From the Dynamic Simulations Assessment of the Hygrothermal Behavior of Internal Insulation Systems for Historic Buildings towards the HeLLo Project

Marta Calzolari, Pietromaria Davoli, and Luisa Dias Pereira

***Abstract*—In the context of functional and performance rehabilitation of existing heritage, internal envelope thermal insulation is often an inevitable option towards improvement of historic buildings' energy efficiency. Nonetheless, besides leading to the loss of useful floor area, this option may also lead to changes on the original hygrothermal behavior of such walls. Applied to a real case study, this paper presents the dynamic simulations assessment of a few thermal retrofitting materials, unveiling the significance of the proper choice of the materials in the software's' library (aiming at avoiding biased results) as well as reinforcing the importance of real in situ measurement for validation of such estimations, e.g. the HeLLo project.**

***Index Terms*—Energy efficiency, energy retrofit, historic building, hygrothermal simulation.**

I. INTRODUCTION

Historic buildings account for 30% of Europe's building stock [1] and, in fact, the field of energy refurbishment of heritage buildings is one of the priorities of the EU policies to reduce fuel consumption and face climate change. That is why a number of recent European guidelines (DIRECTIVE 2012/27/EU [2]), standards (EN 16883 [3], EN 16242 [4], DS/EN 15758 [5]) and scientific projects (RIBuild [1], 3ENCULT [6], Co2olBricks - Climate Change, Cultural Heritage & Energy Efficient Monuments [7], HERACLES [8]) have been addressing this issue.

Concerning historic buildings, the intervention on the envelope is driven by various criteria [9], among which e.g. aesthetic value, targeted energy improvement (U-value) or useful floor area loss [10], [11]. When historic buildings are located in protected areas or present specific heritage values, frequently, besides window replacement and external roof insulation, the intervention is limited to internal thermal insulation of walls, which becomes often an inevitable option towards the energy improvement of such buildings. In this particular case, compatibility issues might occur (between the existing walls and the new added materials).

Until a few years ago, studies on this subject would focus mostly on the thermal transmittance or energy aspects. Peng and Wu [12] presented three methods *'to evaluate the in situ R-value of buildings and to satisfy the requirements of practical projects'*; the research of Giorgi and De Carli [13], showed a comparison between the reference specific thermal conductance (C) values and those calculated from a 4-year in situ monitoring campaign; Ficco *et al.* [14] called on the crucial role of energy audits and reinforce the need of in-field determination of *U*-value of buildings for reaching energy saving; Calzolari *et al.* [15] developed an alternative *in situ* method for the assessment of thermal behaviour of historic envelope in absence of real values of material's conductivity.

Currently, a deeper and more heterogeneous analysis has been proposed on the hygrothermal behaviour of this type of interventions, aiming at supporting better informed technical solutions. It is the case of the non-invasive envelope monitoring method suggested by Litti *et al.* [16], the study of Ascione *et al.* [17] which proposes a 'multidisciplinary approach to structural/energy diagnosis and performance assessment' or the *'hygrothermal assessment of internally added thermal insulation on external brick walls'*, developed by Hamid and Wallenten [18].

Otherwise stated, a conscious choice of the thermal insulation material should also be dictated by an informed hygrothermal behavior of the entire wall, aiming at minimizing undesired hygrothermal risks related [19] (e.g. damages caused by increased moisture accumulation [20], as frost damage or condensation [21] with a decrease of insulation effect). Commonly, this choice is grounded on dynamic hygrothermal simulations (due to the unknown characteristics of the historic wall and impossibility of survey) [22], which, in case of a safe scenario, points at one option or another.

Bottino-Leone *et al.* [23] showed that the 'hygrothermal evaluation is crucial when dealing with internal insulation in historic buildings'. Nonetheless, within the current study the authors unveil some of the still existing frailties of hygrothermal simulation – especially if results might be biased by non-precise data input, reinforcing the importance of real in situ measurement [24] validating such simulations. In this framework, the HeLLo project is developed [25].

II. MATERIALS, METHODS AND PAPER STRUCTURE

The method of this study is motivated by EN 16883 [3], adjusted to one specific part of historic buildings: external walls. After the selection of the thermal insulation materials towards the analysis of interior insulation systems of historic

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walls, it is fundamental to understand their hygrothermal compatibility throughout dynamic simulations.

The next section, corresponding to the application of the method to the ahead presented case-study are divided in four parts: III.A presentation of the case-study; III.B Selection of the insulation materials; III.C Hygrothermal assessment (through dynamic simulations); and III.D Variations of the dynamic simulations.

Following the "Method Step-By-Step" section, in section "Results", these are analyzed and discussed. Paper is ended with Conclusions.

III. METHOD STEP-BY-STEP

A. *Case-Study Presentation*

The method described hereinafter was applied to Palazzo Tassoni Estense, a Renaissance building located in Ferrara (Italy), currently housing the Department of Architecture of the University, in a partition which has still not been refurbished and that is presently used as field work for the EU H2020 MSCA-IF-ES HeLLo project [25].

The palace's original walls are constructed in brick masonry, of different thickness depending on the part of the building. For this specific study, the studied wall corresponds to the one signaled in Fig. 1, which is 300 mm thick. Due to its incompleteness (Fig. 2), external plaster was not considered, contrarily to interior 15 mm coating of lime plaster, and mortar joints between bricks. A schematic representation of the historic wall is presented in Fig. 3.

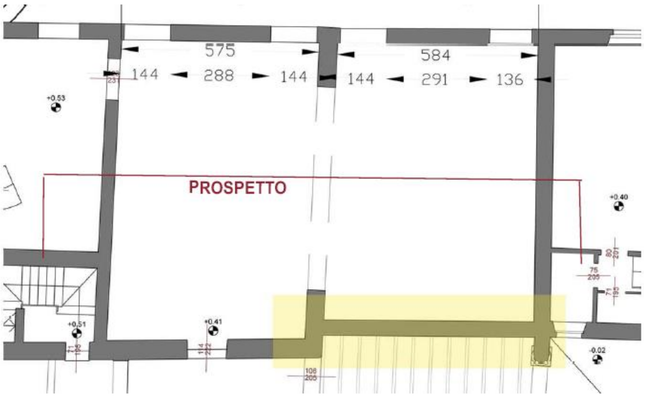


Fig. 1. Plan of the room with rectangle around the studied wall.

Fig. 2. Outdoor picture of the studied wall (located in Palazzo Tassoni internal courtyard, under a porch) [26].

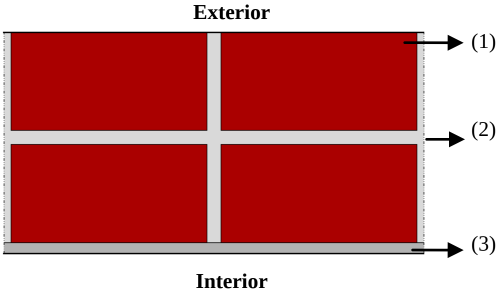


Fig. 3. Representation of the historical wall (horizontal section). (1) Brick wall; (2) Mortar joints; (3) Indoor surface coating.

B. *Selection of the Insulation Materials*

The materials chosen to be tested were selected by their adaptability to historic buildings usage and widely diffused presence in the market. Their choice was grounded on the anticipated materials to be tested in the HeLLo project [25], whose basic condition is that the selected systems feature the possibility of removal at a later state of the application and which respect the original "breathability" (i.e. low vapor resistance or vapor open materials), as *'most historic buildings are "breathable"'* [27]. As such, no vapor barrier was added to any of the selected materials, in order not to limit the inward drying potential, aiming at reducing a moisture accumulation in between the insulation system and the underlying masonry, or, in other words, avoiding the results obtained by Hansen *et al*. [24], where an increased material thickness and vapor tight insulation system choice led to higher relative humidity values *'in the interface between the internal insulation and the original wall'*.

In this case, the following materials, all with 100 mm width, were chosen (a typical market thickness, not chosen with the view of achieving a certain U-value): (A) Calcium silicate panels; (B) Wood fiber boards; (C) Cork boards; (D) Mineral wool boards. Panels (A) were assumed to be glued, thanks to a mortar adhesive 8 mm thick, to the historic wall and given a 10 mm finishing mortar layer; materials (B), (C) and (D) were assumed to be 'dry constructed', therefore supported by their own structure, punctually fixed to the historic wall (very few 'anchor' points and consequently not considered in the simulations) provided of a final gypsum board (12.5 mm).

C. *Hygrothermal Simulation*

The dynamic hygrothermal analysis proposed in this study is performed through a 1D transient heat and moisture transfer model, as suggested by UNI EN 15026 [28], using Delphin software (v. 6.0.20) [29]) to perform the simulation.

Outdoor climate data used in the simulations are 2017's hourly data of temperature (T, ℃) and relative humidity (RH, %) collected from a local weather station [monthly averages of hourly climate data: $1.7 \leq T(℃) \leq 26.5$ and $65 \leq RH\ (\%) \leq 89$], used as 'reference year'. It is worth mentioning that wind speed and direction, rain and solar radiation were neglected as the studied wall (SE oriented) is located under a portico of the courtyard inside the building and therefore it is not directly exposed (Fig. 2). Though this situation does not correspond to a *'worst-case scenario'*, it does in fact present some specificities – rainwater might not reach directly the wall, but neither does the sun, i.e. both the capacities of wetting/absorbing and drying are limited.

Climate data for one year was used for a 5 year-simulation. Only results from the 5th year are presented in this paper.

All the materials used in the simulations, presented in Table I, were chosen from the software database [29]. In the absence of precise hygrothermal characterization of the real historic wall, materials titled ‘historic’ were selected. Considering the most significant layer of this wall typology, the historic brick, the database presents almost 100 different options, which water vapor diffusion resistance factor (μ) value varies between 3.4-168.0. Since the final aim of the study is to underline the divergences of the simulation results obtained using different materials, the authors selected as ‘original’ brick, from the database, the material with the highest μ value.

The indoor climate was defined according to the adaptive indoor climate model present in Delphin database, were T varies between 20 and 25 ℃ and RH ranges between 35 and 65%, as presented in the standard UNI EN 15026 [28].

The outputs chosen for the current assessment were: temperature, relative humidity and moisture content. Considering Ferrara’s averaged outdoor climate, frost damage was neglected (no freeze-thaw cycles were considered).

TABLE I: HYGROTHERMAL PROPERTIES OF THE SELECTED MATERIALS

	r	λ	C$_p$	μ	A$_w$
	[kg/m^3]	[w/mK]	[J/KgK]	[-]	[kg/m^{2}s^{05}]
Historic brick	1980	0.996	834	168.0	0.051
Historic lime plaster	1800	0.820	850	12.0	0.127
Lime mortar	1739	1.050	1057	28.3	0.494
Calcium silicate (CaSi)	125	0.045	968	5.7	0.004
Adhesive mortar	830	0.155	815	13	0.003
Wood fiber (Wf)	150	0.042	2000	3.0	0.070
Mineral wool (Mw)	67	0.035	840	1.0	0.000
Cork (Co)	114	0.047	2253	28.9	0.009
Gypsum board	850	0.200	850	10.0	0.277

Dry density (r), Thermal conductivity (λ), Specific Heat capacity (C$_p$), Water vapor diffusion resistance factor (μ), and Water absorption coefficient (A$_w$). The materials signaled in **bold** correspond to the ‘original’ composition of the historic wall simulation.

D. Variation of Material Parameters

Though 1D models tend to be simplified and historic walls are often addressed as homogeneous layers, within this study mortar joints between bricks were considered. In order to assess the sensitivity of the input data in the dynamic simulation process, two variations were introduced to the ‘original’ historic wall (HW):

1) change of the ‘original’ brick;
2) change of the ‘original’ lime plaster.

TABLE II: HYGROTHERMAL PROPERTIES OF THE SELECTED MATERIALS

	r	λ	C$_p$	μ$_{dry}$	A$_w$
	[kg/m^3]	[w/mK]	[J/KgK]	[-]	[kg/m^{2}s^{05}]
Historic brick II	1759	0.624	1092	24.5	0.185
Historic lime plaster II	1603	0.690	869	19.0	0.179

Considering the absolute randomness of choice - in the case of unknown real characteristics -, the authors choose Historic brick II and Historic lime plaster II defined in the Database which are named after the 3ENCULT [6] European project.

In sum, two historic brick wall types with two lime plasters were combined with four insulation materials to perform 16 simulations. Table II shows the hygrothermal characteristics of the introduced variations. In Table III the 16 scenarios are presented.

TABLE III: SIMULATION VARIATIONS (16 SCENARIOS)

Materials / Simulations	A (CaSi)	B (Wf)	C (Co)	D (Mw)
(1) HW (brick + plaster)	1A	1B	1C	1D
(2) HW (brick II + plaster)	2A	2B	2C	2D
(3) HW (brick + plaster II)	3A	3B	3C	3D
(4) HW (brick II + plaster II)	4A	4B	4C	4D

IV. RESULTS: ANALYSIS AND DISCUSSION

For the present aim of this study only 1D simulations were performed; for a better understanding of the global phenomena of moisture transport within an historic wall, other authors recommend 2D simulation [30].

Fig. 4 and Table IV show the moisture mass within the HW composition/thickness (brick + mortar + brick + plaster, Fig. 3) during the last year of simulation for the four insulation materials (A – D) and the four simulation variations (Table III). Within these four images (one for each material), three general comments can be addressed:

1) for all the materials, changing the type of brick and plaster, within the software library, led to visible changes in the amount of moisture contained in the HW;
2) material A and material B present a similar profile, while C and D contain the lowest and the highest moisture content, respectively;
3) in all cases, introducing a change in the brick led to a more significant moisture content in the HW then the change of the indoor plaster itself, as observed in Table VI. The difference between simulations 1-2 and 1-3 corresponds to Δ_{max} (%) = [23.5÷27] and Δ_{min} (%) = [14.8÷16.1], respectively. This result was expected as the proportion of this material in the HW composition is also more significant than the percentage of plaster. Instead, if both types of brick and plaster are changed (simulations 1-4), the difference between the results is even more significant and reaches up to 39.2-30.0% in the case of material A (CaSi).

As previously stated, when insulating a wall from the inside, one of the most critical points is the one between the existing wall and the new added layer, as such, this point in the inner surface of the wall, behind the insulation (*‘averaged on the first 10mm behind the insulation layer’*[30]), was studied. As there were not very significant changes in the temperature profiles, these results are not shown, contrarily to the RH (%) in this point, exposed in Fig. 5. Alike in Fig. 4, also the RH profile changed expressively. These changes are more visible in some materials than others, but more importantly, the differences in between the same material are especially important:

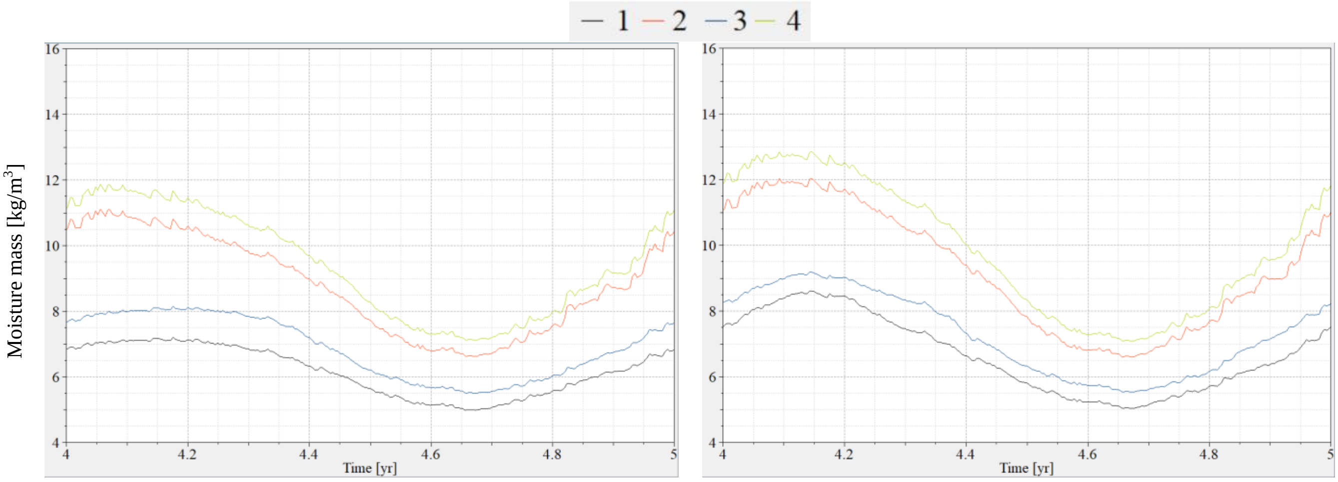
1) in the cases of material B and D, depending on the material selected for the construction of the HW, the interpretation of the result, would lead us to the risk of condensation and decay, or not (when RH > 95%);

2) concurrently, also the evaluation of the mold risk can be biased – some authors defend there is the risk of mold when RH > 80% (and T > 0 ℃) [11].

As anticipated, the risk of frost is highly unlikely in this point as RH > 95% was verified just in brief moments for two of the insulation materials and it is expected just in the concurrency of T < 0 ℃ [11]. Concomitantly, we also looked at the RH profile in the HW (Fig. 6 and Table V). RH was always below 85% [but this was already expected since wind driving rain (WDR) was not accounted on the outdoor climate data as earlier commented], Table V.

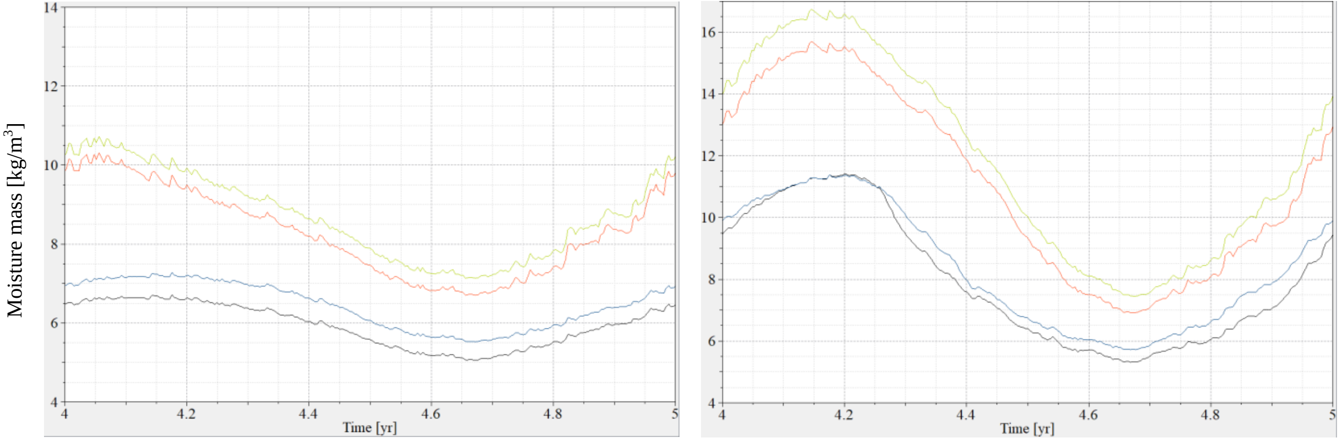
Alike the moisture content in the HW, the influence of brick over the plaster was also verified in the averaged RH in the HW section (Table VII). As observed in Table VII, the difference between simulations 1-2 and 1-3 corresponds to Δ_{max} (%) = [2.0÷3.2] and Δ_{min} (%) = [4.7÷7.5], respectively.

Generally, it can be stated that the percentage difference in the moisture content in between simulations is much more significant than the RH.



(A) Calcium silicate panels

(B) Wood fiber boards



(C) Cork boards

(D) Mineral wool boards

Fig. 4. Moisture mass in the HW section (Fig. 3) during the last year of simulation. Each plot represents the four simulations (see Table III) for the same insulation material to quantify and visualize the differences given by the variation of brick's and plaster's types.

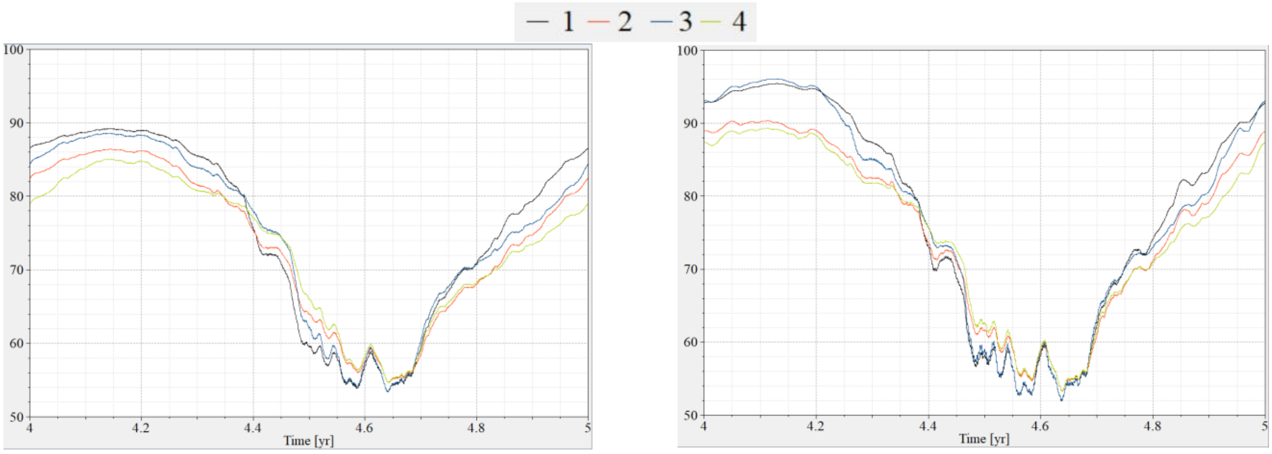
TABLE IV: SYNTHESIS TABLE OF THE MOISTURE MASS [KG/M^3] IN THE HW SECTION (FIG. 3) DURING THE LAST YEAR OF SIMULATION

	1A	2A	3A	4A	1B	2B	3B	4B
MAX ÷MIN	7.21÷4.98	11.11÷6.62	8.16÷5.50	11.86÷7.11	8.62÷5.04	12.03÷6.60	9.19÷5.53	12.85÷7.08
	1C	**2C**	**3C**	**4C**	**1D**	**2D**	**3D**	**4D**
MAX ÷MIN	6.71÷5.06	10.30÷6.70	7.28÷5.52	10.72÷7.13	11.41÷5.31	15.69÷6.91	11.38÷5.71	16.74÷7.45

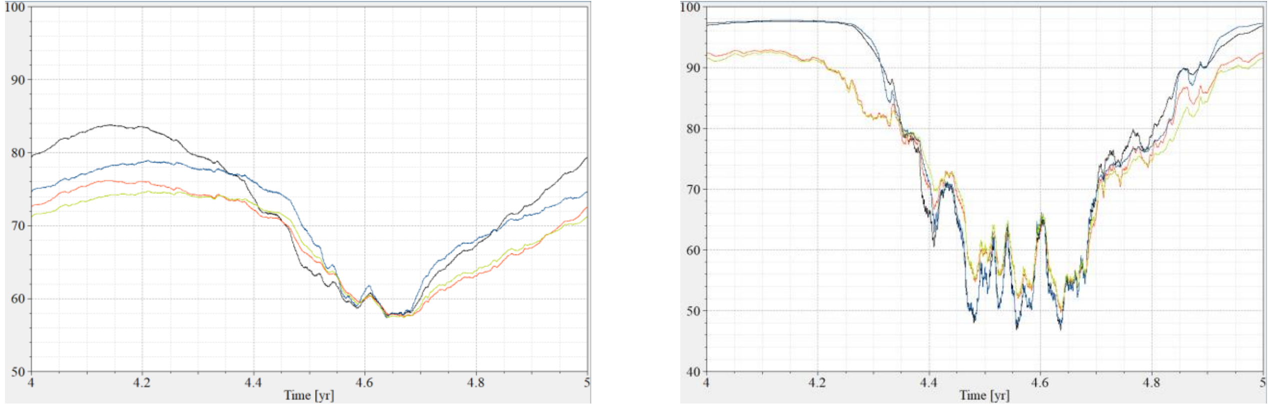
TABLE V: SYNTHESIS TABLE OF THE AVERAGED RH [%] IN THE HW SECTION (FIG. 3) DURING THE LAST YEAR OF SIMULATION

	1A	2A	3A	4A	1B	2B	3B	4B
MAX ÷MIN	73.85÷58.17	74.86÷54.81	74.38÷58.83	76.70÷55.10	76.73÷58.84	78.63÷54.64	76.67÷59.32	78.76÷54.88
	1C	**2C**	**3C**	**4C**	**1D**	**2D**	**3D**	**4D**
MAX ÷MIN	71.58÷58.71	74.07÷55.48	70.58÷59.06	73.60÷55.45	80.65÷61.78	82.86÷56.71	80.28÷61.36	83.29÷57.76

Posani *et al*. [31] highlight two main characteristics of materials influence on the moisture dynamics of retrofitted components, namely Water Vapor Permeability (δ_p) and Water Absorption Coefficient (A_w), also referred in literature as capillary water absorption coefficient. As such, and as evidenced in Fig. 4-5 and Tables IV-VII, there is a big uncertainty on the judgement that can be done on the hygrothermal performance of an insulation material if δ_p and A_w of the materials of the HW are unknown.

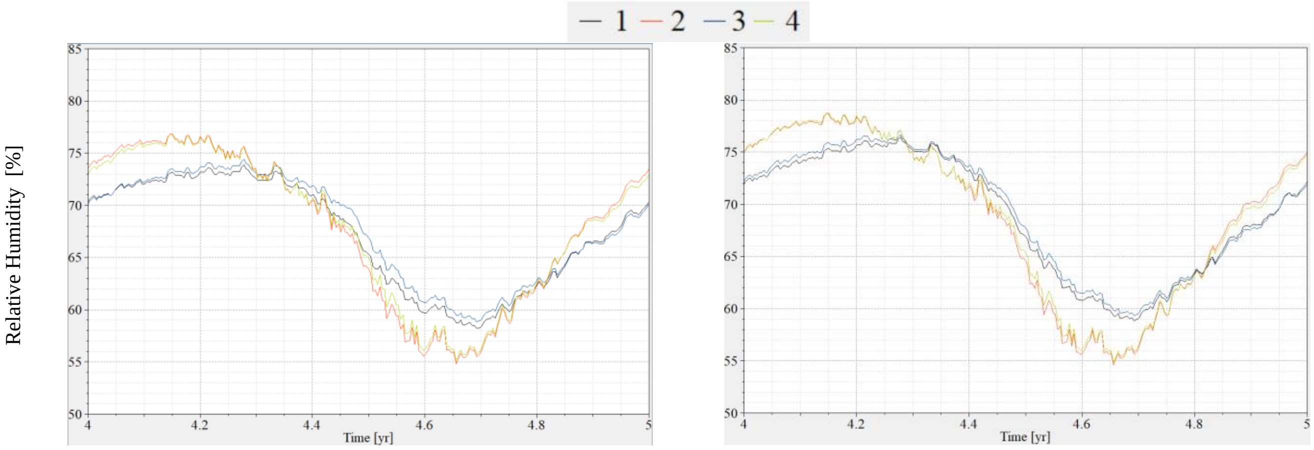


(A) Calcium silicate panels (B) Wood fiber boards

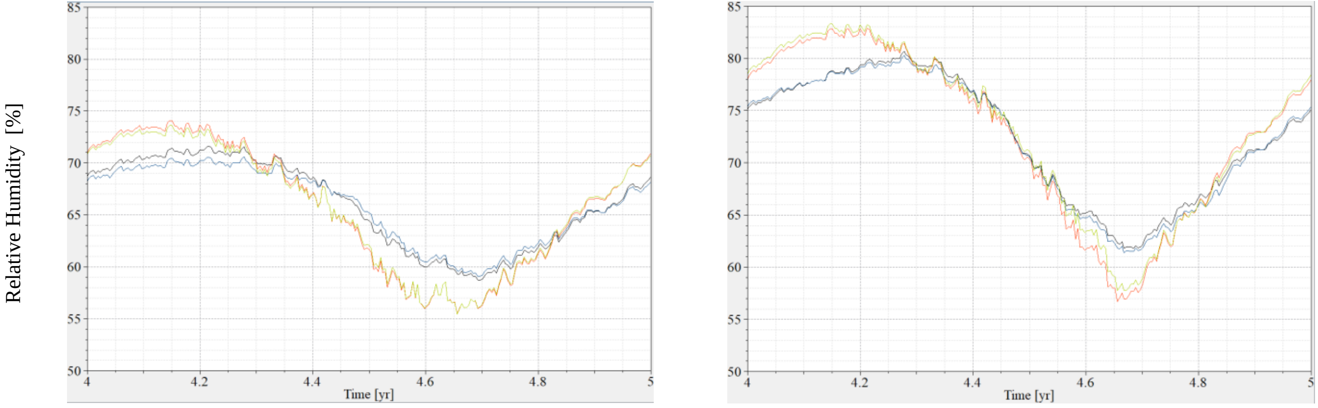


(C) Cork boards (D) Mineral wool boards

Fig. 5. RH [%] in the inner surface of the wall (behind insulation) during the last year of simulation. Each plot represents the four simulations (see Table III) for the same insulation material to quantify and visualize the differences given by the variation of brick's and plaster's types.



(A) Calcium silicate panels (B) Wood fiber boards



(C) Cork boards (D) Mineral wool boards

Fig. 6. Averaged RH [%] in the HW section (Fig. 3) during the last year of simulation. Each plot represents the four simulations (see Table III) for the same insulation material to quantify and visualize the differences given by the variation of brick's and plaster's types.

TABLE VI: PERCENTAGE DIFFERENCE BETWEEN MAXIMUM AND MINIMUM VALUES OF MOISTURE MASS IN THE HW SECTION (FIG. 3) [%]

		1-2	1-3	1-4	2-3	2-4	3-4
A	**MAX**	35.1	11.6	39.2	26.6	6.3	31.2
	MIN	24.8	9.5	30.0	17.0	6.9	22.7
B	**MAX**	28.4	6.2	32.9	23.6	6.4	28.5
	MIN	23.7	8.9	28.8	16.2	6.8	21.9
C	**MAX**	34.8	7.8	37.4	29.4	3.9	32.1
	MIN	24.5	8.4	29.1	17.6	6.0	22.6
D	**MAX**	27.3	0.3	31.9	27.5	6.3	32.0
	MIN	23.1	7.1	28.7	17.3	7.3	23.3

TABLE VII: PERCENTAGE DIFFERENCE BETWEEN MAXIMUM AND MINIMUM VALUES OF RH IN THE HW SECTION (FIG. 3) [%]

		1-2	1-3	1-4	2-3	2-4	3-4
A	**MAX**	3.9	0.7	3.7	3.2	0.2	3.0
	MIN	5.8	1.1	5.3	6.8	0.5	6.3
B	**MAX**	2.8	0.3	3.0	2.5	0.2	2.7
	MIN	7.1	0.8	6.7	7.9	0.4	7.5
C	**MAX**	3.4	1.4	2.8	4.7	0.6	4.1
	MIN	5.5	0.6	5.5	6.1	0.0	6.1
D	**MAX**	2.7	0.5	3.2	3.1	0.5	3.6
	MIN	8.2	0.7	6.5	7.6	1.8	5.9

As observed within the introduced variations on the simulations, Historic brick II presents an A_w value (Table II) more than three times bigger than the 'original' one (Table I), in other words, it expresses a rate of capillarity action in time (*'liquid moisture movement into it'* [32]) more than three higher. Lime plaster II instead, is only 40% bigger than the 'original'. These assumptions can also help explaining *iii)*, i.e. the comments on the results expressed in Fig. 4, Table IV and Table VI concerning the change of brick and change of behavior in the interstitial condensation point.

Delphin software materials library does not show Vapor Permeability (δ_p) values but displays Water vapor diffusion resistance factor (μ_{dry}) instead. Nonetheless, the μ values can be easily converted into δ_p *'by considering: the definition* ([33], p. 44) *of resistance factor as the ratio between permeability of the still air and the one of the considered material (μ = δp,a/δp), an approximated Water vapour permeability of still air (δp,a) of 200 10^{-12} kg/ (m s Pa)'* cited in [31]. Table VIII presents the conversion of these two characteristics of materials for all the simulated ones.

Though it can be mentioned the δp values for both simulated historic bricks are below the minimum value suggested in [31] for this building material, 8.9 10^{-12} kg/ (m s Pa), in the cases of the mortar, wood fiber and mineral wool, values fit perfectly the reference intervals. More importantly, what should be stand out is:

1) Brick II value is more than 6 times less vapor diffusion resistant;
2) Lime plaster II δp value represents circa 65% of Lime plaster I;
3) of all simulated materials, mineral wool is the one presenting higher Vapor Permeability, i.e. *'under specified temperature and humidity conditions'*, it is the material presenting higher water vapor transmission rate.

As briefly shown in the precedent paragraphs, when it comes to historic buildings materials properties, analyses grounded solely on simulations can be biased [34], if the characteristics of the building components are not known. This study reinforces other authors opinions concerning current and future research directions [35]: 'using in situ methods in historical buildings' is needed when the known methods are not sufficient or there is a need for greater detail. The HeLLo project – Heritage energy Living Lab onsite [25] intends to bring the research on this field one step ahead: by creating a true experimental laboratory, in which to test directly on a historic case study the performance of some insulating materials in order to obtain real data, useful for the design of refurbishment interventions and to increase the awareness about criticalities related to the use of simulation tools.

TABLE VIII: WATER VAPOR PERMEABILITY (δ_p) CONVERTED VALUES OF ALL THE SELECTED MATERIALS

	μ [-]	δ_p [10^{-12} kg/ (m s Pa)]
Historic brick	**168.0**	**1.2**
Historic lime plaster	**12.0**	**17**
Lime mortar	28.3	7.1
Calcium silicate (CaSi)	5.7	35
Adhesive mortar (CaSi)	13	15
Wood fiber (Wf)	3.0	67
Mineral wool (Mw)	1.0	200
Cork (Co)	28.9	6.9
Gypsum board	10.0	20
Historic brick II	**24.5**	**8.2**
Historic lime plaster II	**19.0**	**11**

The materials signaled in **bold** correspond to the variations introduced in the simulations.

In situ tests are currently being conducted in Palazzo Tassoni Estense, a monumental building of considerable architectural interest. So far, the laboratory has received stakeholders mostly from the academic sector (e.g. PhD candidates and experienced researchers) and heritage authorities. Lately, in December 2019, this onsite experience was also shared with professionals interested in applying retrofit solutions during an Open Tour Lab, accompanied of several lectures on this theme. The expected results (spring/summer 2020) will be divulged openly and shared with all potential users.

V. CONCLUSIONS

The study herein presented unveils the frailties of hygrothermal dynamic simulations software's library and their significance towards a proper analysis of the hygrothermal performance and refurbishment of existing/historic walls. In order to minimize biased results interpretation, researchers and practitioners in general should be aware of the limitations and implications of choice the materials' library software.

Moreover, the study confirmed other researchers' premises regarding the need of pursuing in situ monitoring to properly validate the dynamic models and obtained data, as sustained by Galliano *et al*. [10] or Bienvenido-Huertas *et al.* [35]: *'(...)Some aspects of thermal transmittance measurement methods have not yet been assessed or need to be assessed in greater detail. These aspects are: (i) using in situ methods in historical buildings; (...)'*. In other words, it claims for urgency of field works as the HeLLo project ([25], https://bit.ly/2zlBAcj).

CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

AUTHOR CONTRIBUTIONS

Authors are listed in alphabetical order. Conceptualization, M.C., P.D., L.D.P.; data analysis: M.C., L.D.P.; simulation: L.D.P.; supervision P.D.; writing, review and editing: M.C., P.D., L.D.P.; all authors had approved the final version.

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