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SAMiRA: A decision framework for hygrothermal modelling implementation in HAMalyser

Author(s)

Bruno VANDERSCHELDEN
Research Group Building Physics,
Ghent University
Bruno.vanderschelden@ugent.be

Kaat JANSSENS
Research Group Building Physics,
Ghent University
Kaat.janssens@ugent.be

PhD Supervisor(s)

Nathan VAN DEN BOSSCHE
Research Group Building Physics,
Ghent University

Tim, DE KOCK
Heritage, University of Antwerp

Veerle, CNUDDE
Geology, Ghent University
Geowetenschappen, Universiteit Utrecht

Abstract

SAMiRA entails a 12-step decision framework for input and model parameters in Heat Air and Moisture simulations (HAM simulations) which goes well beyond the existing standards and guidelines. The proposed framework has significant practical implications for building designers, engineers, and researchers who rely on HAM-simulations to evaluate building performance. The complex process of creating a HAM case is broken down into 12 comprehensive steps covering the scope of the simulation, the prediction of deterioration and performance assessment, boundary conditions of the computational domain, material characterization, initial conditions, selection of appropriate outputs, and reviewing the simulation results. Each step consists of a structured approach for an input parameter selection, with its corresponding model parameters, using three strategic levels with different complexity and granularity. The three levels are referred to as the Superior, Advanced and Minimum Requirement Approach (SAMiRA). While increasing the parameter level from minimum towards superior, the model accuracy and reliability of the simulation will increase but with a higher computational time and financial expenses. The framework can be applied to a wide range of building components, different climates and their projections, and helps practitioners to optimize the energy efficiency, comfort, and moisture prevention in buildings. The results are made publicly available in a webtool called HAMalyser where the user is guided through the 12 steps with some additional help and examples with some critical points. Next to that, the webtool includes a post-processing tool which can calculate several degradation models based on simulation outputs. SAMiRA was presented and discussed, in collaboration with the UKCMB (UK Centre for Moisture in Buildings), with a group of 24 experts from the field. This showed that the framework has valuable significance in educating and raising the awareness of practitioners.

Keywords

Hygrothermal simulations, renovation and new build, performance assessment.

1. Introduction

The building industry has made significant advancements in designing and constructing safe, thermally comfortable, and moisture-resistant buildings. However, a significant portion of existing buildings still suffer from moisture issues because of water and vapor ingress (De Vos et al, 2020; Van Den Bossche et al, 2023). To increase performance and reduce moisture problems, Heat- Air and Moisture simulations (HAM) have become valuable tools by simulating thermal and moisture behaviour in building components. Over the last few decades, numerous numerical models have been developed to predict the hygrothermal behaviour under different and dynamic conditions. Commercial software packages exist, e.g., Delphin and WUFI, and are used worldwide (Nicolai and Grunewald, 2006, Fraunhofer Institute for Building Physics, n.d). These are applied in retrofit and new build projects, and recent developments have made it feasible to assess the impact of climate change on durability of constructions (Vandemeulebroucke et al., 2022).

This paper introduces a decision-making framework, surpassing the scope of the existing standards such as EN15026-2023 and ASHREA 160-2021. The standards do identify various essential input variables for hygrothermal simulations. However, these standards often fall short in providing guidance and addressing challenges of model parameters and input values. Notable, these standards lack provisions for considering the impact of climate change, a critical aspect in today's evolving environmental conditions (Vandemeulebroucke et al, 2021).

2. Methods/Methodology

2.1. SAMiRA approach

The framework provides a step-by-step approach to characterize the input and model parameters for HAM simulations, using a three-level ranking system. Input variables are the values or characteristics to define the conditions and properties for the simulation. For instance, the different material properties. On the other hand, model parameters are internal settings within the simulation that are not controlled by the building component, but are essential for the operation of the model, e.g. the grid resolution. The methodology aims to be generic in nature, designed in a way that it can be adopted regardless of the specific software used.

The ranking system is based on three strategic levels: Superior, Advanced, and Minimum requirements. These reflect to what extent case-specific information can be gathered, measured or determined. This information comprises aspects such as local climate, specific material properties. Furthermore, as the input variables become more uncertain, it is essential to incorporate a sensitivity analysis. From the minimum requirement, one should consider both 'optimistic' and 'pessimistic' scenarios, which would require obtaining corresponding values for each step. The level-system is visualized in Figure 1. A hypothetical case is shown for an individual parameter value, e.g. the rain exposure. It is clear that the spread between the optimistic and pessimistic scenario will decrease with an increase in strategic level. This implies that the parameter uncertainty reduces, while simultaneously increasing the expenses. The latter can be interpreted in different ways, including but not limited to computational, time, material and financial expenses.

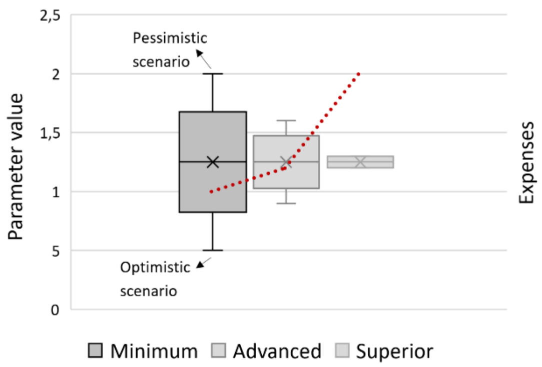

Figure 1: Three-level ranking system: balance between uncertainties and expenses.

The proposed methodology, SAMiRA, is visualized in Figure 2, and includes 12 steps that represent the various decisions that are necessary to construct a case file and perform a HAM simulation. The steps correspond to the different input variables with their corresponding model parameters. The three most difficult steps for practice, based on the workshop and discussion, are elaborated in detail in the results.

The first step involves determining the project design and end goal, containing the purpose and objective of the study. This end goal will define the performance assessment to evaluate the building case. An appropriate prediction or assessment model for performance is selected in the second step. Next, the simulation software is determined, considering the advantages and disadvantages of different software packages relative to the type of project and goal. The following steps (4-9) focus on exposing the building component to different moisture and heat sources, including outdoor and indoor environments, water infiltration, initial moisture content, condensation water, and heating elements. In step 10, all materials properties, with a primary focus on the hygrothermal properties are determined. Once the input variables are defined and the case is set up, the simulation is run, and post-processing of the results is undertaken. During post-processing, the established risk criteria are calculated. The latter is done using available risk prediction models, such as mould growth, wood rot, salt crystallization, frost cycles, biological deterioration, and corrosion prediction models. In the context of this research project the HAMalyser webtool is made publicly available, which includes the web-based calculation of the state-of-the-art performance prediction models based on the uploaded simulation output.

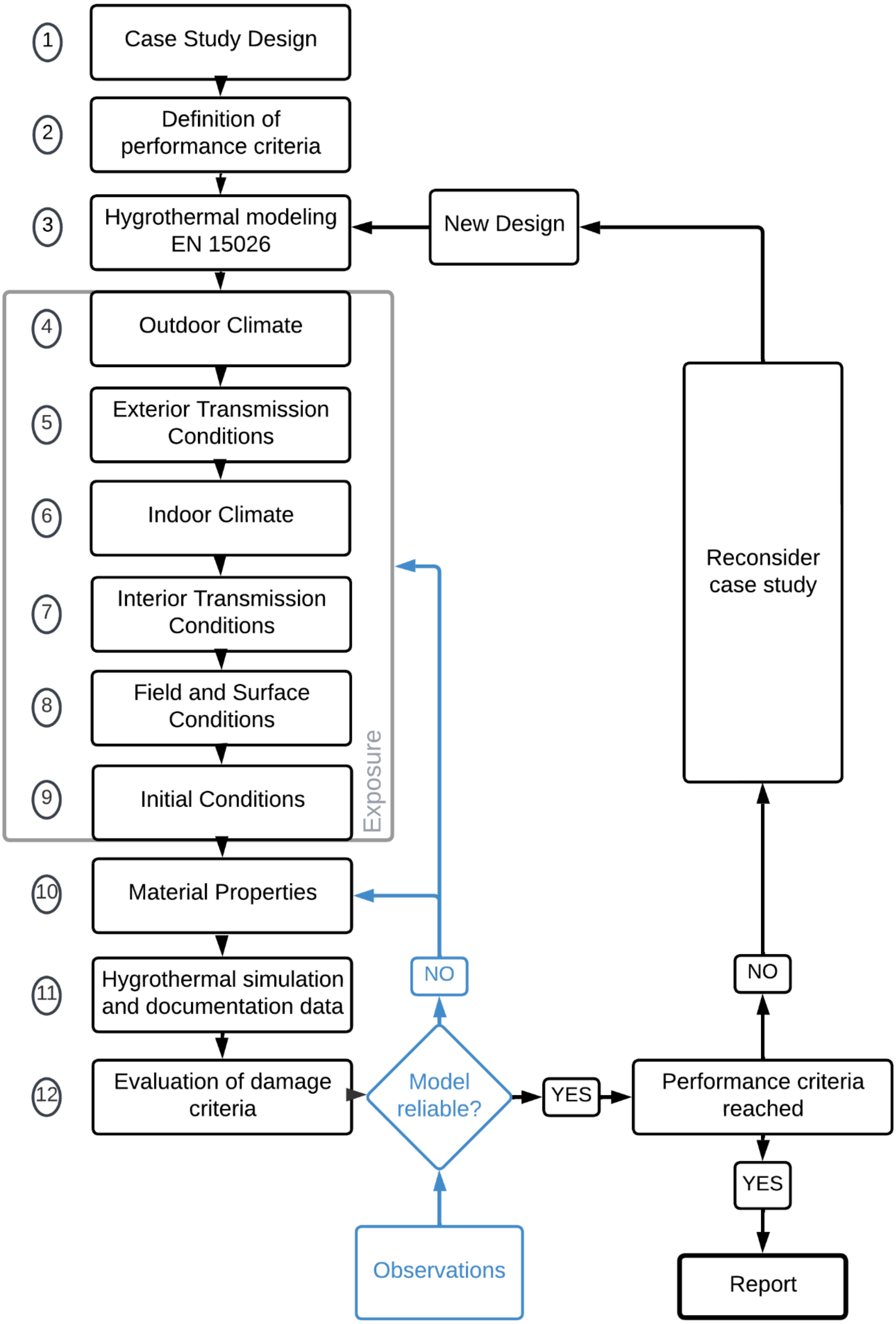

Figure 2: Flowchart summarizing SAMiRA: 12 comprehensive steps for hygrothermal simulations.

For existing structures (e.g. renovation, restauration,…), a feedback loop is integrated as a control mechanism, in which the results of the post-processing should be compared with the occurrence (or absence) of corresponding damage patterns. When the observations do not adequately agree with the predicted degradation risks, the case setup is reconsidered to increase its reliability. This can be done by increasing the strategic level of the material or the exposure parameters.

Once a balance is found between the accuracy and the expenses, the performance is calculated and checked against the selected criteria. When this entails a result that is found unacceptable, a new design or a different retrofit strategy is necessary to meet the predefined requirements.

2.2. SAMiRA in practice

A website tool, named HAMalyser, was developed and includes the SAMiRA framework as well as a post-processing tool for performance analyses. The tool offers two distinct features. First of all, users can follow the decision framework with additional information and examples for different types of configurations, and access the online post-processing tool. Next to that, a rapid assessment tool for traditional masonry allows to quickly scan for performance risks (Janssens et al, 2022).

SAMiRA and HAMalyser were presented and discussed, in collaboration with the UKCMB (UK Centre for Moisture in Buildings), with a group of 24 experts from the field. In an interactive workshop, the framework was introduced with the goal of mapping out the approaches taking by practices and to understand what is feasible to improve through open questions and polls.

3. Results

3.1. Material Properties

Hygrothermal simulations are a powerful tool but heavily rely on the accurate definition of building materials and their properties to calculate the different balance and transport equations. The properties which are relevant for the accurate modelling of heat and moisture flow within building materials are: capillarity, density, specific heat capacity, thermal conductivity, moisture storage, diffusion resistance, liquid transport, open porosity, air permeability (Feng et al, 2015).

When determining material properties, a distinction is made between materials for which a technical datasheet is available and materials for which no properties are known. When a material is recently produced, usually a list of declared properties can be found in the technical datasheet.

Table 1: SAMiRA for newly produced materials

Superior	Advanced	Minimum
An existing comparable material or material file layout is used and modified according to a full characterization of the properties from experimental testing or obtained from the available technical datasheet.	An existing material file is modified to represent the material. The available properties are used to select a comparable material from a hygrothermal material database. Subsequently, the basic properties and moisture-dependent parameters, such as moisture retention, conductivity, and vapor permeability, are scaled or replaced by the known properties from the technical sheets.	After thorough consideration of the technical datasheet, a suitable representative or generic material is selected from the available hygrothermal database. This approach should be accompanied with a sensitivity analysis to determine the dominant parameters and conservative approach.

There are various cases for which the materials are unidentified and technical datasheets are not available, especially in heritage cases. There, the buildings' original material is mostly unknown and may have degraded and modified over time, rendering it a challenge to determine its characteristics. Additionally, the variability within a single type of material may be very large, mainly due to the difference in origin of the raw materials, natural variability of the constituent materials, and fabrication methods (Roels et al, 2023).

Table 2: SAMiRA for undefined materials

Superior	Advanced	Minimum
The material undergoes a complete characterization for all properties. Additionally, the effect of inherent material variability on the output is assessed with sensitivity analysis.	A partial characterization is performed, focusing on the most important material properties. To determine the significance of a parameter, either a sensitivity analysis is conducted, or similar cases described in literature are examined. By doing so, engineers and designers can identify and prioritize the critical material properties that have the most substantial impact on the risk assessment.	When no properties are available, insight about the impact of different properties on the response should be obtained. For each property, a range of values must be considered, including low, average, and high values. Specific quantities can be obtained from material databases or literature. By varying the values, the material's behavior can be observed under different conditions and the most critical properties that impact its performance can be defined.

It is recommended to fit storage and transport measurements to analytical functions. For example, the Van Genuchten (1980) bimodal and trimodal equations are commonly used to fit the moisture retention functions to prevent convergence problems during simulations. The superior category requires a complete characterization of the material which incorporates a stochastic approach for the material and considers the natural variability within a single material. The variation in each material property should cover 95% of its distribution: assuming a normal distribution, this relates to 1 standard deviation around the mean. For the advanced category an increased limit is considered, i.e., + 2 StDev and -2 StDev. For the Minium requirement, low, average and high values are considered based on literature.

3.2. Climate input

The outdoor climate is generally defined as the boundary condition on the exterior surface of the building component. The necessary variables include: temperature, relative humidity or vapor pressure, direct and diffuse solar (shortwave) radiation, downward thermal (longwave) radiation, wind speed and direction, and precipitation on a horizontal plane or normal to the wall (EN15026). Climate data is assessed on three aspects: the spatial resolution, time resolution and the evaluation period.

Not all building components are exposed to outdoor conditions. Components situated adjacent to a crawl space, attic, vented cavities, solid ground, water, and green roofs require a specific approach. There, dedicated approaches, measured data or prior simulation results are necessary to define the exterior boundary conditions (EN 15026). For subsurface building components, ground temperature relates to both ground conditions and observed depth, as described in EN ISO 13370. It is presumed that the relative humidity within the ground remains at a minimum of 99%, unless precise locations-specific data is available.

Spatial resolution

Climatic conditions are highly dependant on the geographical location and this has an important impact on the simulation results (Cornick et al., 2003; Kalamees and Vinha, 2004; Zhou et al. 2016). The geospatial variability of the response of building envelopes depends on orographic features, urbanization etc. For example, two buildings in a mountainous area, only separated by 10 km, may have a different hygrothermal response, same for a building situated in the city centre, compared to another building in the surrounding rural area of the city. In these cases, the climate data need to be specific to the building site and its geographical location.

Table 3: SAMiRA for the geographical location of the building

Superior	Advanced	Minimum
The climatic data are representative and validated for the location of the building site on a micro-scale. At this strategic level, very local phenomena are considered. Therefore, with very local measurements, phenomena such as urban heat island are considered.	The climatic data are representative and validated for the location of the building site on a meso-scale.	The closest available location to the building site is selected. Observations from national weather services can be adopted on a macro-scale.

Time resolution

Different deterioration mechanisms exhibit varying rates of initiation and growth. For example, the crystallization of salts occurs rapidly (Godts et al. 2021) whereas the initiation and growth of mould fungi is much slower (Viitanen 2008). Therefore, it is important to use an appropriate time resolution during hygrothermal simulations to capture the events of interest. The time resolution does not only apply to the resolution of the simulation output, but also on the input conditions. EN 15026 dictates at least an hourly resolution. However, according to Blocken and Carmeliet (2007), arithmetic averaging of 10-minute wind and rain data towards hourly values leads to the loss of information on the co-occurrence of these climate variables. The latter could lead to an underestimation of the wind-driven rain loads up to 45%.

Climate change and evaluation period

The type of climate data used in a study depends on the nature and goal of the research, which can either be focusing a static climate or consider climate change. For static climates, variables are typically measurements and are available in either a long-term continuous dataset or a Moisture Reference Year (MRY) format. When studying the long-term durability of building envelopes, the World Meteorological Organization (WMO) recommendeds a 30-year simulation to account for realistic sequences of weather events and inter-annual climate variability. An MRY is a one-year dataset that is considered representative for a specific location in terms of moisture stress, with a typical return period of 10 years.

Table 4: SAMiRA for the static climate data

Superior	**Advanced**	**Minimum**
Time resolution of 10 min	Time resolution of 60 min	Time resolution of 60 min
The climate input is an entire long-term climate dataset. At least 10 years of (measured) data are used. Ideally, the dataset consists of 30 years of continuous data with 10-min resolution.	A MRY is used as outdoor climate input. The MRY is selected and evaluated within the study. A comprehensive framework to select MRYs is developed by Vandemeulebroucke et al. (2022).	A MRY is used as outdoor climate input. The MRY can be selected from the available databases, or from another source that provides climate files for HAM simulations. Example of an open data: MRY for Brussels. Without specified reference years, a yearly temperature adjustment of 2K can be applied to a representative year, depending on the likelihood of summer or winter condensation issues. The relative humidity remains the same. The modification yields data for a critical year expected to occur once every ten years according to EN 15026.

When climate change is considered, it is recommended that the climate data cover a 30-year period to accurately assess the impact of climate change on building envelopes or materials (WMO, 2015). This climate data is generated from regional climate models and can be used to compare simulation results using a 30-year historical (baseline) period to results using one or more 30-year climate projections. Future climate scenarios can be based on different levels of global warming (GW) or projected emissions of greenhouse gases, such as the Representative Concentration Pathways (RCP) reported in the fifth assessment report (AR5) from the Intergovernmental Panel on Climate Change (IPCC), or the Shared Socioeconomic Pathways (SSP) reported in the sixth assessment report (AR6). The latter features the state-of-the-art CIMP6 models.

However, it is important to note that climate models are subject to biases due to uncertainties in physical processes, parametrization, temporal and spatial resolution, and projected greenhouse gas emissions etc. (Benestad et al. 2017). These biases can lead to errors in the simulation results. For example, a model may be "too wet and too cold" at a particular location, and the bias may not be constant over the entire model territory. To address these biases, there are multiple approaches that can be taken (Benestad et al., 2017). One way is to apply bias-correction techniques to the climate models. This can be challenging as the required climate variables for hygrothermal simulations are correlated in a complex, non-linear way. Another approach is to use an ensemble of different climate projections (Benestad et al., 2017). This involves combining different projections, each with their own biases, to create a range of possible outcomes. By using an ensemble approach, it becomes more certain that the actual situation will fall somewhere within the spread of the ensemble.

Table 5: *SAMiRA to include climate change in studies.*

Superior	**Advanced**	**Minimum**
Time resolution 60 min	Time resolution 60 min	Time resolution 60 min
Multiple climate models, and RCP scenarios or GW levels are included in the ensemble. Per climate model, a 30-year simulated historical (baseline) period is compared with one or more 30-year climate projections (from the same climate model as the baseline period). The ensemble approach accurately quantifies the uncertainty of the results. It is necessary to assess the bias of the models through a comparison with the historical observations. The potential impact of the biases that may arise, is determined.	A 30-year historical (baseline) period is compared with an ensemble of ca. three 30-year climate projections (all from the same climate model). The ensemble members can consist of different future scenarios by one climate model. The ensemble quantifies the uncertainty of the results to a limited extend. It is necessary to assess the bias of the models through a comparison with the historical observations.	A 30-year historical (baseline) period is compared with one 30-year climate projection (both from the same climate model). In this case, biases in the climate model for the specific location are not accounted for. Next to that, the uncertainty induced by uncertainty in climate change effects is unknown.

3.3. Exterior transfer coefficients

External surface transfer coefficients refer to the rate of which heat and mass transfer from the surface of a material to the surrounding environment and the other way around. These coefficients are important in determining the overall hygrothermal performance of a building element, as they affect the heat transport, the moisture uptake and evaporation rate at the surface (Steskens et al. 2009). There are various mechanisms through which external surface transfer can occur. These include convective and radiative heat transfer, the exchange of vapor, and the exchange of the surrounding atmospheric conditions such as solar radiation and rain showers. The spatial distribution of these coefficients at the exterior surface is important because it affects the distribution of temperature and moisture across the building envelope. If these coefficients are unevenly distributed, certain areas of the building envelope may be more prone to moisture accumulation, some areas may be cooler than others or may have a lower drying potential than others.

Convective heat transfer

The convective heat transfer coefficient, h_{ce}, represents the rate at which heat is transferred through convective heat transfer, which is the transfer of heat through the movement of the air boundary layer. Wind speed and direction have a crucial role in this, as well as the roughness of the building surface and the temperature differences (Steskens et al. 2009). The SAMiRA approach is given in **Table *6***.

Table 6: SAMiRA for convective heat transfer coefficients

Superior	Advanced	Minimum
Heat transfer is simulated using Computational fluid dynamics for different wind speeds and orientation, with small cells in the boundary layer of the wall).	Distinct expressions for convective heat transfer coefficients are used. Expressions which consider the effect of wind speed, building height, building width, and wind direction specifically at the windward facades of structures. An example for such approach is developed by Montazeri and Blocken (2018).	If no wind dependent transfer coefficient is available, can be calculated or implemented, a constant value can be used derived from literature. (Minimum0) If local wind speed is available, the surface heat transfer coefficient should be calculated according to EN15026: $$h_{c,se} = 4 + 4v$$ With: v the wind speed [m/s] $h_{c,se}$ convective heat transfer coefficient [W/m^{2}K] (Minimum1)

Radiative heat transfer

The surrounding environment and the building envelope interact in the absorption and emission of heat through radiation, involving the transfer of heat via electromagnetic waves. This process is twofold with a diffuse and direct radiation, respectively from the surroundings and directly from the radiation source. The former can be computed with isotropic or anisotropic sky models. Radiative heat transfer is affected by factors such as the surface temperature, the emissivity of the material and the ambient temperature. Some models combine the convective and radiation component of external heat transfer into a unified representation known as the heat exchange coefficient.

Table 7: SAMiRA for radiation coefficients (absorption and emission)

Superior	Advanced / Minimum
The radiation coefficients are determined based on lab or on site measurements.	The radiation coefficients are determined based on tabulated values from literature.

Vapor transfer

The surface vapor transfer, also known as the surface moisture transfer, represents the transfer of water vapor between the surface of the building and the surrounding air. This occurs due to a vapor pressure difference between the material surface and the surrounding environment and will affect the overall moisture content, potential evaporation and condensation. To simulate the boundary layer at the external surface, an equivalent vapor diffusion thickness is used which depends on the governing wind flow.

***Table 8:** SAMiRA for moisture transfer coefficients*

Superior	Advanced	Minimum
Moisture transfer coefficients are calculated in relation to the wind flow at the boundary layer with Computational Fluid Dynamics, or based on on-site measurements.	When wind speed data is available, the surface vapor transport coefficient should be calculated based on the equivalent vapor diffusion thickness. $\beta_e = 6{,}1 * 10^{-9} * \mathrm{h}_{ce}$ [s/m]	If no wind speed data is available a constant value can be used derived from literature. $\beta_e = 7{,}5 * 10^{-8}$ [s/m]

Rain transfer

Wind-driven rain (WDR) or driving rain occurs when the wind imparts a horizontal velocity to the rain, causing it to fall obliquely (Blocken and Carmeliet, 2004). WDR is the primary source of moisture and the leading cause of deterioration and performance risks on the majority of building envelope components (Van Den Bossche, 2023). The rain exposure, or catch ratio, is the ratio of the wind-driven rain that hits a surface at a certain location to the total rain through the same area as horizontal plane (ISO 15927-3). The exposure evidently depends on the climate, horizontal undisturbed rain intensity, windspeed and wind direction, but also raindrop distribution. The geometry of surroundings and the building itself have a very large impact on the magnitude and spatial distribution of rain load on façades (Blocken and Carmeliet, 2004). Usually, the rain exposure ranges between 0 and 1. When considering runoff water or poor detailing and execution such as drainage leaks, a value higher than 1 can be used to implement extra rain related moisture sources in the calculations. Previous studies by Calle et al. (2021) and Vanderschelden et al. (2022) have shown that the exposure to rain has a crucial impact on the hygrothermal behaviour of historic walls in a warm climate like Belgium (Köppen-Geiger, 2006).

Table 9: *SAMiRA for rain exposure coefficients*

Superior	Advanced	Minimum
The distribution of the catch ratio is determined for the building envelope with CFD-simulations or based on a measuring campaign with rain gauges.	The catch ratio is determined based on CFD simulations or measurements for similar building geometries reported in literature. A sensitivity analysis is conducted with three levels of exposure: a low, average, and high exposure.	A spatially averaged value of the catch ratio is determined based on tabulated values from literature or standards. Use a conservative value to consider the most critical exposure on the façade.

3.1. SAMiRA in practice

The framework was presented, in an interactive workshop, to 24 experts from practice. It immediately became clear which stumbling blocks they encounter when setting up a HAM simulation, namely: the choice of materials, collecting climate data and determining the catch ratio for driving rain shown in Figure 3 on the left. When zooming in on the different aspects according to the SAMiRA approach, Figure 3 on the right, it became clear that in practice, a minimum approach is chosen, and only in a few cases an advanced or superior approach is applied. This has everything to do with the budget and the persuasiveness of the customer. The framework was highly valued for educating and raising users' awareness of the impact of the various choices to be made in HAM simulations.

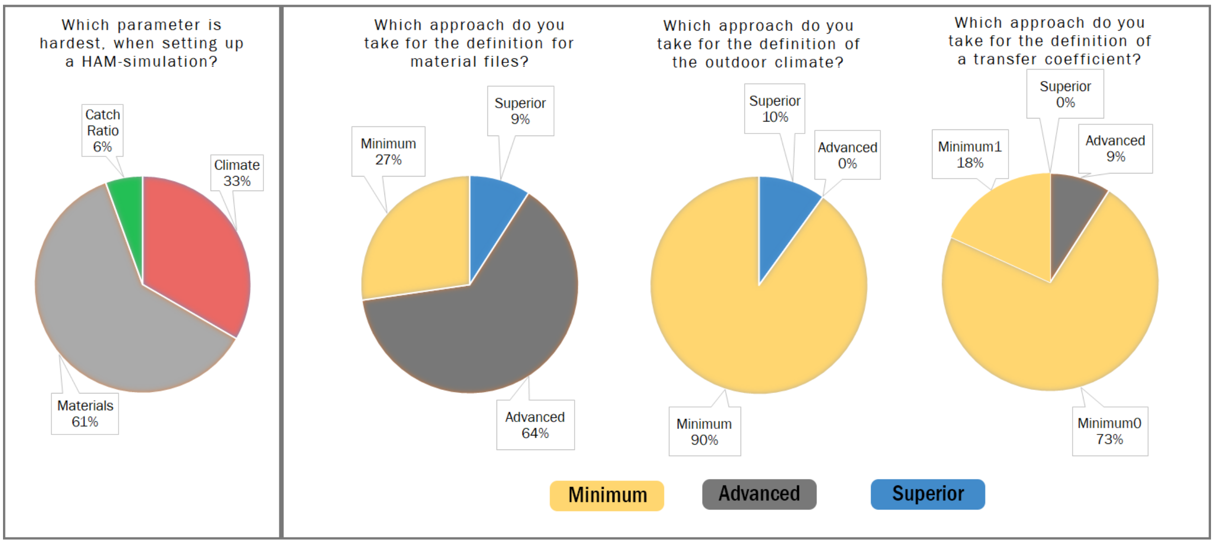

Figure 3: SAMiRA in practice: stumbling blocks and approaches taken for characterization.

4. Conclusions and Discussion

The SAMiRA methodology was developed and offers a stepwise approach to conduct hygrothermal simulations. The decision framework goes well beyond the existing EN 15026 and ASHREA 160 by providing guidelines for various inputs and model parameters and offers three strategic levels: superior, advanced, and minimum. A balance between accuracy and feasibility is recommended but in practice, most of the decisions will be governed by the client choice and the budget.

It is important to note that while the SAMiRA offers guidelines and approaches for conducting hygrothermal simulations, the method still requires professional judgement and expertise on the part of the user. Users must evaluate the specific requirements for their project and determine which approach is most suitable for all parties involved. The method should not be solely relied upon without careful consideration of the project and its unique circumstances and requirements.

The method is developed based on the current state-ot-the-art and may require updates over time. As new research and information become available, simulation models improve, data becomes available, material-specific dose-response functions develop, and material characterization advances, it is important to review and update the methodology accordingly. The framework is made publicly available in a webtool called HAMalyser[1].

[1] https://hamalyser.shinyapps.io/HAMalyser/

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6. Short bio

Bruno Vanderschelden holds a Master of Engineering degree from Ghent University, specializing in Architectural Design and Building Technology. His 2020 Master's thesis explored cluster techniques for historic bricks, integrating material properties and hygrothermal behaviour. Following a research stay in Canada on the development of generic climate input, he joined Ghent University as a researcher on the forgiveness of bio-based materials in timber frame walls exposed to leakages. Currently pursuing a joint Ph.D. with the University of Antwerp, focusing on the hygrothermal behaviour and pathologies on heritage structures, studying wetting and drying patterns through wind and rain models.