Friulian Journal of Science **27.** 2019, 69-80

Durability of building materials: evaluation of alternative moisture reference years generation procedure for the Udine climate

MICHELE LIBRALATO[1], GIOVANNI MURANO[2], ALESSANDRA DE ANGELIS[3], ONORIO SARO[4], VINCENZO CORRADO[5]

Abstract. The durability of a building could be improved by a proper moisture design, using an advanced coupled heat and moisture simulation. The weather files used as boundary conditions are not usually suited for moisture-related analysis and the standard weather reference year generation procedures are not intended to represent moisture-related weather variables. In this study, a procedure was proposed to design appropriate reference years (Moisture Reference Years, MRY), using a modification of the method described in the standard EN ISO 15927-4:2005 as a starting point.

Key words. test reference year, building envelopes, heat and moisture transfer, moisture reference year, hygrothermal simulations.

1. Introduction. One of the main causes of damage in buildings is uncontrolled moisture migration in the materials. Moisture-related damage is soon visible on poorly maintained buildings, in the form of dark-coloured spots of mould on the walls, as superficial damage on the external surfaces due to freeze-thaw cycles, or as structural damage in the inner layers of the envelopes (rotting of wood or metal corrosion).

[1] Polytechnic Department of Engineering and Architecture, University of Udine. Udine. Italy. E-mail: michele.libralato@uniud.it
[2] Department of Energy, Polytechnic University of Turin, Turin. Italy.
[3] Polytechnic Department of Engineering and Architecture, University of Udine. Udine. Italy.
[4] Polytechnic Department of Engineering and Architecture, University of Udine. Udine. Italy.
[5] Department of Energy, Polytechnic University of Turin, Turin. Italy.

Such damage may also occur in occupied buildings where the hygrothermal design of the envelope has been incorrectly performed. The common practice among designers is to assess the risk of mould growth and interstitial condensation using steady state simulations and the Glaser method (described in the standard EN ISO 13788:2012) as design tools. This method is based on relevant simplifications and is not intended to represent and simulate the moisture migration phenomenon. Recently, advanced assessment tools have been developed and more accurate models are available to perform better moisture design and risk assessment. Even though these advanced models have been widely validated and used in research, some relevant sources of error still affect the reliability of simulations and risk evaluations. The two most relevant causes of uncertainty are the unavailability of the hygrothermal material properties used in the model, and the weather data used to define the boundary conditions for the model.

The weather data used in advanced hygrothermal models is based on hourly weather measurements that include air temperature, relative humidity, irradiation, wind speed, rainfall. The intent is to simulate all the moisture and heat sources that could influence the moisture content of building envelopes.

The common approach used in the assessment of moisture-related risks is to use a single reference year weather file, generated from the measured weather files (here referenced as a multiyear weather file), and to repeat it over a longer period until the water content of the wall has stabilised, and the moisture content and temperature at the first time step of the year are locally equal to the values at the last time step of the year. If this condition is not reached, then the wall is at risk of moisture accumulation.

According to EN 15026:2007, the reference years used for advanced moisture migration simulations should be designed following the procedure described in EN ISO 15927-4:2005. The resulting reference years are a composition of measured months chosen among the multiyear using the Finkelstein-Schafer statistical method (Finkelstein, Schafer 1971). The reference years designed with this method are, by definition, intended to represent the typical and mean year, not a critical year. Moreover, the Finkelstein-Schafer statistical method is only applied to energy-related weather variables: rain is not considered.

This kind of reference year could be representative when used for energy purposes in whole building simulations, but in moisture migration simulations they could result in an oversimplification. For this reason, several alternatives to the energy simulation reference years have been proposed for moisture simulations.

Two different types of approaches could be considered in the weather months selection: a construction-dependent approach, based on the envelope characteristics, materials, wall orientation and position; or a construction-independent approach, based on a selection that considers the weather file features only. Depending on the application, one or the other method could lead to more reliable results. For example, a construction-dependent method could produce a conservative risk assessment for the considered walls but would require a weather analysis and many simulations for each wall type. On the other hand, a construction-independent method could produce a single MRY that could be used for any kind of building envelope. As a further example, in Kalamees and Vinha (2004) the saturation deficit, a construction-independent parameter, is used as an evaluation parameter to find two different critical weather files respectively for mould risk and condensation risk assessment. An example of moisture reference year construction-dependent selection methodology is described in Zhou et al (2016), where the critical year is chosen comparing the simulation results from a set of three years selected using the Climate Index criterion.

In this study, the construction-independent approach is used, in order to produce MRY that may be used by practitioners for moisture-related risk assessments. The statistical framework of the EN ISO 15927-4:2005 is extended to rain fall, and weighting factors are introduced to evaluate the influence of rain fall and rain duration. The weighting factor approach has been used for energy consumption evaluations in Murano, Dirutigliano and Corrado (2018) and in Kalamees (2012).

2. Method

2.1. MRY generation. The MRY comprises the most representative months in the multiyear weather file. The method used in this work was a modification of the one described in the standard EN ISO 15927-4:2005 and is described in-depth in Libralato et al. (2018). For each month of the multiyear, the representativeness of all the same months of the multiyear was calculated separately for each weather variable, using the FS statistical method (Finkelstein, Schafer 1971). Then, combining the FS statistic for a set of weather variables, the most representative month was selected among the same calendar months (e.g. the most representative January among the Januarys in the multiyear for temperature and relative humidity). The resulting year was the most representative year, made of a selection of twelve months, for the set of weather variables considered. With this procedure it was possible to obtain a different reference year for each set of weather variables considered.

Combining the FS statistic for the weather variables in the set ensured that the selected months would be representative for those variables. The FS statistics can be combined with weighting factors.

The standard EN ISO 15927-4:2005 method for the TRY uses a set of variables including temperature, relative humidity and irradiation, with wind speed as a secondary variable. In Libralato et al (2018), alternative weather variable sets have been proposed to generate MRY weather files and these have been evaluated

Table 1. Description of the building envelopes considered in this analysis. The walls are described by thickness *d*, total thermal transmittance *U*, total thermal resistance *R*, and diffusion-equivalent air-layer S_d.

Identification	*Description*	*d* (*m*)	*U* (*W/m²K*)	*R* (*m²K/W*)	*Sd* (*m*)
SW	Stone wall	0.38	0.70	1.44	5
SWi	Well-insulated stone wall	0.53	0.13	7.76	50
HB	Hollow brick wall	0.49	0.39	2.59	7
HBi	Well-insulated hollow brick wall	0.58	0.15	6.72	41
TWa	Timber wall with internal vapour barrier	0.53	0.13	7.45	56
TWb	Timber wall with external vapour barrier	0.53	0.13	7.45	56

Table 2. Description of the failure modes considered in the analysis. The parameters involved are relative humidity φ and temperature *T*.

Failure mode	*Position*	*Condition*
Mould growth	Internal surface	φ > 80%
Moisture Accumulation	Internal layers	φ > 95%
Freeze damage	External surface	φ > 98% and T > 0°C

for the climate of Turin. The sets of variables included rain fall on a horizontal surface and driving rain in 4 different orientations.

In this study, rain duration was added to the weather variables for the MRY month selection, to consider long-lasting rain as a single event in the statistic. Rain duration was calculated as the number of consecutive hours of rain and was recorded as the last hour of the rain event. In this analysis, only rain fall on a horizontal plane was considered.

2.2. MRY evaluation. The MRY evaluation was performed by comparing the failure probability for three failure conditions, presented in Table 2, for six wall types typically used in the Friuli region. The wall layers are listed in Table 1 and the layer compositions are shown in Figure 1. The material properties are taken from the Delphin material database, and the conductivity, moisture retention curve, vapour permeability and liquid diffusivity of each material are provided as a function of the relative humidity.

2.3. Simulations. The model considered in this work is implemented in the DELPHIN 6.0.17 software (Sontag et al. 2013), which was used for the calculations. The one-dimensional section of the wall was considered as made of porous materials and the migration of moisture coupled to heat was evaluated using the following model:

$$\begin{cases} \dfrac{\partial \rho^{m_v}}{\partial t} = \dfrac{\partial}{\partial x}\left(j_c^{m_v} + j_d^{m_v}\right) + \sigma_e & \textit{vapour mass balance} \\ \dfrac{\partial \rho^{m_w}}{\partial t} = \dfrac{\partial}{\partial x}\left(j_c^{m_w}\right) - \sigma_e & \textit{liquit mass balance} \\ \dfrac{\partial \rho^{U}}{\partial t} = \dfrac{\partial}{\partial x}\left(j_c^{U} + j_d^{U}\right) & \textit{energy balance} \end{cases} \tag{1}$$

The quantities are densities and the quantities are flux densities. The apex m_v indicates that the value is related to the mass of water vapour, the apex m_w to the mass of liquid water, and the apex *U* to energy. The quantity is the evaporation rate of the mass of moisture. The transport mechanism is distinguished between diffusion and convection respectively by the subscripts *d* and *c*.

Failure risk was calculated using hourly transient one-dimensional simulations with the generated reference years as boundary conditions. The internal conditions were set to “normal moisture load”, defined in the standard EN 15026:2007. The initial conditions of the walls were set to constant, the temperature to 20°C and the relative humidity to 80%. The wall was set as horizontal, fully exposed to rain.

2.4. Failure criteria. The risk evaluations were performed for mould growth conditions, interstitial condensation conditions and freeze-thaw cycle conditions. The failure criteria used were simplified, for the sake of the MRY comparison. Risk was calculated as the fraction of days in which the risk condition was found. The risk conditions are described in Table 2.

2.5. Multi-year Weather file. The multiyear weather file used as a source was measured by the Udine San Osvaldo station (Lat: 46.035212 - Lon: 13.226672), at a height of 91 m above sea level. The data was kindly supplied by ARPA FVG. The most detrimental missing data rate was the 1.5% for the wind direction measurements. For the other variables, the missing data rate was less than 1%. Any missing data was corrected with linearization in cases where the missing data was less than 5 hours, and with averaging between the previous known day and the following known day in the case of larger data gaps. For gaps larger than seven days, found in rain and wind data series only, the values were integrated with values from previous years. The weather file is described in Figure 2.

Table 3: Combinations of weighting factors of the variables used for the Moisture Reference Year (MRY) generation procedure. The MRY numbers are used to identify the combinations.

MRY number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Air temperature	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0
Vapour pressure	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1
Irradiation	1	1	0	0	1	0	1	1	0	0	1	0	1	1	0	0	1	0	1	1	0	0	1	0	1	1	0	0	1	0	1	1	0	0	1	0
Wind speed	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
Rain intensity	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0.2	0.2	0.2	0.2	0.2	0.2	0.8	0.8	0.8	0.8	0.8	0.8	0	0	0	0	0	0
Rain duration	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0.8	0.8	0.8	0.8	0.8	0.8	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0	0	0	0

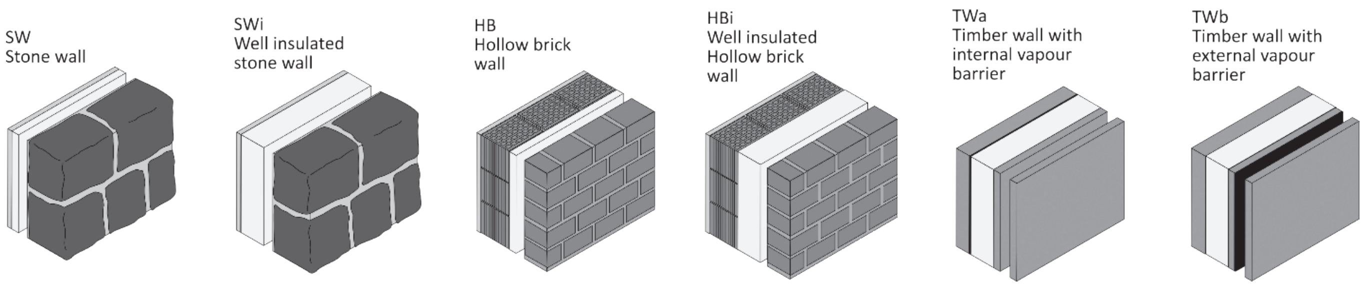


Figure 1. Wall types considered for the evaluation of MRYs. These walls are typical of the Friuli region. The internal surface is considered to be the one on the left.

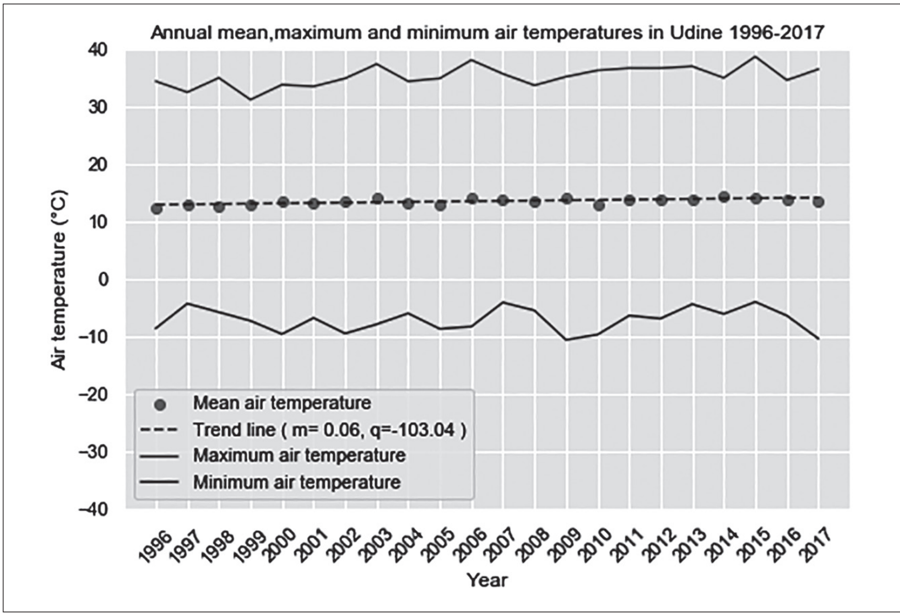
3. Results. The risk analysis was performed on the resulting distributions of relative humidity and temperature. As an example, the relative humidity distribution of wall TWa for the year 2000 of the multi-year is shown in Figure 3. For each wall, the calculated risk for each MRY was compared with the calculated risk of the multi-year. The superficial mould growth risk was found to be 0% for every simulation performed in agreement between the multi-year results and the MRY results. As shown in Figure 3, the internal relative humidity was lower than the 80% measured for the whole year on the internal surface (0 cm). For the accumulation risk assessment calculation, the external layers of the walls, exposed to rain, were not considered.

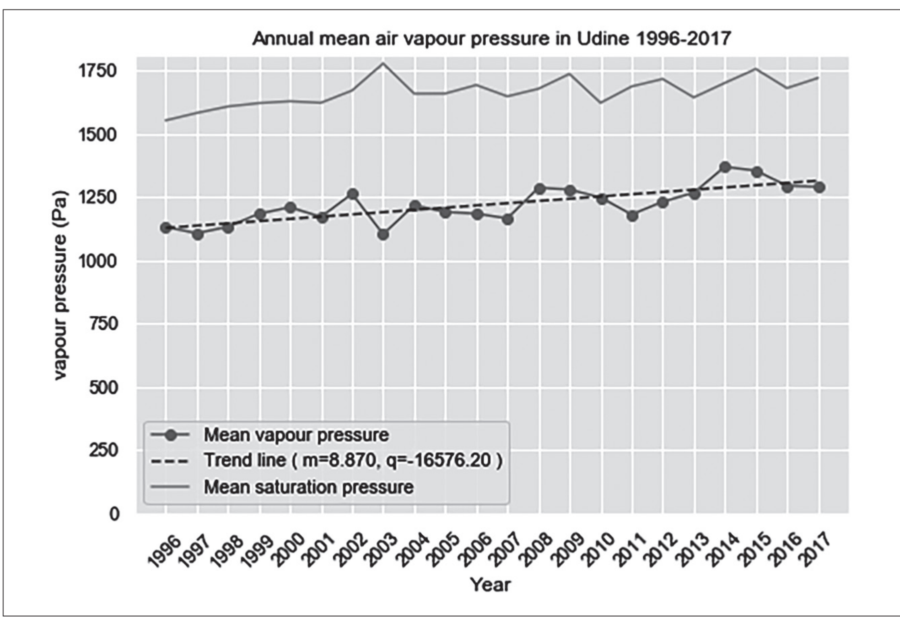
The resulting moisture accumulation risks for the six walls and for every MRY and the multi-year were used to compare the MRY generation set of variables. For the comparison, the risk differential between each MRY and the multi-year was calculated for every wall, with the mean differential value shown in Figure 4. The mean differences in freezing risk are shown in Figure 5.

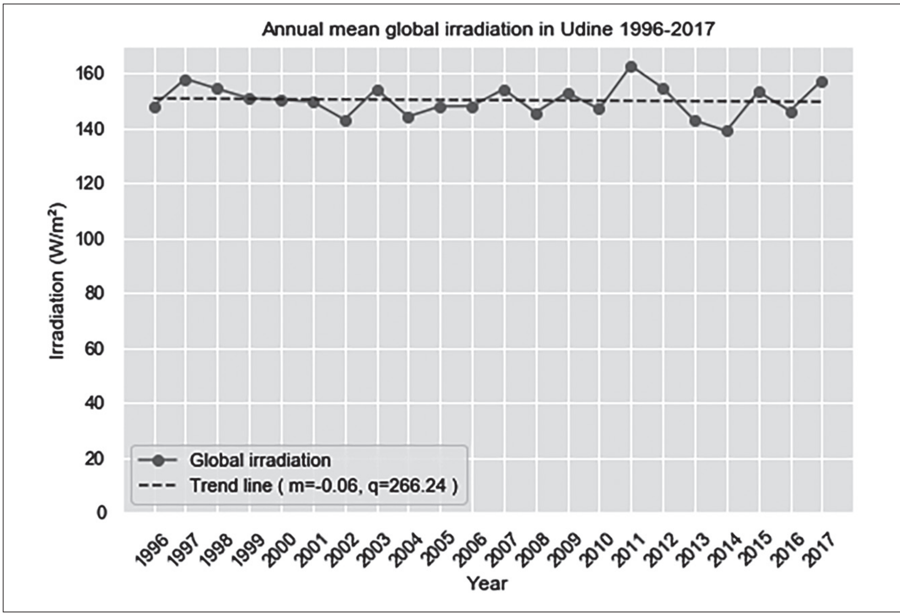
The water accumulation risk of the multi-year was found to be best represented by the results of MRY 2, 8, 14, 20 and 26, generated by the combination of air temperature, vapour pressure, global irradiation and a combination of rain intensity and rain duration. Among the combinations of rain duration and intensity, the one with the lowest mean risk difference was the one obtained with coefficients 0,8 for rain duration and 0,2 for rain intensity (MRY from 19 to 24).

The MRY that resulted in the best representation of the multi-year freezing damage risk were MRY 1, 7, 13, 19, 25 and 31, based on the combination of air temperature, vapour pressure, irradiation, wind speed, and a combination of rain intensity and rain duration. The combination of rain duration and rain intensity that resulted in the most representative year was the one of the years from 1 to 6, with rain intensity multiplied by a factor of 1 and rain duration by 0.

4. Conclusions. Thirty-six Moisture Reference Years (MRY) were generated for the Udine climate using a modified version of the EN ISO 15927-4:2005, intended for use in risk assessments of mould growth, moisture accumulation and freeze damage. Risk assessments were performed on the three risk types and on six wall types, with the percentage of failure days being calculated for every MRY and compared against the multi-year. The mould growth risk was found to be zero for every wall type in every simulation. The moisture accumulation risk was well represented in the MRY obtained by combining air temperature, vapour pressure, global irradiation and a combination of rain intensity and rain duration. The most effective rain combination was the group with the coefficients 0.8 for rain duration and 0.2 for rain intensity (MRY 19 to 24). Even though the most representative risk was obtained from MRY number 2, MRY number 20 should be considered as the inter-


Annual mean,maximum and minimum air temperatures in Udine 1996-2017
Air temperature (°C)
40
30
20
10
0
−10
−20
−30
−40
Mean air temperature
Trend line (m= 0.06, q=-103.04)
Maximum air temperature
Minimum air temperature
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year


Annual mean air vapour pressure in Udine 1996-2017
vapour pressure (Pa)
1750
1500
1250
1000
750
500
250
0
Mean vapour pressure
Trend line (m=8.870, q=-16576.20)
Mean saturation pressure
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year



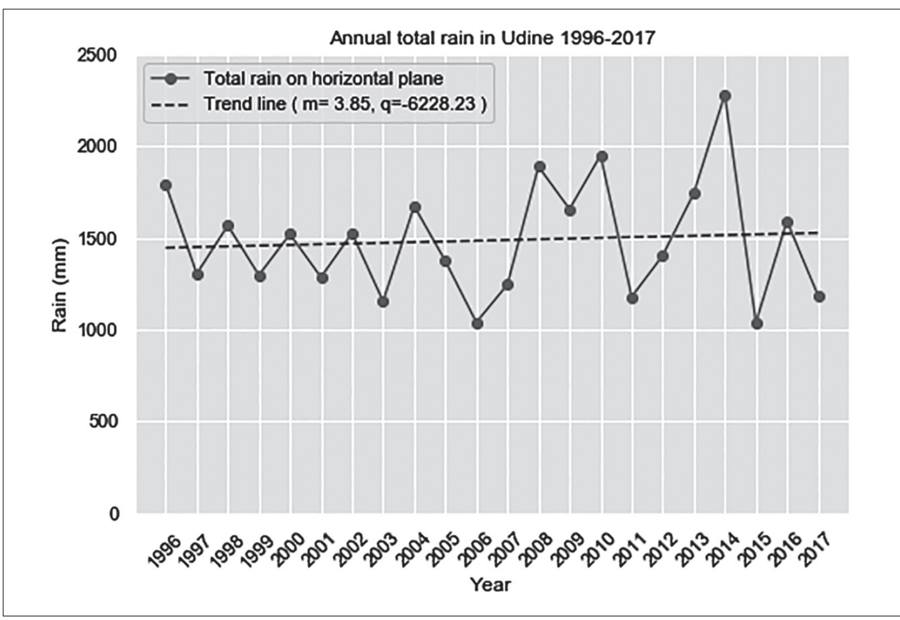


Figure 2. Weather measurements from 1996 to 2017 in Udine, Italy. The plots show the annual mean values and trend line of air temperature (above left), vapour pressure (above right), global solar irradiation (down left) and total rain on horizontal plane (down right).

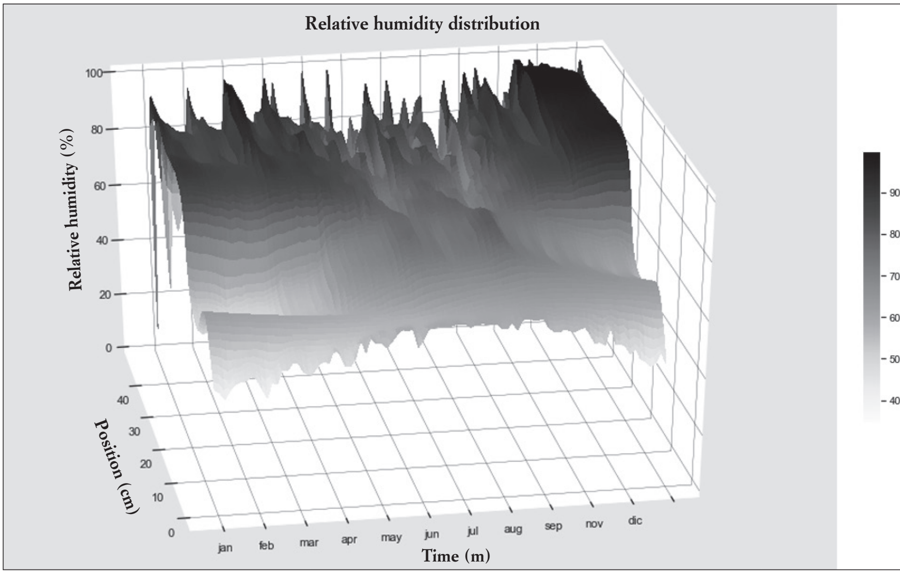


Figure 3. Relative humidity distribution in the TWa timber wall, plotted over time for the year 2000 of the multi-year. The internal surface position is at 0 cm, while the external position is at 53 cm.

section between the most representative groups of MRYs, with a result similar to the one of MRY number 2. MRY number 20 is intended to be more representative of rain duration than of rain intensity, which is a secondary factor in moisture accumulation risk (a light but longer rain is likely be more influential than a short but intense rain, which would saturate the surface of the porous material quickly).

The same comparison could be done for the freeze risk analysis: the lowest mean risk difference was found in MRY number 32, while the most representative groups of MRY are the ones obtained from combinations of air temperature, vapour pressure, global irradiation, wind speed and a combination of rain intensity and rain duration (1, 7, 13, 19, 25 and 31). The combination of rain intensity and rain duration with the lowest mean risk difference was that with the null coefficient for rain duration and 1 for rain intensity. The intersection of these two groups occurred in MRY number 1. A wall's moisture content is not the only relevant variable for freeze risk; so, too, is its temperature. In addition to this, the risk is evaluated for the external surface only, with the penetration of the rain being of no interest. This concurs with the results obtained.

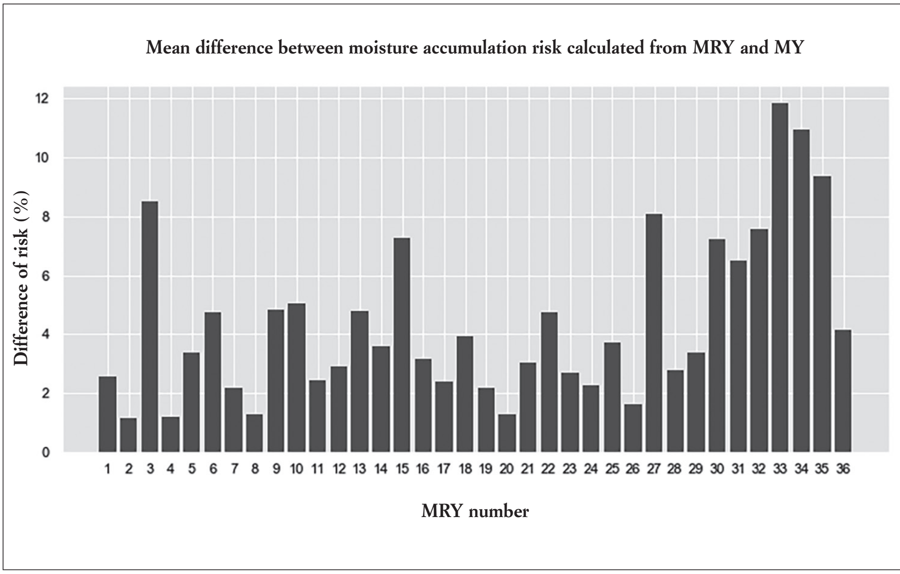


Figure 4. Mean differences between the moisture accumulation risk calculated using the MRY weather file and the risk calculated using the multi-year weather file for the six wall types considered (described in Fig. 1).

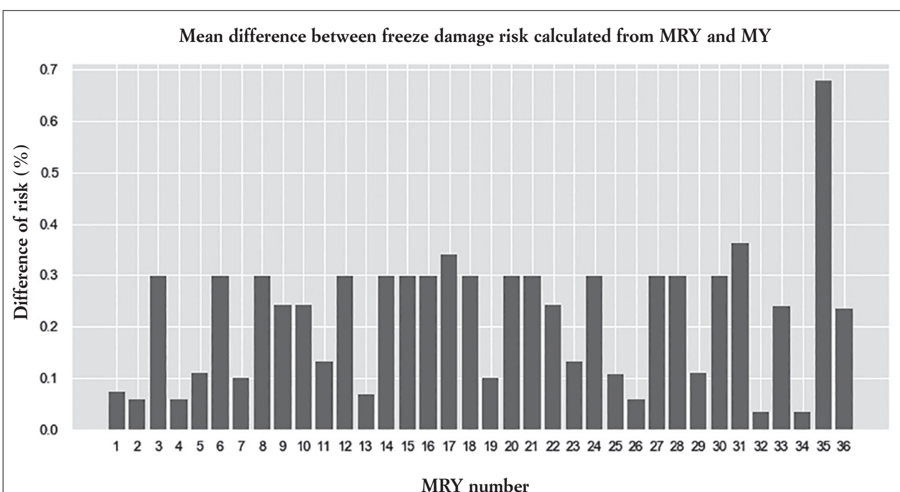


Figure 5. Mean differences between the risk calculated using the multi-year weather file and the risk calculated using the MRY weather file for the six wall types considered (described in Fig. 1).

Acknowledgments. The authors would like to thank the ARPA FVG for providing the meteorological data used in this study. This research has been made possible thanks to PhD funding by Udine Province.

Bibliografie/ References

CEN European Committee for Standardization (2005). *EN ISO 15927-4:2005. Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 4: Hourly data for assessing the annual energy use for heating and cooling*. CEN: Bruxelles, Belgium.

CEN European Committee for Standardization (2007). *EN 15026:2007. Hygrothermal Performance of Building Components and Elements – Assessment of Moisture Transfer by Numerical Simulation*. CEN: Bruxelles, Belgium.

CEN European Committee for Standardization (2012). *EN ISO 13788:2012. Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods.* CEN: Bruxelles, Belgium.

Finkelstein J.M., Schafer R.E. (1971). Improved goodness-of-fit tests. *Biometrika*, 58, 3: 641-645.

Kalamees T., Vinha J. (2004). Estonian Climate Analysis for Selecting Moisture Reference Years for Hygrothermal Calculations. *Journal of Thermal Envelope and Building Science*, 27, 3: 199-220.

Kalamees T., Jylhä K., Tietäväinen H., Jokisalo J., Ilomets S., Hyvönen R., Saku S. (2012). Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. *Energy and Buildings*, 47: 53-60.

Libralato M., Saro O., De Angelis A., Spinazzè S. (2017). Comparison between Glaser method and Heat, Air and Moisture transient model for moisture migration in building envelopes. *Applied Mechanics and Materials*, 887: 385-392.

Libralato M., Murano G., De Angelis A., Saro O., Corrado V. (2018). Hygrothermal modelling of building enclosures: reference year design for moisture accumulation and condensation risk assessment. *Proceedings of the IBPC 2018 Conference Healthy, Intelligent, and Resilient Buildings and Urban Environments.* Syracuse, NY.

Murano G., Corrado V., Dirutigliano D. (2016). The new Italian Climatic Data and their Effect in the Calculation of the Energy Performance of Buildings. *Energy Procedia* 101: 153-160.

Murano G., Dirutigliano D., Corrado V. (2018). Improved procedure for the construction of a Typical Meteorological Year for assessing the energy need of a residential building. *Journal of Building Performance Simulation*, 13: 139-151.

Riva G., Murano G., Corrado V., Baggio P., Antonacci G. (2012). *Aggiornamento parametri climatici nazionali e zonizzazione del clima nazionale ai fini della certificazione estiva*. ENEA, Ministero dello Sviluppo Economico.

Riva G., Murano G., Corrado V., Baggio V., Antonacci G. (2010). *Definizione degli anni-tipo climatici delle province di alcune regioni italiane (Emilia Romagna - Friuli Venezia Giulia – Liguria – Lombardia – Piemonte – Toscana – Trentino Alto Adige – Valle D'Aosta - Veneto)*. ENEA, Ministero Dello Sviluppo Economico.

Sontag L., Nicolai A., Vogelsang S. (2013). *Validierung der Solverimplementierung des hygrothermischen Simulationsprogramms DELPHIN*. Institut für Bauklimatik. Technische Universität Dresden. Persistent URL: urn:nbn:de:bsz:14-qucosa-128968.

Zhou X., Derome D., Carmeliet J. (2016). Robust moisture reference year methodology for hygrothermal simulations. *Building and Environment*, 110: 23-35.