The "Waaghaus" of Bolzano

Energy efficiency, hygrothermal risk and ventilation strategy evaluation for a heritage building

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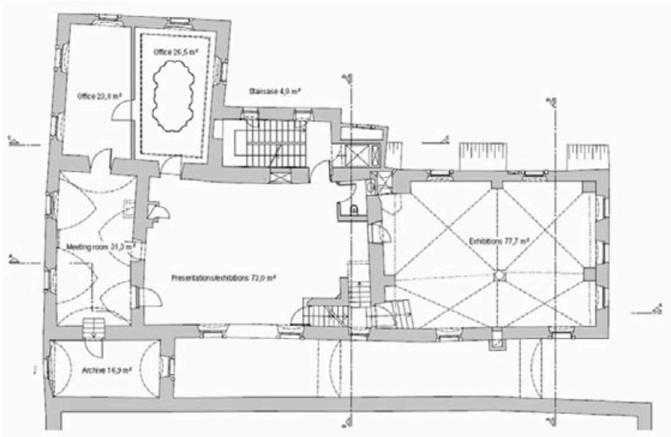
Abstract – The present paper analyzes the renovation project of a heritage medieval building located in the city center of Bolzano–the "Waaghaus". The building has been used as case study in the EU-project 3encult, where it has been extensively studied both from heritage and energy efficiency points of view. Our analysis, partly based on the experience gained in the EU-project, aims at validating and improving the renovation project that was developed by a design team commissioned by the owner. In particular three aspects of the renovation are mainly investigated: 1) Reduction of the energy demand 2) Indoor climate and air quality 3) Hygrothermal risk in critical points. Results show that the proposed renovation cuts the energy demand to 60 percent. Moreover they demonstrate that, when renovating a historic building, it is crucial to carefully investigate the ventilation strategy and the critical construction details. Not considering these two aspects can lead to poor air quality and to a significant risk of surface mould and condensation formation.

Keywords – historic building, energy retrofit, natural & active overflow ventilation, thermal bridge evaluation, hygrothermal risk evaluation, from research to practice

1. INTRODUCTION

The "Waaghaus" is an extraordinary medieval monument in the centre of Bolzano, Italy. Its refurbishment has to consider heritage and environmental aspects. The distinctive urban location, the rich extensive presence of historic plaster and wall paintings both indoors and outdoors, and the building structure developed over different periods, requires thereby a highly sensitive treatment of the building. The building already served from 2010 to 2014 as a case study in the FP7 EU-Project 3encult "Efficient Energy for EU Cultural Heritage". Comprehensive historical study, urban analysis, energetic calculations, and hygrothermal monitoring, as well as the development of new technical solutions, allowed the interdisciplinary research group to propose a renovation project mainly based on passive architectural solutions. This would have reduced the energy demand of the building by 56 percent while respecting the rich heritage value [1].

In 2017 a design team developed new plans for the transformation of the Waaghaus in a centre for cultural associations, including meeting spaces and café. Achieving a sensible restoration that was compatible with the conservation of the heritage value of the building limited the extent to which the energy performance was improved. Although the refurbishment still aims at meeting the criteria of the ClimaHouse R certification [2], the energy interventions developed in 3encult had to be adjusted to the new design, user requirements and financial resources. As a result, the ventilation system was planned only for the ground floor and attic, but not anymore for the two middle floors, due to the absence of space for ventilation ducts. Coupled with the existing poor thermal quality of the exterior walls, this can have three main consequences: Firstly, it will result in a higher energy demand. Secondly, uncontrolled ventilation rates might lead to increased internal humidity and CO_2 levels and thirdly, uninsulated components will cause low surface temperatures – both aspects could lead to significant hygrothermal risk increase.



- Date of construction: Romanesque origins
- Heated net floor area: 878,7 m^2
- Heated gross floor area: 1.178 m^2
- Heated gross volume: 4.776 m^3
- S/V ratio: 0,41
- HDD: 2791 (HDD)

Figure 1. Medieval Waaghaus in Bozen/Italy (© EURAC); 1st floor plan. © Architekten Piller Scartezzini).

Therefore, to prevent building damage and guarantee adequate comfort levels, it was necessary to carefully analyse the ventilation strategy and evaluate its impact on the internal climate. Moreover, all the single construction details were analysed and accordingly improved in order to verify the compatibility with the expected internal climate from a hygrothermal point of view. This paper will analyse the consequences of the new renovation project on three crucial aspects of the building, namely 1. Energy demand, 2. Indoor climate and air quality, 3. Hygrothermal risk in critical points.

2. METHODOLOGY

2.1 RETROFIT SOLUTIONS AND ENERGY BALANCE

The energy demand was evaluated for the existing building and for the renovation project, using PHPP (Passive House Planning Package) [3].

2.2 STUDY OF INDOOR AIR QUALITY

As the 1st and 2nd floor cannot be ventilated with a traditional mechanical ventilation system, the design team proposed a natural ventilation approach. In the present paper we evaluate three ventilation strategies with the multi-zone air flow and contaminant transport analysis software CONTAM [4]. Two strategies follow the natural ventilation approach proposed by the designers, while a third strategy introduces a ductless ventilation system [5]:

a) natural ventilation with windows operated three times a day (morning 15 min. windows open, windows tilted 45 min. during lunch break, late afternoon 15 min. windows open);
b) natural ventilation with windows tilted once a day 45 min. during lunch break;
c) active overflow ventilation [5] with 1500 m^3/hr supplied in the central hall next to the staircase on 1st floor and extracted at the end of the corridor at 2nd floor.

Main aim of these simulations is to investigate indoor relative humidity levels and air quality regarding CO_2 concentrations. Rooms' occupancy rates are defined according to the national standard UNI 10339:2005 [6], with e.g. 0.12 pers/m^2 in office rooms and 0.7 pers/m^2 in exhibition area. The schedule foresees typical working days in office rooms, while exhibition areas are assumed to be used from Monday to Saturday from 10 to 18. Occupants are assumed to generate 38 g/h of CO_2 and 55 g/h of water vapour. Outdoor CO_2 concentration is set to 320 ppm (CONTAM default value). The leakage area is distributed uniformly along the envelope in order to have 1.5 ach of infiltration under pressurization test at 50 Pa. The window opening is modelled through a two-way model for single opening, while leakages through the "powerlaw" model.

2.3 STUDY OF THE HYGROTHERMAL RISK AT CRITICAL POINTS

The study of critical construction details is performed with the thermal bridges software Mold- and FrameSimulator [7]. The analysis is done according to the Italian national standard UNI EN ISO 13788:2013 [8]. It considers a thermal calculation with stationary boundary conditions and follows two different calculation procedures for opaque components with high thermal mass and transparent components with low thermal mass, as reported in Table 1.

Table 1. Calculation method and boundary conditions of mould and condensation risk calculation

Component type	Calculation method	Internal surface heat transfer resistance	External surface heat transfer resistance	Critical RH on internal surface for hygrothermal risk	Internal tempe-rature
opaque	monthly	0.25 m^2K/W	0.04 m^2K/W	80%	20°C
transparent	daily	0.13 m^2K/W	0.04 m^2K/W	100%	20°C
frame corners		0.2 m^2K/W*			

* according to UNI EN ISO 10077-2:2012 [9] (reduced convection and radiation at frame corners)

The thermal quality of every construction detail is characterized by the temperature factor $f_{Rsi} = \frac{\theta_{si}-\theta_e}{\theta_i-\theta_e}$ [8], where θ_{si} is the lowest simulated surface temperature for the construction detail, while θ_e is the external ambient temperature and θ_i the internal room temperature. We then verify that the simulated temperature factor is larger than the critical temperature factor $f_{Rsi} > f_{Rsi,\,crit}$, which is the temperature factor that would lead to a critical hygrothermal behaviour. In our case, the critical temperature factor is calculated for the most critical day or month of the year, which means it is defined as the largest of all temperature factors computed on a daily or monthly basis. The critical temperature factor strongly depends on the interior climate of the building. Several specific assumptions for the interior climate will therefore result in several values for $f_{Rsi,\,crit}$. Considering the interior climate prescribed by the CasaClima R certification (1), the one of the Italian national appendix of the standard (2) and the results of the CONTAM simulations with the three ventilation strategies described above (3a, 3b, 3c), different critical temperature factors $f_{Rsi,\,crit}$ are obtained and compared. In particular for the national standard we show $f_{Rsi,\,crit}$ for two different moisture classes [8]: moisture class 2, "dwellings with mechanical ventilation, offices and shops" and moisture class 3 "dwellings without mechanical ventilation or buildings with unknown occupancy". From the CONTAM simulation we obtain different internal climates for each single room of the building. We calculate $f_{Rsi,\,crit}$ for the average interior climate conditions (average) as well as the one for the most critical room (maximum).

3. RESULTS AND DISCUSSION

3.1 RETROFIT SOLUTIONS AND ENERGY BALANCE

Window replacement: The major part of the historic windows were replaced by box-type windows in the 1950s/60s – which actually do not have any historic or architectural value from a conservation point of view [10]. In the actual renovation project, they should be replaced, matching the heritage requirements in terms of the proportions, design of profiles and dimensions, by using a simple wooden frame with double glazing.

Table 2. Energy related parameters of the existing window and the retrofit option

Window types	U-value glazing Ug [W/m²K]	U-value frame Uf [W/m²K]	g-value glazing
Existing box-type	2.8	2.5	0.77
Retrofit project	1.1	1.55	0.64

Insulation of opaque components of the thermal envelope: Base on the comprehensive study of the historic value of the single building elements, a renovation concept was proposed, improving energy performance while maintaining the architectural and aesthetic value of the building. As described above, no intervention on the opaque part of the façade is possible for conservation reasons, thus heritage compatible energy interventions concentrate on other parts of the thermal envelope [1]:

Table 3. Enhancement of other envelope parts

	Roof	Baseplate to ground	Basement ceiling	Slabs toward arcades
Existing construction	Partly 8 cm of rock wool	Concrete slab	Vaulted natural stone ceiling. lime mortar joints	Wooden beams; sand & pebble filling; underside ceiling lime plastered. floor wooden substructure and boards
U-value [W/m²K]	1.4 – 2.6	2.7	1.0	0.44
Renovation project	19 cm insulation (λ 0.042) 11–13 cm between rafters. 8 cm from below	10 cm PU-insulation (λ 0.03) and 10 cm of foam concrete (λ 0.12)	6 cm PU-insulation (λ 0.03) 4 cm foam concrete (λ 0.12). 10 cm perlite (λ 0.09) as levelling fill on the vault	19.5 cm compressed wood fibres (λ 0.038). Between beams substituting existing filling. additionally 1.5–2 cm footfall sound insulation
U-value [W/m²K]	0.22	0.20	0.22	0.21

Ventilation: For conservation reasons, the retrofit project foresees a traditional mechanical ventilation system with heat recovery only for the top and ground floor, while the necessary air change rates in the 1st and the 2nd floor should be provided with a ductless ventilation strategy. The simpler approach is the use of natural ventilation while a more advanced approach would be the use of an active overflow ventilation system, which avoids the usual invasive implementation of an air-duct distribution system, but still gives the possibility to have a heat exchanger which contributes to the reduction of the energy losses [5].

Heating demand comparison: The calculation of energy demand for the existing building and for the renovation project shows that the foreseen renovation measures lead to a decrease of energy demand of around 40 %, when considering the ventilation strategy of the renovation project with controlled ventilation system with heat recovery on ground and top floor and natural ventilation on 1st and 2nd floor, as well as with improved thermal bridges (like proposed in 3.3).

3.2 STUDY OF INDOOR AIR QUALITY

Indoor air quality simulations for the three cases show that only the continuous air exchange with active overflow ventilation (strategy “c”) can assure acceptable CO_2 levels during working hours, i.e. CO_2 concentrations at least within category III according to EN 15251:2008 [11], see Figure 2. Operating windows for three times a day (strategy “b”), can assure up to 65 % of the occupied time with acceptable CO_2 concentrations. Operating windows only one time a day (strategy “a”) leads to acceptable CO_2 levels for less than 25 % of the time.

Looking at the daily average values of relative humidity (Figure 3a), we can see that active overflow ventilation keeps the relative humidity under 40 % for most of the winter period (average 1st and 2nd floor winter period: 29.1 %). Slightly higher values are obtained when ventilating three times a day (average 1st and 2nd floor winter period: 32. 8 %). Ventilating only once a day results in even higher humidity levels (average 1st and 2nd floor winter period: 41.5 %). This is mainly due to the fact that excess humidity cannot be disposed at the end of the day and remains in the building overnight. Whether this is still acceptable from hygrothermal point of view is discussed in the next section (3.3).

Figure 2. Percentage of occupied time when CO_2 levels are within Category I (CO_2 < 670 ppm), II (670 ≤CO_2< 820 ppm) and III (820 ≤CO_2< 1120 ppm) according to [10] in each office zone at 1st and 2nd floor for (a) natural ventilation one time/day, (b) natural ventilation three times/day and (c) active overflow ventilation.

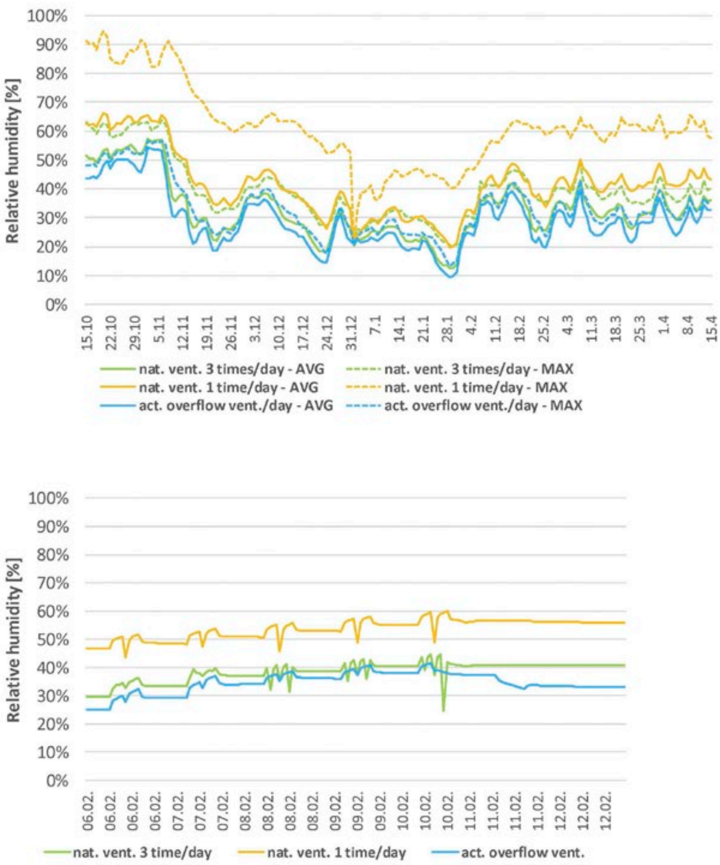


Figure 3. (a) Trend of daily average relative humidity [%] of 1st and 2nd floor (solid lines) and daily max. average of one room (dashed lines) for the winter period. (b) Trend of hourly average of 1 room for 1 week in February for the three simulation cases (natural vent. 3 or 1 times/ day, active overflow vent.), (© EURAC).

3.3 STUDY OF THE HYGROTHERMAL RISK AT CRITICAL POINTS

The results presented in Table 4 show that CasaClima R standard imposes a requirement which is on the safe side if the building is sufficiently ventilated. In fact $f_{Rsi,\ crit}$ for the CasaClima R certification is one of the highest of the table, the only exception are situations with poor ventilation, e.g. the CONTAM simulation with natural ventilation 1 time per day (3a), which lead to even more critical values.

Table 4. Critical temperature factor for the evaluation of the hygrothermal risks for different calculation methods and design variants. Connection details with a temperature factor lower than the one reported in the table will lead to mould growth or condensation. The critical temperature factors represent the (i) average value for the 1st and 2nd floors and (ii) the daily average of the room with the highest humidity

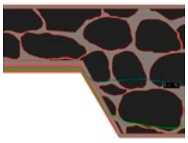
Calculation method	$f_{Rsi,crit}$ – mould growth monthly calculation, valid for opaque components		$f_{Rsi,crit}$ – condensation daily calculation, valid for transparent components	
1) CasaClima R Certification	0.587			
	Class 2	*Class 3*	*Class 2*	*Class 3*
2) UNI EN ISO 13788, National Appendix	0.380	0.571	0.435	0.593
	average	*maximum*	*average*	*maximum*
3a) CONTAM, NatVent – 1 time per day	0.614	-	0.392	-
3b) CONTAM, NatVent – 3 times per day	0.271	0.552	0.094	0.357
3c) CONTAM, Active overflow	0.063	0.199	0.028	0.189

Since the aim is to certify the building according to the CasaClima R certification, we have been analysing all the connection details in order to fulfil the requirement imposed by this standard, i.e. $f_{Rsi} > f_{Rsi,crit} = 0.587$. This choice is on the safe side compared to the national standard and also to the CONTAM simulations – with the important prescription that the building has to be ventilated well, to avoid that excess humidity remains in the building overnight.

Opaque components connection details: In Table 5 we present the analysis of the most critical connection details, calculating the corresponding f_{Rsi} (i) without any further intervention and (ii) improving the thermal performance and thus increasing surface temperatures with a preferably heritage compatible solution. For most critical connection points of the exterior wall, we suggest to apply a layer of lime-based insulating plaster (λ 0.057 W/mK), which can follow the uneven historical wall surface. From the result presented in the table one can see that the proposed intervention is crucial in order to fulfill the CasaClima R requirement.

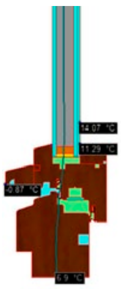
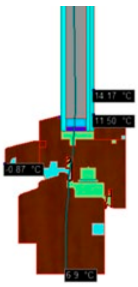
Window spacer detail: The thermal simulation of the bottom profile of the new proposed window results in a thermal bridge coefficient of the glazing edge, ψ_g of 0.063 W/mK and a condensation temperature factor, fRsi, of 0.583. The latter does not fulfil the requirements of the Casaclima R protocol. We therefore propose to increase the spacer's performance improving the originally foreseen stainless steel spacer (1) to a stainless steel spacer with optimized geometry (2)

Table 5. Thermal bridge analysis – most critical connection details selection and corresponding f_{Rsi}

	Picture thermal simulation (optimized)	*f_{Rsi} (i) without any further intervention*	*Proposed intervention*	*f_{Rsi} (i) with proposed intervention*	*Result*
Horizontal connection parapet – exterior wall		0.477 (< 0.587)	+ min. 4 cm lime-based insulating plaster (λ 0.057W/mK) on parapet and wedge-shaped (from 2–0 cm) on the reveal	0.636 (> 0.587)	Requirements met. No condensation and mould growth risk*
Horizontal connection bay windows – exterior wall		0.356 (< 0.587)	+ min. 2 cm lime-based insulating plaster on inner surfaces of bay window; + 4 cm on the outermost wall (λ 0.057W/mK)	0.617 (> 0.587)	Requirements met. No condensation and mould growth risk*

*see mould isotherm in green/purple at 12.6°C; acc. to CasaClima certification criteria

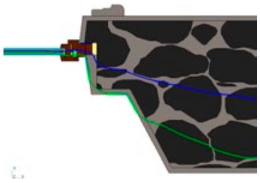
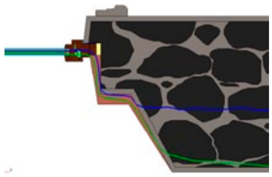
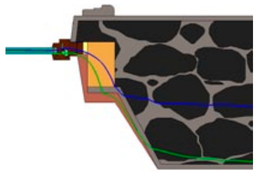
Table 6. Analysis for glass spacer

Glass spacer	*Spacer 1*	*Spacer 2*	*Spacer 3*
Thermal simulation with 3 different solutions			
Description	6.5 mm warm edge spacer of 0.18 mm stainless steel	7 mm warm edge spacer with 0.15 mm stainless steel with slots for light refraction	Reduced spacer height 6.9 mm; low heat loss: stainless steel 15.0 W/(mK). specialist plastic 0.17 W/(mK)
f_{Rsi}	0.583	0.593	0.640
ψ_g in W / m	0.063	0.060	0.0458

or to a hybrid spacer consisting of hard plastic and a fine stainless steel structure (3). As shown in Table 6 those spacers do not cause any hygrothermal risks and lead to an improved thermal performance.

Window-wall connection detail: Table 7 summarizes three design variants for the window-wall connection after the renovation intervention. It shows that replacing the window without any further intervention is not recommended from a hygrothermal point of view. We suggest, (i) to insulate the parapet and the reveals with a minimum of four cm of insulating plaster (λ 0.057 W/mK) and (ii) to add flexible insulation in the potential cavity behind the existing plaster or below the window (where this appears when removing the old window). Furthermore, we recommend improving the airtightness at the window-blind wall connection and to reduce the insulation thickness of the insulating plaster gradually with a wedge-shaped structure to avoid hygrothermal risks at the transition point.

Table 7. Thermal bridge improvement (exemplary for the lateral window-wall-connection)

Connection detail	**Horizontal lateral connection window-natural stone wall**		
	Existing window-wall-connection	*Improvement*	*Further improvement*
Horizontal connection parapet – exterior wall			
Intervention	Window replacement only	+ 4 cm parapet insulation + 0-2 cm wedge on reveal	+ insulation in cavity next to the window
fRsi	0.447 (< 0.587)	0.688 (> 0.587)	0.688 (> 0.587)
Result	Requirements NOT met. Condensation & mould growth risk*	Requirements met. No condensation & mould growth risk*	Requirements met. No condensation & mould growth risk*

*see mould isotherm in green/purple at 12.6°C; acc. to CasaClima certification criteria

4. CONCLUSIONS

We have shown the importance of considering the correlation between energy interventions, ventilation strategies and the effect on hygrothermal risks, when renovating a historic building. It is crucial on the one hand to carefully investigate the critical construction details. On the other hand, it is necessary to do it simultaneously with the evaluation of the ventilation strategies. Not considering these two aspects can lead to poor air quality and to a significant risk of surface mould and condensation formation. The evaluation of the hygrothermal risk with an oversimplified approach based on national or certification standards might lead to wrong conclusions, especially in the case of non-residential buildings manually ventilated. Natural ventilation, if not operated properly, can lead to continued hygrothermal risks and poor indoor air quality in terms of CO_2 concentrations.
It is therefore important to carefully design the ventilation strategy, even when relying on natural ventilation, and provide building users with precise instructions on window opening. Alternatively, it would be necessary to foresee mechanical solutions for window opening. An active overflow ventilation system reduces the hygrothermal risks, leads to better indoor air quality and contributes to the reduction of the overall building's energy demand. The final decision will therefore be made based on the weighting of the different options: a ventilation system or appropriate processes that ensure adequate natural ventilation.

5. ACKNOWLEDGMENTS

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