attempting to represent mould growth activity [3-6]. Discrepancies have been found when comparing these models with each other, or when analyzing their validity with results from experimental research [2]. These differences and discrepancies may

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impose challenges for selecting the adequate model. Therefore, this paper's scope is to provide clarity in this field, by offering the end-user basis and background for the selection of the most applicable model to the specific case at hand.

2. Methodology

This article is a complementary work of a systematic literature review [2] investigating the criteria and models representing mould activity in wood-based materials. The review methodology and its application can be found in [2]. The validity and limitation of the models compared to the results from the experimental research review is also discussed in [2]. The scope of the present paper is to extent the previous work by providing a summary and more clarity of the differences between mould models, and therefore improve their applicability, by:

- Identifying and describing current available mould models applicable to wood-based materials.
- Creating a scheme derived from results in [2] that presents the mould governing factors and their features that should be considered when opting the representation of mould growth activity.
- Converting this scheme into a generic framework which can be used: a) to inform and guide researches of the necessary steps and features to be considered when developing new models applicable to building engineering and/or b) to structure, evaluate and compare current models by creating a neat outline.
- Adapting this framework to current models to show in a structured manner their computation procedure.
- Creating an overview table that shows and compares the characteristics of mould models including the governing factors and their extension, experimental basis used and characteristics of the assessment procedure.

3. Results

3.1. Proposed scheme and generic framework

From the review of experimental research [2], mould governing factors are identified and brought schematically in Fig. 1 (a). This scheme is further developed and converted into a generic framework showing the general approach to mould growth assessment (see Fig. 1 (b)) that accounts for these factors and how they are considered in current models.

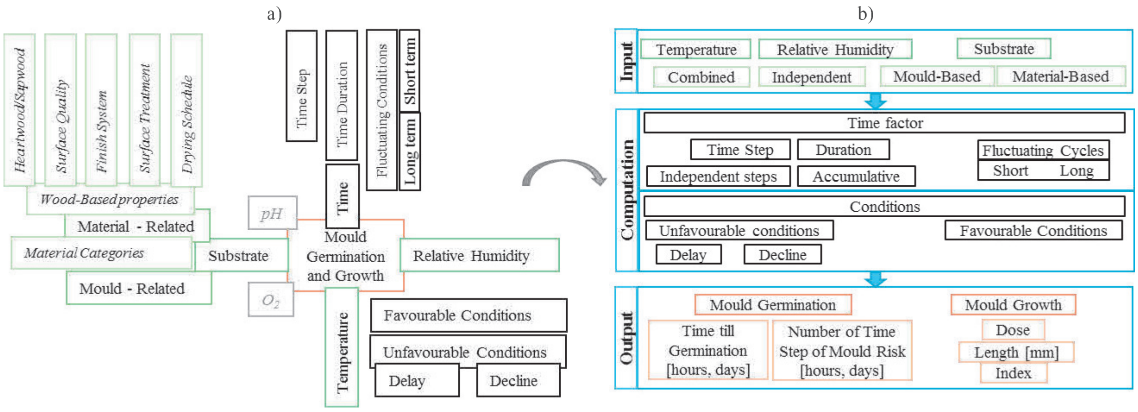

Fig. 1. Proposed scheme presenting mould governing factors and their features (a) and generic framework (b).

Three main parts are categorized; input (governing parameters that depend on the material and its exposure, temperature T and relative humidity RH), computation procedure and output (how results are communicated). Models are established as mould-based or material-based. Mould-based models are developed considering either the most common mould fungi, and thus excluding potential others; or as the mould fungi with the lowest requirements for growth, and thus considering the worst-case scenario; or several categories of mould fungi. Material-based models may create a more realistic basis for mould computation as in real-life situations. Materials' variation consideration are based on mould growth susceptibility, varying from broad categories up to specific materials with specific properties. Consideration should be put while defining the range of categories, since unrealistic mould computation may result due to the incorrect assumed substrate class or broad categorization. Small differences in material properties may provide different mould growth result [2]. Additionally, these models are fitted based on measurement of specific materials or mould fungi and therefore attention is required when using them outside the domain and conditions they were derived from. The computation procedure and methodology used to establish the model are two other crucial characteristic. Careful attention should be put on modelling the fluctuating condition, on the assessment duration and on a time-step that considers the variation of the hygrothermal properties. Two main mould outcome are calculated, mould germination (the onset of the fungi) and/or its growth (expressed in different levels or units). The outcome should be clearly defined, expressed in realistic unit and applicable to real-life situation and if categorized, a clear distinction of the categories should be available. Complementary to this framework, Table 1 provides suggestion when developing or improving mould model and Table 2 gives an overview of how current mould models (identified below in 3.2) consider these characteristics of the three main parts.

Table 1. Suggestions regarding what to consider when developing or improving mould models.

Input	The ranges of T (both low T<5ºC and T>30ºC) and RH (70 - 80 %) should be carefully considered. These two variables should be considered as joint contribution to mould growth [2].
	Material variation is very important and clear distinguishment of materials or groups of materials should be available, since different material own different mould growth susceptibility. Wood-based properties that affect mould growth should be also considered.
Computation	Time step should be sufficiently short to consider the variation in time of temperature and relative humidity. One hour is suggested.
	The assessment duration should account for the total service life of the construction which is checked for mould occurrence.
	Fluctuating condition must be carefully modeled, accounting for both long and short cycles.
	A delay and a decrease of mould growth should be both considered depending on the encountered unfavourable conditions.
Output	Clear ranges of mould germination and growth should be available, where it is possible to derive the consequences of the specific range. It is suggested to use the standard available scales, used for inspection as in the guidelines, for example as in EN 927-3.
Method	Consideration when extending the model from the measurements and domain that were considered during the experimental set-ups. Isopleth considers the worst-case scenario, while regression technique might not include potential scenarios of mould growth.
	Model should account for uncertainties, both for the data retrieved from the experiments and when modeling the computational equations.
	Calibration of models with real-life situation should be an ongoing update project.

3.2. Identification of mould models and individual application of generic framework

VTT Model - The VTT model [7] consists of a differential equation based on laboratory studies in [8-10]. The model is improved [11] by investigating the variation of different materials. Four sensitivity classes are considered based on different coefficients and minimum requirements of RH. The mould growth is quantified by the mould index varying from zero to six where mould index 1 indicates germination. The model accounts for long seasonal cycles (> 24 hours), where during unfavourable conditions growth is modeled with a linear decrease.

MRD (Mould Resistance Design) model - This dose-response model [12] predicts mould germination (corresponding to VTT Index 1) based upon the results of experimental data [8, 10]. The model is originally based on daily averages of RH and T, however later is modified with 12 hour averages [4]. 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 [13]. The model considers results from [14] for unfavourable conditions, and [13] for the effect of cyclic RH and T. The difference between wood-based materials is considered from the factor μ_x.

m-model - The m-model calculates the 'accumulated risk time' until germination (VTT Index 1) based on hourly-data [5]. The model is based on the laboratory studies [8, 9, 15, 16], where six mathematical expressions of the critical humidity are calculated for six duration. The total accumulated risk is the sum of all time steps where the parameter $m \geq 1$ considering unfavourable conditions. This model has similarities regarding the concept of 'm' as in [17].

Biohygrothermal IBP – This model combines Lowest Isopleth Model (LIM) model that determines germination time for spores and mycelium growth rate, and a transient biohygrothermal model that considers the influence of varying conditions [3, 18]. Four substrate categories are used. The LIM curves for each category represent minimum requirements assuming worst-case scenario. Mould growth is modeled as a non-declining and expressed in mm.

Johansson et al. Model - The model is based on results from house façades exposed in outdoor conditions over a 20-month period, investigating the influence of the thermal inertia, surface colour and compass directions [19]. Three different indices are used to express mould growth. The first index is based only on the RH at room T. In the second index, two functions are introduced to account for the interaction between RH and T, derived from literature data for

Cladosporium spp. The third index includes a delaying function when the organism has been outside its growth limits (when either both or one of functions equals zero), however the duration of this time is not provided.

Gobakken et al. Model - A cumulative logit model is developed from extensive experimental studies investigating large variation of wood substrates, surface structure, paint system, coating typology in [20-22]. The latest model is a function of wood substrate, coating typology, exposure time, RH higher than 80 % and T higher than 5 °C.

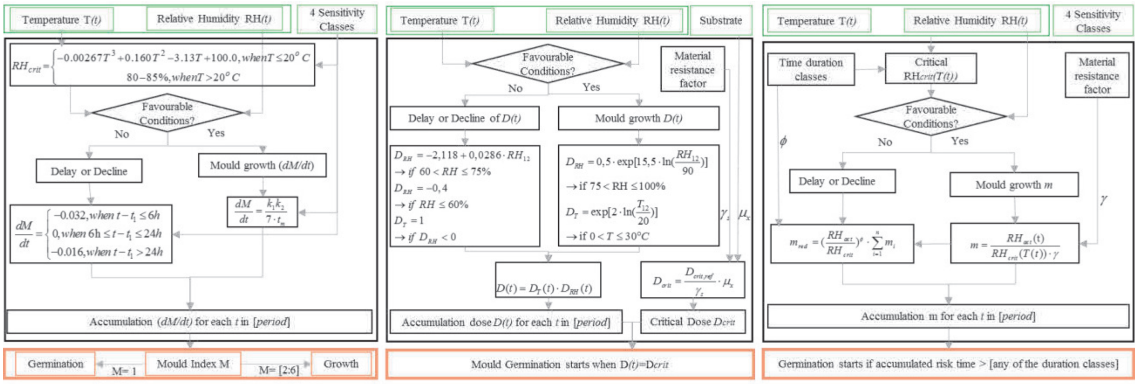

Fig. 2. Individual Generic Framework for VTT- (left), MRD- (middle) and m-model (right).

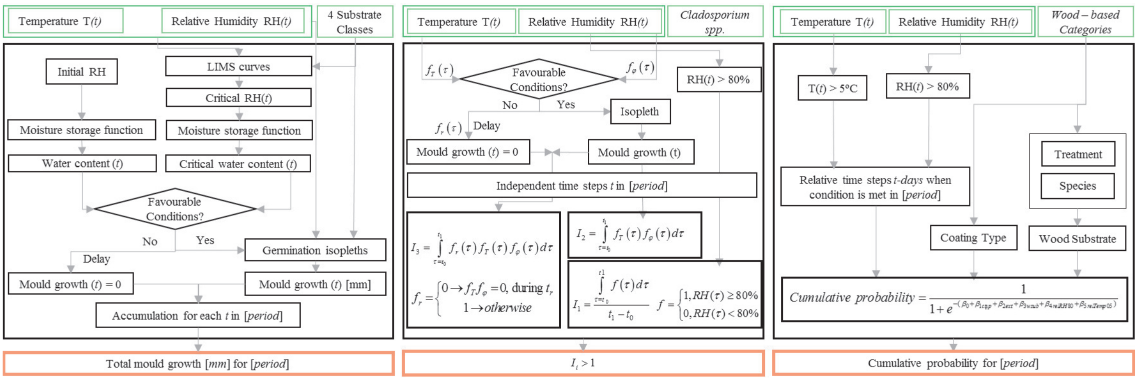

Fig. 3. Individual Generic Framework for Biohygrothermal- (left), Johanson et al. - (middle) and Gobakken et al.-model (right).

Mould Germination Graph Method – The model [23] accounts for previous time steps of RH and T to consider the effect of the fluctuating conditions. Mould growth is expressed as the number of mould risky days over a simulation period. During unfavourable conditions, the exposure time is set to zero. The graph is based on the isopleths of *A. Restrictus* [24, 25]. Each state condition is assigned into one of the groups presented at the mould germination graph. The effect of different building materials is not considered, however a correction factor can be used.

Max-days Model - The Max-days model [26, 27] assesses the mould growth based on weekly averages of hygrothermal properties. The mould growth potential 'Max-days' is calculated for one-year period. The relative growth rate is calculated for each week and is summed for a year and the result is expressed as the number of days with maximum conditions for germination. The model is derived using the experimental results from [8].

ESP-r Model - A literature review [28] investigated mould species affecting UK dwellings, which were grouped in six categories possessing similar growth requirements in terms of T or RH [29]. For each category, growth limit curves are generated from experimental data. The effect of exposure time and transient conditions is neglected.

Other models [24, 25, 30-34] are no further discussed due to restricted applicability or the same principles and data are advancements by other authors. Studies suggesting ergosterol as an indicator of mould growth, are not intended to use for prediction of mould germination and therefore are not treated any further in this article.

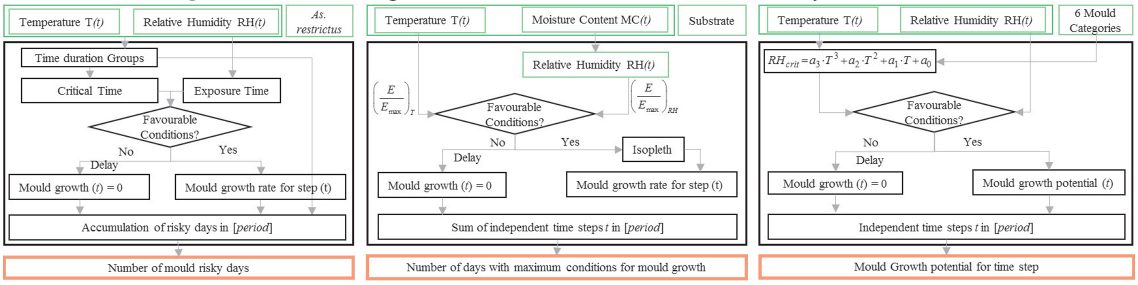

Fig. 4. Individual Generic Framework for Mould Germination Graph- (left), Max Days- (middle) and ESP-r model (right).

Table 2. Overview of characteristics of mould models (symbol '✓' stands for 'accounted or covered in the model', symbol '-' stands for 'not accounted or not covered', symbol 'Y/N' stands for Yes/No).

Factor \ Model		ESP-r (1996)	Max days – Model (1997)	VTT Model (1999)	Biohygro-thermal (2001)	Mould Germinatio n Graph (2004)	Johansson et al. Indices (2001)	MRD Model (2010)	Gobakken et al. model (2010)	m - model (2011)
RH	<75 %	-	-	-	✓	✓	-	-	-	-
	75 % - 80 %	✓	✓	-	✓	✓	-	✓	-	-
	>80 %	✓	✓	✓	✓	✓	✓	✓	✓	✓
T	<0 °C	-	-	-	✓	-	✓	✓	-	✓
	0 °C – 5 °C	-	✓	✓	✓	-	✓	✓	-	✓
	5 °C - 30 °C	✓	✓	✓	✓	✓	✓	✓	✓	✓
	>30 °C	✓	✓	✓	-	✓	✓	-	✓	✓
Experi-ments	Agar	✓	-	-	✓	✓	✓	-	-	-
	Laboratory	✓	✓	✓	✓	-	-	✓	-	✓
	Exposed	✓	-	-	-	-	✓	-	✓	-
	Visual	✓	✓	✓	✓	-	✓	✓	-	✓
	Microscope	✓	-	✓	✓	✓	✓	✓	✓	-
Assess-ment	Germination	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Growth	-	✓	-	✓	-	✓	-	✓	-
	Unit to express	Y/N	Y/N	VTT Index	mm, Index	Time	Mould Indices	Time, Index	logit ratio	Time, Index
Comp-utation	Delay	-	-	✓	✓	✓	✓	✓	implicit	✓
	Steps	hourly	weekly	hourly	hourly	daily	hourly	12 hours	daily	hourly
	Decrease	-	-	✓	-	-	-	✓	implicit	✓
	Ass. Period	no limit	one year	no limit	no limit	no limit	no limit	no limit	12 years	4 years
	Mould-based	Six mould categories				*A. Versicolor*	*Cladosporium spp.*			
	Material-based		Wooden materials	Four classes	Four classes		Wooden materials	Variation of wooden materials	Wooden materials & properties	Four classes
Methodology		Equation & Isopleths	Equation	Equation	Isopleths & Equation	Isopleths & Equation	Indices & Isopleth	Dose & Isopleths	Probabilistic model	Equation

4. Conclusions

Current mould models possess different characteristics and assumptions that contradict each other. They differ with respect to governing factors and interrelations, methodology, experimental set-ups, substrate and extensiveness, and how they express mould. In order to assure better adequate applicability, a clear overview of mould models accompanied with a sound comparison revealing characteristics, limitation and extensiveness is provided by:

- Identifying current mould models applicable to wood-based materials by conducting a systematic literature review.
- Proposing a generic framework which can be used: a) to inform and guide researches of the necessary steps and what to be considered when developing new models and/or b) to structure, evaluate and compare current models

by creating a neat outline. Through adapting this framework to each mould model, a clearer overview of the individual computation procedure of each model is provided, and therefore the comparison is clearer and simpler.
- Creating an overview table of comparison showing clearly the differences between mould models.

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References

[1] WHO, WHO Guidelines for indoor air quality, Selected pollutants, 2010.
[2] K. Gradeci, N. Labonnote, B. Time, J. Köhler, Mould Occurrence Criteria and Design Approaches in Wood-Based Materials – A Systematic Review (Manuscript submitted for publication.), 2016.
[3] K. Sedlbauer, Prediction of mould fungus formation on the surface of and inside building components, Fraunhofer Institute, 2001.
[4] S. Thelandersson, T. Isaksson, Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions, Build. Environ. 65 (2013) 18-25.
[5] Togerö, Åse, Tengberg, The m-model: a method to assess the risk for mould growth in wood structures with fluctuating hygrothermal conditions., NSB 2011 - 9th Nordic Symposium on Building Physics, Tampere, Finland, 2011.
[6] H. Viitanen, T. Ojanen, Improved model to predict mold growth in building materials, Proceedings of the X International Conference on the Performance of the Exterior Envelopes of Whole Buildings, Clearwater, FL, 2007.
[7] A. Hukka, H. Viitanen, A mathematical model of mould growth on wooden material, Wood Science and Technology 33(6) (1999) 475-485.
[8] H. Viitanen, A. Ritschkoff, Mould growth in pine and spruce sapwood in relation to air humidity and temperature, Uppsala, 1991.
[9] H. Viitanen, J. Bjurman, Mould growth on wood under fluctuating humidity conditions, MATER.ORG. 29(1) (1995) 27-46.
[10] H.A. Viitanen, Modelling the time factor in the development of mould fungi-The effect of critical humidity and temperature conditions on pine and spruce sapwood, Holzforschung-International Journal of the Biology, Chemistry, Physics and Technology of Wood 51(1) (1997) 6-14.
[11] H. Viitanen, T. Ojanen, Improved Model to Predict Mold Growth in Building Materials, (2007).
[12] T. Isaksson, S. Thelandersson, A. Ekstrand-Tobin, P. Johansson, Critical conditions for onset of mould growth under varying climate conditions, Build. Environ. 45(7) (2010) 1712-1721.
[13] P. Johansson, G. Bok, A. Ekstrand-Tobin, The effect of cyclic moisture and temperature on mould growth on wood compared to steady state conditions, Build. Environ. 65 (2013) 178-184.
[14] H. Viitanen, Critical conditions for mould and decay resistance of wood, VTT Symp (263) (2010) 114-118.
[15] H. Viitanen, Factors affecting the development of mould and brown rot decay in wooden material and wooden structures, (1996).
[16] L. Nilsson, Kunskapsläge och råd kring fuktsäker projektering och tillämpning av fuktkrav i BBR för träkonstruktioner, TVBM (2009).
[17] C.-E. Hagentoft, Probabilistic Analysis of Hygrothermal Conditions and Mould Growth Potential in Cold Attics. Impact of Weather, Building System and Construction Design Characteristics, International Conference on Durability of Building Materials and Components, 2011.
[18] K. Sedlbauer, Prediction of Mould Growth by Hygrothermal Calculation, J. Build. Phys. 25(4) (2002) 321-336.
[19] S. Johansson, L. Wadsö, K. Sandin, Estimation of mould growth levels on rendered façades based on surface relative humidity and surface temperature measurements, Build. Environ. 45(5) (2010) 1153-1160.
[20] L.R. Gobakken, P.K. Lebow, Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors, Wood Sci Technol 44(2) (2010) 315-333.
[21] L.R. Gobakken, O.A. Høibø, H. Solheim, Mould growth on paints with different surface structures when applied on wooden claddings exposed outdoors, Int. Biodeterior. Biodegrad. 64(5) (2010) 339-345.
[22] L.R. Gobakken, O.A. Høibø, H. Solheim, Factors influencing surface mould growth on wooden claddings exposed outdoors, Wood Mater. Sci. Eng. 5(1) (2010) 1-12.
[23] H.J. Moon, Assessing Mold Risks in Buildings under Uncertainty, College of Architecture, Georgia Institute of Technology, USA, 2005.
[24] G. Ayerst, The effects of moisture and temperature on growth and spore germination in some fungi, Journal of Stored Products Research 5(2) (1969) 127-141.
[25] S.L. Smith, S.T. Hill, Influence of temperature and water activity on germination and growth of Aspergillus restrictus and A. versicolor, Transactions of the British Mycological Society 79(3) (1982) 558-560.
[26] S. Geving, Moisture Design of Building Constructions, Norwegian University of Science and Technology, Trondheim, 1997.
[27] S. Geving, Hygrothermal conditions in wooden claddings: test house measurements: report from Climate 2000, Byggforsk (2006).
[28] J. Anderson, J. Clarke, N. Kelly, R. McLean, N. Rowan, J. Smith, Development of a technique for the prediction/alleviation of conditions leading to mould growth in houses' Final Report for Contract Number 68017 Scottish Homes, Edinburgh, 1996.
[29] J.A. Clarke, C.M. Johnstone, N.J. Kelly, R.C. McLean, J.A. Anderson, N.J. Rowan, J.E. Smith, A technique for the prediction of the conditions leading to mould growth in buildings, Build. Environ. 34(4) (1999) 515-521.
[30] N. Magan, J. Lacey, Effect of water activity, temperature and substrate on interactions between field and storage fungi, British Mycological Society 82(1) (1984) 83-93.
[31] IEA, Guideline & Practice, ANNEX XIV : Condensation and Energy, 1990.
[32] H. Hens, Mold in dwellings: field studies in a moderate climate, BETEC Conference, 2003, pp. 12-14.
[33] H. Hens, Fungal defacement in buildings: A performance related approach, HVAC&R Research 5(3) (1999) 265-280.
[34] P. Johansson, T. Svensson, A. Ekstrand-Tobin, Validation of critical moisture conditions for mould growth on building materials, Build. Environ. 62 (2013) 201-209.

Paper IV

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

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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.

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:

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- 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:

2.1.1. 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.

2.1.2. 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.

2.1.3. 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.

2.1.4. 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.

2.1.5. 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:

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

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.

$$T_t = Cst_t + Seasonal_t + f_t(autocorrelation,\ regressive) + \varepsilon_t \quad (2)$$

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

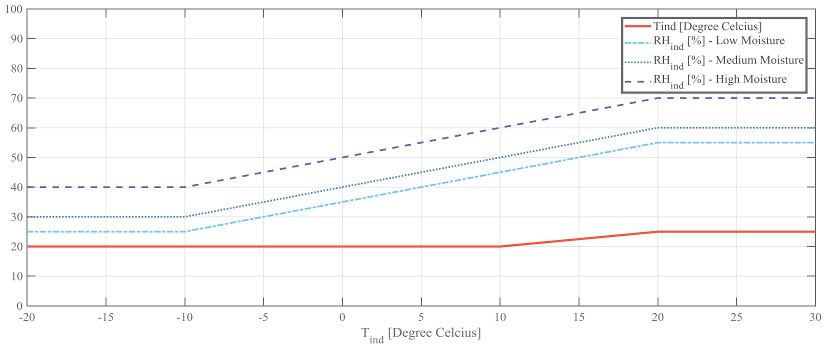

Fig. 1. Calculation of the inner climate based on the outdoor conditions according to EN 15026 [25].

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 Fig. 1). 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 Ref. [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%.

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

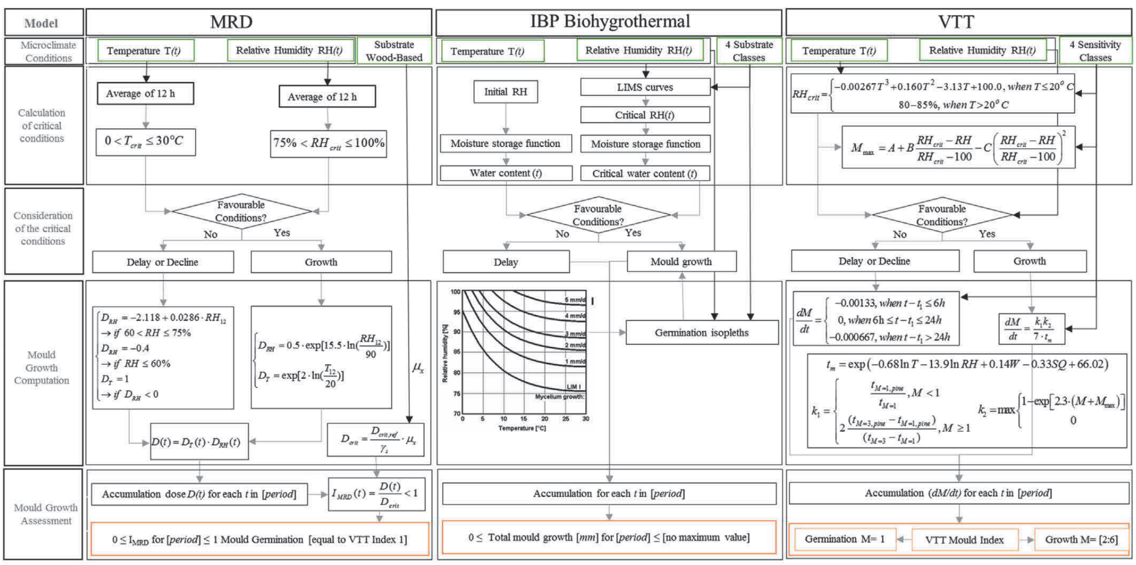

Fig. 2. Schematics of the three mould models (MRD, IBP Biohygrothermal and VTT – model) by adapting the framework presented in Ref. [9].

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 h	✓	no limit	Variation of wooden materials	Dose model and isopleths	WUFI

daily averages of RH and T, however later is modified with 12-h averages [39]. The total dose $D(t)$ for n days is the sum of the 12-h averages doses D. It is further calibrated with new laboratory data for wooden materials by Ref. [43]. The model considers results from Ref. [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 modelled as a non-declining and expressed in mm, as the blotch diameter. Fig. 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.

2.4.1.1. 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.

2.4.1.2. Mould growth assessment criteria. The models differ in the way they express and assess the mould growth outcome (see Fig. 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.

2.4.1.3. 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 Fig. 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.

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

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 %	1	Biodegradable building materials	76 %	Spruce and Pine (Original and Planed)	75 %
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 %		

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 Fig. 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:

$$F = \{C - D \leq 0\} \tag{3}$$

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:

$$P[F] \cong N_{\mathcal{F}}/N \tag{4}$$

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. Fig. 3 presents the schematic workflow. Seamless workflow enables to efficiently convert the variability of the input parameters into a probabilistic representation of the output.

3. Application of the proposed methodology

3.1. Materials

This work focuses in the investigation of a timber façade

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

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

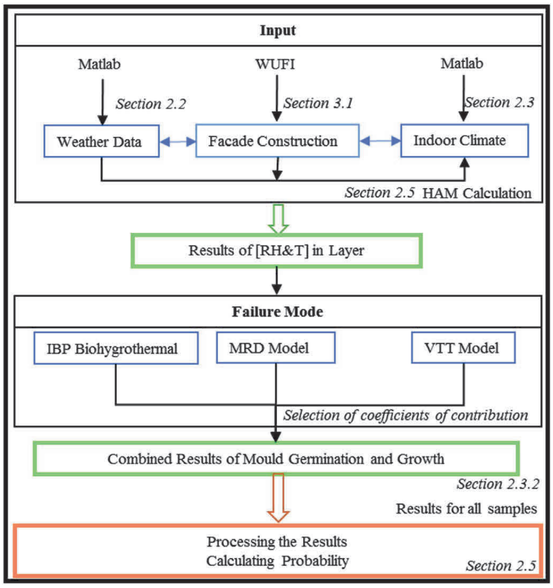

Fig. 3. Schematic seamless and integrated workflow.

constructions (see Fig. 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 Fig. 4 and Table 4).
- Secondly, three additional façade constructions, made from cross-laminated timber (CLT), gypsum board and one highly insulated constructions (see Fig. 4 and Table 4), are investigated to point out the influence of the configurations and different materials applied.

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 Fig. 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 Ref. [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

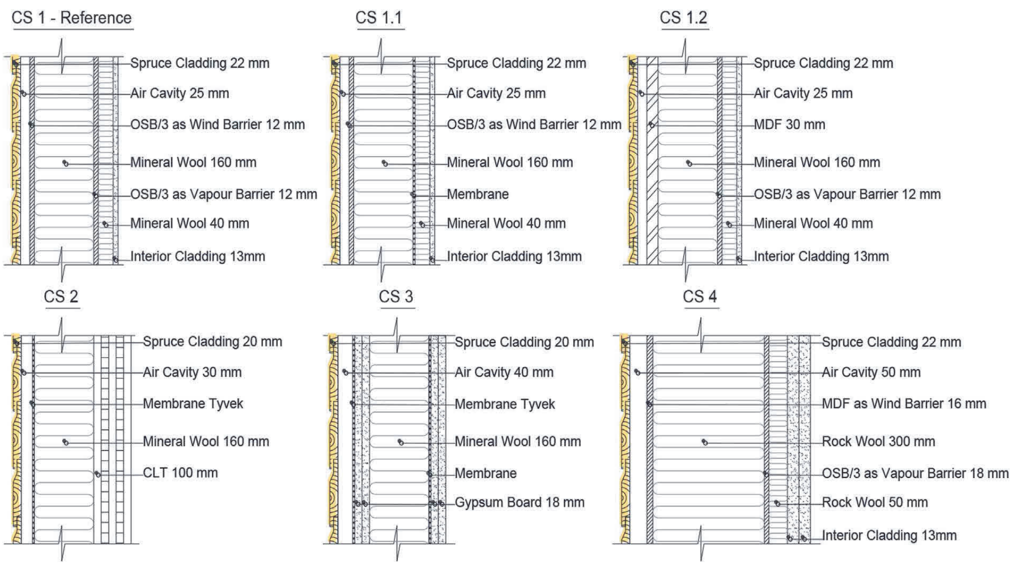

Fig. 4. Façade cross-sections.

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/m^3]	[J/kgK]	[m^3/m^3]
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

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 Ref. [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 Fig. 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 °C. 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. Fig. 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

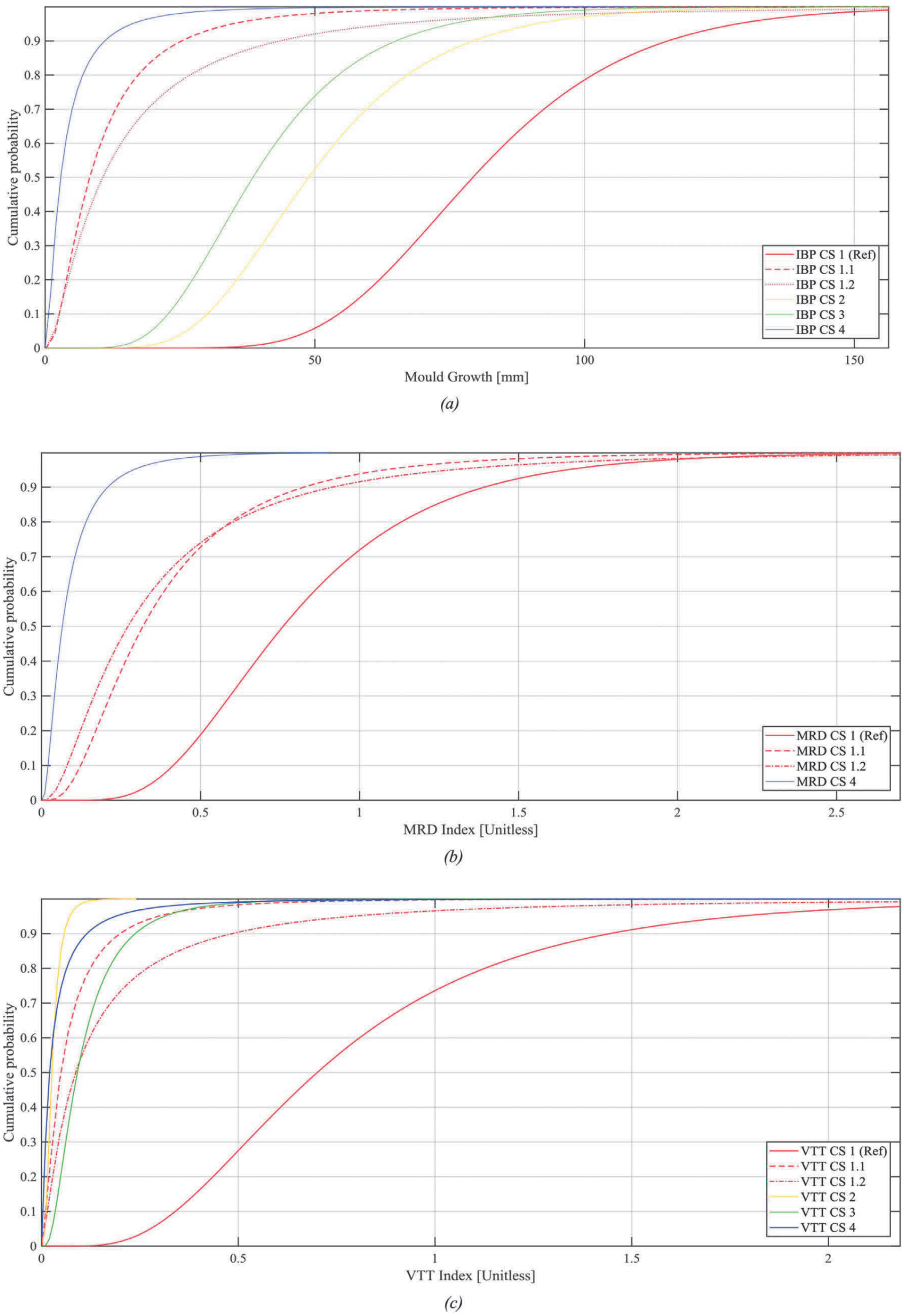

Fig. 5. The cumulative density function of mould growth according to IBP Biohygrothermal (a), MRD (b) and VTT (c) model for a duration of one year.

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.

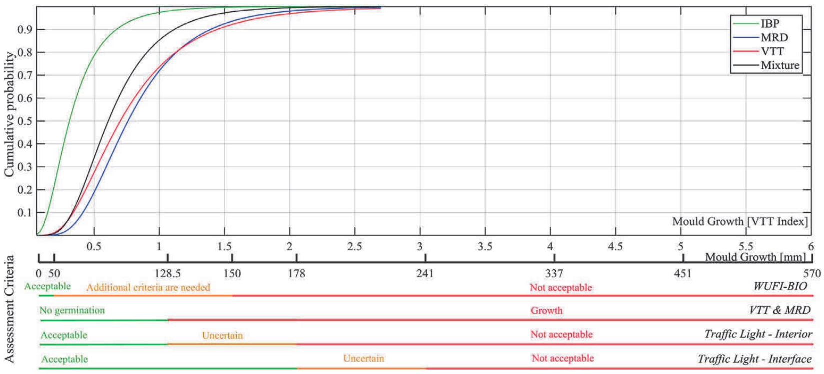

Fig. 6. Cumulative density distribution of mould growth for three models and mixture for a duration of one year together with different assessment criteria.

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

Model	Mould Growth	Case						
		1	1.1.	1.2.	1.3.	2	3	4
VTT	Index 1	0,736	0997	0,966	0952	1	0,999	0998
	Index 2	0,968	1000	0,990	0983	1	1	1
MRD	Index 1	0,719	0938	0,913	0913	NA	NA	0,999
	Index 2	0,980	0993	0,982	0982	NA	NA	1
IBP	50 mm	0,058	0980	0,921	0921	0,525	0738	0,997
	100 mm	0,786	0998	0,979	0979	0,971	0990	1
	150 mm	0,985	1	0,992	0992	0,998	1	1

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).

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 Fig. 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.

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. Fig. 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 Fig. 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.

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-h to 12-h [39]. This influence is possible to be analysed for the VTT and MRD and shown in Fig. 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-h 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.

4.2.3. Influence of initiation time of the simulation

The initiation of the simulation may have a strong influence when

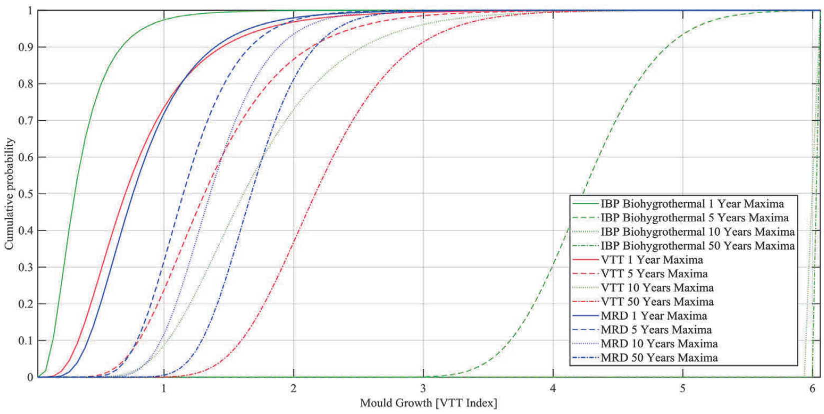

Fig. 7. The cumulative density function of mould growth according to three models. The influence of time duration.

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 Fig. 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.

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 Fig. 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.

5. Discussion

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

The probabilistic-based methodology is a very efficient technique 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

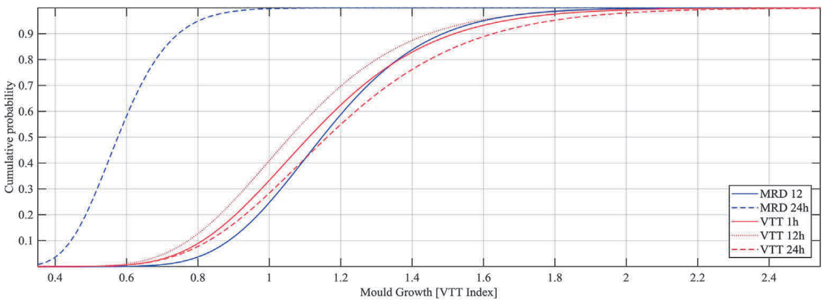

Fig. 8. Cumulative density function for MRD and VTT model during 50 years. The influence of time-step.

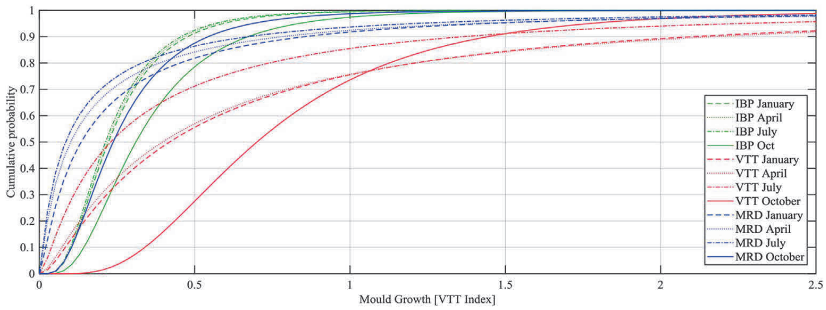

Fig. 9. The cumulative density function of mould growth according to three mould models for the duration of one year. The influence of the initiation date.

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 categorization 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 categorization 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 Ref. [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

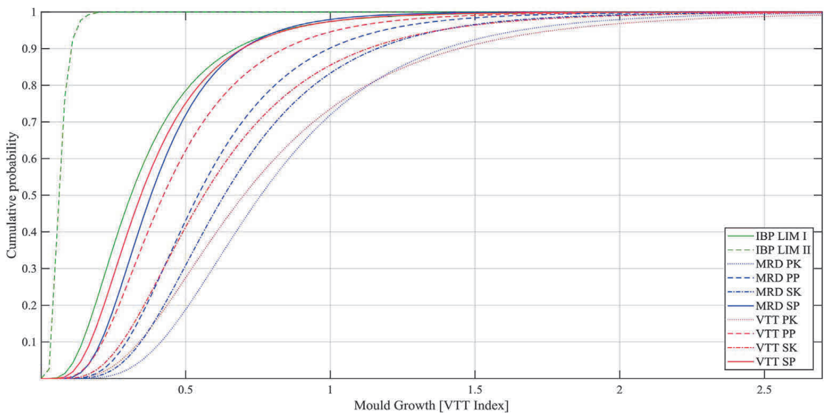

Fig. 10. The cumulative density function of mould growth according to three mould models for the duration of one year. The influence of the substrate choice.

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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References

[1] WHO Guidelines for Indoor Air Quality, (2010).
[2] R. Arthur, Damp indoor spaces and health, J. Public Health 27 (2) (2005) 234–234.
[3] IOM, N.A. Press (Ed.), Damp Indoor Spaces and Health, 2004 Washington DC.
[4] C. Rode, Danish Mould Research Programme, Department of Civil Engineering, Technical University of Denmark, 2005.
[5] M.I. Gunnbjörnsdóttir, et al., Prevalence and incidence of respiratory symptoms in relation to indoor dampness: the RHINE study, Thorax 61 (3) (2006) 221–225.
[6] D. Mudarri, W.J. Fisk, Public health and economic impact of dampness and mold, Indoor air 17 (3) (2007) 226–235.
[7] U. Haverinen-Shaughnessy, et al., Occurrence of moisture problems in schools in three countries from different climatic regions of Europe based on questionnaires and building inspections–the HITEA study, Indoor Air 22 (6) (2012) 457–466.
[8] K. Gradeci, N. Labonnote, B. Time, J. Köhler, Mould growth criteria and design avoidance approaches in wood-based materials – a systematic review, Constr. Build. Mater. Rev. 150 (2017) 77–88.
[9] K. Gradeci, N. Labonnote, J. Köhler, B. Time, Mould models applicable to wood-based materials – a generic framework, Energy Procedia 132 (2017) 177–182.
[10] E. Vereecken, S. Roels, Review of mould prediction models and their influence on mould risk evaluation, Build. Environ. 51 (2012) 296–310.
[11] C. Flink, Utvärdering Av M-modellen I Jämförelse Med Andra Mögelriskmodeller, Rapport TVBM (5000-serie) (2012).
[12] E. Vereecken, K. Vanoirbeek, S. Roels, Towards a more thoughtful use of mould prediction models: a critical view on experimental mould growth research, J. Build. Phys. 39 (2) (Sep 2015) 102–123.
[13] K. Gradeci, N. Labonnote, B. Time, J. Köhler, A proposed probabilistic-based design methodology for predicting mould occurrence in timber façades, World Conference on Timber Engineering, Vienna, 2016.
[14] K. Gradeci, N. Labonnote, B. Time, J. Köhler, A probabilistic-based approach for predicting mould growth in timber building envelopes: comparison of three mould models, Energy Procedia 132 (2017) 393–398.
[15] S. Geving, A systematic method for hygrothermal analysis of building constructions using computer models, Proceedings of the Building Simulation, vol. 2, 1997, pp. 355–361 (Citeseer).
[16] C.-E. Hagentoft, Probabilistic analysis of hygrothermal conditions and mould growth potential in cold attics. Impact of weather, building system and construction design characteristics, International Conference on Durability of Building Materials and Components, 2011.
[17] C.-E. Hagentoft, A. Sasic Kalagasidis, Moisture safe cold attics-Assessment based on risk analyses of performance and cost, Proceedings of 10th Nordic Symposium on Building Physics, 2014, pp. 1366–1373.
[18] Z. Sadovsky, O.G. Koronthalyova, P. Matiaovsky, K. Mikulova, Probabilistic modelling of mould growth in buildings, Journal of Building Physics 37 (4) (2014) 348–366.
[19] O.C. Adan, R.A. Samson, Fundamentals of Mold Growth in Indoor Environments and Strategies for Healthy Living, Wageningen Academic Publishers Wageningen, The Netherlands, 2011.
[20] K. Pietrzyk, A systemic approach to moisture problems in buildings for mould safety modelling, Build. Environ. 86 (2015) 50–60.
[21] S. Thelandersson, T. Isaksson, M. Häglund, E. Frühwald, Probabilistic Methods for Performance Based Service Life Evaluation of Wooden Components, Applications of Statistics and Probability in Civil Engineering, 2011, p. 401.
[22] V. M. Nik, A. Sasic Kalagasidis, and E. Kjellström, "Assessment of hygrothermal performance and mould growth risk in ventilated attics in respect to possible climate changes in Sweden," Build. Environ., vol. 55, pp. 96–109, 2012/09/01/2012.
[23] C.E. Hagentoft, A.S. Kalagasidis, C. Rode, 55, Reliability of Energy Efficient Building Retrofitting-probability Assessment of Performance & Cost (RAP-RETRO)," Framework for Probabilistic Assessment of Performance of Retrofitted Building Envelopes, (2015).
[24] S. Geving, Hygrothermal analysis of building structures using computer models, J. Therm. Envelope Build. Sci. (2000) 224–243.
[25] EN-15026 Hygrothermal Performance of Building Components and Building Elements, (2004).
[26] S. Geving, Moisture Design of Building Constructions. Hygrothermal Analysis Using Simulation Models, Department of Building and Construction Engineering, The Norwegian University of Science and Technology, NTNU, 1997 PhD.
[27] K. Sedlbauer, Prediction of mould growth by hygrothermal calculation, J. Build. Phys. 25 (4) (2002) 321–336.
[28] K. Sedlbauer, Prediction of Mould Fungus Formation on the Surface of and Inside Building Components, Fraunhofer Institute, 2001 PhD.
[29] G.E. Box, G.M. Jenkins, G.C. Reinsel, G.M. Ljung, Time Series Analysis: Forecasting and Control, John Wiley & Sons, 2015.
[30] W.A. Woodward, H.L. Gray, Global warming and the problem of testing for trend in time series data, J. Clim. 6 (5) (1993) 953–962.
[31] Sean D. Campbell, Francis X. Diebold, Weather forecasting for weather derivatives, J. Am. Stat. Assoc. 100 (469) (2005) 6–16, http://dx.doi.org/10.1198/016214504000001051.
[32] L. Magnano, J. Boland, R. Hyndman, Generation of synthetic sequences of half-hourly temperature, Environmetrics 19 (8) (2008) 818–835.
[33] A. Hukka, H. Viitanen, A mathematical model of mould growth on wooden material, Wood Sci. Technol. 33 (6) (1999) 475–485.
[34] H. Viitanen, T. Ojanen, Improved Model to Predict Mold Growth in Building Materials, (2007).
[35] T. Ojanen, H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, K. Salminen, Mold growth modeling of building structures using sensitivity classes of materials, Thermal performance of the Exterior Envelopes of Whole Buildings XI International Conference, 2010, pp. 1–10.
[36] T. Ojanen, R. Peuhkuri, H. Viitanen, K. Lähdesmäki, J. Vinha, K. Salminen, Classification of material sensitivity–new approach for mould growth modeling, 9th Nordic Symposium on Building Physics, vol. 2, 2011, pp. 867–874.
[37] S. Thelandersson, T. Isaksson, A. Ekstrand-Tobin, P. Johansson, Modelling of Onset of Mould Growth for Wood Exposed to Varying Climate Conditions, (May 2009), p. 2009 Beijing, China24-28.
[38] T. Isaksson, S. Thelandersson, A. Ekstrand-Tobin, P. Johansson, Critical conditions for onset of mould growth under varying climate conditions, Build. Environ. 45 (7) (2010) 1712–1721.
[39] S. Thelandersson, T. Isaksson, Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions, Build. Environ. 65 (2013) 18–25.
[40] H. Viitanen and A. Ritschkoff, "Mould growth in pine and spruce sapwood in relation to air humidity and temperature," Uppsala1991, vol. 221.
[41] H. Viitanen, J. Bjurman, Mould growth on wood under fluctuating humidity

conditions, Mater. Org. 29 (1) (1995) 27–46 (in English).
[42] H.A. Viitanen, Modelling the time factor in the development of mould fungi-The effect of critical humidity and temperature conditions on pine and spruce sapwood, Holzforschung-International J. Biol. Chem. Phys. Technol. Wood 51 (1) (1997) 6–14.
[43] P. Johansson, G. Bok, A. Ekstrand-Tobin, The effect of cyclic moisture and temperature on mould growth on wood compared to steady state conditions, Build. Environ. 65 (2013) 178–184.
[44] H. Viitanen, Critical conditions for mould and decay resistance of wood, 2009 Wood and Fiber Product Seminar: VTT and USDA Joint Activity, Conference Paper No. 263, 2010, pp. 114–118.
[45] H. Viitanen, M. Krus, T. Ojanen, V. Eitner, D. Zirkelbach, Mold risk classification based on comparative evaluation of two established growth models, Energy Procedia 78 (2015) 1425–1430 11//.
[46] WUFI®Bio, "WUFI®Bio," ed: Fraunhofer IBP.
[47] P. Johansson, T. Svensson, A. Ekstrand-Tobin, Validation of critical moisture conditions for mould growth on building materials, Build. Environ. 62 (2013) 201–209.
[48] M. U. S. Guide, "The MathWorks Inc," Natick, MA, vol. vol. 4, p. 382, 1998.
[49] W.L. Martinez, A.R. Martinez, Computational Statistics Handbook with MATLAB, CRC press, 2007.
[50] R.E. Melchers, Structural Reliability, (1987) Horwood.
[51] S. Korsnes, B. Time, M. Vågen, H. Halstedt, S. Geving, J. Holme, Moisture risk in prefabricated wooden wall elements (TES-elements) with a vapour retarder of OSB/3, Passivhus Norden, 2013, pp. 336–348.
[52] A. Tietze, S. Boulet, S. Ott, S. Winter, Consideration of disturbances and deficiencies in the moisture safety design of tall timber facades, World Conference on Timber Engineering, Vienna, 2016.
[53] J. Vihna, Hygrothermal Performance of Timber-framed External Walls in Finnish Climatic Conditions vol. 658, Tampere University of Technology, Tampere, 2007 PhD.
[54] Y. Sudiyani, S. Horisawa, K. Chen, S. Doi, Y. Imamura, Changes in surface properties of tropical wood species exposed to the Indonesian climate in relation to mold colonies, J. Wood Sci. 48 (6) (2002) 542–547.
[55] N. M. Institute. (2016). www.eklima.met.no.
[56] C. Bludau (Ed.), Private Correspondence with WUFI Support Team, 2015.
[57] M. Salonvaara, A. Karagiozis, A. Holm, Stochastic Building Envelope Modeling—the Influence of Material Properties, (2001) Thermal Performance of Exterior Envelopes of Whole Buildings vol. III.
[58] EN-13788 Hygrothermal Performance of Building Components and Building Elements. Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation. Calculation Methods, (2012).
[59] H.M. Künzel, "Simultaneous Heat and Moisture Transport in Building Components," One-and Two-dimensional Calculation Using Simple Parameters, IRB-Verlag Stuttgart, 1995.
[60] Eurocode 0—Basis of Structural Design, (1990).
[61] Part 1–Basis of Design:-joint Committee of Structural Safety–JCSS, (2000).
[62] K. Gradeci, M. Baravalle, B. Time, J. Köhler, Cost-optimisation for timber façades exposed to rot decay, 12th International Conference on Structural Safety & Reliability Vienna, 2017.

Paper V

Uncertainty and sensitivity analysis for evaluating highly insulated walls to withstand rot decay and mould growth.

Uncertainty and sensitivity analysis for evaluating highly insulated walls to withstand biodeterioration

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ABSTRACT

The performance to withstand biodeterioration is evaluated for highly insulated timber walls. A probabilistic-based methodology is developed to account for the involved uncertainties and investigate their contribution to the output uncertainty. 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 investigated by carrying out lab measurements, and subsequently, a stochastic model is developed to represent this property. Deficiencies, considering penetration of wind-driven rain, are accounted for and represented by different moisture sources. Different sensitivity analysis techniques are applied and discussed. The outdoor and indoor climate, the thermal conductivity of the insulation material and the vapour diffusion factors of the vapour barrier are identified as the most dominant input variables. The timber ventilated walls show satisfactory performance to withstand biodeterioration unless potential deficiencies ware accounted for. The study shows that probabilistic-based methodology enables a more systematic approach to the evaluation of wall constructions. It accounts for the involved uncertainties, provides a clear association of the microbial growth and 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.

1 INTRODUCTION

Passive house is a leading standard for energy-saving constructions since it offers heating energy savings up to 80% [1]. Highly insulated walls have found increasing acceptance over the last few years in order to reduce the heat flow across the construction, and considering the requests of new building codes for higher minimum R-values. However, by increasing the insulation, the critical hygrothermal conditions of the layers on the colder side of the insulation will rise in cold weather or during summertime, and thus the likelihood of moisture-related damages increases significantly [2, 3]. Especially when wood-based materials are used, biodeterioration presents a serious concern due to the lower requirements for their growth [4, 5]. Mould and rot decay are biodeterioration phenomena that may jeopardise the integrity, functionality and durability of timber façade constructions, and violate the comfort and health of the occupants [6-9]. Comprehensive conclusions in terms of the moisture performance of highly insulated walls are needed in order to ensure their long-term performance and durability, and subsequently to support their wider implementation.

The design of façade constructions is replete with uncertainties. They are related to the outdoor and indoor climate, physical parameters of the materials properties and geometries, and the transfer of physical phenomena into numerical equations and models. The conventional design approaches, characterized by a deterministic nature, cannot account for the involved uncertainties. Contrarily, probabilistic-based approaches can account for these uncertainties, and thus have found increasing application during the last years [10-22]. However, an accurate stochastic representation of the system together with a comprehensive evaluation of biodeterioration is necessary to exploit the application of this methodology.

The system representation constitutes the probabilistic modelling of the outdoor and indoor climate and material properties and geometry. The outdoor climate is a very important variable affecting the design of building envelopes; hence, assumptions regarding its representation should be reliable. Its representation should consider the temporal and spatial variability of weather phenomena and resemble the expected service life of the constructions. Moreover, 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 the temperature. However, this modelling approach has resulted simplified and not fully representative in climates where temperature conditions diverge significantly from conditions at which thermal conductivity tests are conducted [23, 24]. Consequently, an accurate stochastic model representing this property is required. Lastly, in real life conditions, deficiencies from water leakages and workmanship quality increase moisture problems. The drying capacity of highly insulated walls is very slow due to the decreased heat flux [25]. Therefore, the impact of such deficiencies should be accounted for during the design stage. Once these uncertainties are accounted for, the hygrothermal results can be a better representative of the probable situation and subsequently be used as input in the models representing decay and mould growth.

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 [4, 5, 26]. Previous studies concern only of mould growth. 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. Moreover, design criteria against biodeterioration are not currently available in codes or guidelines. Due to this lack, a comprehensive overview of the probable situation should associate the occurrence of the possible levels of biodeterioration to their respective likelihoods.

This study aims to evaluate the performance of highly insulated walls to withstand biodeterioration by applying a probabilistic-based methodology, which accounts for the uncertainties in the input variables and studies their significance in the output uncertainty. The following objectives are addressed:

- identification of uncertainties related to the performance evaluation of façade constructions
- development of a probabilistic-based methodology to account for these uncertainties
- application of sensitivity analysis to study the significance that uncertainties in the input variables contribute to the output
- experimental study to develop a model representing the temperature-dependent thermal conductivity of insulation
- performance evaluation of the walls by considering the joint occurrence of rot decay and mould growth
- investigation of the influence of different approaches to representing the outdoor climate
- consideration of potential deficiencies in the hygrothermal performance of highly insulated walls.

2 UNCERTAINTIES INVOLVED IN THE DESIGN OF BUILDING ENVELOPES

The workflow of the performance evaluation enables a more systematic identification of uncertainties, their involvement, and nature. They are grouped in Figure 1 by adapting the schematic for the structural reliability in [27] by including:

1- *Physical uncertainties* are those identified with the inherent natural variability [27]. They may be associated with the meteorological phenomena such as wind, clouds, rainfall or to the physical properties of the materials such as thickness, thermal conductivity, density. The latter may result due to the material's inhomogeneity, manufacturing, production, and measurement process and may be reduced with greater availability of the data derived from experimental investigation or field measurements, or with greater effort in quality control. However, they cannot be totally eliminated [27].

2- *Modelling uncertainties* are associated with the use of simplified relationships [27], or modelling, the variables that represent the building envelope, its boundary conditions and their interrelationship. They may be subcategorised to:

   a. Uncertainties related to the modelling of meteorological phenomena. These include the uncertainties in representing the outdoor weather exposure and climate change into stochastic models that are transferable as input for the HAM (Hygrothermal Air and Moisture) software.

b. Uncertainties related to the modelling of failure events. These include the uncertainties that are related to the mathematical representation of biological phenomena such as mould and rot decay that are very complex [4]. They are derived from experiments to predict their growth under arbitrary conditions in wall constructions.

c. Uncertainties related to the representing the material properties.

d. Uncertainties related to the modelling of indoor scenarios. The use of indoor space is uncertain considering the different usage scenarios that depend on zone volume, typology, time and operation.

e. Uncertainties related to the modelling of transfer functions. These include 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 façade. 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. It can be partly incorporated by letting the parameters that describe the distributions be themselves random variables [27].

4- *Uncertainties due to human factor* can be considered as those due to the effect of human error or intervention [27]. While these uncertainties are inevitable, they can be reduced with greater effort in quality control. In the performance evaluation of façade constructions, the latter are interconnected and related to the design, building process, and the operation stage.

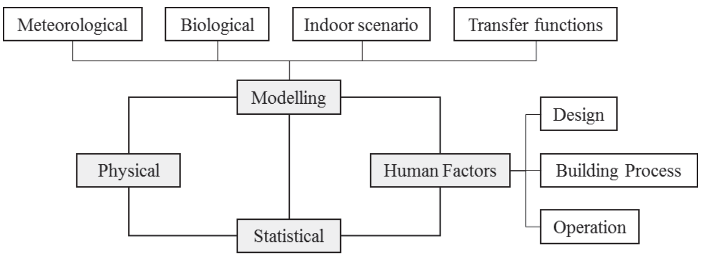


Figure 1. Uncertainties involved in the design of building envelopes.

Uncertainties are generally very interconnected to each other. An example can be the representation of mould growth. The uncertainties due to inherent natural variability would be the uncertainties associated with the biological growth of this phenomenon. The mathematical representation of this phenomenon in time would introduce model uncertainties. The parameters of the model would introduce statistical uncertainties related to parameter estimations since it is based on a finite number of experiments. Moreover, the prediction of the mould growth from the model would also introduce additional model uncertainties. The decision considered in any of the previous steps would also introduce uncertainties due to the human factor.

3 METHODOLOGY

3.1 Global sensitivity analysis

Sensitivity analyses related to the performance evaluation of façade constructions have been previously conducted by using the moisture content [2, 10, 28] as the indication of microbial growth. The latter can merely provide a rough overview of the likelihood of mould growth and decay [4, 5, 26]. Therefore, the outcome of this study is the decay and mould growth, and cumulative heat losses during the coldest month of the year. These quantities constitute directly the performance of the wall. Different sensitivity techniques are used to evaluate the relationship input-output (see Figure 2). A Latin Hypercube Sampling (LHS) technique is applied to generate the samples of the input variables by using the software SimLab [29]. They are further used to perform the heat, air and moisture (HAM) simulations. The hygrothermal conditions are retrieved and are used to calculate the rot decay and mould growth and heat losses. Lastly, the influence of each variable if investigated.

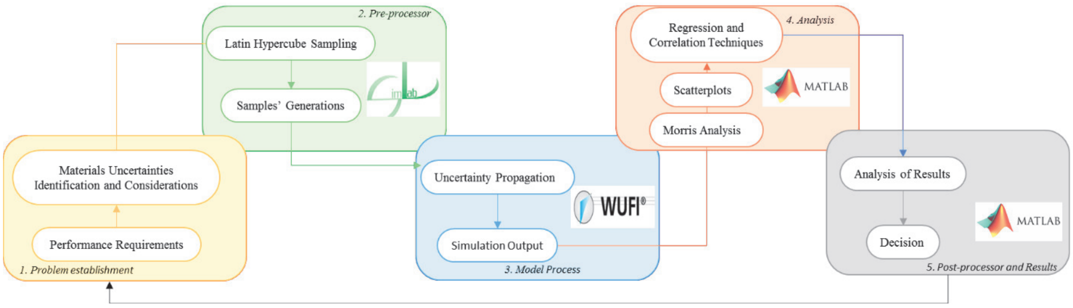


Figure 2. Methodology of sensitivity analysis.

3.1.1 Morris method

The Morris method [30] varies one parameter at a time and screens important or negligible parameters. The method calculates two sensitivity measures for each parameter: a) the mean μ indicating the overall effect of the parameter and b) the standard deviation σ indicating either interaction with other parameters or non-linear behaviour. A total number of 11 parameters are considered for this study including material uncertainties, indoor and outdoor climate (see section 0). Therefore, a total of $(11 + 1) \times 4 = 48$ simulations [29] are performed. Three case scenarios are considered depending on the amount of wind-driven rain (WDR) penetration (0 %, 1 % or 2 %) and the duration of the simulations (1 year, 3 years or 5 years).

3.1.2 Scatter plots and PCC, PRCC, SRC, SRCC, Pearson and Spearman indices

The Monte Carlo Latin Hypercube Sampling can propagate in a stratified way input variables by the simulation model to output variables. A total of 100 simulations are performed with this technique. Scatterplots are applied to reveal whether the relationship between model input and model output is linear or monotonic [29]. Other techniques applied in this study include regression- and correlation-based techniques: Standardized Regression Coefficients (SCR), Partial Correlation Coefficient (PCC), Standardized Rank Regression Coefficients (SRRC), Partial Rank Correlation Coefficient (PRCC) and Pearson and Spearman [30]. SRC, PCC and Pearson coefficients are suitable for linear relationships while SRRC, PRCC and Spearman coefficients can be used for non-linear but monotonic relationships among inputs and outputs.

3.2 Probabilistic-based methodology

The probabilistic-based approach is implemented in the form of a seamless and integrated parametric flow as shown in Figure 2. The probabilistic approach employed as part of this study has been further developed from [14]. The failure presents the event that mould or decay endanger the functionality of the wall construction (see section 5.5). In relation to the structural reliability applications, the negative difference between the capacity and demand for a given limit state defines the failure [27], according to the following condition:

$$\mathcal{F} = \{C - D \leq 0\} \tag{1}$$

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

In our case study, demand is expressed as the predicted rot decay and mould growth for each simulation, while capacity is expressed according to the criteria set out in section 5.5. The approximate probability of failure is given by the following:

$$P_{\mathcal{F}} \cong N_{\mathcal{F}}/N \tag{2}$$

where $N_{\mathcal{F}}$ is the number of trials of which $\mathcal{F} \leq 0$ and N is the number simulations.

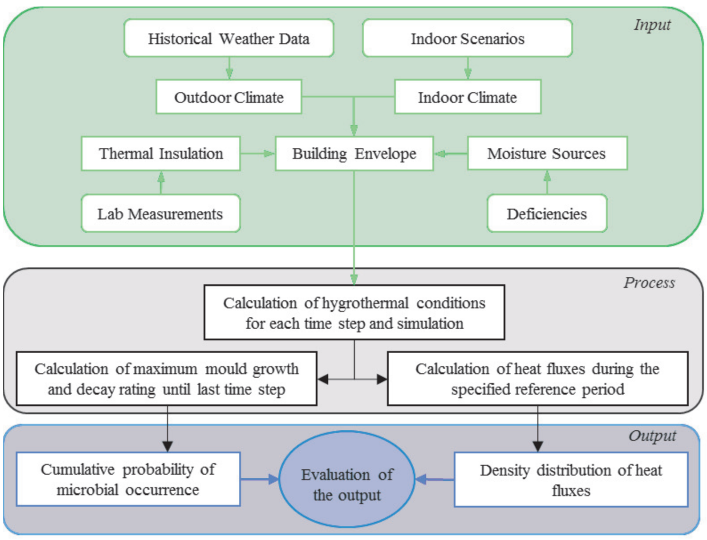


Figure 3. Schematic workflow of the probabilistic evaluation procedure.

4 Materials - Highly insulated walls

Three highly insulated walls are investigated in this work. First, constructions that have a layer made of wood-based material are selected due to their higher susceptibility to biodeterioration. Second, 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, selected from [1], are presented in Figure 4 and Table 1.

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

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

c) The last case (AWI 01) is a wood post outside wall that uses a membrane as the wind barrier and an OSB as the vapour barrier.

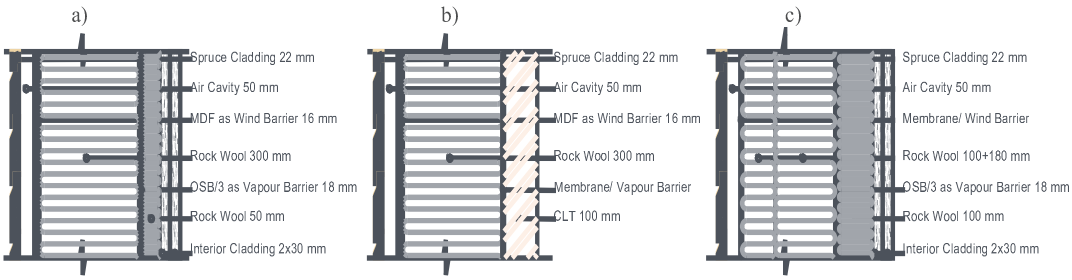


Figure 4. Configuration of the wall constructions: a) AWI 05, b) AWh 01 and c) AWI 01.

Table 1. Material properties of the wall constructions.

Material	thermal conductivity	water vapour diffusion factor	density	heat capacity	porosity
	λ	μ	ρ	c	Φ
	[W/mK]	[-]	[kg/m³]	[J/kgK]	[m³/m³]
Spruce Cladding	0.09	130	455	1500	0.73
MDF-board	0.12	15	508	1700	0.667
Membrane (Wind Barrier)	s_d=0.1 m				
Insulation (rock wool)	0.033	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

5 SIMULATION SET-UP AND REPRESENTATION OF THE VARIABLES

5.1 System representation

5.1.1 HAM calculations

The heat and moisture simulations are performed by WUFI 6.1 ® [31], which has been validated by experimental studies [3] for constructions similar to the ones in this study. WUFI does not entirely model the air layer [32]; therefore, this study assumes that the temperature and relative humidity in the air are similar to exterior conditions. The cladding and air layer are neglected in the simulation, while the effect of the wind-driven rain is considered by applying moisture sources.

5.1.2 Deficiencies

Wall constructions are subject to moisture loads from a number of sources including wind-driven rain, 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]. Many of the latter may originate from human errors. They are difficult to identify and interconnect, and thus 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:

- 0.5 % moisture source representing small moisture leaks that may originate from human errors or wind-driven rain [33],
- 1 % moisture source representing moisture leaks from wind-driven rain according to ASHRAE recommendations [31],
- 2 % moisture source representing a window leak [2].

5.2 Representation of outdoor climate

The weather exposure is a stochastic variable that plays an important role in the design of the wall construction. 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 stochastically represent the outdoor weather exposure with the following approaches:

Version A – Each year among the 20-year long historical measurements is randomly distributed for each simulation. This method has been applied in [12]. The time series include relative humidity, temperature, solar radiation, and rain. However, in the current 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 [14].

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 [34] are applied to construct the outdoor weather simulations with a duration as long as the expected service life of the façade constructions (50 years). This approach has been applied in [14, 35]. 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 [36, 37] 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.

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

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	**Strength**	**Limitation**
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.

5.3 Representation of the indoor climate

A simplified model for representing the indoor climate is assumed based on EN 15026 [25]. 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. In order to account for uncertainties related to the indoor climate, this study uniformly distributes the moisture categories assuming different operation of indoor space. Model uncertainties related to the equations according to EN 15026 are also accounted for. The final values RH_{ind} and T_{ind} are represented as normal distributions with mean values calculated according to EN 15026 and coefficient of variations equal to 4 % and 5 % by approximating the results of indoor measurements in [60]. The hourly values are assumed as highly correlated.

5.4 Representation of the material properties

5.4.1 Experimental Investigation

Laboratory experiments were performed to assess the thermal conductivity of the insulation material and its dependency on the temperature. The thermal conductivity of the samples was measured using the heat flow meter apparatus HFM 436 Lambda shown in Figure 5. The apparatus was calibrated with a standard fibreglass board. Specimens sized with variable thicknesses were placed between the hot and cold plates and the thermal conductivity was measured by the heat flux sensor upon reaching the thermal equilibrium at defined temperature difference and for a uniform temperature gradient throughout the sample. The sample size was 305×305 mm^2, although the heat flow was measured in the central 100×100 mm^2 area of the sample. The large sample size compared to the measurement area ensured the steady-state thermal conditions for the measuring area so the surrounding area of the transducer acted as an effective guard against lateral heat flow. The temperature difference between the hot and cold plates was set to 20°C, and a set of eight or seven temperature levels, ranging from -20 °C to +50 °C was used at 10 °C increments. Samples were removed from the humidity chamber upon reaching a constant mass, immediately wrapped with a thin plastic film to maintain their moisture content and then measured. Samples were weighed before and after thermal measurement using a digital scale with a 0.1g accuracy to keep track of the moisture content.

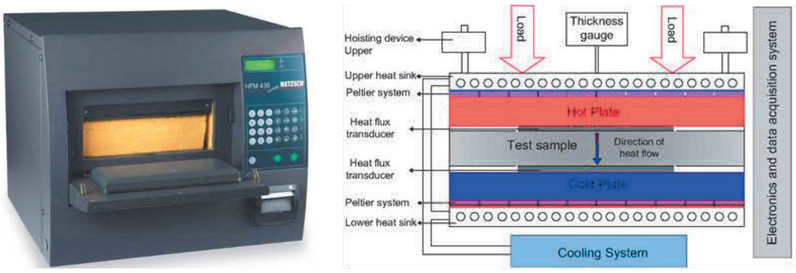


Figure 5. Heat flow meter NETZSCH HFM 436 Lambda apparatus (left) and its schematic design (right).

5.4.2 *Preliminary results – Representation of the temperature-dependent thermal conductivity*

The results of each sample are shown in Figure 6. The relationship is mainly linear; however, when the temperature level ranges at around -10 ºC and between 20 and 40 ºC this relationship becomes less linear. 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 7). 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 to the residuals. The second residuals series 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:

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

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

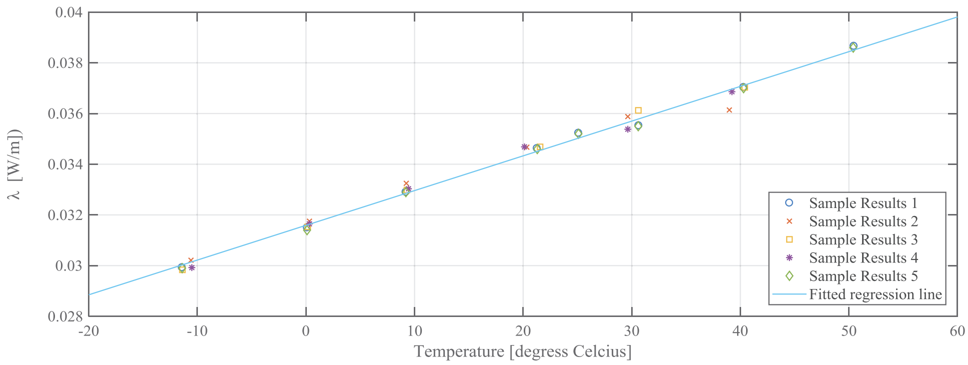


Figure 6. The measured temperature-dependent thermal conductivity under envelope conditions for five samples.

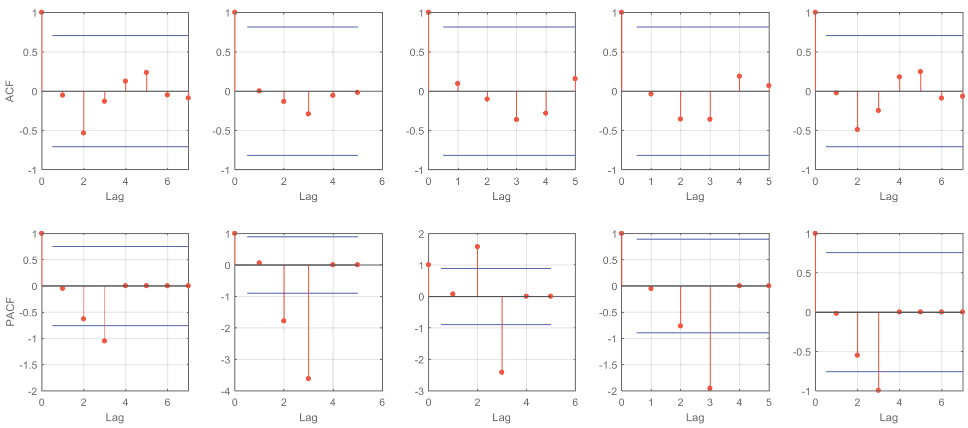


Figure 7. ACF and PACF of the residuals of each test result.

5.4.3 Uncertainties in other material's parameters

Uncertainties in the other material properties, which was not possible to measure, are accounted for by assuming a normal distribution [38, 39] with mean values as presented in Table 1. The coefficient of variation is assumed 15 % for the vapour diffusion resistance, 8 % for the thermal conductivity of material other than insulation, and 5 % for the density.

5.5 Representation of the failure event

The occurrence of microbial growth is directly related to the consequences that endanger the integrity of the façade. Different models have been developed to calculate rot decay and mould growth, and they are characterised by specific strengths and limitations [4, 5, 26]. In the current study, mould growth is calculated according to VTT model [40, 41], MRD model [42, 43] and IBP-biohygrothermal model [44]. The decay degree is calculated according to Logistic dose–response model (LDR) [45] and VTT decay model [46]. Due to the lack of established design criteria, the results are expressed as a density function associating levels of microbial growth to their respective likelihood. The rating scales of the microbial growth are shown in Table 3 and Table 4 according to the models above. On the left of the tables are proposed three types of consequences, related to the aesthetic, IAQ/health and structural aspects. A coloured rating scheme is suggested based on the severity (indirect consequences) that these levels may cause. The severity of the joint contribution is proposed in Table 5 where green means low or unimportant, yellow means medium and red high severity.

Table 3. Rating scale of the evaluation of rot decay according to [47] together with the suggested coloured severity of consequences.

	Rating	Description	Consequences		
			Aesthetic	IAQ/ Health	Structural
Decay Rating (DR)	0	No attack- No change perceptible by the means at the disposal of the inspector in the field. If only a change of colour is observed, it shall be rated 0.			
	1	Slight attack - Perceptible changes, but very limited in their intensity and their position or distribution: superficial degradation or softening of the wood.			
	2	Moderate attack - Clear changes: softening of the wood to a depth of at least 2 mm over a surface area covering at least 10 cm2.			
	3	Severe attack - Severe changes: marked decay in the wood to a depth of at least 3 mm over a wider surface (covering at least 25 cm2), or softening to a depth of at least 10 mm over a more limited surface			
	4	Failure - Impact failure of the stake in the field.			

Table 4. Mould growth evaluation according to [40, 41] together with the suggested coloured severity of consequences.

	Rating	Description	Consequences		
			Aesthetic	IAQ/Health	Structural
Mould Growth (VTT Index)	0	No growth			
	1	Small amounts of mould surface (microscope), initial stages of local growth			
	2	Several local mould growth colonies on surface (microscope)			
	3	Visual findings of mould on surface, <10% coverage, or <50% coverage of mould (microscope)			
	4	Visual findings of mould on surface, 10 - 50 % coverage, or >50% coverage of mould (microscope)			
	5	Plenty of growth on surface, > 50% coverage (visual)			
	6	Heavy and tight growth, coverage about 100%			

Table 5. Proposed severity levels of the joint contribution of the mould and rot decay.

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

6 RESULTS

6.1 Sensitivity analysis results

The sensitivity analysis was performed only for the reference configuration. Similar results may be transferred to similar configurations as used in this study; however, individual computations are required when opting an accurate optimisation process. Full visual results are not presented due to lack of space. The results of Morris Analysis conclude that:

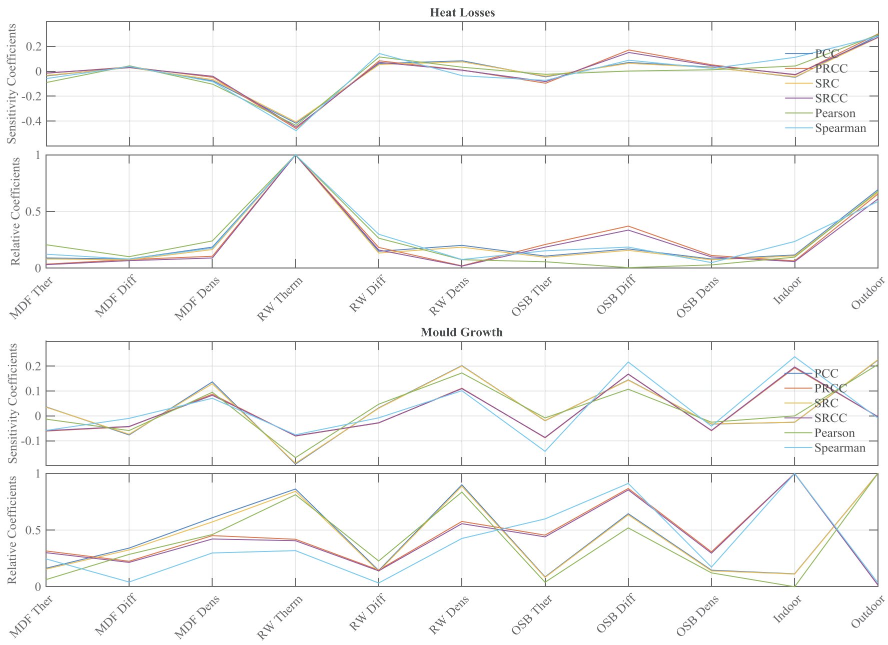
- The influential parameters for the Heat Losses are the Rock Wool Thermal Conductivity, Indoor Climate, Rock Wool Vapour Diffusion Factor and MDF Density, while for the Mass Losses is MDF Vapour Diffusion Factor. Other parameters are screened as non-significant.
- The influence of several parameters becomes more dominant when the wind-driven rain infiltration increases. The reason might be since when WDR = 0 %, there is a small amount or zero of mould growth according to each model.
- Even though not screened as an important parameter, the OSB Vapour Diffusion Factor shows large mean and standard deviation value for many outputs. Similarly, with smaller values is the OSB Thermal Conductivity, MDF Thermal Conductivity and MDF Vapour Diffusion Factor. The outdoor climate was not found to be influential, with mean and standard deviation equal to zero.

The results of the scatterplots conclude that:

- Most of the relationships are nonlinear and non-monotonic.
- The only relationship that can be considered linear is the Heat Losses and the Rock Wool Thermal Conductivity.
- For the outputs DR and ML, the effect of wind-driven rain is very influential as can be observed from the changes of the relationship between them and several parameters.
- The most dominant parameters according to the scatterplot results are the Rock Wool Thermal Conductivity, OSB Vapour Diffusion Factor, MDF Vapour Diffusion factor.

The results of the sensitivity analysis according to PCC, PRCC, SRC, SRCC, Pearson and Spearman indices are gathered together in Figure 8 and Figure 9. In the former are shown the absolute and relative sensitivity coefficients (as determined by comparison of the highest absolute sensitivity coefficient) when the WDR=0%. In the latter are shown the relative sensitivities while parametrizing the amount of WDR penetration. The following results are drawn:

- The most influential parameters are the Rock Wool Thermal Conductivity, Indoor Climate, OSB Vapour Diffusion Factor, Outdoor Climate and Rock Wool Density.
- In general, the relative sensitivity results agree between each of the techniques. Particularly, for the output of Heat Losses and Decay Rating, the results are very similar. For mould growth, the results can be divided into two similar groups: Spearman, PRCC and SRRC that are suitable for monotonic relationships in one group and the rest in the other group that is suitable for linear relationships.
- The outdoor climate is the most scattered variable among the results.
- MRD and slightly ML are mostly affected by the changes of the infiltrated amount of wind-driven rain. Other outputs appear insensitive to this parameter.
- The same parameters affect similarly the mould growth independent of the mould model. MRD experiences some deviations and is mostly affected by the infiltration of wind-driven rain. While for the decay rating, this is not true.



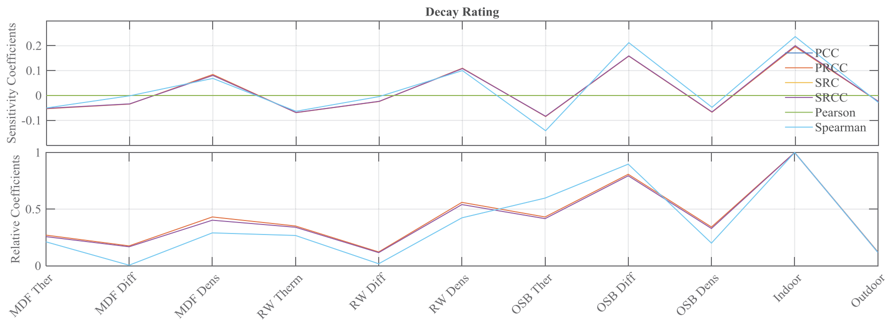


Figure 8. Absolute and relative sensitivity coefficients according to different techniques for: Heat Losses in January (top), the case of Mould Growth according to VTT model (middle) and Decay Rating according to LRD model (bottom), where 0 means the output uncertainty is not sensitive to the input uncertainty and 1 or -1 means they are strongly sensitive.

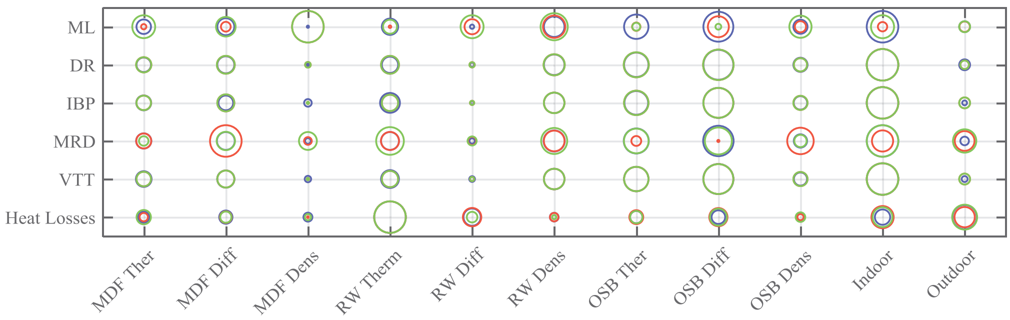


Figure 9. The influence of different parameters (x-axis) to different outputs (y-axis) according to Spearman coefficients as demonstrated though the radius of circles (red: WDR = 0%, blue: WDR = 1%, green: WDR = 2%). The smaller the diameter of the circle, the smaller is the output uncertainty sensitive to the input uncertainty and vice-versa.

6.2 Probabilistic evaluation of the performance of highly insulated walls

6.2.1 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 10 by varying the outdoor climate representation. 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 with duration as short as 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 set to one year, such uncertainty of the results is observed to be less scattered.
- 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.
- Results from simulations that represent the weather according to B version are more conservative when compared to the results of the same evaluation time from simulations that represent the weather according to C version.

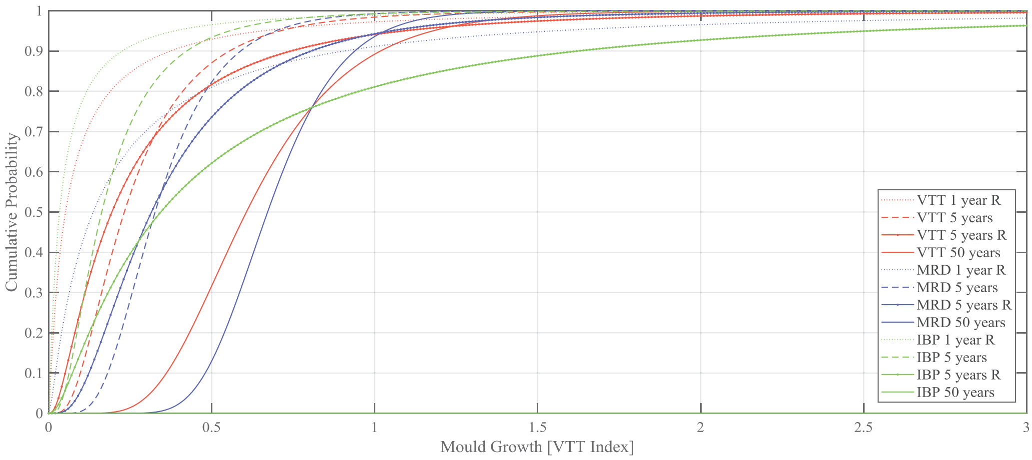


Figure 10. Cumulative density function of the mould growth. 'VTT' stands for mould growth results according to VTT model, 'MRD' stands for mould growth results according to MRD model and 'IBP' stands for mould growth results according to IBP model. '5 years R' stands for the representing of outdoor climate according to B-version. '1 years' stands for the representing of outdoor climate according to version A. '50 years' and '5 years' stands for the representing of outdoor climate according to C- version (see section 5.2).

6.2.2 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 11 and Figure 12 respectively, where the penetration for the wind-driven rain is varied. The results show that:

The perf r an e f he referen e ase is highly influenced by the amount of penetration of wind-driven rain.

- The perf r an e f he referen e ase withstand mould growth is jeopardised when wind-driven rain is nsidered, even f r he l wes pene ra i n f 0.5 %.

The differen e in the results between mould models is not affected by the amount of wind-driven rain pene ra i n.

When he wind-driven rain penetration is assumed 0 %, no decay problems are observed. When the penetration in reases, he results according to VTT decay model show a very high amount of mass loss with considerable probability (see Figure 12). This n radi s he results fr L R del, whi h sugges ha he perf r an e f he referen e ase is sa isfa ry.

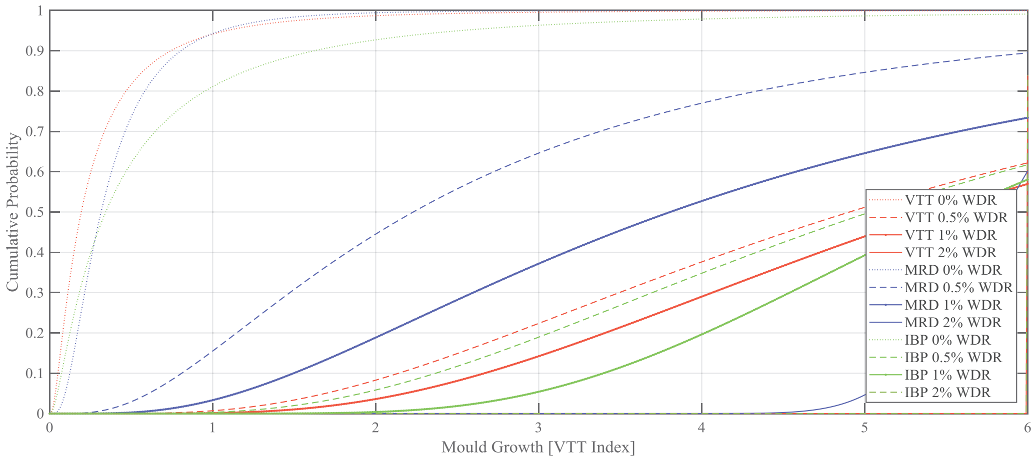


Figure 11. Cumulative density function of the mould growth. Consideration of deficiencies from moisture leaka s.

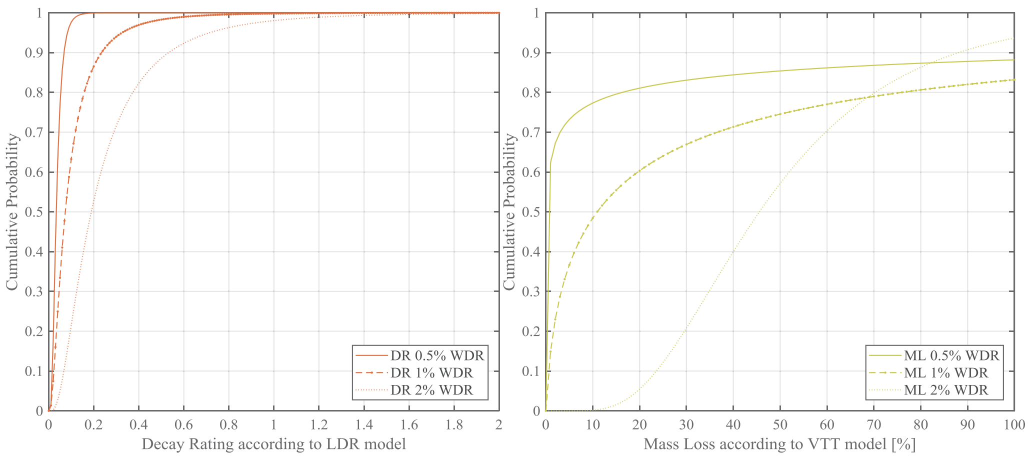


Figure 12. Cumulative density function of decay rating (left) and mass loss (right). Consideration of deficiencies from moisture leaka s.

6.2.3 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 13. The decay rating results are not presented when no penetration is assumed since the values were zero for each simulation. The weather is represented by version B for a duration of 5 years. The performance is assessed according to the criteria set in section 5.5. The results are:

- Each of the cases shows a satisfying performance to withstand mould growth VTT Index 3 when no wind-driven rain penetration is accounted for. The difference between the cases increases when mould growth reaches Index 2 and lower.
- 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 01 show similar performance.
- The results show similar performance against rot decay for each case.
- 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 (see Table 5).

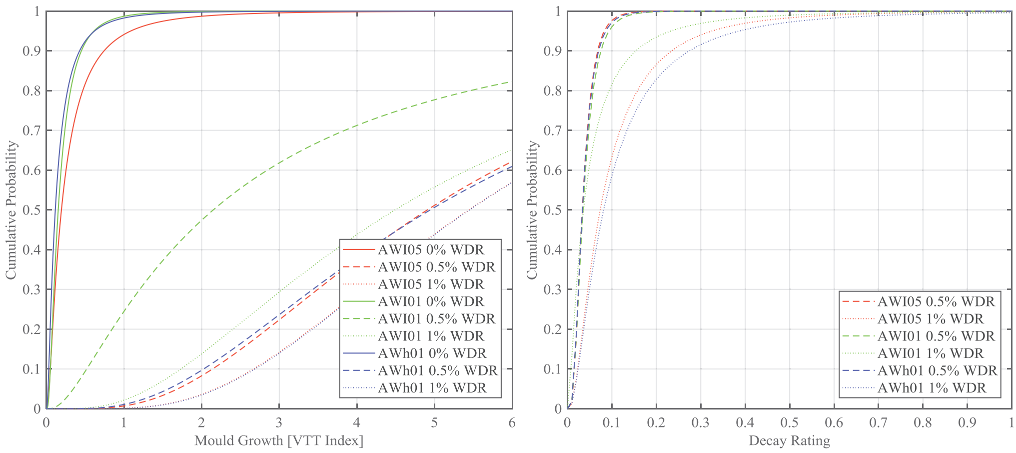


Figure 13. Cumulative density function of mould growth (left) and decay rating (right) for three cases. Consideration of deficiencies from moisture leakages.

7 DISCUSSION

7.1 Performance evaluation of highly insulated walls with probabilistic method

The highly insulated walls showed satisfying performance to withstand biodeterioration when no deficiencies were accounted for. Their performance decreased abruptly when applying moisture sources, even for penetration equal to 0.5 %. Therefore, strategies and designs should be considered during the design stage to systematically reduce similar deficiencies.

The sensitivity analysis concluded that the outdoor and indoor climate, the thermal conductivity of the insulation material, and water vapour diffusion factor of vapour barrier are the most dominant variables. The results regarding the significance of outdoor climate as calculated from different techniques were the most scattered. From practical experience, this is a dominant variable. However, quantitative results may seem difficult to be drawn since this variable is represented by a time series of joint other variables including rain, radiation, temperature and relative humidity. This representation poses difficulties to quantify the variation between samples and subsequently their contribution in the output.

Advantages of the probabilistic approach compared to the conventional approach include:

- 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
- it enables the association of potential level of microbial growth to their respective likelihoods.

7.2 Assumptions and accuracy of the results

The sensitivity analysis and probabilistic evaluation are very efficient tools to investigate the performance of wall constructions. Attention is required when using the results from 1D hygrothermal simulation tool with the rating scales of microbial growth that are derived in 2D from lab data on small specimens while assessing parts of a building that are highly 3D. The accuracy of the results also depends on the assumptions and representation of variable inputs and their representations, which are related to; a) predicting capabilities of microbial models, b) accuracy of HAM tools and modelling of the deficiencies, and c) the system representation.

7.2.1 Outdoor Climate

Results showed that computations based on one-year long data deliver limited outcomes leading to overestimation of the façade 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 façade construction has enough dry-out capacity that during unfavourable conditions the growth returns to zero, or when the acceptance criteria (from building codes or guidelines) are derived for such short time. Nevertheless, 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 [31] 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 analyze façade performance under unfavourable climate conditions. However, it remains unclear how a sufficiently unfavourable one year climate can be identified.

7.2.2 Indoor Climate

The sensitivity analysis results concluded that the indoor climate is a very dominant 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 where the corresponding results represent the hourly usage of indoor space based on the type of façade, zone volume, typology, time and operation for a representative set of indoor spaces accounting for their hourly regression and correlation parameters.

7.2.3 Material uncertainties

The temperature-dependent thermal conductivity was investigated through experimental work. However, the moisture content dependency should also be investigated in further studies. Results from literature review were used to develop models that account for uncertainties in other material properties. The development of a database containing the distributions of the properties of different materials, such as proposed in [13], is suggested since it highly increases the accuracy of the probabilistic evaluation and enables its wider implementation in the design of highly insulated walls.

7.2.4 Deficiencies and their simulation

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 an important deficiency that should be considered [2, 48, 49]. However, 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. As a result, the consideration of air leakages falls out of this study's scope.

7.3 Sensitivity analysis – Limitations and choice between different techniques

Morris method is suitable and time-efficient technique when there are a few influential factors and a majority of non-influential factors. The main advantage is its low computation cost. The limitation of this technique is its qualitative nature to measure the significance of input factors. Thus, it cannot quantify the effects of different factors on outputs compared to other global sensitivity analysis techniques. The results from this technique suggested that only a few parameters were considered significant for a few outputs. Nevertheless, the identified and rank of significant parameters agreed with other techniques. Regression and correlation techniques are more computationally expensive; however, they can also be considered efficient since they can be used with a Monte Carlo analysis. They are easy to comprehend and in illustrating the results. SRC, PCC and Pearson coefficients are only suitable for linear relationships while the rank transformation (SRRC and PCC) and Spearman coefficients can be used for non-linear but monotonic relationships. Scatterplots are also very time-efficient and can be used with a Monte Carlo Analysis. They are easy to compute and can identify significant parameters. They allow for the identification of the linearity and monotonicity of the relationship input-output. Nevertheless, they do not provide a quantified sensitivity measure. The judgement of the remaining parameters cannot be fully comprehensive.

The choice of sensitivity analysis technique depends on many factors including the purpose, model and computational cost, number of input variables and their correlation. Practical recommendations are drawn from this study and include:

- For computational expensive simulations, Morris method can provide time-efficient results by screening the most significant parameters. This is recommended when many input variables are involved and from a basic engineering judgement, only a few of them may be significant.
- Regression and correlation techniques may be a more reliable choice due to their quantitative nature. It is recommended to use scatterplots as a complementary technique before selecting which regression or correlation technique will be used.

7.4 Design criteria and consequences

The results of probabilistic evaluation were 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 is the only norm that has implemented a mould model (VTT) and suggests the growth not to exceed Index 3 [46], while for decay none are available. A qualitative approach was applied in the current study to associate different levels of microbial growth to acceptable levels. However, the selection of the design criteria depends on several characteristics of the project since its consequences can vary from marginal to substantial, even for the same rating scale. In light of this, it is suggested the development of design criteria relating target reliabilities (or probabilities of failure) with a different classification of consequences, as already developed in structural engineering [47]. The development of design criteria can be approached by categorising direct and indirect consequences of microbial growth based on the following aspects:

1. *Hazards*. The direct consequences of the hazards, mould and decay rot, are related to three different perspectives: IAQ/health, aesthetics and structural.

2. *Rating scales*. There are different models that may express the occurrence and growth of microbial growth with different rating scales. A standard and defined rating scale should be selected and approached.

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 followings:

- the depth of the wall (outer part of the wall, inside the façade construction and inner part or contact with the indoor environment)
- the height of the building (i.e. underground, first floor, upper floors)
- part of the building (close to risk spots, the front part of the building)
- typology of 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 structures. This will simplify the implicit application of probabilistic approach in the field of building physics. Furthermore, it can facilitate the development of cost-optimal design and risk-based inspection planning. It can also be integrated into the formulation of a simplified semi-probabilistic design concept as part of future building codes such as in structural engineering [50, 51], where partial safety factors can be introduced into the limit stated function (see equation 1 at section 3.2). On this basis, the selected solution for the façade construction and its optimisation can be based on established criteria.

8 CONCLUSIONS

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. It also delivers a clearer association of the microbial growth and its likelihood; hence, it facilitates a more comprehensive evaluation regarding the performance of the constructions. Furthermore, the application of sensitivity analysis is very beneficial in the design of wall constructions since it identifies and ranks the most dominant parameters influencing the outcome. The latter is crucial since they measure the overall influence of each property, material and potential design of walls, and therefore can efficiently optimise the construction while maintaining the required standard of performance.

9 ACKNOWLEDGMENTS

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10 REFERENCES

1. Waltjen, T., W. Pokorny, T. Zelger, K. Torghele, H. Mötzl, B. Bauer, P. Boogmann, G. Rohregger, and U. Unzeitig, *Details for passive houses. A catalogue of ecologically rated constructions*. 2008, Springer, Wien.
2. Lepage, R., C. Schumacher, and A. Lukachko, *Moisture management for high R-value walls*. 2013, Building Science Corporation, Somerville, MA.
3. Mundt Petersen, S. and L.-E. Harderup. *Control of moisture safety design by comparison between calculations and measurements in passive house walls made of wood*. in *XII DBMC-XII International Conference on Durability of Building Materials and Components*. 2011. FEUP Edicoes.
4. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review.* Construction and Building Materials, 2017. **150**: p. 77-88.
5. Brischke, C. and S. Thelandersson, *Modelling the outdoor performance of wood products–A review on existing approaches.* Construction and Building Materials, 2014. **66**: p. 384-397.
6. WHO, *WHO Guidelines for indoor air quality*, in *Selected pollutants*. 2010.
7. Arthur, R., *Damp Indoor Spaces and Health.* Journal of Public Health, 2005. **27**(2): p. 234-234.
8. Jaakkola, M.S. and J.J. Jaakkola, *Indoor molds and asthma in adults.* Advances in applied microbiology, 2004. **55**: p. 309-338.
9. Eaton, R.A. and M.D.C. Hale, *Wood: decay, pests and protection.* 1993.
10. Holm, A.H. and H.M. Kuenzel, *Practical application of an uncertainty approach for hygrothermal building simulations—drying of an AAC flat roof.* Building and Environment, 2002. **37**(8): p. 883-889.
11. Pietrzyk, K., *A systemic approach to moisture problems in buildings for mould safety modelling.* Building and Environment, 2015. **86**: p. 50-60.
12. Hagentoft, C.E., A.S. Kalagasidis, and C. Rode, *55, Reliability of Energy Efficient Building Retrofitting-Probability Assessment of Performance & Cost (RAP-RETRO)*, in *Framework for probabilistic assessment of performance of retrofitted building envelopes*. 2015.
13. Zhao, J., R. Plagge, N.M. Ramos, M.L. Simões, and J. Grunewald, *Concept for development of stochastic databases for building performance simulation–A material database pilot project.* Building and Environment, 2015. **84**: p. 189-203.
14. Gradeci, K., N. Labonnote, B. Time, and J. Köhler, *A probabilistic-based methodology for predicting mould growth in timber façade constructions (in press).* Building and Environment, 2017.
15. Geving, S. *A systematic method for hygrothermal analysis of building constructions using computer models*. in *Proceedings of the building simulation*. 1997. Citeseer.
16. Hagentoft, C.-E. *Probabilistic Analysis of Hygrothermal Conditions and Mould Growth Potential in Cold Attics. Impact of Weather, Building System and Construction Design Characteristics*. in *International Conference on Durability of Building Materials and Components*. 2011.
17. Hagentoft, C.-E. and A. Sasic Kalagasidis. *Moisture safe cold attics-Assessment based on risk analyses of performance and cost*. in *Proceedings of 10th Nordic Symposium on Building Physics*. 2014.
18. Pallin, S., *Risk Assessment of Hygrothermal Performance-Building Envelope Retrofit*. 2013: Chalmers University of Technology.
19. Sadovsky, Z., O.G. Koronthalyova, P. Matiaovsky, and K. Mikulova, *Probabilistic modelling of mould growth in buildings.* Journal of Building Physics, 2014. **37**(4): p. 348-366.
20. Nevander, L.E. and B. Elmarsson, *Fuktdimensionering av träkonstruktioner: riskanalys*. 1991: Byggforskningsrådet (BFR).
21. Johansson, P. *Assessment of the risk for mold growth in a wall retrofitted with vacuum insulation panels*. in *Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland, 29 May-2 June, 2011*. 2011.
22. Thelandersson, S., T. Isaksson, M. Häglund, and E. Frühwald. *Probabilistic methods for performance based service life evaluation of wooden components*. in *Applications of Statistics and Probability in Civil Engineering*. 2011.
23. Berardi, U. and M. Naldi, *The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance.* Energy and Buildings, 2017. **144**: p. 262-275.

24. Berardi, U., *The impact of temperature dependency of the building insulation thermal conductivity in the Canadian climate.* Energy Procedia, 2017. **132**: p. 237-242.
25. Straube, J.F. and E.F. Burnett, *Building science for building enclosures*. 2005: Building science press.
26. Vereecken, E., K. Vanoirbeek, and S. Roels, *Towards a more thoughtful use of mould prediction models: A critical view on experimental mould growth research.* Journal of Building Physics, 2015. **39**(2): p. 102-123.
27. Melchers, R.E., *Structural reliability*. 1987: Horwood.
28. Nielsen, A., E.B. Møller, T.V. Rasmussen, and E.J.d.P. Hansen. *Use of sensitivity analysis to evaluate hygrothermal conditions in solid brick walls with interior insulation*. in *5th International Building Physics Conference IBPC*. 2012.
29. Giglioli, N. and A. Saltelli, *SimLab 1.1, Software for Sensitivity and Uncertainty Analysis, tool for sound modelling*, in *arXiv preprint cs/0011031*. 2000.
30. Saltelli, A., M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola, *Global sensitivity analysis: the primer*. 2008: John Wiley & Sons.
31. Hartwig Michael Künzel, *Simultaneous heat and moisture transport in building components, One-and two-dimensional calculation using simple parameters. IRB-Verlag Stuttgart* 1995.
32. Andrea Tietze, S.O., Sylvain Boulet, Klodian Gradeci, Nathalie Labonnote, Steinar Grynning, Joakim Noreen, Anna Pousette *Tall Timber Facades – Identification of Cost-effective and Resilient Envelopes for Wood Constructions*. 2017.
33. Recatala, M.A., S.G. Morales, and N. van den Bossche, *Experimental assessment of rainwater management of a ventilated façade.* Journal of Building Physics, 2017: p. 1744259117719077.
34. Box, G.E., G.M. Jenkins, and G.C. Reinsel, *Time series analysis: Forecastingand control*. San Francisco: Holdenday. 1976.
35. Häglund, M., T. Isaksson, and J. Holst, *Time-series modeling of moisture exposure on timber structures.* Building and Environment, 2007. **42**(3): p. 1515-1521.
36. Tietze, A., S. Boulet, S. Ott, and S. Winter. *Consideration of disturbances and deficiencies in the moisture safety design of tall timber facades*. in *World Conference on Timber Engineering*. 2016. Vienna.
37. Vihna, J., *Hygrothermal performance of timber-framed external walls in Finnish climatic conditions*. 2007, Tampere University of Technology: Tampere.
38. Salonvaara, M., A. Karagiozis, and A. Holm, *Stochastic building envelope modeling—the influence of material properties.* Thermal Performance of Exterior Envelopes of Whole Buildings VIII, 2001: p. 2-8.
39. Zhao, J., R. Plagge, A. Nicolai, J. Grunewald, and J.S. Zhang, *Stochastic study of hygrothermal performance of a wall assembly—The influence of material properties and boundary coefficients.* HVAC&R Research, 2011. **17**(4): p. 591-601.
40. Ojanen, T., H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, and K. Salminen. *Mold growth modeling of building structures using sensitivity classes of materials*. in *Proceedings Building XI*. 2010.
41. Viitanen, H. and T. Ojanen. *Improved model to predict mold growth in building materials*. in *Proceedings of the X International Conference on the Performance of the Exterior Envelopes of Whole Buildings, Clearwater, FL*. 2007.
42. Thelandersson, S. and T. Isaksson, *Mould resistance design (MRD) model for evaluation of risk for microbial growth under varying climate conditions.* Building and Environment, 2013. **65**: p. 18-25.
43. Isaksson, T., S. Thelandersson, A. Ekstrand-Tobin, and P. Johansson, *Critical conditions for onset of mould growth under varying climate conditions.* Building and Environment, 2010. **45**(7): p. 1712-1721.
44. Sedlbauer, K., *Prediction of Mould Growth by Hygrothermal Calculation.* Journal of Building Physics, 2002. **25**(4): p. 321-336.
45. Brischke, C. and L. Meyer-Veltrup, *Modelling timber decay caused by brown rot fungi.* Materials and Structures, 2016. **49**: p. 3281-3291.
46. Viitanen, H., T. Toratti, L. Makkonen, R. Peuhkuri, T. Ojanen, L. Ruokolainen, and J. Räisänen, *Towards modelling of decay risk of wooden materials.* European Journal of Wood and Wood Products, 2010. **68**(3): p. 303-313.
47. *EN-252: Field test method for determining the relative protective effectiveness of a wood preservative in ground contact*, in *Attack by microorganisms*. 2014.
48. Wang, L. and H. Ge, *Effect of air leakage on the hygrothermal performance of highly insulated wood frame walls: Comparison of air leakage modelling methods.* Building and Environment, 2017. **123**: p. 363-377.
49. Relander, T.-O., *Airtightness of wood-frame houses*. 2011.
50. BDS, E., *Eurocode 0—Basis of structural design*. 1990.
51. JCSS, *Part 1–Basis of Design:-Joint Committee of Structural Safety*. 2000.

Paper VI

Cost-Optimisation for Timber Façades Exposed to Rot Decay.

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