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Hygrothermal assessment of external walls in Arctic climates: Field measurements and simulations of a test facility

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A B S T R A C T

The Greenlandic building sector is under pressure due to ever-changing building trends and a building shortage. Regrettably, there have only been made small efforts to investigate the performance of the existing buildings, and few resources have been dedicated to learning from previous attempts. Consequently, the available information and research are insufficient to ensure the construction of robust and well-functioning buildings. This knowledge gap motivated the ABC project, which had the goal of collecting and sharing information about optimal building practices in Greenland. As a part of the ABC project, this study aimed to determine which building practice is the most suitable for Greenlandic conditions. To this end, several real-time experiments were created, including a test pavilion in Nuuk consisting of five different wall constructions oriented towards north and south. This article presents the measured data from this pavilion. The performance of each construction type was compared with each other and to simulations performed in the hygrothermal analysis software Delphin. Furthermore, the robustness of the facades was tested by performing simulations with weather data for different towns in Greenland, including quantification of mould growth risk using the Viitanen model. It was found that the facades were unevenly affected by orientation. Nevertheless, none of the constructions could be labelled unsuitable for the Arctic climate as the assessments revealed no risk of mould growth. Additionally, reanalysis weather data from ERA5 was found to be suitable for performing hygrothermal simulations. It was also found that Nuuk is a favourable location for future test facilities.

1. Introduction

1.1. Changing building styles

The Greenlandic construction industry is relatively new and, to a high degree, affected by other cultures, especially Danish traditions. This has resulted in rapidly changing building traditions. E.g. according to Møller and Lading [1], the Greenlandic building style has fundamentally changed multiple times since the 1950s. Originally, the tendency was to build small Norwegian-style standard houses of 1–2 storeys, but over time concrete buildings up to four storeys became more common. The most recent tendency has been to build groups of identical multistorey buildings (up to seven storeys) with ventilated air cavities in the façade construction. The main drivers for the changing building style are typically economical and political [2]. Meanwhile, the research on the performance of each building style has been very limited, with the majority of research being performed within the last ten years. Consequently, new construction types have been implemented without validated experiences and sufficient technical knowledge to justify the design choices. To overcome this knowledge gap, several long-term experiments of different construction types were performed within the Arctic Building and Construction (ABC) Project [3]. These experiments were carried out at different locations on the west coast of Greenland, including a test pavilion located in Nuuk, which provided the data used in this article. The overall goal of the ABC project was to identify current challenges and present possible solutions to improve the quality of future constructions in Arctic climates, with a primary focus on the Greenlandic industry and society.

1.2. Indoor climate, mould, and renovation

While the literature concerning construction practices in Greenland is limited, there has been significant research on the indoor climate, especially focusing on moisture and mould. Poor indoor climate can cause discomforts such as headaches, asthma, eczema, coughing, and irritation of mucous membranes [4]. Additionally, diseases like

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tuberculosis thrive better in poor indoor climates and appear 20 times as often in Greenland compared to the rest of the Nordic countries [5]. According to Kotol [6], the indoor environment often suffers due to a lack of ventilation in the kitchen and bathrooms, as well as drying of clothes indoors during winter and not using the kitchen hood during cooking. Thus, attempts have been made to increase public awareness of the issues [7]. Regardless of the reason, a poor indoor climate can affect the building envelope and cause condensation in the construction, potentially leading to rot and a reduction of the building life span. Helgason [8] presented several examples of severe moisture problems, including high humidity in a bathroom ruining the building façade, disintegrating wind barriers due to driving rain, and mould issues caused by implementing moist or mouldy building materials into new constructions. Despite moisture and mould issues, the indoor relative humidity (RH) in Greenlandic buildings is generally low. A study from 2014 performed in Sisimiut found that the average RH in 79 bedrooms were 42% and 26% during summer and winter, respectively. The average indoor night temperature was 22 °C [9].

Water is another considerable risk factor in façade constructions. Both regarding the risk of mould, but also due to thaw-freeze processes, which can cause leaks or expansion of cracks. Nevertheless, this study focuses on mould as the main failure mechanism since wood decay caused by other fungi starts at higher moisture levels, and frost damage is less likely.

Wind is another risk factor, e.g., Lading and Møller [10] reported of a concrete construction where the lack of wind barrier combined with poor labour quality resulted in colder surfaces than expected [11]. The discussion presented in Ref. [11] emphasised the need for solutions without unnecessarily complex solutions. This was also emphasised by de Place when surveying moisture-related challenges in the Greenlandic building sector [12].

Simultaneously with the aforementioned issues, there has been a massive building shortage. For example, in 2019, there were 2000 people on waiting lists for housing, and 10.000 new residents are expected in Nuuk during the next ten years [13]. In addition to the economic infrastructure causing bottlenecks in the construction of new buildings [14], there is a need for increasing the service life of future constructions to meet expected needs, as well as a strategy for maintaining the existing building mass. According to a recent article in the Greenlandic newspaper Sermitsiaq, the Greenlandic self-government has put aside 1.5 billion DKK in the national budget to renovate existing buildings [15]. While this is a decent start, lector Tove Lading from DTU pointed out that it is too unambitious, considering that more buildings will decay during the renovation period.

1.3. Sustainability

While sustainability in the construction sector is a hot topic globally, the literature within this field concerning Greenlandic conditions is minimal. Morten Ryberg et al. [16] conducted a comparative sustainability study of four buildings in Greenland, representing the current construction methods. Specifically, the study considered a CLT construction, a concrete construction, a timber frame construction, and a renovation case. The study concluded that renovating old buildings was the most environmentally friendly option. Due to the limited local resources in Greenland, most building materials must be transported long distances, which contributes to the environmental impact. However, according to an Icelandic study [17], the impact of long-distance overseas transport of building materials is negligible within most sustainability impact groups. The exceptions are acidification and eutrophication, where transportation contributes 25% and 31%, respectively. Friis et al. [18] also found that transportation is insignificant to the level of CO_2 emissions when considering various types of insulation. Besides smaller sustainability projects, the Green Building Council Denmark [19] has recently DGNB-certified a residential building in Nuuk [20]. The German certification system, DGNB, aims to improve and quantify the social, economic and environmental performance of buildings [21]. According to Leif Hansen Bygherrerådgivning [22], the certification requirements have been adjusted to Greenlandic conditions in order to make the certification criteria "ambitious but fair". Some adjustments were necessary due to the climatic conditions, e.g., the demand of planted trees was revised as they cannot grow north of the tree line, and the allowed energy consumption per square meter was increased to match the available technical solutions and harsh climate. Furthermore, as all land in Greenland is public, the DGNB requirements for parking lots and gardens have been adjusted. The ambitions of DGNB stand in stark contrast to the current Greenlandic building regulation from 2006 [23], which is currently under revision.

1.4. Aim and research questions

Due to the limited research on the hygrothermal conditions of façade constructions in Greenland, this study aims to evaluate current construction methods and identify possible unfavourable construction tendencies in a Greenlandic context. The study is based on experimental data from a test pavilion in Nuuk, which included five different construction types. A test pavilion, i.e., an experimental test facility consisting of a container with a controlled indoor climate, was chosen to minimise uncertainties compared to conducting measurements in existing buildings. As the pavilion was constructed meticulously in a lab facility at the Technical University of Denmark (DTU), the data represents the performance of the technical design solutions concerning the climate without accounting for poor workmanship or building errors. Consequently, the test pavilion does not necessarily represent similar conditions as construction made on-site locally in Greenland. The collected data for each construction type are compared with each other and with the results of hygrothermal Delphin simulations to evaluate if the conditions behave as intended and expected. With the fitted hygrothermal models, it is possible to analyse the behaviour of the various construction types in different climates. The present study seeks to answer the following research questions.

1) Are any of the considered construction types unsuitable for the Arctic climate in Nuuk?
2) How robust are the constructions to the climatic conditions in other regions of Greenland?
3) Which parameters are essential to the robustness of the façade construction?

2. Methods

This study is based on experimental data from the test pavilion in Nuuk and hygrothermal simulations produced using the software Delphin. Delphin is a Coupled Heat, Air, Moisture and Pollutant Simulation for Building Envelope Systems (CHAMPS-BES) simulation tool, which has been verified by Nicolai et al. [24]. This section first introduces the pavilion, the different integrated constructions, and descriptions of how the data were analysed, compared, and assessed. This is followed by a thorough description of the hygrothermal simulation method. Finally, the investigation of the risk of mould growth using the Viitanen model implemented in WUFI VTT [25] is described. The process flow of this study, from data collection to analysis, is presented in Fig. 1.

2.1. The test pavilion

The experimental test facility was a closed pavilion similar to a container located in Nuuk. More specifically, the pavilion consisted of a small building with a single room with a controlled indoor climate of 20 °C air temperature and 50% relative humidity. As presented in Section 1.2, the relative humidity indoors is typically much lower in Greenland, while the temperature is representative. The high indoor relative humidity was chosen as a worst-case scenario. The outer walls

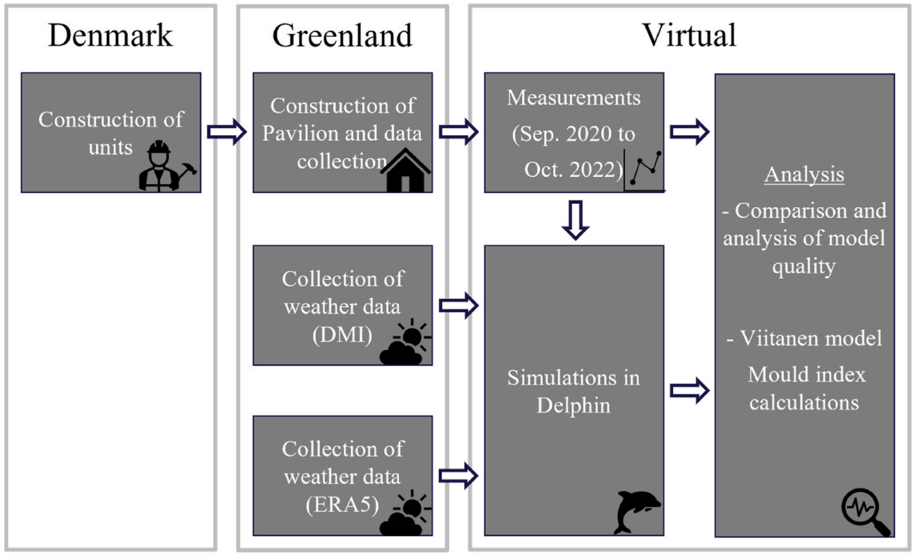

Fig. 1. Relation between collected data and applied methods during this study.

consisted of five differently designed façade elements, which for the remainder of this paper are referred to as "units". The orientation of the pavilion and the placement of the five different units (A-E) are shown in Fig. 2. All units were produced in two or three replicates, with the individual units facing different directions. The gables were constructed using units A and E. Data from the roof and floor units were also logged, although this article only focuses on the wall constructions. The pavilion was oriented at an angle of 40° from north (see Fig. 2). This means that what is referred to as the "northern side" in this study is actually offset 5° from north-east. The entrance door was placed in the western gable, A_W.

2.2. Construction of the pavilion units

All the constructions were designed to replicate existing facade types found in the construction industry in Greenland. All units had a ventilated air gap behind a cladding of watertight plywood.

Details of the thermal transmittance of the walls, the material types, and material thicknesses are given in Fig. 3 and Table 1. In Unit B, fibre cement boards were used to replicate concrete to ensure the buildability of the test pavilion. The materials were not identical regarding hygrothermal properties, but considering the large span of properties for different concrete products, it was considered an acceptable approximation.

Several temperature and relative humidity sensors were installed within each unit. The specific number of sensors installed was dependent on the construction type and the number of material layers. As a minimum, measurements were made on each side of the vapour barrier and behind the wind barrier. As the air gap, cladding, and U-value were approximately the same in all units, the conditions in the air gaps were only measured in one unit for each orientation. The conditions in the air cavity were measured in Units C_N, C_S, A_W, and E_E. The location of the sensors in each unit is shown in Fig. 3, where the dots and triangles represent the sensors. Dots indicate sensors that are available in all orientations of that unit, while triangles mark sensors that are only available in one orientation. The colours of the sensors correspond to the lines in the graphs in Section 3. The sensors used in the test facility are of

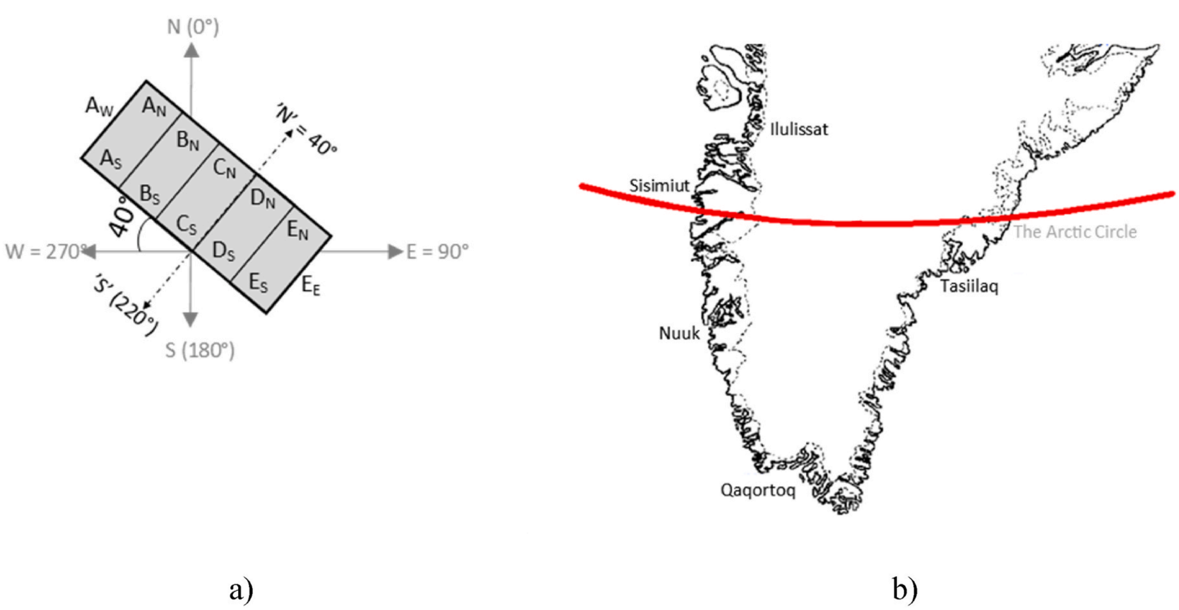

Fig. 2. a) Orientation and division of the wall units of the test pavilion. b) Geographic overview of the considered cities in Greenland (adapted from BR2006 [23]).

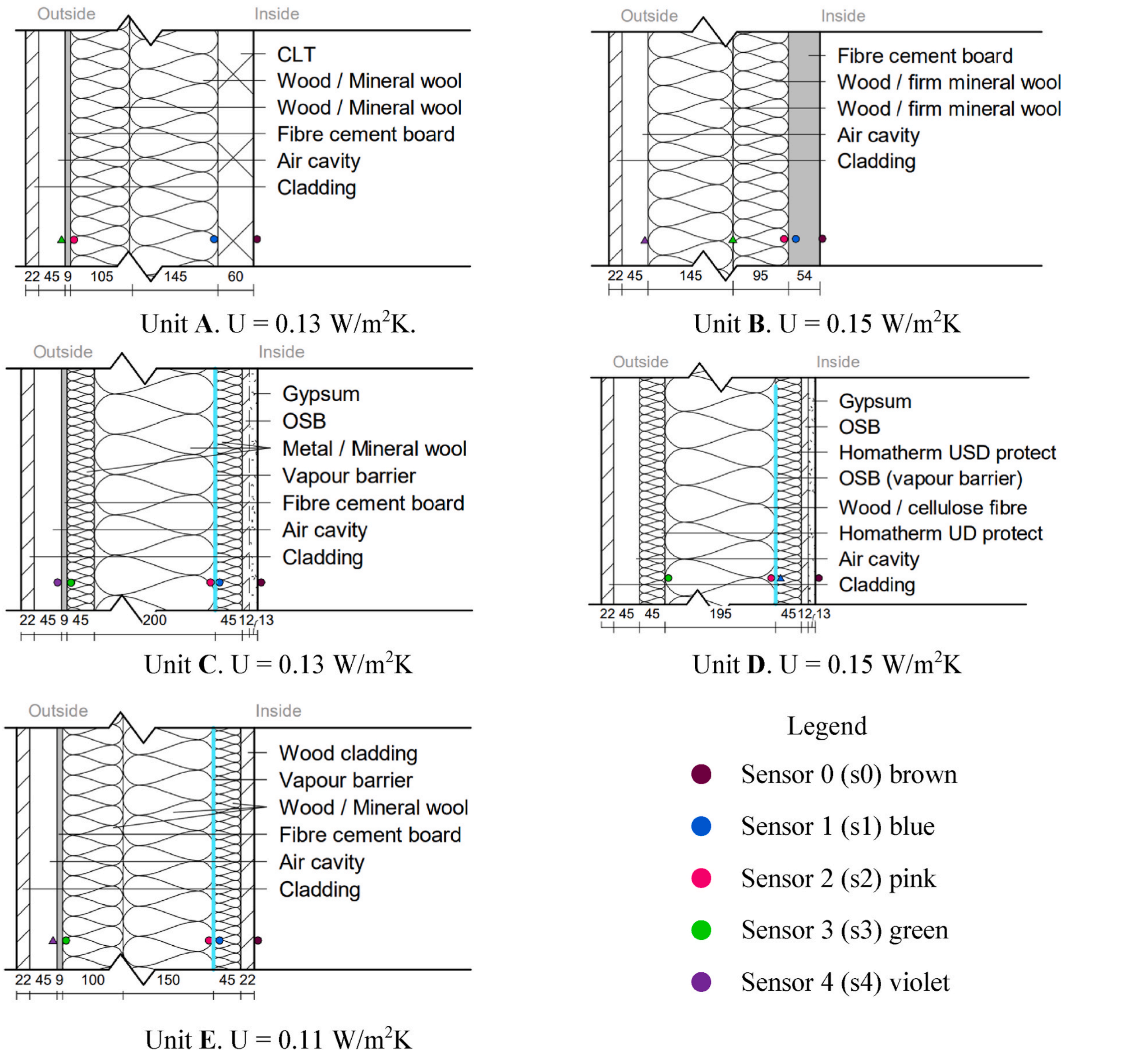

Fig. 3. Details of the construction of each unit and placement of the sensors. Sensor locations are either represented as dots (multiple orientations) or triangles (single orientation). The sensor colour corresponds to the lines in the graphs in Section 3. The sensors are named s0 to s4, starting from the interior side of the wall. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Material properties applied in Delphin. Asterisks (*) indicate calibration and grey values are from the Delphin database.

Material	λ	μ	ρ	Cp	A_w	W_{sat}	W_{80}	$K_{l,eff}$	A	B	C	D	E
	W/mK	–	kg/m^3	J/kgK	kg/m^{2}s^{½}	kg/m^3	kg/m^3	s					
Mineral Wool $_{(731)}$	0.035	1.5*	67	840	0	900	0.1	0	x				x
Fibre cement board $_{(265)}$	0.24 [38]	20 [39]*	1424 [38]	900 [40]	0.01	419.0	40.0	0	x	x	x		x
Air cavity $_{(17)}$	0.222	0.25	1.3	1050	0	1000	0	0	x	x	x	x	x
Cladding, external $_{(279)}$	0.067 [41]	80	500 [41]	1880 [42]	480.2	215	0	–	x	x	x	x	x
CLT $_{(626)}$	0.12	73	425	1245	0.0024	590.2	72.6	9.5e^{-10}	x				
Firm mineral wool $_{(731)}$	0.04*	1.5*	85 [38]	1030 [43]	0	900	0.1	0		x			
Gypsum $_{(599)}$	0.14*	20*	745.1	1826	0.18	574.9	8.8	6.6e^{-11}			x	x	
OSB $_{(650)}$	0.13	165	595	1500	0	847	95.7	–			x	x	
Mineral wool/metal $_{(731)}$	0.042*	1	67	840	0	900	0.1	0			x		
PE-foil $_{(174)}$	0.32*	100.000	1500	2100	0	0	0	0			x		x
Homatherm USD $_{(580)}$	0.042 [44]	3 [44]	190 [44]	2100 [44]	0.56	780	6.3	3.5e^{-6}				x	
Cellulose $_{(580)}$	0.048	2.05*	55.2	2500	0.56	780	6.3	3.5e^{-6}				x	
Homatherm UD $_{(580)}$	0.044 [44]*	3 [44]	160 [44]	2100 [44]	0.56	780	6.3	3.5e^{-6}				x	
Wood cladding $_{(844)}$	0.148	3.81	414.6	2416	0.01	718.9	76.3	–					x

the type HYT 221 from Innovative Sensor Technology [26]. The sensors are pre-calibrated and can digitally measure relative humidity from 0% to 100% and temperature from −40 °C to +125 °C. The accuracy is declared to be ±1.8% RH at 23 °C in the range 0% RH to 90% RH (no uncertainty information is specified above 90% RH, although it is expected to be higher) and ±0.2 K (in the range 0 °C to +60 °C).

2.3. Construction process of test pavilion

As the pavilion was designed and erected as a test facility, its construction was untraditional and highly meticulous. To ensure high-quality workmanship, each unit, including the sensors, was pre-assembled by skilled workers at a test facility at the Technical University of Denmark (DTU) in Denmark. Subsequently, the units were shipped to Nuuk, where they were implemented in the pavilion. It is important to note that there are a few inconsistencies in the test setup, which could affect the results. These include.

- Cut-out in fibre cement boards in Unit B to make space for a sensor.
- Inconsistent placement of the external sensor (s3/s4) in Unit B.
- Faulty measurements in sensor s1 in Unit D_S.

Except for s1 in Unit B, all sensors are placed next to an insulation layer, making room for the sensors without specific holes in the construction layers. Furthermore, at the time of writing, the sensors are still implemented in the test pavilion, which is why they have not been recalibrated after the data collection. Also, the elements have not been visually analysed for mould growth.

2.3.1. Experimental data

All of the experimental data, i.e., temperature and relative humidity measurements, are presented in graphs and compared based on the construction units. The pavilion was constructed in June 2019, and data has been logged hourly since October 29th, 2020. Based on these data, the vapour content at each sensor point was calculated. The equation for calculating the vapour content, υ (g/m^3), is given in Eq. (1) [27], where the φ is the relative humidity (−), and θ is the temperature (°C). All three parameters are analysed for all orientations and construction types and finally compared to the simulated data.

$$\begin{aligned}\text{For } \theta \geq 0\,^{\circ}\text{C}, \upsilon = \varphi \bullet \frac{610.5 \bullet e^{\frac{17.269 \bullet \theta}{237.3+\theta}}}{0.4615 \bullet (\theta + 273.15)} \\ \text{For } \theta < 0\,^{\circ}\text{C}, \upsilon = \varphi \bullet \frac{610.5 \bullet e^{\frac{21.875 \bullet \theta}{265.5+\theta}}}{0.4615 \bullet (\theta + 273.15)}\end{aligned} \quad [\text{g}/\text{m}^3] \tag{1}$$

2.4. Hygrothermal simulations

2.4.1. Weather data

When simulating in the hygrothermal simulation program, Delphin 6.1 [28], it is necessary to set boundary conditions which highly impact the quality of the results. The air temperature and relative humidity were measured in the ceiling of the test pavilion and used as the interior boundary condition. The external boundary condition was defined using weather data sourced from Asiaq, a government-owned institute operating weather stations across Greenland [29]. The weather station, "Nuuk City" (64.183333, −51.730833) [30], was placed approximately 300 m from the pavilion (64.185879, −51.731583) [31]. The weather station measured most of the necessary parameters required for Delphin, including ambient temperature (°C), relative humidity (%), wind direction (°), wind velocity (m/s), air pressure (Pa), and rain (l/m^{2}h). Delphin can also consider long-wave counter radiation, but this parameter was not measured in Nuuk. The considered weather station measured global shortwave radiation, but Delphin requires direct and diffuse radiation. Therefore, these two parameters were calculated from the global radiation using the Orgill & Holland decomposition algorithm [32]. All parameters exhibited 430 missing data points, except air pressure, with only 225 missing observations. For air pressure, the longest period of consecutive missing data was 137 h (almost six days) and 287 h (nearly 12 days) for the remaining parameters. Due to the limited number of missing data, linear interpolation was applied for all parameters except solar radiation. For solar radiation, linear interpolation was applied for instances where data was missing for less than one day. In cases where data was missing for more than one day, the missing data were filled by substituting the missing data with data from the same time of day from the previous and following available days. The exchange coefficients for heat transmission and vapour diffusion were the same for all simulations. For the inner side of the façade constructions, the heat transmission exchange coefficient for still air was assumed to be 8 W/m^{2}K and for vapour diffusion it was 1e^{-8} s/m. Externally, the effective heat conduction exchange coefficient was 25 W/m^{2}K, while the vapour diffusion mass transfer coefficient was 7.5e^{-8} s/m. For wind driven rain, the reduction coefficient was set to 0.7, which is standard for vertical walls in Delphin, and the solar adsorption coefficient was defined to be 0.7. The initial conditions of the simulation model were defined to be 20 °C and 50% relative humidity, corresponding to the indoor climate conditions.

2.4.2. Air change rate in cavity

The airflow in the ventilated air cavity is a challenging parameter to define. Hence this parameter is often discussed in studies concerning hygrothermal conditions and simulations. According to Brozowsky et al. [33], air change rates (ACH) varying from 0 to 650 h^{-1} have been reported in the literature. Langmans and Roles [34] described four measuring techniques to identify cavity ventilation rates. Falk and Sandin [35] conducted a field study and found that the orientation of the battens in the air cavity had a significant impact on the ACH. For vertical battens, the ACH was 230–310 h^{-1}, and for horizontal battens, it was 60–70% lower. Furthermore, solar irradiance could cause the ACH to increase by a factor of three. Moreover, Girma and Tariku [36] found that narrow air cavities reduce airflow and increase heat gain. In this study, no measurements were performed to identify the air change rate. As the ACH is already affected by significant uncertainty, it was decided to assume a constant flow. Based on simulation results and considering the range of 0–650 h^{-1}, the ACH was set to 60 h^{-1}. The sensitivity of this factor is investigated in Section 3.2.4.

2.4.3. Modelling in delphin

The procedure for modelling the constructions in Delphin was to replicate each construction, as shown in Fig. 3, and define the sensor locations and the material properties as accurately as possible. Unfortunately, datasheets for the applied materials were unavailable, which is why the material properties in the Delphin models were iteratively calibrated to get the best fit between the model output and the measured data. The iterations have been conducted by changing single parameters for one or, preferably, more units and analysing the impact on the results. The chosen ranges of the parameter variation were based on literature or materials from the Delphin database. The materials used in this study are described in Table 1, including the required parameters in Delphin, which are: thermal conductivity (λ), water vapour diffusion resistance factor (μ), density (ρ), specific heat capacity (Cp), water uptake coefficient (A_w), water content at saturation (W_{sat}), water content at 80% RH (W_{80}), and liquid water conductivity at effective saturation ($K_{l,eff}$) [37]. Some of these values were based on more specific material properties, including open porosity (Θ_{por}), effective saturation (Θ_{eff}), capillary sorption value at 80% RH (Θ_{80}), capillary saturation content (Θ_{cap}), and air permeability (K_g) [37]. In Table 1, the material ID from the Delphin database is given in parentheses, and the original data are shown in grey. Modified material data are specified with their respective sources. Asterisks (*) indicate that material properties were adjusted during the model calibration and deviated from the references. The materials are identical regardless of which unit they are applied to, as only one type of each material was purchased for the test pavilion. Not all materials require all properties due to airtightness or water tightness; however, they are available in Delphin and thus reported in the table.

The simulations are run with the standard grid mesh generated by Delphin, which varies from 1 mm to 50 mm with a stretch factor of 1.3. This results in a mesh of 71–102 grid elements, depending on the specific unit. According to Ruiz et al. [45], the obtained mesh leads to very high accuracy, as a grid of 20 elements was found sufficient for walls of high complexity.

2.4.4. Evaluation method

To quantify the difference between the measured and simulated data, the Root Mean Square Error (RMSE) is introduced [46]. The RMSE quantifies the error between the simulated data and measured data (considered the truth). The equation for RMSE is presented in Eq. (2), where N is the number of datapoints, $x_{sensor,i}$ is the observed data in the respective unit and, $x_{delphin,i}$ is the simulated data in the respective unit for the $i'th$ time step. RMSE is always positive, and thus it cannot describe in which direction the modelled data deviates from the measured data. The unit of the parameters x_{sensor} and $x_{delphin}$ defines the unit of the RMSE. The coefficient of variance of RMSE, CV(RMSE), is often used to compare hygrothermal measurements with simulations. The advantage is that the unit is in percentage, which is easier to interpret. In this case, the errors will depend significantly on the position of the sensor, as low values result in higher errors. Therefore, RMSE is used in this study.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(x_{delphin,i} - x_{sensor,i}\right)^2}{N}} \quad 2$$

2.5. Model applications to various locations

To evaluate the robustness of the constructions in the climatic conditions in other regions of Greenland, the Delphin models are run with weather data from various locations to investigate how different weather conditions can be expected to affect the hygrothermal conditions of the façade constructions. The pavilion models have been simulated using weather data for Tasiilaq, Sisimiut, Ilulissat, and Qaqortoq to test the robustness of the façades. The towns are geographically located, as shown in Fig. 2. Sisimiut is chosen as it is the second largest town in Greenland, after Nuuk, and therefore holds a large building mass. Ilulissat is another relatively large town located north of Sisimiut. Qaqortoq is located south of Nuuk and thus has a higher moisture level. Tasiilaq is located on the east coast, where the climate is more extreme. All simulations were carried out using reanalysis weather data for 2021 from ERA5 provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [47]. The missing data were interpolated, and the global solar radiation was derived using the Erbs decomposition algorithm [32].

2.6. Quantifying the risk of mould growth

The robustness of a construction in the Arctic climate depends on many parameters, including the risk of mould growth, which in turn depends on the materials, temperature, and humidity. The mould index was chosen as the focus of this evaluation because the conditions for mould growth have lower limit values than wood-decaying fungi, i.e., the construction is more vulnerable to mould than wood-decaying fungi. The software WUFI Mould Index VTT 2.3 [25] was used to determine the Mould Growth Index based on the three conditions using the Viitanen model [48]. As the intention was to assess a critical scenario, the analysis was performed with a highly sensitive material for all units; pine sapwood from the WUFI material database was chosen for this purpose. The mould growth index was calculated for the sensor locations, which were considered the most critical based on the results.

3. Results and analysis

This section only presents the essential graphs produced. Additional figures can be found in the supplementary figures [49]. It should be noted that all of the presented graphs show either 7 or 30-day moving means in order to visualise the long-term trends. The moving mean period is specified in the captions of each figure. The following graphs were generated and analysed for all units and all directions.

- Temperature graphs of sensor data for all orientations of the same construction.
- Relative humidity graphs of sensor data for all orientations of the same construction.
- Temperature graphs, including sensor data and Delphin results.
- Relative humidity graphs, including sensor data and Delphin results.
- Vapour content graphs for both sensor data and Delphin results.

3.1. Evaluation of experimental data

All available data from 2020-09–29 to 2022-10-20 are shown in Fig. 4, including interpolated values. The graphs had two purposes. First, to visually check for any remarkable changes in the measurements over time, which could indicate sensor drift. Second, to illustrate the differences between the units and the orientations. Noticeably, there was a decrease in the interior relative humidity during spring 2022, which did not seem to be caused by temperature changes. Plausible explanations could be that the humidifier, controlling the indoor relative humidity, stopped working or that the water tank connected to the humidifier was empty. Besides this, small deviances in the interior climate were noticeable, caused by maintenance activities in the pavilion, such as filling the humidifier tank and ensuring continuous data logging. From Fig. 4, it can also be seen that the temperatures in the exterior layers were highest in the south-oriented directions, lowest for the northern orientation, and in between for east and west orientations. A plausible explanation of these differences is heat contribution from direct solar irradiation. This could be seen for all units except B, as the sensors were placed differently in the north and south direction. Another general observation was that none of the constructions was exposed to 100% relative humidity for longer periods of time.

Based on s1 in Unit A, it is noticeable that the temperature was lower in the western orientation than in the north and south. As there were no visible differences between the orientations in the exterior layers, this temperature difference might have been caused by improper assembly of the entrance door, which could result in thermal bridges or wind flow in the construction. Given that the relative humidity was also lower in the western orientation, this may very well be the case. The relative humidity in s1 in Unit C stands out, as it was very different for the two orientations. The relative humidity was highest for the north orientation and never overlapped with the measurements for the south orientation. The temperature was also slightly lower in the north than in the south. In Unit E_N, there was a peak in temperature in March 2021. The peak in temperature occurred throughout all the northern units.

3.2. Comparison of measured and simulated data

3.2.1. Root Mean Square Error

The following section focuses on the year 2021. Table 2 shows the Root Mean Square Errors (RMSE) (see Eq. (2)) of the Delphin simulations. The first two sections of the table compare the original hourly data, while the last section compares the seven-day moving mean relative humidity. The latter indicates whether the model is able to capture the general tendency, despite the high RMSE caused by short-term peaks and outliers. When developing the Delphin models, the aim was to

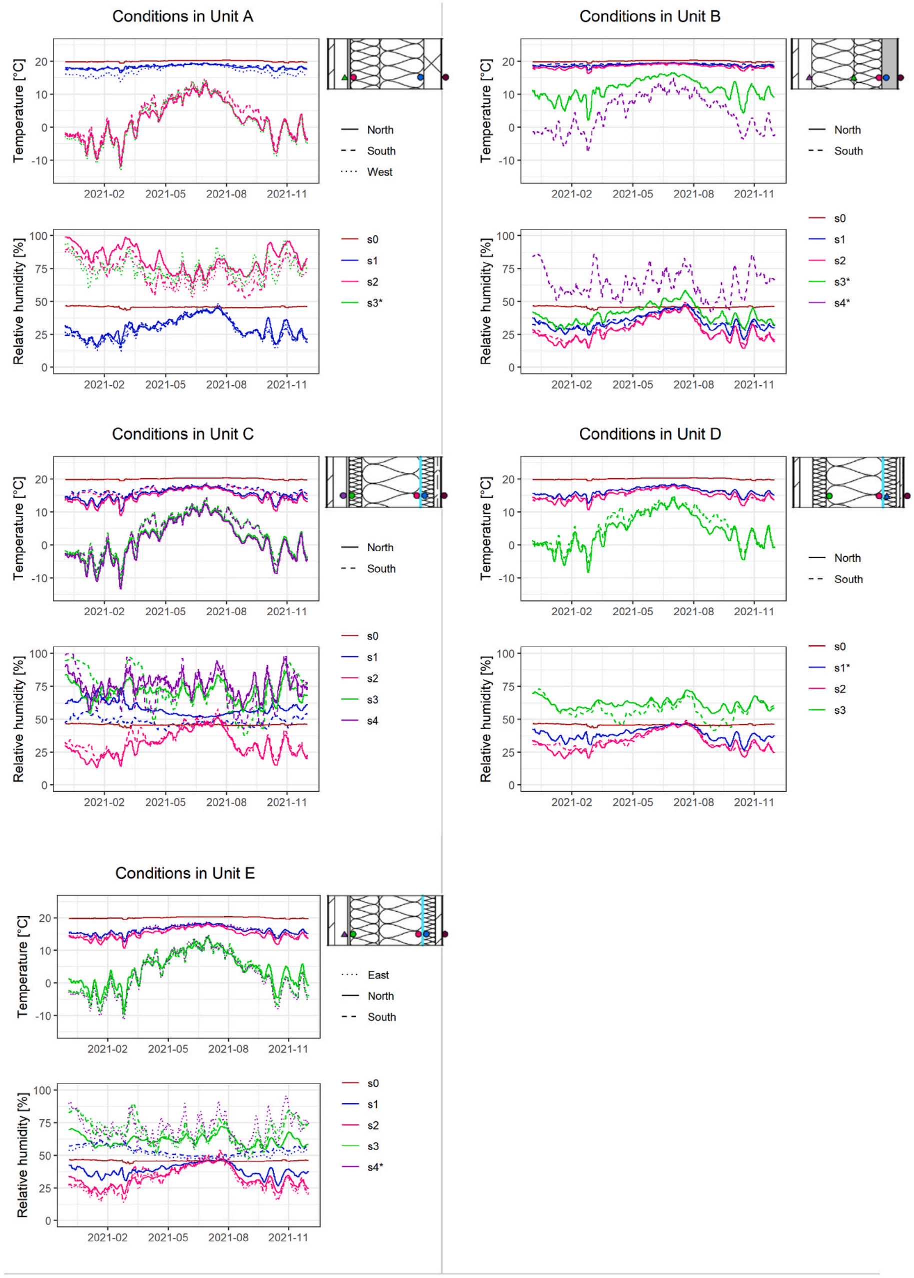

Fig. 4. Hygrothermal conditions in Units A – E (seven-day moving mean). The asterisks (*) indicate that the measurement point was only found in one direction of the unit (equal to a triangle in Fig. 3).

achieve an error of less than 5 °C for temperatures and less than 10% for relative humidity. The primary purpose of these limits was to easily identify at which sensor points the model deviated significantly from the measured data. The additional benefit was that the limits could be used as a benchmark for when the model is "good enough," as simulations can be improved infinitely without significant scientific gain. The cells exceeding the threshold limits are marked with yellow. The first table section shows that the modelled temperature was generally sufficiently accurate, as none of the RMSEs exceeded 5 °C. For relative humidity, the highest errors were found at the sensor positions closest to the exterior climate, which is to be expected due to the stable indoor climate and highly varying external climate. The sensitivity of the ACH and the vapour diffusion mass transfer coefficients are investigated in Section 3.2.4. Generally, the model for Unit D seemed to fit the best, while the model for Unit C performed the worst.

Since the measured interior climate was used as an input for Delphin, it might seem strange that there was an error at this measurement point. The reason is that the measured data is used as the room conditions, while the modelled data point corresponds to the surface conditions. Therefore, the room conditions (s0) from the Delphin output are not illustrated on the graphs throughout this section.

3.2.2. *Comparison of conditions in the air cavities*

As presented in Fig. 3, not all units had a sensor in the ventilated air cavity, but still, there was at least one representative sensor for all orientations. To identify how the orientation affected the hygrothermal conditions in the air cavity, the measurements in the ventilated air cavities are compared in Fig. 5.

The lowest temperatures were found in the northern-oriented Unit C, which can be explained by the fact that this orientation received the least amount of solar irradiation. Some of the highest relative humidity conditions were also detected in this unit. The vapour content in Unit A_W

Table 2
Root Mean Square Error of each unit comparing the Delphin models with the measured data. Yellow cells indicate that RMSE is higher than desired.

	Temperature [°C]					Relative humidity [%]					RH (7-day moving mean) [%]				
	S0	S1	S2	S3	S4	S0	S1	S2	S3	S4	S0	S1	S2	S3	S4
$A_{N(10)}$	0.3	0.5	1.9	-	-	0.9	5.6	9.4	-	-	0.8	3.9	8.0	-	-
$A_{S(1)}$	0.3	0.6	3.7	-	-	0.8	5.5	9.1	-	-	0.8	3.3	7.5	-	-
$A_{W(15)}$	0.3	0.7	3.1	3.3	-	0.9	7.3	9.0	15.6	-	0.8	4.3	7.8	8.5	-
$B_{N(11)}$	0.4	0.4	0.8	2.3	-	1.0	4.5	3.4	3.3	-	0.9	4.0	2.5	2.1	-
$B_{S(2)}$	0.4	0.4	0.8	3.2	-	0.9	5.0	3.5	-	10.6	0.9	4.6	2.4	-	5.2
$C_{N(12)}$	0.5	1.2	1.4	2.0	2.3	1.3	15.5	11.0	8.5	14.6	1.2	13.4	3.1	5.5	10.5
$C_{S(3)}$	0.5	2.2	2.1	3.8	4.2	1.2	9.4	13.5	15.0	19.9	1.2	4.2	4.4	13.6	13.7
$D_{N(13)}$	0.4	0.5	1.2	1.6	-	1.0	8.4	3.6	4.3	-	1.0	8.0	2.8	3.9	-
$D_{S(4)}$	0.4	-	1.1	2.5	-	1.0	-	3.5	5.2	-	0.9	-	2.8	4.7	-
$E_{N(14)}$	0.3	1.0	1.4	2.1	-	0.8	7.3	11.9	8.9	-	0.6	2.7	4.7	7.6	-
$E_{S(5)}$	0.3	1.3	1.7	4.1	-	0.8	6.7	13.0	9.2	-	0.6	1.2	3.8	7.7	-
$E_{E(17)}$	0.3	1.0	1.4	4.4	4.8	0.8	7.8	14.4	10.0	17.5	0.6	3.5	3.4	8.1	5.9

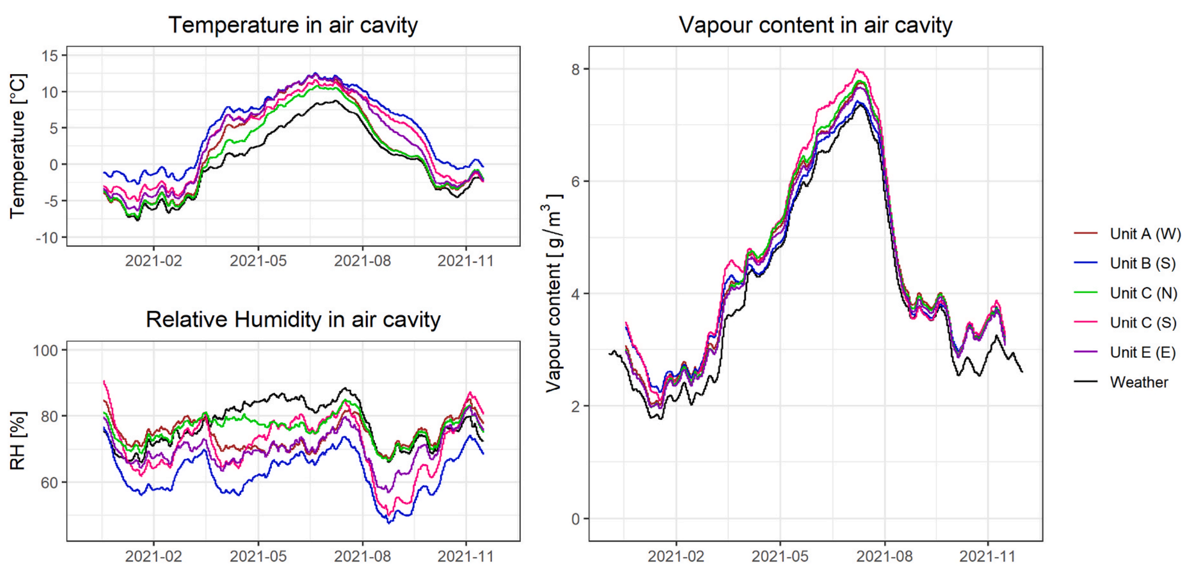

Fig. 5. Graphs for temperature, relative humidity, and vapour content in the air cavity in the year 2021. The graphs display the 30-day moving means to visualise the long-term trends.

and Unit C_N were similar, but in A_W, the temperatures were higher, and in the summer months, the RH was lower. It was expected that in each direction, the conditions in the air cavity would be very similar. However, this was not the case, as Unit B_S had higher temperatures and lower RH than Unit C_S. It did not seem to be caused by drifting of the sensors, as they were not displaced equally during the year. The temperature difference between B_S and C_S could be caused by B_S having a higher U-value (U = 0.15 W/m^{2}K) than C_S (U = 0.13 W/m^{2}K), which allowed a higher heat loss through the surface.

It was found that the vapour moisture content exceeded 10 g/m^3 at sensor point s2 for all elements with fibre cement board as the wind barrier. The vapour moisture content also exceeded 15 g/m^3 for all units except the ones facing north.

3.2.3. *Visual comparison – measurements and simulations*

To compare the simulations with the measurements, the focus will be on the sensors where the RMSE was highest. In the following section, data will be specified according to the sensor position and data origin, e.g., m_3 or d_3 corresponds to measured and simulated (Delphin) data at sensor position 3, respectively. Figs. 6–10 presents the 7-day moving means to make it easier to detect long-term trends. Based on these graphs, the following is noticed.

- The simulation of A_W generally performed worse than A_N and A_S. Unit A_W is the gable with the entrance door, which might affect the hygrothermal performance of the unit. Fig. 5 shows that the RH in the air cavity was high in this orientation compared to the other orientations, which is also shown in Fig. 6, where the RH in d_3 was lower than m_3.
- In Unit B_s, the simulated relative humidity (d_4) was higher than the measured (m_4) (see Fig. 7). As for Unit A_W, this could be traced back to the hygrothermal conditions in the air cavity, where m_4 for B_s had the lowest relative humidity.

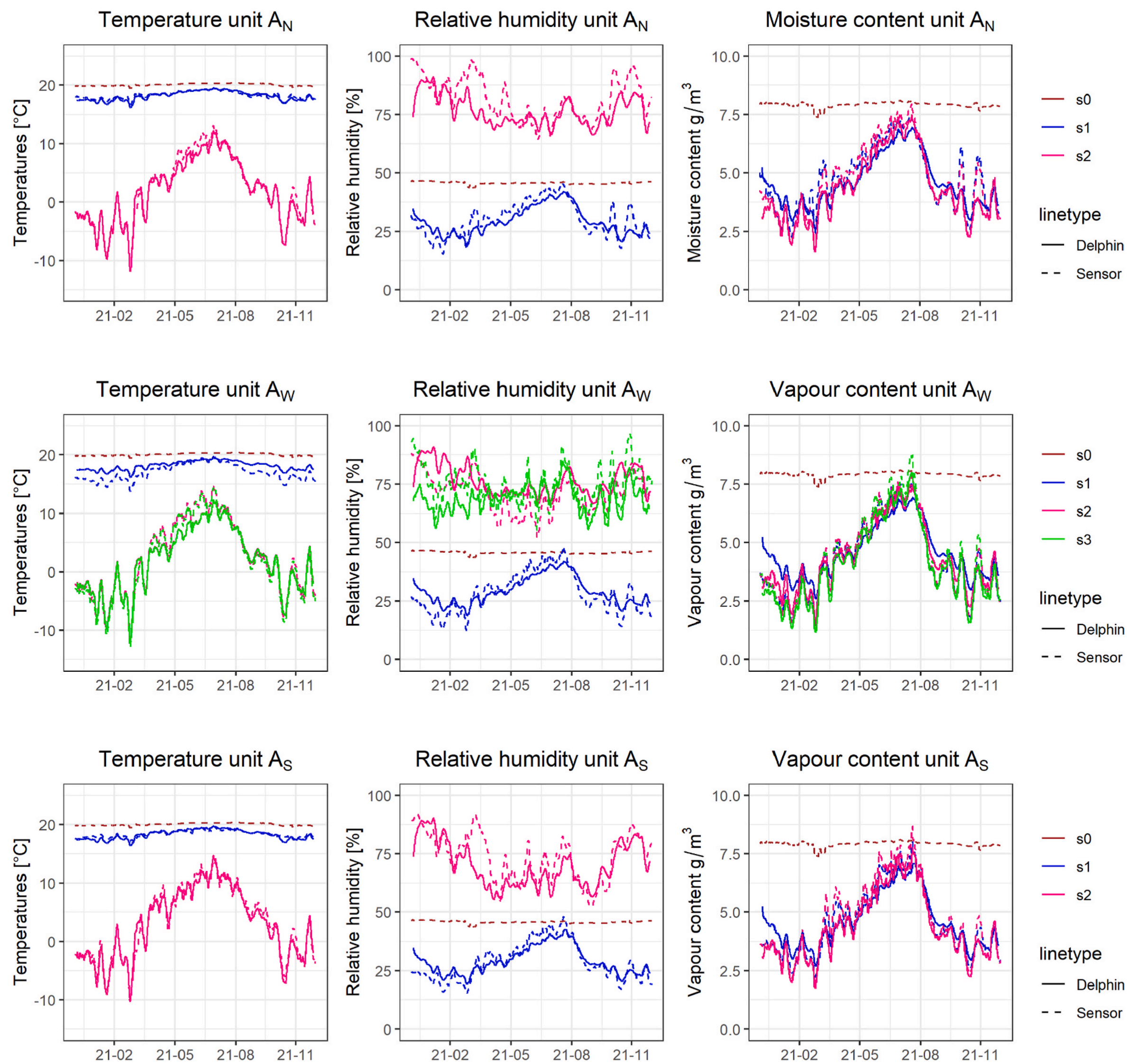

Fig. 6. Hygrothermal conditions for Unit A. Time format yy-mm.

- Both C_N and C_S had sensor points with high RMSE, even for the moving mean of RH. The measured values were very different at s1 compared to s2 and s3, e.g., the peaks were much higher in the southern direction (see Fig. 8). This difference challenged the model fitting in Delphin, as solar irradiation seemed to have a bigger impact on the orientation in the measured data than in Delphin. The high RH in m_1 in the north end (see Fig. 8) does not indicate a perforated vapour barrier, as that would cause the humidity level to align closer with the interior climate. In theory, the difference can be caused by poor sensor calibration, but as described in Section 3.1, Fig. 4 does not indicate such a situation.
- All orientations for Unit E had high RMSE for relative humidity at sensor point s2. According to the low RMSE for the moving mean values, the error occurred due to short-term spikes in the data. The RMSE for s3 in E_S was also high, where the modelled parameters from Delphin were higher than the measured (m_3). In the gable, E_E, d_4 had smaller peaks than m_4 (see Fig. 10).

All simulations are imperfect. In this specific case, the type of imperfection does not seem to be directly connected to the construction type or the orientation. Furthermore, the measurements did not indicate any severe consequences, such as frost close to the interior climate or high levels of relative humidity over long periods of time. This was also true for the simulated results.

3.2.4. Sensitivity of flow in the air cavity

This analysis was performed on the model for Unit B, i.e., the unit where simulations fit the measurements best according to the RMSEs presented in Table 2.

The results of the sensitivity analysis are presented in Table 3 and were calculated as the difference in the RMSE in percentage as described in Eq. (3), where $RMSE_{change}$ is the new value and $RMSE_{basic}$ is the original RMSE value. The results revealed that changes could improve the simulation model at sensor points s0 and s1, although at the expense of the precision at s2 and s3. It also showed that the air change rate, ACH, has a reduced impact on the RMSE closer to the interior climate. Also, the RMSE can be considered insensitive to the ACH, as even a reduction of 60% or a doubling of the value has an insignificant effect. The effect is only significant when the ACH is very low (less than 24 h^{-1}).

$$sensitivity = \frac{(RMSE_{change} - RMSE_{basic})}{RMSE_{basic}} \bullet 100\ [\%] \qquad 3$$

As identified in Section 3.2.1, the largest RMSEs were found for the sensors in the exterior layers of the constructions. The results of the sensitivity analysis of the ACH, presented in Table 3, showed that the

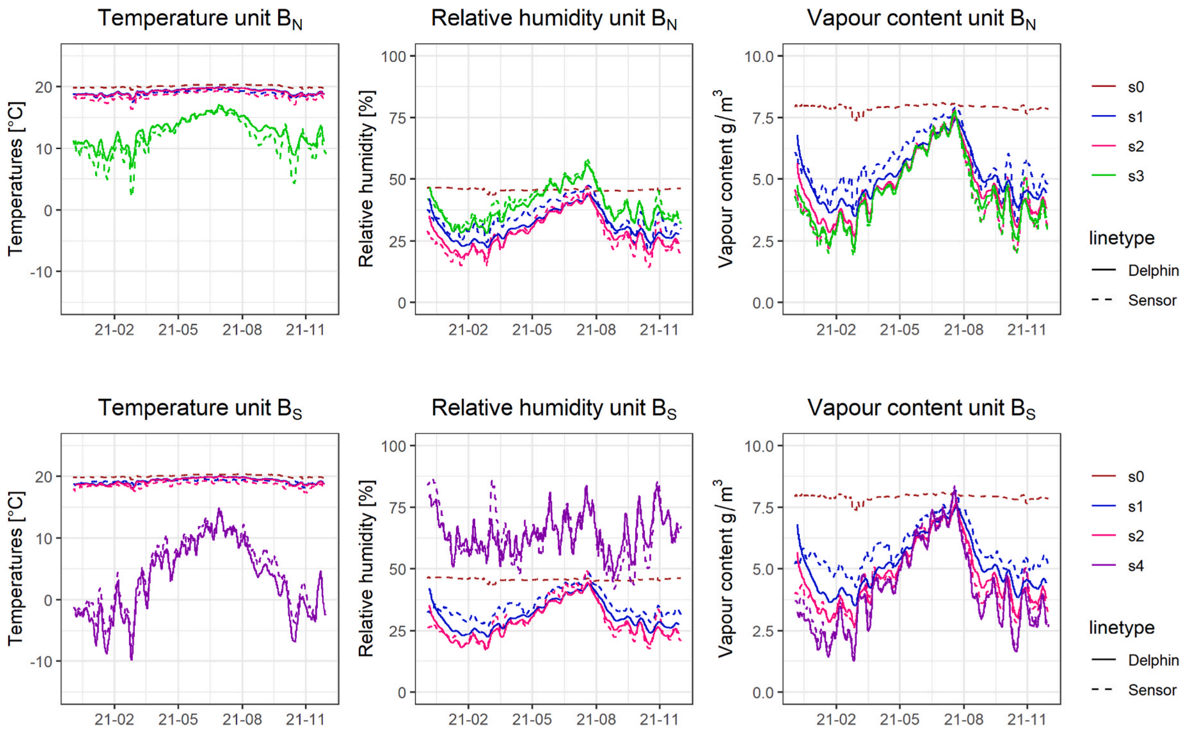

Fig. 7. Hygrothermal conditions for Unit B. Time format yy-mm.

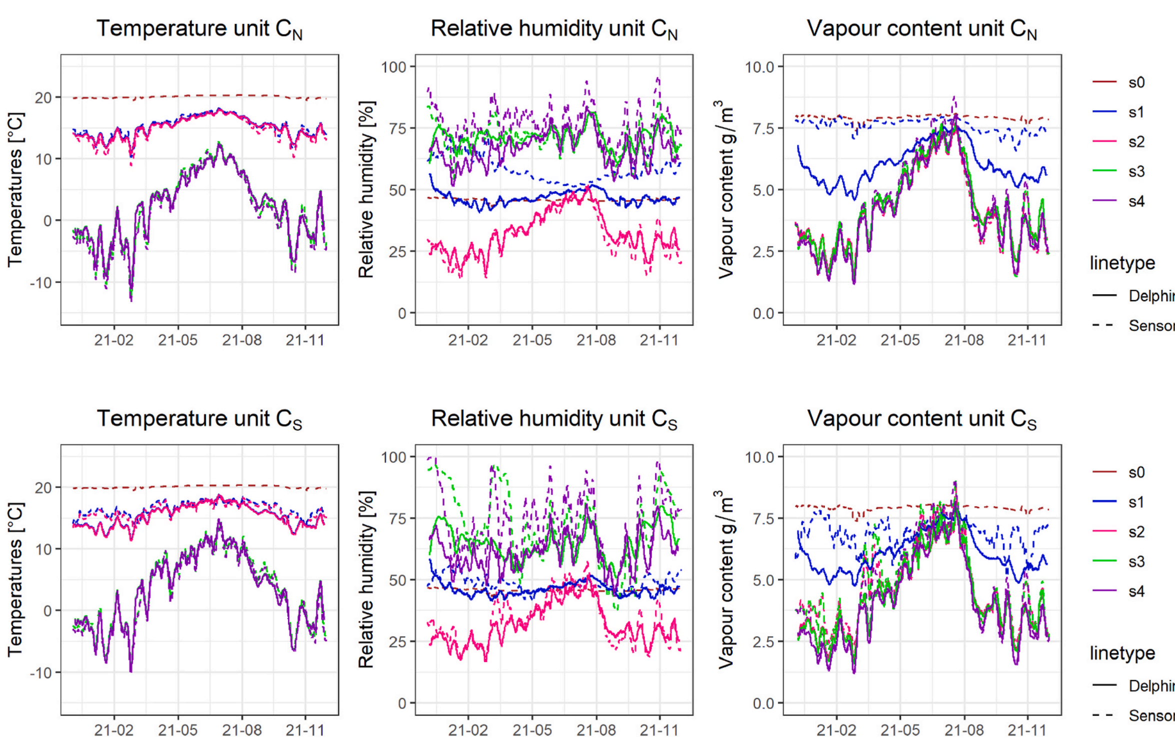

Fig. 8. Hygrothermal conditions for Unit C. Time format yy-mm.

sensitivity of the ACH was highest at the two exterior sensor locations, meaning that this parameter might contribute to the initially high errors along with the varying weather conditions. The sensitivity of the vapour diffusion mass transfer coefficient was investigated for Unit A_N based on the same methodology as for ACH. The initial value was $7.5e^{-8}$, and the tested alternative values were $7.5e^{-6}$, $7.5e^{-10}$, and $7.5e^{-12}$, causing a maximum change of 0.65% of the RMSE occurring for the temperature at sensor point s2. Therefore, the effect of changing the vapour diffusion mass transfer coefficient was considered negligible.

3.2.5. *Consequences of cut-out*

As presented in Section 2.3, there was a hole in the layer of fibre cement boards in Unit B. This was neglected in the hygrothermal simulations, but a small analysis has been conducted to investigate how this

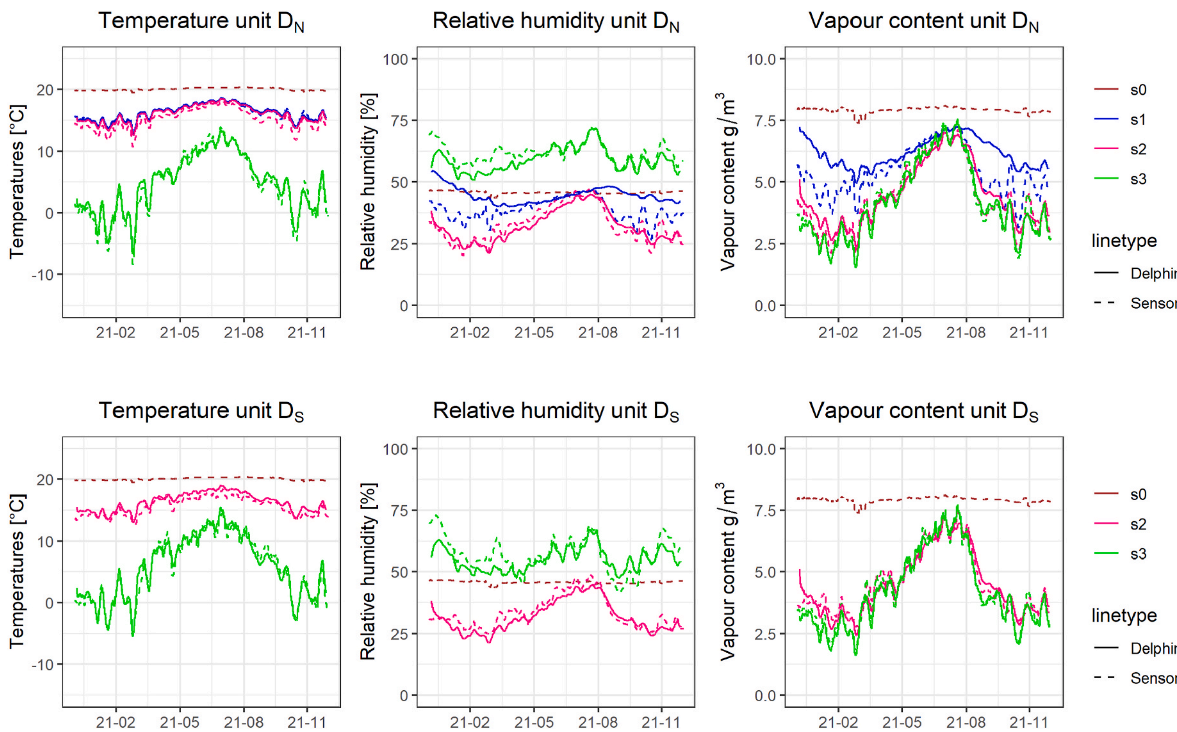

Fig. 9. Hygrothermal conditions for Unit D. Time format yy-mm.

decision affects the quality of the model. An alternative simulation model was built with a 27 mm air cavity (Delphin ID 16) with no airflow. The air gap was placed 18 mm from the interior side of the fibre cement board, which left a 9 mm board between the insulation and the sensor on the other side. The impact is small when comparing the measured values with simulations of solid boards and simulations with holes. However, the temperature is slightly higher at sensor points s1 and s2 for the cut-out simulation. The maximum temperature difference was 1.8 °C, while the mean difference was less than 0.3 °C. The comparison of the temperatures and relative humidity is presented in the repository [49].

3.3. Other climates

The temperature and relative humidity from the ERA5 reanalysis dataset for the five locations is presented in Fig. 11.

The graphs in Fig. 12 were made using a seven-day moving mean and show the hygrothermal conditions at each sensor point for all considered locations. When evaluating the results, it must be considered that the ERA5 weather data are modelled and not measured. The location had almost no influence on the temperature and minimal impact on the relative humidity at the inner layers (sensor points s1 and s2). Therefore, these are not included in Fig. 12. Neither are the graphs representing humidity levels below 75%. The absent graphs can be found in the repository [49]. At the other sensor points (s3 to s4), the highest relative humidity appears in Ilulissat and Sisimiut, followed by Nuuk.

3.4. Risk of mould growth

The constructions and locations at the highest risk of mould growth are identified from the graphs in Fig. 12. The analysis in WUFI VTT is based on the Viitanen model [48] and is made for both measured and simulated values. For all assessments, the material was defined as pine sapwood, which is very sensitive and thus represents a worst-case scenario. The upper part of Table 4 presents the results for the included sensor points analysed with the measured interior conditions from the test pavilion (constant interior conditions of approximately 50% RH and 20 °C). Because of the controlled indoor climate, an additional analysis was made to see the impact of the potentially inappropriate use of a residential building causing high indoor relative humidity. The indoor temperatures were still taken from the measured values from the pavilion, but the RH was changed to 70% and 80%. The calculated mould indexes are presented in Table 4. The mould index ranges from 0 to 6 [50], and according to Ojanen et al. [50], the infestation level is considered acceptable when the index is 2 or less for surfaces inside a construction. The mould index itself is less important as it is based on a relatively short period, but it illustrates the differences and sensitivity for different conditions.

4. Discussion

4.1. Uncertainties and limitations

The intention was to install sensors on each side of the vapour barrier and on the internal side of the wind barrier. However, due to misunderstandings, a hole was created in the fibre cement board in Unit B to make space for a sensor, even though the construction did not contain a vapour barrier. According to simulations in Delphin, this cut-out had small consequences for the hygrothermal conditions in Unit B.

Another uncertainty that caused challenges in replicating the constructions in Delphin was that there were no datasheets for the applied materials. If these data had been available or measured in the lab, the simulations might have been more precise; however, lab measurements of material parameters were not part of this study.

The lack of sensor calibration caused the last apparent uncertainty. Prior to the start of the experiments, the sensors were calibrated at the factory, but it would be valuable to calibrate them after the measuring period. Especially relative humidity sensors are known to drift over time. The data was considered reliable despite the missing calibration based on Fig. 4, which showed a continuity of the yearly cycle and no apparent sensor drift.

The weather data were another source of uncertainty. As described in Section 2.4.1, there was some missing data for each weather parameter. The most uncertain of these was global radiation, as this parameter has the highest variability, e.g., 1 h can be very sunny, while the next can be

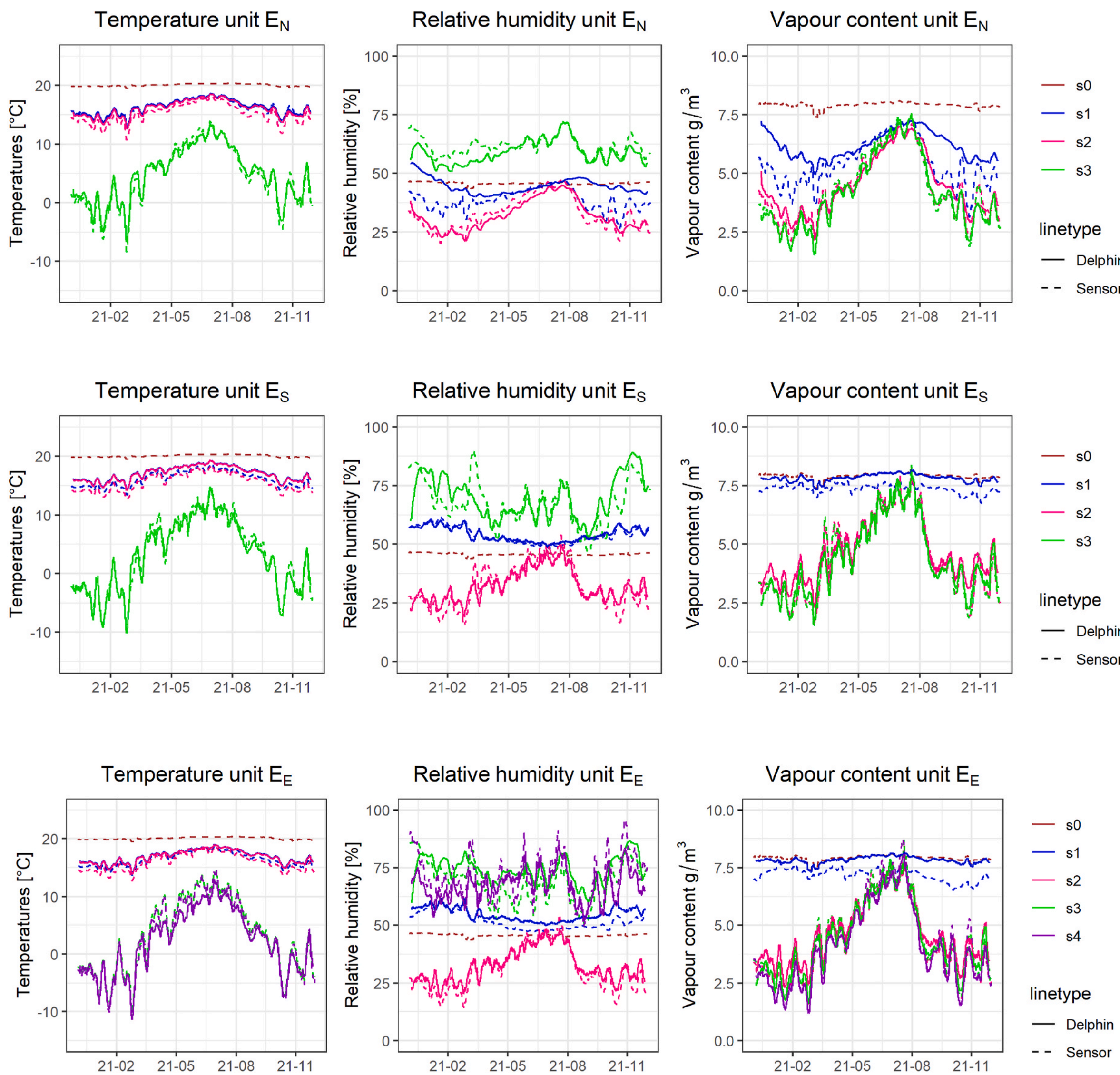

Fig. 10. Hygrothermal conditions for Unit E. Time format yy-mm.

Table 3
Sensitivity of the air change rate in the ventilated air cavity in Unit B. The results are given as the change of RMSE in percentage.

	Temperature				RH			
Change	S0	S1	S2	S3	S0	S1	S2	S3
−10%	0%	0%	0%	0%	0%	0%	1%	0%
−60%	−1%	3%	2%	3%	−1%	−5%	9%	5%
−80%	−2%	4%	2%	4%	−1%	−11%	23%	19%
10%	0%	0%	0%	0%	0%	0%	−1%	0%
100%	1%	−3%	−2%	−3%	2%	2%	−3%	−3%
500%	4%	−8%	−5%	−8%	5%	3%	−6%	−9%
1000%	6%	−11%	−6%	−10%	6%	3%	−6%	−10%

very cloudy or after sunset. This makes it very difficult to fill out the missing data with reliable values. An additional source of uncertainty for the solar radiation data is the decomposition of global radiation into direct and diffuse radiation.

Another uncertainty was caused by the air change rate, ACH, in the ventilated air cavity surrounding the test pavilion. As shown in Fig. 5, the hygrothermal conditions varied, even on the same side of the pavilion. If another facility like this should be planned or if this one was to be improved, it would be beneficial to install sensors to measure the wind speed inside the cavity; however, measuring the airflow is a challenge because the measuring equipment alters the airflow. The sensitivity analysis of the ACH showed that the airflow was insignificant, and each adjustment, whether it was negative or positive, caused both positive and negative changes in the RMSE. The surroundings of the pavilion can also affect the measurements, e.g., altering the airflows and casting shadows. This may very well have been the case as the pavilion was placed on pillars on a sloped surface and close to another test house.

As described in the introduction, user behaviour tends to play a significant role in the quality and long-term conditions of a building. This perspective cannot be evaluated by the presented test facility, as the

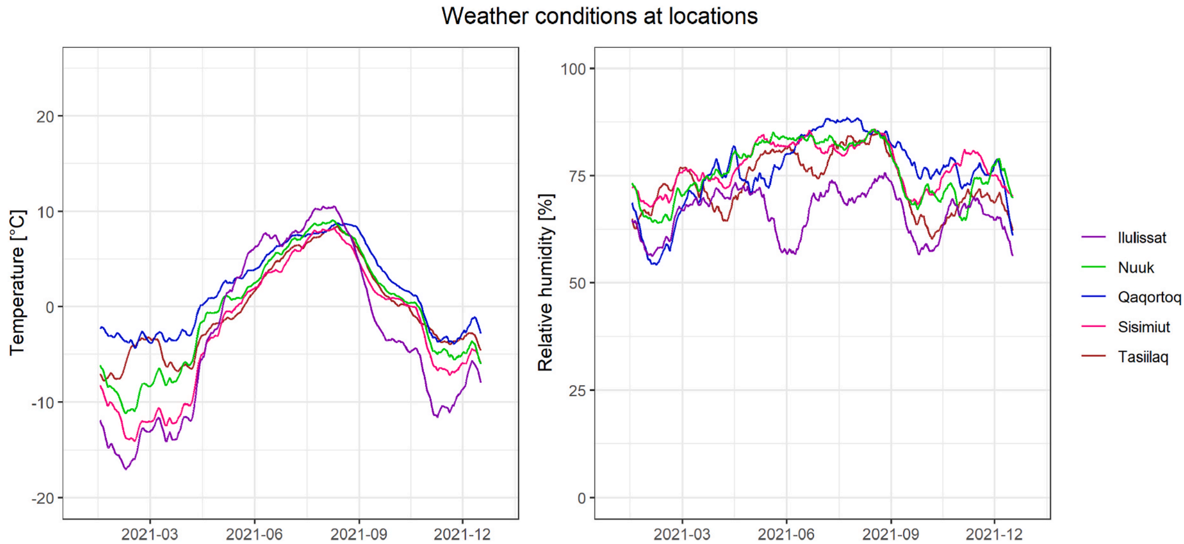

Fig. 11. Weather conditions at the five locations in 2021 (seven-day moving mean).

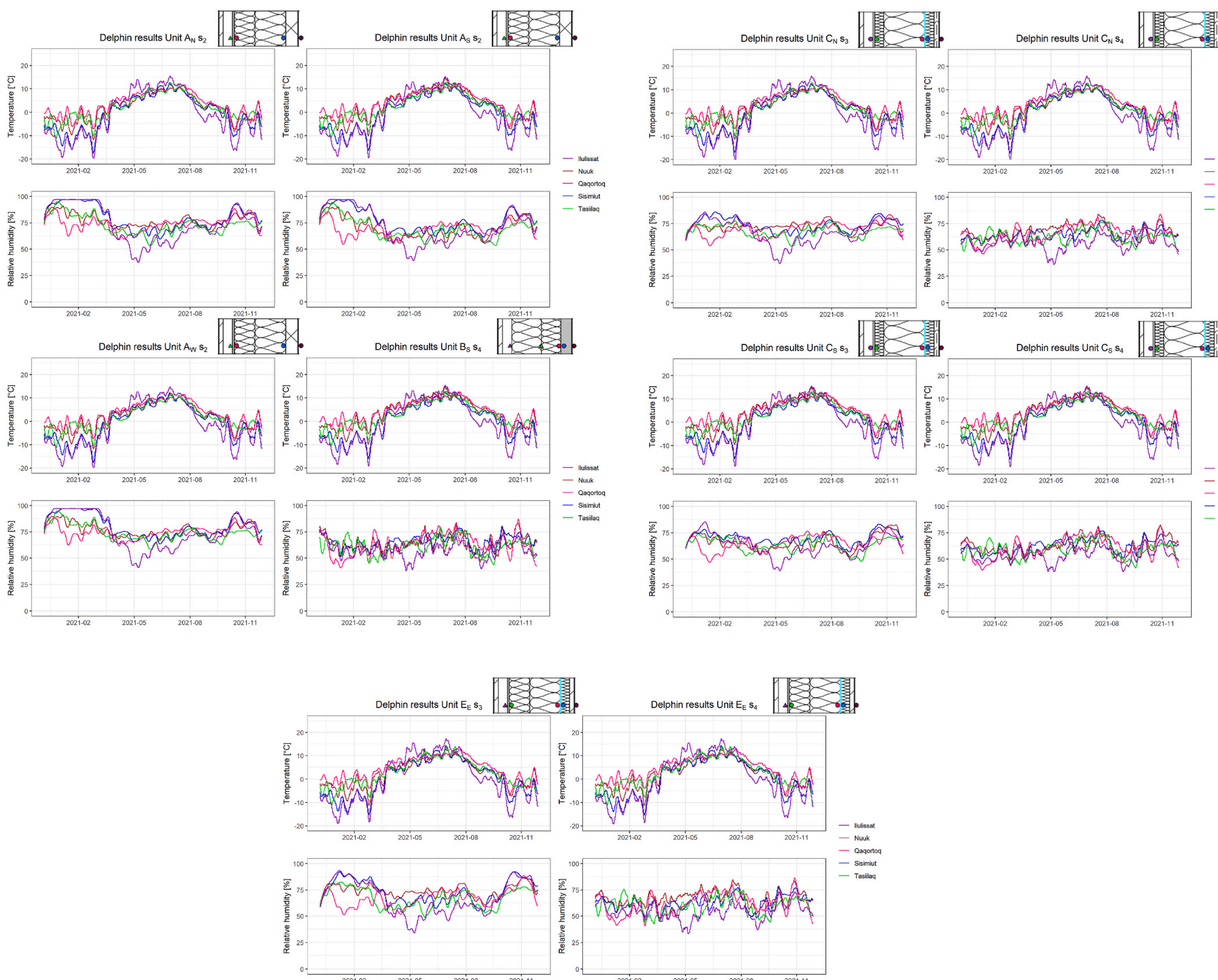

Fig. 12. Comparison of results for multiple Greenlandic locations.

Table 4
Mould index for different simulation scenarios. The interior conditions in the pavilion in Nuuk were set to 50% RH and 20 °C. The measured conditions were used for all assessments.

City	Unit	sensor	Index	Interior conditions	Note
Nuuk	C_S	3	0.00	Measured	0 for all other locations (ERA5)
Nuuk	C_S	4	0.04	Measured	
Sisimiut	A_S	2	0.00	Measured	
Sisimiut	A_N	2	0.00	Measured	
Sisimiut	A_W	2	0.00	Measured	
Ilulissat	A_S	2	0.01	Measured	
Ilulissat	A_N	2	0.02	Measured	
Ilulissat	A_W	2	0.02	Measured	
Nuuk	E_S	3	0.00	Measured	0 for all other locations (ERA5)
Nuuk	C_S	3	0.04	RH = 70%	
Nuuk	C_N	3	0.11	RH = 70%	
Nuuk	C_S	4	0.04	RH = 70%	
Nuuk	C_N	4	0.07	RH = 70%	
Nuuk	C_S	3	0.21	RH = 85%	
Nuuk	C_N	3	0.62	RH = 85%	
Nuuk	C_S	4	0.04	RH = 85%	
Nuuk	C_N	4	0.07	RH = 85%	

interior climate was controlled, and the pavilion was not inhabited. This was also not the intention of this study, as the primary aim was to assess the constructions under real outdoor conditions while minimising other uncertainties. However, a few Delphin assessments were made for constant humidities of 70% and 85% and showed no risk of mould growth with an index of maximum 0.62, which is much lower than the acceptance limit of 2. This indicates that the observed mould problems in buildings with these constructions are not the result of high indoor relative humidity. Instead, it is more likely that other problems, such as leakages or thermal bridges, possibly in combination with high indoor relative humidity, may be the cause.

4.2. Evaluation of weather data

As described in Section 2.5, the simulations made for alternative locations were conducted using reanalysis weather data. Reanalysis data are considered better than Test Reference Years (TRY) as they represent conditions for a specific time, although they are not measured by rather derived from a weather model. It is relevant to evaluate how it affects the simulation quality by comparing the simulation results made with ERA5 and measured data from Asiaq. This is shown in Fig. 13, along with the data from the sensors. The results are shown for Unit E as it is representative of all units. The rest of the graphs can be found in the repository [49].

The results from Delphin generated using measured weather data (Asiaq) for Nuuk in 2021 are very similar to the results obtained with the modelled weather data (ERA5). The maximum change of RMSE for the temperatures was 0.65 °C, and for RH, it was 6.84% (41 of 48 RMSE-values are below 2.13%). This indicates that the reanalysis weather data can be used as an alternative to measured weather data for studies investigating the impact of different locations. Coincidentally, it can be observed that the modelled weather results in a better fit for RH than the measured weather.

4.3. Experiment improvement and future work

For future setups like the test pavilion presented in this study, there are some takeaways that could improve the quality and reliability of the results. From a more technical perspective, it can be recommended to install sensors in the air cavity detecting the wind speed, to improve the reliability of the hygrothermal models regardless of the software program. In future studies, it is also recommended to calibrate the sensors before and after the test program.

Furthermore, it could be considered to carry out a blower door test on the pavilion to investigate the tightness of the constructions, but with the current layout, any leaks would be hard to locate. It might, however, be possible in combination with thermography. If air tightness is a central parameter to future studies, dividing the test facility into sections should be considered.

Just like the designed models were used to test the façade constructions for robustness in other regions of Greenland, they can be used to evaluate the consequences of climate change, using predicted future weather data.

4.4. Results

Based on the results, it was not possible to determine a best or worst

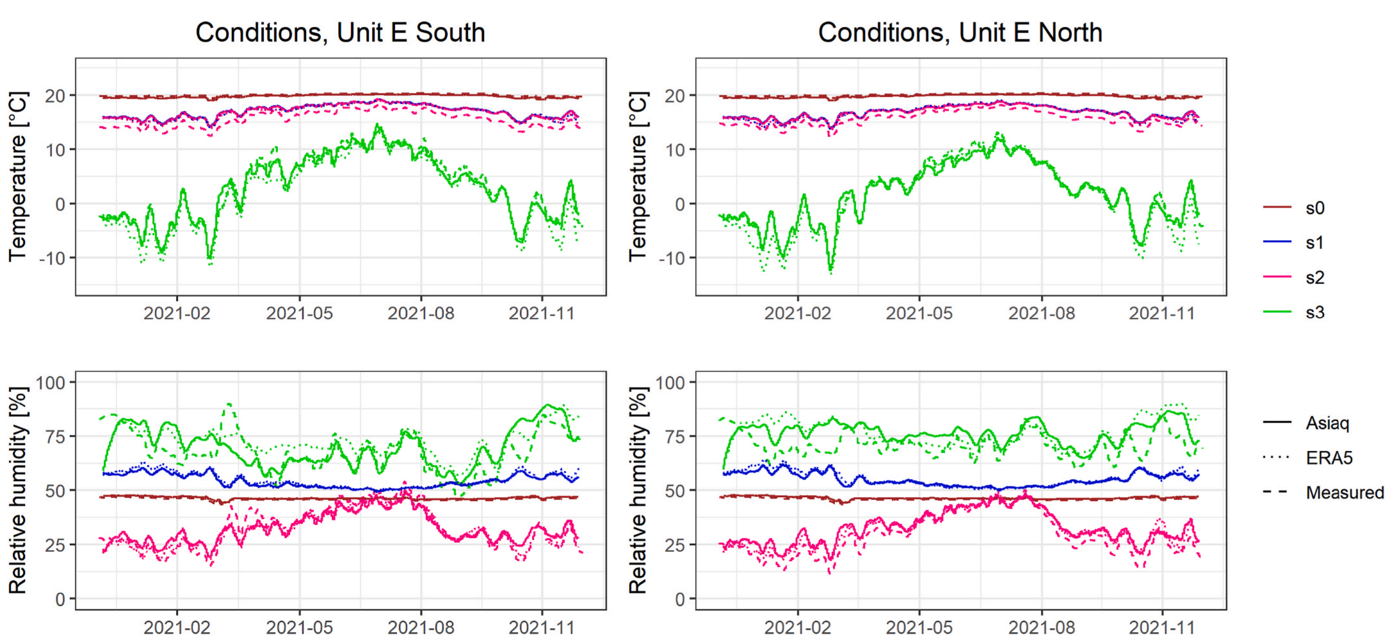

Fig. 13. Simulated and measured conditions in Unit E for different weather data sources for Nuuk.

construction for the Arctic climate. None of the constructions showed a risk of mould growth, which would have been indicated by a Mould Growth Index above 2. Still, it was possible to identify which construction types are sensitive to other things, such as orientation or location. For example, the temperature and relative humidity in the inner layers of the traditional half-timber construction (Unit C) differed for the north and south. This observation does not prove that this construction type should be avoided, but in this experiment, it either shows sensitivity to orientation, a challenge in the buildability, or an error in the sensors. As the simulations were very insensitive to the orientation in Unit C and the other units, the cause is most likely either faulty installation or sensor errors.

4.5. Location of test facilities

When constructing test facilities such as the presented pavilion, choosing a representative or worst-case location is of interest while making it as accessible and cheap as possible. Based on the results presented in Section 3.3, Nuuk is representative of most locations in Greenland. Furthermore, placing a test facility in Nuuk is advantageous as it is by far the biggest city (Nuuk has 19.000 inhabitants, second largest town has 5.500 [5]). Therefore, it has relatively easy accessibility, local technical competencies, and available weather data. Additionally, Nuuk has the largest building stock in Greenland, making the results directly applicable.

4.6. Perspectivation

4.6.1. Sustainability

Assessing which construction type performs the best could also include a sustainability study. As presented in the introduction, Ryberg et al. [16] made a comparative sustainability study in 2021, including four construction methods: concrete, CLT, timber frame, and renovation. As three of these are included in this study, it led to the following reflection. In the discussion, Ryberg et al. wrote, "*While there is a difference in the impact scores for the three new buildings, neither of the buildings outperforms the others across all midpoint impact categories.*" This means that the technical and practical aspects become even more critical to the decision regarding the construction method because flawed constructions can lead to increased heat loss and reduced lifetime, eventually compromising the sustainability performance. Exactly this is also the conclusion made by Ryberg et al. [51], who also highlight that correction of potential errors can have substantial environmental impacts.

4.6.2. Concrete constructions without wind barriers

The introduction also presented a previous study of a concrete construction without a wind barrier [11]. One of the construction types in the test pavilion was inspired by this construction; thus, it was considered suitable to discuss the findings here. The previous study found that wind penetrating the insulation layer caused the concrete to cool down. Theoretically, the wind barrier is redundant, as the combination of concrete and firm tight-fitting insulation boards should be wind-tight. Due to a combination of rough concrete surfaces and poor execution of the construction work, it did not work as planned in the case described in Ref. [11]. This resulted in poor thermal performance of the insulation, specifically the heat loss coefficient was found to be $\lambda = 0.3$ W/(m•K), while the declared value was $\lambda = 0.033$ W/(m•K). The present study found that the simulation model of Unit B, which is similar to the aforementioned concrete wall, performed reasonably, especially when compared to the other units, where the RMSE was worse (see Table 2). When making this comparison, it is essential to know that the pavilion unit was built with fibre cement boards and not concrete as in the original building. Together with a relatively small unit fitted to the size of insulation mats, the unit benefited from the smooth surface to limit wind-induced convection between the insulation and fibre cement board. However, this study demonstrates that the design is technically possible, but it does not answer whether it is suitable for Greenlandic conditions, where practical issues may make it difficult to build precisely as designed. The buildability of a solution can be dependent on location.

Furthermore, there may be additional challenges that would occur in real-life cases. E.g., unit A with CLT elements will be more exposed to moisture in a real construction process, but over time it will dry and shrink, which could lead to cracks and result in air gaps. Such air gaps can cause increased heat loss and moisture problems. This could be a topic for further investigation.

5. Conclusion

Large amounts of data have been collected from the test pavilion, which can be analysed and investigated in many ways. Currently, data has been collected for two years, starting at the end of October 2020 (data logging is still ongoing). The pavilion comprises of five construction types: CLT, concrete, steel frame with mineral wool, timber frame with cellulose insulation, and timber frame with mineral wool. These five constructions represent the current building methods in Greenland as of 2023. Despite the high ambitions, there were many uncertainties connected to the experiment, which can and should be avoided in future test facilities.

The study had three research questions; the first was whether the studied constructions were unsuitable in Nuuk, and the second if the constructions were robust enough for other regions in Greenland. The study showed that all investigated constructions could function acceptably in Nuuk and in other Greenlandic climates if built as designed and prescribed by the manufacturer. Furthermore, it showed that the conditions in the ventilated air cavity were, to some extent, depending on the surface's orientation. However, the ventilation rate had very little influence when defined within a normal range. The conditions in the air cavity had an insignificant impact on the hygrothermal conditions inside the wall.

The modelled weather data from ERA5 were found to be adequate to replace measured weather data in cases where it is desirable to study the effect of climate and measured weather data is unavailable.

The third research question was whether any parameters are essential to the robustness of the constructions. The study did not reveal any parameters that may be critical to achieving a good performance in the Arctic, as a comparison between the measured data with simulated data produced in Delphin, did not reveal any severe issues. Still, the results indicated that some of the units reacted differently to the boundary conditions than the simulations.

This leads to the conclusion that all the investigated constructions perform acceptably in theory and when meticulously executed. As other studies have shown problems with some of the constructions, these problems are expected to be due to insufficient level of detail in the design or poor quality of the labour. The design, proper instructions, and labour quality are essential to the performance of at least some constructions. Therefore, the need for supervision of the building process, and quality assurance on site are also important findings.

CRediT authorship contribution statement

Naja Kastrup Friis: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Eva B. Møller:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Tove Lading:** Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] E.B. Møller, T. Lading, Current building strategies in Greenland, E3S Web Conf. 172 (2020), https://doi.org/10.1051/e3sconf/202017219004.
[2] Departementet for Boliger og Infrastruktur, Redegørelse Af Grønlandske Byggematerialer, 2019.
[3] Technical University of Denmark, Om Projektet - ABC - Arctic Building and Construction, 2022 [Online]. Available: https://abc-byg.dtu.dk/om-projektet. (Accessed 5 May 2022).
[4] Indeklima - sundhedsstyrelsen [Online]. Available: https://www.sst.dk/da/Viden/Forebyggelse/Miljoe/Indeklima. (Accessed 19 November 2022).
[5] Statistics Greenland, Greenland in Figures 2022 19 (2022) 36.
[6] M. Kotol, Survey of occupant behaviour, energy use and indoor air quality in Greenlandic dwellings, in: Proc. 5th Int. Build. Phys. Conf. (IBPC 2012), 2012, p. 7. Kyoto, Japan.
[7] I.N.I. As Boligselskabet, Skimmelsvamp." [Online]. Available: http://www.byginfo.gl/media/1124/ini-as-skimmelsvamp.pdf.
[8] J. Helgason, Fugtpåvirkning Af Ydervægge I Grønland, 2017.
[9] M. Kotol, C. Rode, G. Clausen, T.R. Nielsen, Indoor environment in bedrooms in 79 Greenlandic households, Build. Environ. 81 (2014) 29–36, https://doi.org/10.1016/j.buildenv.2014.05.016.
[10] T. Lading, E.B. Møller, Evaluering af unaaq 13-19 BYG R-407 , 2019, BYG R-407 (2019) 54.
[11] N.K. Friis, E.B. Møller, T. Lading, Can collected hygrothermal data illustrate observed thermal problems of the façade? - a case study from Greenland, J. Phys. Conf. Ser. 2069 (1) (2021), https://doi.org/10.1088/1742-6596/2069/1/012071.
[12] E. Jan de Place Hansen, Moisture related challenges in the Greenlandic building sector – results from a survey, J. Phys. Conf. Ser. 2069 (1) (Nov. 2021), 012072, https://doi.org/10.1088/1742-6596/2069/1/012072.
[13] M. Rønberg, Hvordan bygger vi bæredygtigt, når der er 30 graders frost, og alt skal fragtes tusindvis af kilometer? Bygge- & Anlægsavisen, 2021.
[14] K. Seidelin Pedersen, Massiv Mangel På Boliger I Grønland, 2019 [Online]. Available: https://fagbladetboligen.dk/alle-nyheder/2019/januar/massiv-mangel-pa-boliger-i-gronland/. (Accessed 10 March 2020).
[15] J.A. Wille, Chefredaktøren Anbefaler: Halvdelen Af Alle Boliger Skal Renoveres | Sermitsiaq.AG," *Sermitsiaq*, 2022 [Online]. Available: https://sermitsiaq.ag/chefredaktoeren-anbefalerhalvdelen-boliger-renoveres. (Accessed 3 December 2022).
[16] M.W. Ryberg, P.K. Ohms, E. Møller, T. Lading, Comparative life cycle assessment of four buildings in Greenland, Build. Environ. 204 (May) (2021), https://doi.org/10.1016/j.buildenv.2021.108130.
[17] N. Emami, B. Marteinsson, J. Heinonen, Environmental impact assessment of a school building in Iceland using LCA-including the effect of long distance transport of materials, Buildings 6 (4) (2016), https://doi.org/10.3390/buildings6040046.
[18] N.K. Friis, J.E. Gaarder, E.B. Møller, A tool for calculating the building insulation thickness for lowest CO2 emissions—a Greenlandic example, Buildings 12 (8) (2022), https://doi.org/10.3390/buildings12081178.
[19] Green Building Council Denmark, Green building Council Denmark [Online]. Available: https://dk-gbc.dk/. (Accessed 21 November 2021).
[20] K. Peitersen, Bæredygtigt Byggeri Vinder Frem I Grønland, 2022. Business - Review.
[21] Green Building Council Denmark and DGNB, Guide Til DGNB, Green Build. Counc. Denmark, 2021.
[22] Iserit, in: Iserit A/S Opfører Grønlands Første Bæredygtigheds-Certificerede Byggeri I Nuuk, 2022, p. 48.
[23] Direktoratet for Boliger og Infrastruktur, Bygningsreglement, 2006, 2006.
[24] A. Nicolai, J. Grunewald, J.J. Zhang, Recent improvements in HAM simulation tools: Delphin 5/CHAMPS-BES, in: Conf. Proc. 12th Symp. Build. Phys, 2007, pp. 866–876. June 2015.
[25] Fraunhofer Institute for building physics, "WUFI® Mould Index VTT." [Online]. Available: https://wufi.de/en/2017/03/31/wufi-mould-index-vtt/. (Accessed 26 January 2023).
[26] Innovative Sensor Technology, "HYT 221 Digital Humidity and Temperature Module." p. 3.
[27] ISO, Hygrothermal Performance of Building Components and Building Elements – Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation – Calculation Methods, ISO 13788, second ed., 2012.
[28] Baumklimatik-Dresden, DELPHIN," 2022. [Online]. Available: http://bauklimatik-dresden.de/delphin/index.php. (Accessed 23 January 2021).
[29] Asiaq, About Asiaq, 2023 [Online]. Available: https://www.asiaq-greenlandsurvey.gl/about-us/. (Accessed 28 February 2023).
[30] Asiaq, Vejret nu, Nuuk city [Online]. Available: http://vejr.asiaq.gl/#/station/Nuuk?tab=META. (Accessed 21 November 2022).
[31] Asiaq, Satellitfoto grønland beta [Online]. Available: https://asiaq.maps.arcgis.com/apps/webap/pviewer/index.html?id=6fda5f51a2824934b11058a9c4d1c34d. (Accessed 21 November 2022).
[32] J.A. Duffie, W.A. Beckman, J. McGowan, Solar engineering of thermal processes, Am. J. Phys. 53 (4) (1985) 382, https://doi.org/10.1119/1.14178, 382.
[33] J. Brozovsky, A. Nocente, P. Rüther, Modelling and validation of hygrothermal conditions in the air gap behind wood cladding and BIPV in the building envelope, Build. Environ. 228 (November 2022) (2023), 109917, https://doi.org/10.1016/j.buildenv.2022.109917.
[34] J. Langmans, S. Roels, Experimental analysis of cavity ventilation behind rainscreen cladding systems: a comparison of four measuring techniques, Build. Environ. 87 (2015) 177–192, https://doi.org/10.1016/j.buildenv.2015.01.030.
[35] J. Falk, K. Sandin, Ventilated rainscreen cladding: measurements of cavity air velocities, estimation of air change rates and evaluation of driving forces, Build. Environ. 59 (2013) 164–176, https://doi.org/10.1016/j.buildenv.2012.08.017.
[36] G.M. Girma, F. Tariku, Experimental investigation of cavity air gap depth for enhanced thermal performance of ventilated rain-screen walls, Build. Environ. 194 (2021), 107710, https://doi.org/10.1016/j.buildenv.2021.107710. October 2020.
[37] S. Vogelsang, H. Fechner, A. Nicolai, Delphin 6 Material File Specification, 2013, Version 6.0.
[38] P. Mukhopadhyaya, M.K. Kumaran, J. Lackey, N. Normandin, D. van Reenen, F. Tariku, Hygrothermal properties of exterior claddings, sheathing boards, membranes, and insulation materials for building envelope design, Therm. Perform. Exter. Envel. Whole Build. 1 (2007) 1–13.
[39] Cembrit, Cembrit windstopper [Online]. Available: https://www.cembrit.com/download/CHDK/datasheets/cembrit-windstopper-basic-datasheet, 2018.
[40] Cembrit, Cembrit multi force [Online]. Available: https://www.cembrit.dk/download/SDK/montagevejledninger/montagevejledning-cembrit-multi-force, 2017. (Accessed 31 January 2023).
[41] F. Tariku, D. van Reenen, M.K. Kumaran, J.C. Lackey, N. Normandin, Summary report from task 3 of MEWS project at the institute for research in construction – hygrothermal properties of several building materials, *Natl. Res. Counc. Canada*, no. March (2002) 71, https://doi.org/10.4224/20386076, 2002.
[42] W. Sonderegger, P. Niemz, Thermal conductivity and water vapour transmission properties ofwood-based materials, Eur. J. Wood Wood Prod. 67 (3) (2009) 313–321, https://doi.org/10.1007/s00107-008-0304-y.
[43] A./S. Rockwool Danmark, FLEXIBATTS 37." [Online]. Available: https://www.rockwool.com/dk/produkter-og-konstruktioner/produktoversigt/bygningsisolering/flexibatts-37/#Tekniskeegenskaber&sortiment. (Accessed 29 November 2022).
[44] Homatherm, Homatherm Produktkatalog, 2015 [Online]. Available: http://2a6616e28592bb9cbad5b4f0860dbb9b88ecc84a.web26.temporaryurl.org/wp-content/uploads/HOMATHERM-produktkatalog-nov-2015.pdf. (Accessed 31 January 2023).
[45] M. Ruiz, V. Masson, M. Bonhomme, S. Ginestet, Numerical method for solving coupled heat and mass transfer through walls for future integration into an urban climate model, Build. Environ. 231 (January, 2023), https://doi.org/10.1016/j.buildenv.2023.110028.
[46] R.J. Hyndman, A.B. Koehler, Another look at measures of forecast accuracy, Int. J. Forecast. 22 (4) (2006) 679–688, https://doi.org/10.1016/j.ijforecast.2006.03.001.
[47] European Centre for Medium-Range Weather Forecasts, "ERA5 | ECMWF." [Online]. Available: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. (Accessed 17 January 2023).
[48] A. Hukka, H.A. Viitanen, A mathematical model of mould growth on wooden material, Wood Sci. Technol. 33 (6) (1999) 475–485, https://doi.org/10.1007/s002260050131.
[49] N.K. Friis, E.B. Møller, Repository (2023), https://doi.org/10.11583/DTU.21971789.
[50] T. Ojanen, H. Viitanen, R. Peuhkuri, J. Vinha, K. Salminen, Mold Growth Modeling of Building Structures to IMPROVE the MODEL, 2010.
[51] M.W. Ryberg, T. Serrano, E. Møller, T. Lading, Life-cycle assessment of construction errors on buildings in Greenland, IOP Conf. Ser. Earth Environ. Sci. 1085 (1) (2022), https://doi.org/10.1088/1755-1315/1085/1/012064, 66DUMMY.