Space4Free: A feasibility study on the conversion of historic 100+ year old brick basements (type “Gründerzeit”) to flats in downtown Vienna

Thomas Lewis thomas.lewis@tuwien.ac.at
TU Wien, Austria
Paul Wegerer p.wegerer@gassner-partner.at
Gassner & Partner, Austria
Simon Hinterseer s.hinterseer@gassner-partner.at
TU Wien, Austria
Thomas Bednar thomas.bednar@tuwien.ac.at
TU Wien, Austria

Abstract The article examines the moisture risk associated with the conversion into flats of cellars in historic (100+ years) multifamily houses in a temperate climate for the case of downtown Vienna/Austria. The goal is to use the thermal losses of the flat above the cellar through the ceiling for heating the new living space (-> project title: “Space4Free”, Wegerer *et al.* 2022) using the tempering properties of the soil. Further framing conditions are acceptable hygienic conditions and thermal comfort. The cellar’s brick walls are not sealed off the soil for technical and economic reasons during refurbishment. The concept includes the installation of a mechanical ventilation plant.

A three dimensional simulation of moisture and heat transport was carried out the coupling building parts to the indoor air. Focus was on designing a moisture based control algorithm for the mechanical (automated) ventilation plant which resulted in a decision tree with 8 states of ventilation operation.

The simulation showed that such a cellar refurbishment – from a building physics point of view – is feasible. A main result is that the annual moisture immissions are driven by the moisture loads induced by the inhabitants such as cooking rather than by moisture originating from building components which are in contact with the soil. This result is corroborated by the fact that such conversion has been successfully practiced by a company represented among the authors since several years. A practical implication that – in the current case – insulating building components against moisture from the soil is less important than controlling user driven moisture loads.

Keywords: **cellar, basement, hygrothermal, moisture, simulation**

1 Introduction

Vienna is an example for some European cities, such as Berlin or Budapest, where large residential buildings had been erected in the second half of the 19th century up to the end of World War I in and closely around what today is acknowledged as historic centre. These buildings have large cellars used at those times for storage purpose only. Today’s increasing pressure on available space in the downtown area raised the question under which conditions, in particular from a building physics point of view, such cellars may be converted to living space. This question was at the origin of the research project “space4free” started in 2017 and finished in autumn 2021. Such urban densification using space which is available below ground is already practiced by a Viennese construction company with few cases of mould so far. The project described in the article should shed light on the corresponding scientific background.
The ambition with regard to energy consumption was to keep the total heating energy consumption unchanged

with regard to the status quo while creating additional living space via refurbishment. This should be achieved using the current heat losses from a heated ground level flat to the cellar as “free” heating energy for the cellar in its refurbished state.

In addition, as a contribution to keeping the moisture risk low, a tailored algorithm for a mechanical ventilation plant should be developed taking into account the moisture difference between indoor and outdoor air as well as the indoor air quality.

Furthermore, long-term indoor climate measurements were carried out, which are continued after the end of the project as part of ongoing quality assurance. An essential part of the project was the assessment of the risk of damage to building components with ground-contact. This was examined in the course of masonry examinations and long-term component monitoring. The two latter activities are not dealt with in the current article.

Section 2 provides a literature review, sec. 3 shows the methodological approach taken for assessing the feasibility of the refurbishment concept, sec. 4 describes key aspects of the hygrothermal model, sec. 5 shows the findings incl. their discussion and sec. 6 presents the conclusions incl. an outlook on further steps.

2 Literature Review

The current work differs from all reviewed works in particular by considering a mechanical ventilation plant with a dedicated control algorithm.

Source	Short description
Wegerer *et al.* 2022	The final report of the project underlying the current article
Asphaug, Time, *et al.* 2021	Most comprehensive and recent literature review on *hygrothermal simulations on basements* (living space below ground). Thorough analysis of 10 according studies. Main conclusions: 1) Existing hygrothermal simulation tools are inadequate “to replicate actual hygrothermal conditions in basement envelopes” 2) boundary conditions (climate, soil properties) specific to the below ground situation should be made available more broadly.
Zelger *et al.* 2017	A parametric study on moisture and heat transport phenomena of refurbished and unrefurbished cellars
Asphaug, Kvande, *et al.* 2020	Focus on moisture control strategies for habitable basements in western cold climate countries. Method: Analysis of national Scandinavian and Canadian building recommendations for new buildings in comparison with Norwegian guidelines (baseline). Refurbishment is explicitly excluded. Good literature overview in table 1, International research sorted on the ten key challenges for habitable basements. References in the table do not relate exclusively to cellars but rather to influences on the moisture balance in general.
Pallin and Kehrer 2012	Focus is on the influence of soil properties on the hygrothermal simulation of basements. Work includes a literature review, the description of a simulation tool and measurements.
Fedorika *et al.* 2019	Recent hygrothermal simulation based on the simulation software Delphin 5.8. of a basement with a risk assessment on mould formation for a refurbishment with interior insulation.
Annila *et al.* 2018	A study on the repair need related to moisture- and mould damages in 168 Finnish public buildings. 56–85% of the examined buildings showed a need for repair. Moisture- and mould damage were found to be common in structures with soil contact, in basements or spaces in ground floors.
Pallin 2013	Hygrothermal 2D analysis based on WUFI-2D of a retrofitting measure for below-grade walls of an inhabited basement (case study 4) in Gothenburg/Sweden. An exterior combination of a thermal insulation/drainage layer and an outer final sealing layer is applied to the below ground level parts of the outer walls. Only the year after the refurbishment was simulated (no stationary state). The system boundary for moisture balance is the outer surface of the exterior wall. Moisture flows is outwards during the majour part of the year (drying of the wall). Moisture profiles from users were taken into account.
Rantala *et al.* 2009	Focus is on the heat, air, and moisture conditions of *slab-on-ground* of a heated building measuring temperature, moisture as well as bacterial and fungal growth (however, in the fill layer below the slab and the soil).

Tab.2.1: Works dealing with the hygrothermal performance of cellars

Benefits and challenges of using space below ground as living space From a building physics point of view the advantages of living space below ground is the damped soil temperature curve with regard to the outdoor air temperature curve (Hagentoft 2001, Hausladen *et al.* 2012, Hens 2012, DIN EN ISO 13370:2015). For the summer case this results in increased resilience against overheating and for the winter case in a reduced heating demand. However, the biggest challenge in using a more than 100 year old cellar is dealing with moisture, in particular with the according risk of mould or even salt efflorescence and condensation: In most cases outer and inner walls are in direct hygric contact with the soil, i. e. there is no sealing against water intrusion, which allows soil damp to enter the walls via capillary and diffusion transport. Since moreover walls are strongly thermally coupled to the soil they remain relatively cool during the warmer parts of the year. This increases the relative humidity at the walls' surface. Conventional strategies for ventilation in inhabitances are not suitable for the described situation (DIN 1946-6-5:2015).

3 Research Methodology

Hygrothermal simulation and measurements The project tried to assess the feasibility of the above approach via:

(1) *hygrothermal simulations* including a mould model for various scenarios. Simulations were done with the software HAM4D_VIE (Deseyve *et al.* 2006, Bednar *et al.* 2010).

(2) *measuring* heat consumption data and *observing* mould appearance of already refurbished cellar flats.

Simulation results were compared against measured data and observations.

At the beginning of the project, material tests were carried out in the laboratory generating essential input parameters for the hygrothermal component simulations. In the second half of the project, the effectiveness of certain ventilation strategies was investigated by means of simulation, taking into account the determined material parameters and the assumed boundary conditions. In addition, several room climate sensors provided data on the actual usage of the flats. The simulation results were partially compared with the monitoring data to allow conclusions about the quality of the simulation results and the functionality of the actual ventilation controls. The energy requirements of refurbished basement apartments were collected from actual consumption data in four selected buildings by an industrial partner. This data was compared with simulation results of an unused and naturally ventilated cellar.

Description of the simulated flat and refurbishment measures The cellar flat is equipped with heating, a mechanical ventilation plant with heat recovery and windows that can be opened. There is no cooling and no air conditioning. Walls mainly consist of plastered bricks, the innermost layer of the suspended ceiling after refurbishment is plasterboard, the floor is parquet on screed. Neither interior nor exterior insulation is applied to wall parts adjacent to the soil, sealing against external liquid water is only applied in the floor region.

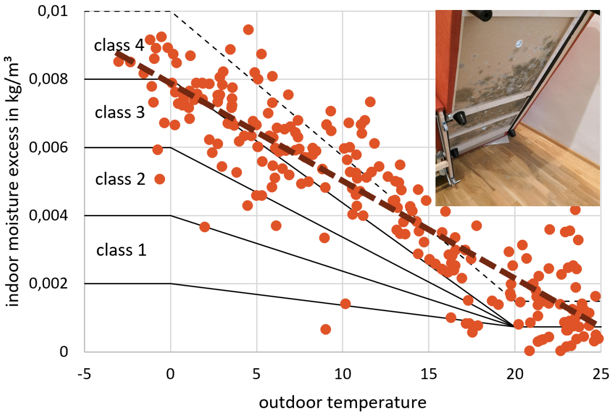

Fig. 3.1: Mould below a couch (see photograph) in a monitored flat: Interior climate classification of the flat according to DIN EN ISO 13788:2013

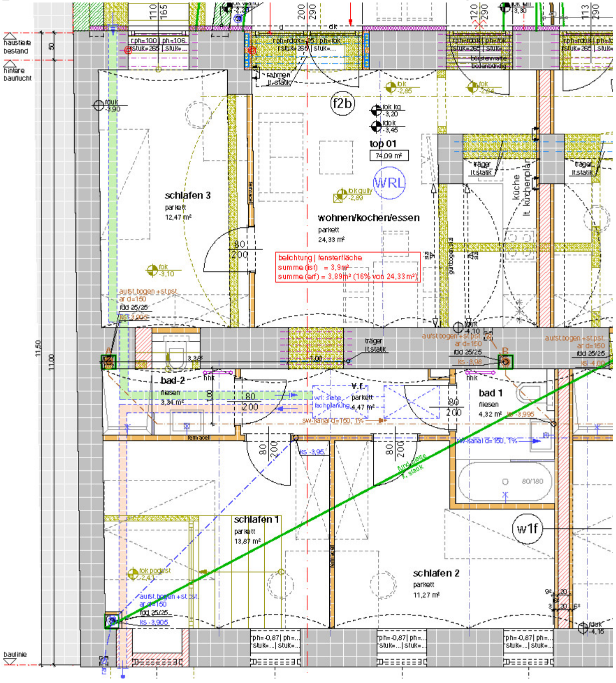

Fig. 3.2: Floor plan of a cellar flat

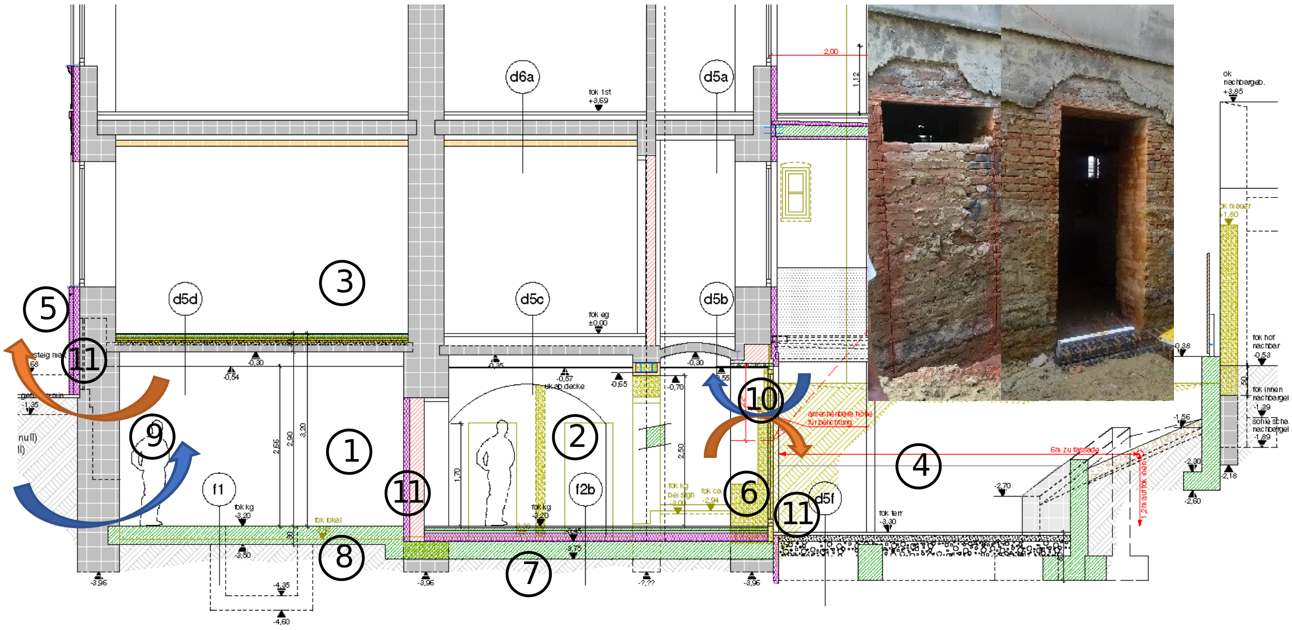

Fig. 3.3: Vertical section of the building with labels indicating where refurbishment actions were taken split into living and storage space. In the upper right a typical construction site where the soil level has been lowered to a sub street level in a buildings backyard and window openings have been accordingly extended to floor level (right part of photograph).

(1) storage cellar
(2) cellar flat
(3) ground floor flat
(4) lowered courtyard level
(5) upper lighting sashes at streetside
(6) windows facing courtyard lowered to floor level
(7) thermally insulated floor
(8) uninsulated concrete slab
(9) mechanical ventilation of the cellar with supply air fan and interior air flow openings
(10) mechanical ventilation of the living space
(11) thermal insulation of the living space

4 The hygrothermal model of the flat and assumptions for the dynamic hygrothermal simulation

For the *geometric model of the flat* (**Fig. 3.2**) exterior walls, floor and ceiling were modelled unfolding the thermal hull to two dimensions thereby neglecting interactions at wall joints, surface areas of the reveals of windows and doors were added to the 2D unfolding approximating thereby the according heat-bridges. Interior walls were modelled taking account only of their heat capacity and moisture buffering capacity.
The exterior climate was assembled from data measured at several sites in Vienna in 2019 avoiding any temperature extremes (**Fig. 4.1**)

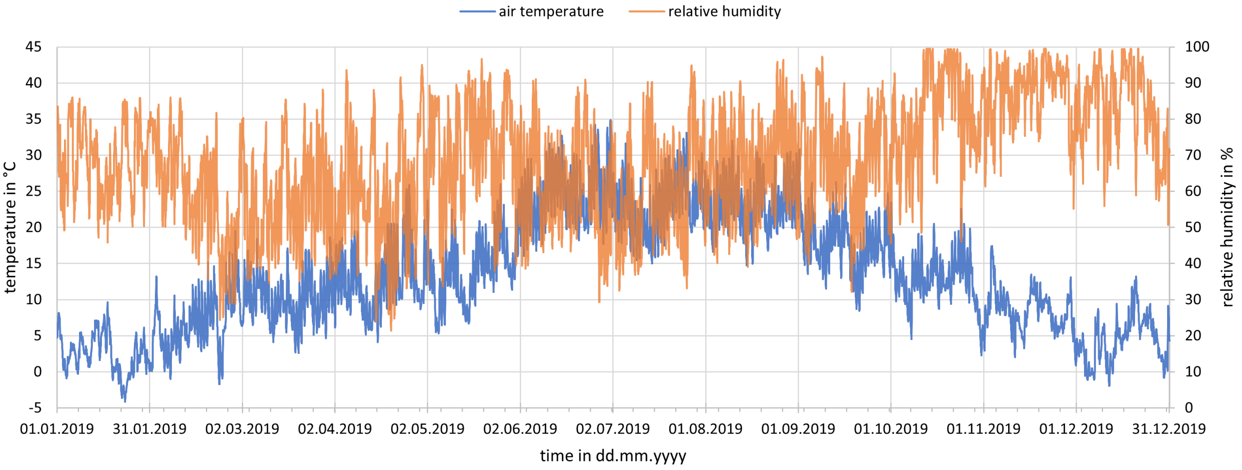

Fig. 4.1: Moisture and temperature curve of the semi synthetical outdoor climate used for the simulation

Capillary pressure of the soil The capillary pressure used at the boundary of the soil was assumed to be 25 kPa reflecting wet but not saturated clay. The value is based on a parameter study carried out in a precursor project (Zelger *et al.* 2017), The influence of the assumption on the capillary pressure and hence on the water distribution inside the building components is significant (Fig. 4.2). Retention curves for the soil types of clay, clay loam, loam and loamy sand are presented in Pallin 2013.

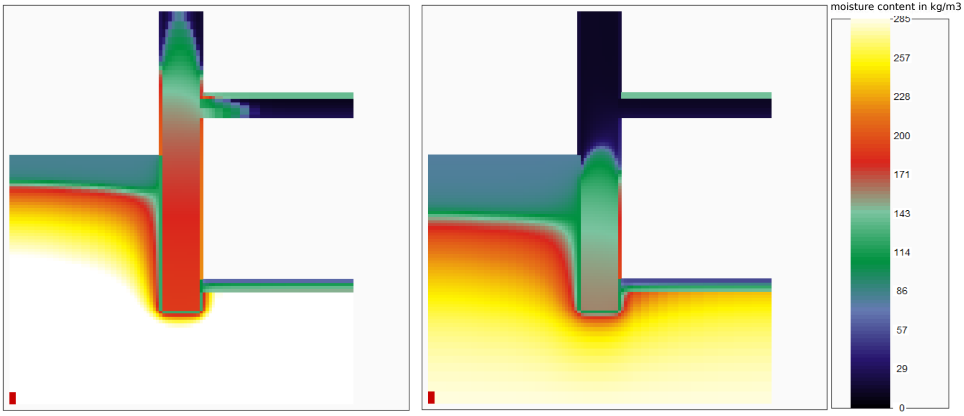

Fig. 4.2: Distribution of the water content in the soil and building components for 10 kPa (left) and 25 kPa (right) capillary pressure (→ degree of saturation of the soil) at the outer soil boundary according to the hygrothermal simulation

Interior moisture loads were determined from existing studies and real room climate measurements. Typical user profiles what regards time of presence in the flat were defined for various user types such as student, full-time employee, infant etc. Missing data or boundary conditions were supplemented by plausible assumptions and literature sources.

The *ventilation algorithm* was subjected to a "proof of concept" by means of component simulations.

The boundary condition for the *soil temperature* was defined via a sine wave with a mean of 11.9 °C, a ΔT of 7 K and a phase shift with regard to the outdoor air temperature of $\approx$ two months, conditions based on a hygrothermal simulation of just the soil (without a building). *Heat load profiles* were based on a basic heat power per person type, the same times of presence as for the moisture loads and the activity of cooking. Simulations were done for the unrefurbished as well as for the refurbished case. For the unrefurbished case also the flat above the cellar was simulated assessing its heat losses through the cellar ceiling.

The risk assessment for mould formation was based on the so-called "Viitanen-model" described for mineral substrates in Ojanen *et al.* 2011.

Mechanical ventilation control algorithm The guiding principle of the ventilation control algorithm is to dehumidify the flat whenever possible all across the year. The parameter to be compared between indoor and outdoor is the absolute humidity in g/kg. This approach is based on the hypothesis that this helps keeping the risk for moisture damage low dehumidifying not only the indoor air but as well the building components raising their moisture buffering capacity. An exception to the dehumidification principle is made if the indoor relative humidity is too low (< 30%), then the mechanical ventilation is switched off. If the indoor quality is 'bad' (approximating the according CO2 concentration as an indicator by using the time of presence of persons) the plant operates at maximum power. The conflictual situation, marked as red path in Fig. 4.3, is when the absolute outdoor humidity is higher than indoors and ventilation leads to moistening while from a CO2 concentration perspective ventilation would be needed. The decision here was to ventilate and thus give priority to the need for fresh air. Only at a later stage in the project it turned out that the according tradeoff in mould risk is negligible (Fig. 5.4) and thus the decision to prioritize fresh air over maximizing dehumidification in every instance fits well with the hygienic goals.

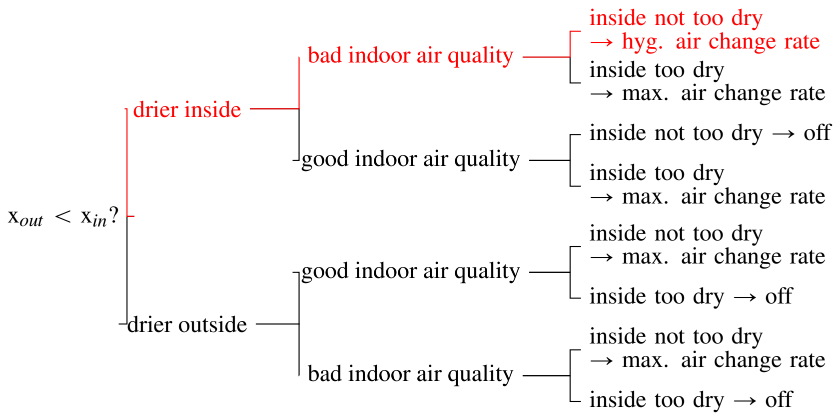

Fig. 4.3: Decision tree for the air change rate of the mechanical ventilation based on indoor and outdoor air properties. The max. air change rate depends on the according value in a parameter study, varying between 0.4/h and 2.0/h

The assumption of this ventilation model is only a rough approximation of reality: Monitoring of the real flats revealed that some users do open the windows at high CO2-values or deactivated mechanical ventilation if it turned out to be too noisy.

5 Findings and Discussion

5.1 Findings

Heat balance as resulting from simulation Heat losses from the ground level flat into the unrefurbished cellar serve as reference value for judging if the "space4free goal" is achieved. The simulation shows that this reference level depends considerably on the unrefurbished cellars air change rate resulting in a simulated bandwidth of annual losses between 55 and 88 kWh/m^2a (**Fig. 5.1**). An increased air change cools the cellar and increases the heat losses. Moreover, the figure shows that the heat demand of the cellar flat (bars in the figure) lies well below the bandwidth of the heat losses through the cellar flats ceiling in its unrefurbished state.

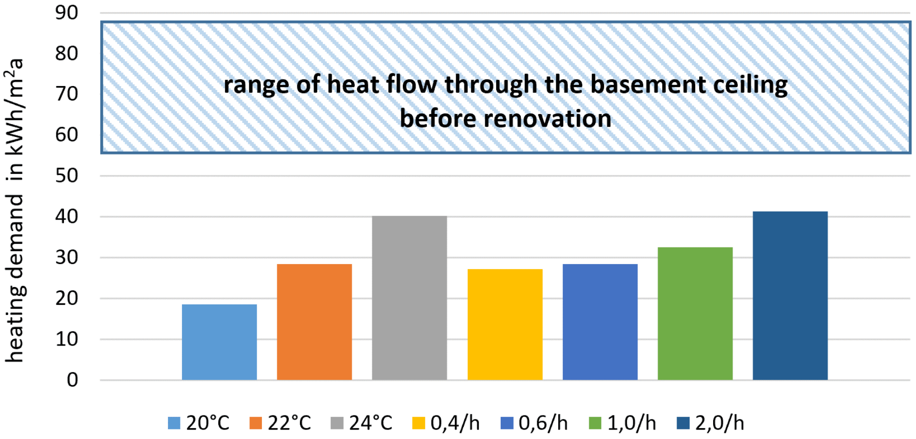

Fig. 5.1: Comparison: 1) Bandwidth of heat losses from the ground level flat to the unrefurbished cellar (shaded rectangle in the top area) versus 2) simulated heat demand of the refurbished cellar (bars). The heat demand of the cellar flat varies according to different assumptions on the temperature set point (heating case) and the air change rate of the mechanical ventilation.

Other sources for the heating demand (validation) For some real cellar flats space heating was calculated according to the procedures defined in Austria for the energy performance certificate (on a monthly basis) as well as measured (**Tab.5.1**).

calculated space heating demand (energy performance certificate)	measured space heating demand	living area of flat
kWh/m^{2}a	kWh/m^{2}a	m^2
45.1	97.8	87.9
36.9	43.2	102.5
38.9	no data	87.6
50.5	41.9	74.1

Tab.5.1: Space heating demand: As resulting from the Austrian energy performance certificate versus measured.

Moisture balance

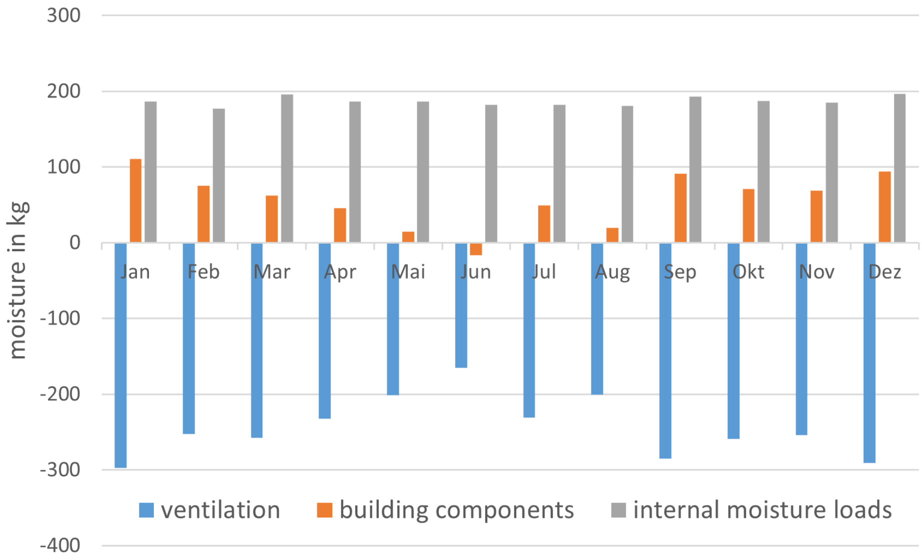

Fig. 5.2: Monthly moisture balance between ventilation, building components and moisture loads. Indoor temperature set point 22 °C, max. air change rate 0.6/h

Fig. 5.2 shows that while monthly internal moisture loads (stemming from human activities) remain more or less constant over the year moisture flows from the surrounding surfaces vary considerably. Foremost during the heating season (Sep. - April) the moisture input from the surfaces is considerable. The low relative vapour pressure of the outdoor air becoming indoor air when entering the flat causes a high difference in water vapour pressure with regard to the warm surfaces. With increasing temperatures from January onwards the partial pressure of the outdoor and hence indoor air rises and lowers the pressure difference. Flows from the surrounding surfaces decrease. During summer the flow direction is even reversed with the surfaces taking up moisture from the indoor air.

In the steady state – which was achieved after 70 years of simulated time – the vapour emission rate from the building components into the indoor air hardly depend on the air change rate. No differences are discernable in Fig. 5.3.

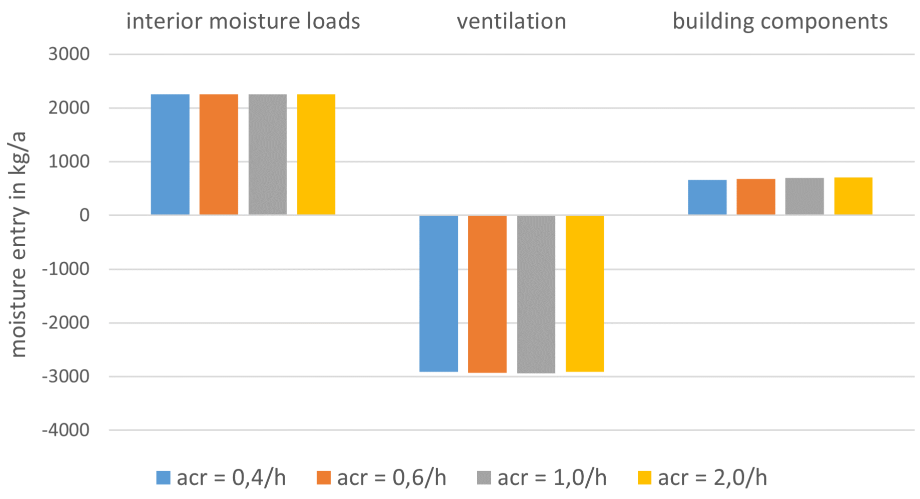

Fig. 5.3: Annual moisture balance for moisture loads, building components (hull) and ventilation depending on the mechanical air change rate with an indoor air temperature set point of 22 °C in the steady state (after 70 years simulation time)

Mould risk The mould risk resulting from the simulation is very low: The below figure shows an excerpt of a vertical axis that would extend to a level of 6 (Mould Index 6 = area fully covered with mould). At a level of 1 which is the maximum value in the figure according to the used mould model spores start to germinate and could however be seen only under a microscope. The figure includes the effect of a furniture placed before the outer wall which was modelled as a thermal resistance of 0.5 $(m^2 \cdot K)/W$.

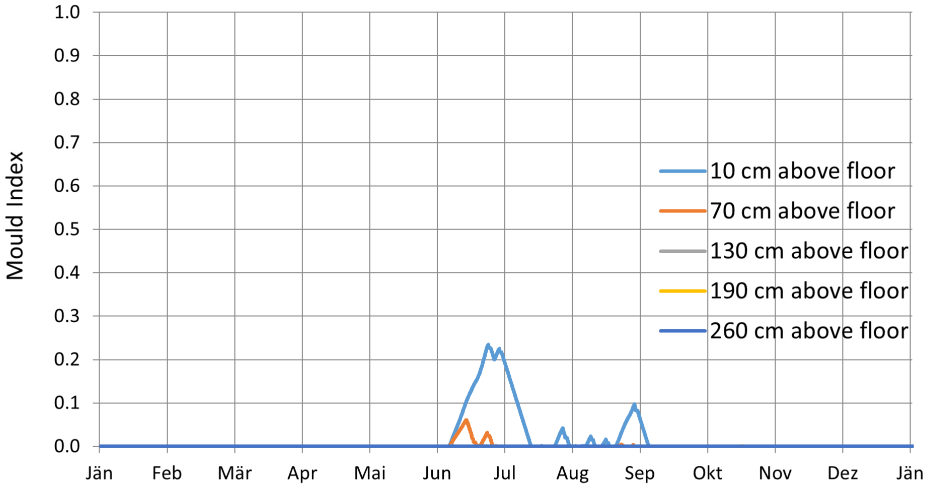

Fig. 5.4: Development of the Mould Index at the inner surface of an outer wall of a refurbished cellar in direct contact with the soil according to the Viitanen-model throughout the year. The curves show the index at different wall heights.

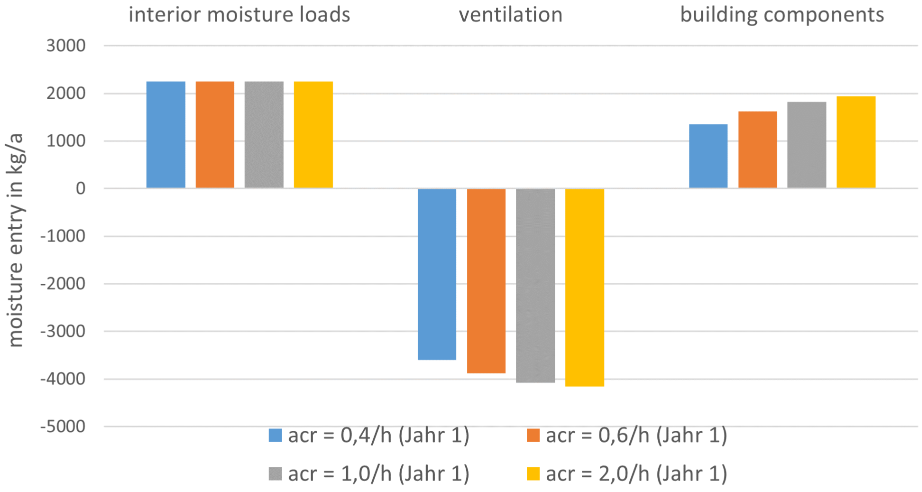

Fig. 5.5: Moisture balance depending on the air change rate with an indoor air temperature set point of 22 °C before a stationary state was reached. Discussion of the figure in section 5.2.

5.2 Discussion

(1) According to the simulation and measurement "space4free" in the cellar is possible (**Fig. 5.1**): The simulated annual heat needed to keep a cellar thermally comfortable which was refurbished to a flat is significantly lower than the simulated heat losses of an existing above-located ground level flat to the unrefurbished cellar (**Fig. 5.1**). The plausibility of the result is confirmed by the fact that the range of measured heat consumption of four cellar flats from the industrial project partner (Wegerer *et al.* 2022) almost coincides with the range of the according simulated heat losses (**Tab.5.1**).

(2) The mould risk of a refurbished cellar flat calculated according to the "Viitanen-model" is negligible (**Fig. 5.4**). This simulation result matches the experience of the above-mentioned industrial partner who is putting cellar refurbishment into practice already since several years. The mould risk simulation also took account of an increased thermal insulation via furniture which would be placed in front of outer cellar walls. However, practice has shown that this tolerance cannot be put to the extreme: In two of the eight apartments examined in long-term monitoring an increased risk of mold formation was found due to high humidity of the room air (see **Fig. 3.1**). The simulation result as well as observations in practice indicate that mould, if at all, will first grow in places hidden by furniture or other objects with insulating properties and become recognisable only at a considerably later stage, e. g. by odor, compared to a visual detection.

(3) The hygrothermal simulations, taking into account the intelligent ventilation control, show that user behaviour is usually the decisive factor for the moisture balance.

(4) A main simulation result is that the annual moisture immissions, a key parameter for the feasibility assessment, are driven by the moisture loads induced by the inhabitants such as cooking rather than by moisture originating from building components which are in contact with the soil. Results are indicative and cannot be generalized but have to be seen in the context of various assumptions regarding the input parameters for the hygrothermal simulation, in particular material properties and boundary conditions. For a concrete site material properties – including the soil – should be taken from samples as input for the simulation.

Moisture emission rates not depending on the air change rate in the steady state This can hardly be attributed to a simulation software fault because **Fig. 5.5** shows that the emission rates for the start phase of the simulation where no equilibrium is yet reached clearly do depend on the air change.

A first temptative explanation could be that at high air change rates no more differences can be observed since the moisture content of the indoor air is already approximately equal to the outdoor air moisture content. However, this cannot apply – or at least is not exhaustive as explanation – because the parameter study also includes low air change rates so the partial vapor pressures of the indoor air differ significantly between the scenarios. A further potential explanation could be that the with an increasing air change rate the dehumidified surface layer grows in thickness and hence the average vapour diffusion resistance from the moisture contained in the building components to the indoor air increases. In a transient process of drying this effect is since long known to lead to a reduced drying rate according to 'Krischer drying curve' (Krischer *et al.* 1963). For the assumed material parameters and the range of boundary conditions reached within the parameter study the overall effect could – by coincidence – be a nearly constant vapour emission rate.

Limitations Main limitations consist of the uncertainties which may be broken down to

(1) *material properties*, in particular regarding water capillary transport, for instance concerning the water absorption coefficient of the brick-plaster compound samples which turned out quite scattered in laboratory experiments and the water retention curves of different types of soil at various sites in downtown Vienna (see **Fig. 4.2**).
(2) the *simplified 2D geometry* in the model treating the outer hull as an unfolded drawing
(3) *user behaviour*, in particular with regard to window ventilation which was not considered in the simulation.
(4) *the mould model*: The Viitanen-model, even though considered as state-of-the-art at the time of the project, was never largely validated in situ, moreover its basic equations were originally developed for wooden substrates and only later adapted to mineral substrates. A thorough critical review of the model can be found in Vereecken *et al.* 2012.
(5) *the used exterior climate*: The semi-synthetic data combining several sites in Vienna is only based on the year of 2019. It does not contain longer warm-humid periods which are the most critical with regard to a moisture risk. A deeper analysis is needed to check if this assumption is sufficiently conservative and in particular compliant with forecasts of current climate change models.
(6) the *indoor climate* is based on 8 cellar flats in four buildings. A larger sample would be desirable.

A further limitation is that the results are valid for cellar walls made of brickwork (not for concrete).

6 Conclusions and Further Research

In this work the feasibility – from a building physics point of view – of the conversion of cellars of historic 100+ old in downtown Vienna avoiding a full sealing against water intrusion from the soil has been shown via a hygrothermal simulation. The simulated feasibility is corroborated by the fact that such conversion has been successfully practiced by a company represented among the authors since several years. The simulation takes into account heating, mechanical ventilation controlled by an air quality-based algorithm and user behaviour. A practical implication is that – in the current case of Vienna climate and assumptions on boundary conditions – insulating building components against moisture from the soil is less important than controlling user driven moisture loads when trying to minimise the moisture risk. At urban scale project results can help to increase densification in downtown areas with a historic building stock.

Outlook, further research The assumptions on material properties, especially with regard to liquid water conduction and moisture buffering, as well as the effect of simplifying of real three-dimensional modelling to a 2D-unfolding of the envelope require further research. The ventilation control algorithm will be further revised passing from current on/off and threshold values to a more sophisticated control such as using hystereses, ramps or PID controllers. A goal for improving the humidity and energy performance could be the inclusion of weather forecasts.

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