AIRTIGHTNESS IN THE RETROFIT OF HISTORIC BUILDINGS

IS HIGH AIRTIGHTNESS NECESSARY TO ACHIEVE TARGET ENERGY SAVINGS IN TRADITIONAL HISTORIC BUILDINGS?

Renovating historic (pre-1945) buildings is crucial to meet global climate objectives. A lack of comprehensive retrofit guidelines tailored to their unique characteristics, however, hinders efficient retrofitting efforts and overall building performance improvements.
This research challenges the conventional assumption that improved building performance relies upon improved airtightness. Instead, it investigates a potential retrofit strategy that leverages the building's air leakage to enhance its post-retrofit performance – in an aim to optimize its energy-efficiency, indoor environment quality, and heritage preservation.

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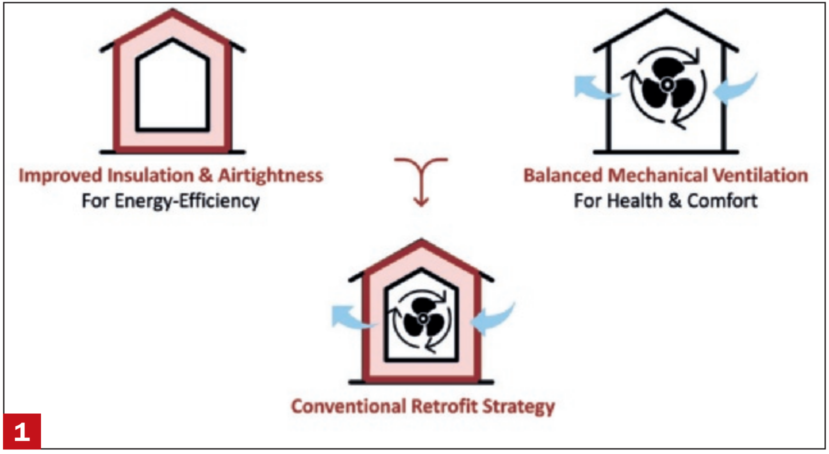
MENTIONS

This article is based on the graduation research 'Airtightness in the Retrofit of Historic Buildings', by ir. Yara Ibrahim – under the supervision of dr. ir. H.R. Schipper and dr. ir. Z. Huijbregts from TU Delft, and ing. Ad van der Aa from ABT – in fulfillment of the requirements for the MSc in Civil Engineering (Building Engineering Track, Building Physics and Technology specialization) at TU Delft.

CURRENT PRACTICES AND LIMITATIONS

Strongly influenced by current building standards – catering for stricter energy performances – a predominant reliance on the same retrofit strategies is detected, despite contrasting climates and building characteristics [1]. A separation of the indoor and outdoor environments – through improved insulation and airtightness for reduced energy loss – is combined with balanced mechanical ventilation to ensure fully-controlled indoor health and comfort performances, as shown in Figure 1.

While effective in many cases, conventional retrofit methods face significant limitations when implemented to solid wall brick masonry historic buildings. They fail to address two critical aspects:
First, their traditional breathable fabric is an integral part in their complex bioclimatic operations and relies heavily on air leakage, making its sealing harmful to both construction durability and indoor environment quality [2, 3].
Second, their monumental standing and heritage protection requirements restrict the nature and extent of permissible interventions, often making conventional measures impractical [4, 5].
A need for retrofit strategies tailored to the unique attributes of traditional historic buildings is raised. Emphasizing the preservation of their breathable nature by positively exploiting air leakage is investigated as a promising approach.



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Conventional retrofit measures.

IMPACT OF AIR LEAKAGE ON BUILDING PERFORMANCE

Building energy estimates conventionally decouple conduction and air leakage heat fluxes through the envelope [6, 7], calculating their thermal load as:

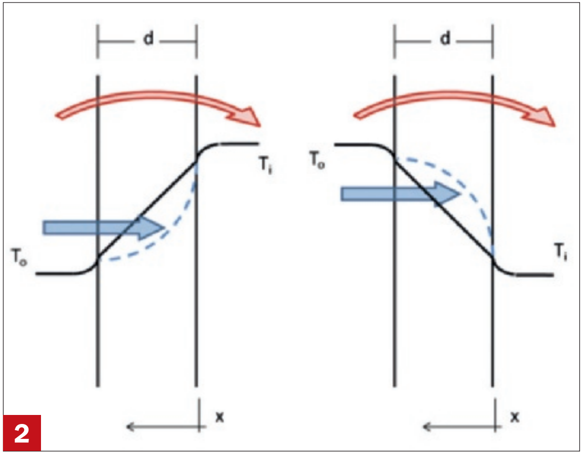
$$Q_{convention} = Q_{conduction} + Q_{leakage}$$
$$Q_{convention} = UA\ T_i - T_o + mC_p\ (T_i - T_o)$$

Where
Q – heat flow [W]
U – construction thermal transmitance [W/m^{2}K]
A – construction surface area [m^2]
m– air leakage mass flowrate [kg/s]
C_p – air specific heat capacity [J/kgK]
T_i – T_o – indoor and outdoor temperatures [K]

This model considers air leakage as a notable source of heat loss and attributes significant energy savings to an improved airtightness. It thus drives the prevalent reliance on airtightness for improved building performance.
However, air leakage's impact on energy-efficiency is often misrepresented, particularly in breathable constructions with wide networks of diffuse air leakage pathways.

In contrast to Concentrated Air Leakage through relatively large gaps, **Diffuse Air Leakage** occurs through a network of minute cracks and openings with longer air paths in the building envelope. The increased contact surface and transit time of the leaking air within the building fabric entails much greater heat exchange between the solid and air phases.

The heat exchanges between air leakage and conduction fluxes are referred to as **Infiltration Heat Recovery (IHR)**, and are neglected in conventional energy estimates [6, 7, 8]. IHR affects the construction's steady-state temperature distribution, shifting it from a linear to a curved profile



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Impact of airflow on a construction's temperature distribution [6]. Shown is a schematic representation of two walls with air leakage flowing from the outdoor to the indoor environment, under a heating-season scenario (left) and a cooling season scenario (right). Represented, in black, is the pure conduction's linear temperature profile and, in blue, the air leakage-modified temperature profile

influenced by the indoor-outdoor temperature difference, and the direction and velocity of the leakage airflow [6, 7].

The contribution of air leakage to the building energy demand could be overestimated. This misrepresentation may result in discrepancies between estimated and actual performances, thereby misinforming retrofit decisions [6].

IHR IN BUILDING DESIGN: DYNAMIC INSULATION AS RETROFIT SOLUTION

The intentional utilization of the IHR effect in design produces construction elements, known as Dynamic Insulations (DI), in which air leakage could act as [9, 10]:

- Heat exchanger
- Diffuse ventilation source
- Airborne contaminant filter
- Vapor diffusion barrier

A **Dynamic Insulation (DI)** is a building envelope system whose base principle introduces a running fluid – in this case air – into the building's static construction to recover some of the conductive heat loss through the envelope [8].

Breathable constructions reveal similarities with purpose-designed DI systems. This suggests potential for their retrofit to act as efficient DI systems, thus exploiting their air leakage for building performance improvements.

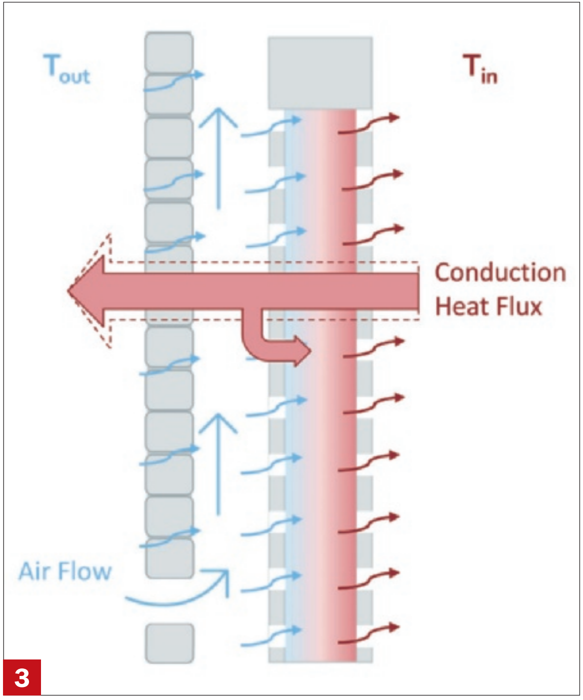
Despite being introduced over 30 years ago, design guidelines for implementing dynamic insulation are underdeveloped for both new and existing buildings, limiting its application [8].

The prevalence of the decoupled approach to building energy estimates presents a challenge for designers:

- How can IHR be efficiently accounted for in building performance estimates?

When it comes to the implementation of this concept in building retrofit, key questions for designers include:

- Which retrofit strategies efficiently exploit IHR, to optimize energy-efficiency, indoor environment quality, and heritage preservation?



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Breathing wall dynamic insulation system. Shown is a dynamic insulation system consisting of the existing masonry wall and an internal breathable insulation layer. Represented is the heat flux without the IHR effect (dotted arrow) and with the IHR effect (solid arrow). The temperature gradient across the insulation is color graded.

- Can these retrofit strategies achieve target performance improvements, when conventional retrofits are taken as performance benchmark?

IHR IN ENERGY ESTIMATES: DYNAMIC U-VALUE

Existing building energy simulation (BES) tools rely on the conventional decoupling of conduction and airflow heat fluxes, and consequently fail to model the IHR effect accurately.

To address this limitation, a purpose-built and validated model was developed by integrating an analytical DI model into EnergyPlus, which combines multi-zone energy and airflow network capabilities.

The Taylor Model [11] introduced the concept of dynamic U-value, correcting the conduction heat flux for the heat recovered by air leakage. Their thermal load is then estimated as:

$$Q_{convention} = Q_{conduction} + Q_{leakage}$$
$$Q_{convention} = U_{dyn} A \, (T_i - T_o) + mC_p \, (T_i - T_o)$$

Where

U_{dyn} – dynamic thermal transmittance [W/m^{2}K]

The dynamic U-value is a function of the air flow, density, and specific heat capacity, and the material's static thermal resistance. Its equivalent dynamic thermal conductivity then acts as the model's time-variant material property, updated for each surface at each time-step based on the detected infiltration airflow [12].

$$U_{dyn} A = \frac{\nu \, \rho_a \, C_p}{e^{\nu \, \rho_a \, C_a \, R} - 1}$$

$$\lambda_{dyn} = \frac{\nu \, \rho_a \, C_a \, L}{e^{\nu \, \rho_e \, C_a \, L/\lambda} - 1}$$

▶

Where
U_{dyn} – dynamic thermal transmittance [W/m^{2}K]
λ_{dyn} – dynamic thermal conductivity [W/mK]
ν – air infiltration flow velocity [m/s]
ρ_a – air density – 1.204 kg/m^3
C_p – air specific heat capacity – 1006 J/kgK
R – material static thermal resistance – L/λ [m^{2}K/W]
L – material thickness [m]
λ – material static thermal conductivity [W/mK]

Despite neglecting the air film resistances, the Taylor model is valid for buildings with low air change rates [13]. However, its main limitation is assuming a homogeneous spread of the diffuse air leakage and IHR across each envelope surface, which may not be guaranteed in existing buildings.

QUANTIFYING BUILDING PERFORMANCE

To evaluate a retrofit approach, the building's overall performance must be quantified pre- and post-retrofit. Addressing the trade-off between energy-efficiency and indoor health and comfort, however, requires a systematic evaluation framework with relevant parameters and criteria.

The guiding principle for defining the parameters is their direct relevance to the study's scope – particularly to air leakage's impact on buildings – and their compatibility with the BES tool, ensuring computational feasibility and accessibility through the model's outputs.

One the one hand, energy efficiency is measured by the building's final energy demand – a quantifiable variable independent of system and source efficiencies not addressed in this study.

On the other hand, indoor health and comfort is gauged by four parameters: winter indoor operative temperature, summer adaptive thermal comfort temperature, air change rate, and indoor air relative humidity. These parameters are simulated hourly and their annual performance is quantified through their respective IEQ scores.

Indoor heath & comfort performance levels are categorized as outlined in the EN 16798 standard [14]. The **IEQ score** – or **Indoor Environmental Quality score** – is a weighted performance metric assessing the building's annual performance across these categories.

Each parameter's score is calculated as:

$$S_{IEQ_p} = \sum_{i} n_i \text{ x } W_{IEQ_i}$$

Where
S_{IEQ_p} – weighted IEQ score for parameter p [hr]
n_i – number of hours in IEQ category i [hr]
W_{IEQ_i} – hourly weight of IEQ category i [-]

Table 1: Input parameter ranges

	Surface Permeability	Insulation Thickness	Fan Flowrate (Building Depressurization)
	kg/s.m^2	m	l/s.m^2 (Pa)
Walls	[0.000001 - 0.0004]	[0 - 0.15]	
Roofs	[0.00001 - 0.004]	[0 - 0.30]	
Fans			[0.9 - 5.93] ([1 - 30])

Optimal building performance then seeks to minimize energy demand while maximizing the IEQ scores for winter and summer thermal comfort, ventilation and indoor air quality, and indoor air humidity.

IDENTIFYING OPTIMAL RETROFIT SOLUTIONS

The retrofit variants – inspired by dynamic insulation systems – address different conditioned zone boundaries, envelope properties, and ventilation strategies. Foundational assumptions across variants include sealing concentrated leakages and implementing exhaust air heat recovery at 85 % efficiency.

A traditional single-family dwelling from 1750 in Leiden serves as a representative Case Study building and validates the model's air leakage behavior against its in-situ measurements.

The performance evaluation compares variants against the base case and a conventional retrofit case, serving as benchmark for target improvements. These variants consider combinations of the buildings' thermal boundary (i.e. loft configuration), envelope properties (i.e. insulation thickness and airtightness), and ventilation strategies (i.e. ventilation systems and flowrates).

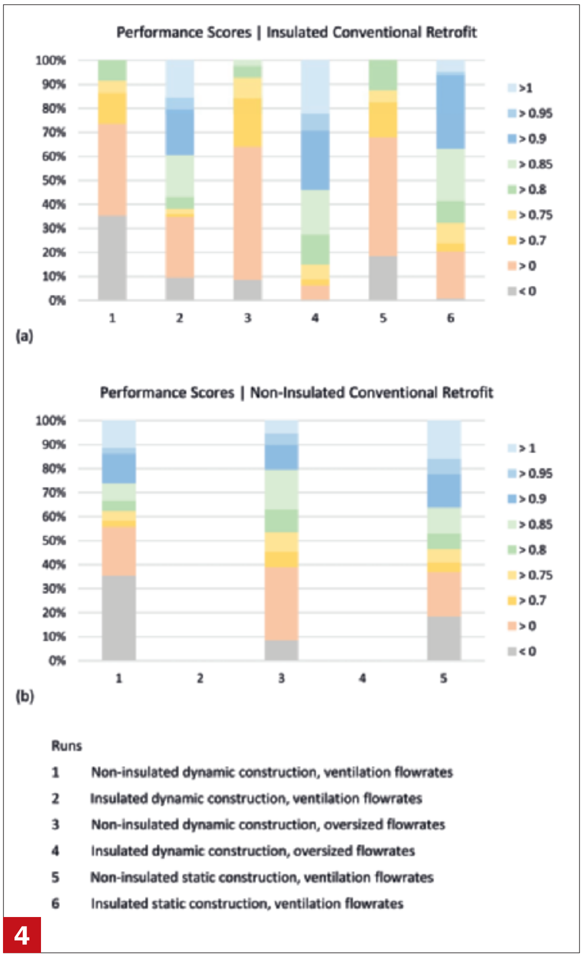
All variants are studied under two scenarios – insulated and non-insulated – that reflect different heritage protection levels: protected exteriors only, or both exteriors and interiors.

The variants are analyzed in 3-steps.

First, Morris sensitivity analyses – a one-step-at-a-time method [15] – are performed in 4 runs for both dynamic and static constructions, considering two loft configurations under two building depressurization levels (1-2Pa and 30Pa, for normal and under-pressure operations). The analyses evaluate the potential of cold and warm loft configurations to preserve surface permeability while ensuring energy-efficiency. By qualitatively assessing the sensitivity of the building's energy demand to surface permeability under the two depressurization levels, they reflect how the variation in loft configuration and the building's thermal boundary influence energy loads and infiltration heat recovery.

Second, focusing on the warm loft configuration, 6 NSGA-II evolutionary optimizations [16] identified optimal insulation and ventilation designs – i.e. optimal combinations of surface permeabilities, insulation thicknesses, and fan flowrates – under the 6 different retrofit variants (static vs. dynamic constructions, non-insulated vs. insulated, ventilation-based flowrates vs. oversized flowrates) as shown in Figure 4, thus generating their Pareto-optimal solution sets. The parameter ranges encompassed all virtually achievable values for such buildings, under all types and levels of finishing, retrofitting, and replacement. These ranges are shown in Table 1 below.

Pareto-optimal Solutions are the set of non-dominated solutions resulting from a multi-objective optimization. These achieve optimal trade-off between conflicting objectives, so that improving any objective must degrade another. In absence of additional preference information, all pareto-optima are considered equally good.



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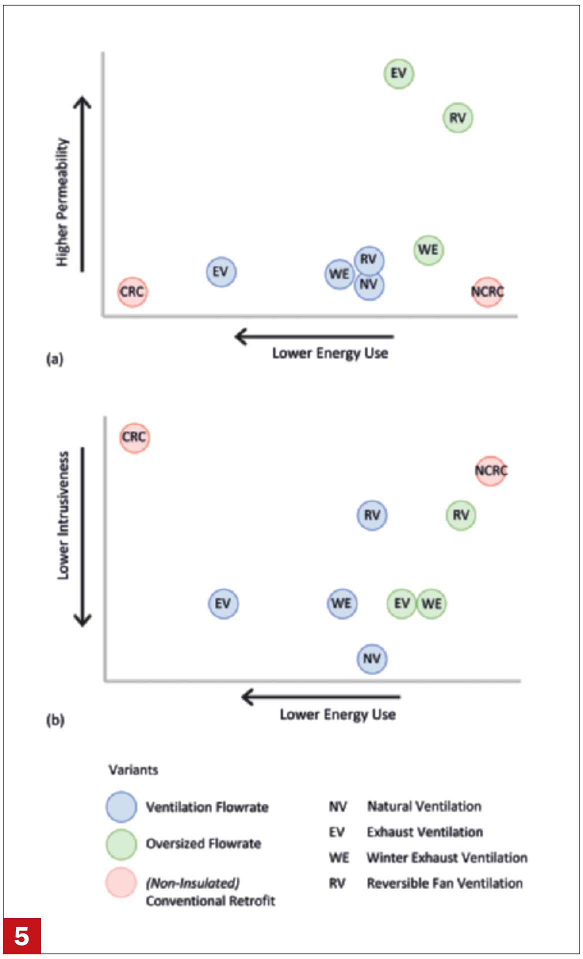
Distribution of the performance scores of the Pareto optimal solutions of each run, relative to the insulated conventional retrofit (a), and non-insulated conventional retrofit (b). The scores are scaled so that a score of 0 reflects the Base Case's performance (no improvements) and a score of 1 reflects the Conventional Retrofit's performance (Benchmark improvements).



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Qualitative summary of the overall analysis results. Shown is the permeability vs energy performance (a) and intrusiveness vs energy performance (b) for each ventilation regime variant under ventilation flowrates (in blue) and oversized flowrates (green) relative to the conventional retrofit references (red).

Third, a systematic scoring system ranks the resulting optimal solutions. The TOPSIS multi-criteria decision analysis [17] characterizes each solution by a 'closeness factor' – reflecting its relative performance within its Pareto set. Normalizing these factors against the base case and conventional retrofit case generates an objective score that weighs the solution as a fraction of the conventional retrofit's performance improvement.

Target solutions aim to match or exceed the conventional retrofit's performance, while preserving existing air leakage to a practical extent. Assuming a 10% tolerance, solutions scoring over 0.9 are selected and further compared based on airtightness, insulation, and fan flowrate to ensure practicality and effectiveness.

RESULTS: CONNECTING LOFT CONFIGURATION, BUILDING PRESSURE AND IHR POTENTIAL

For computational efficiency, the evaluation of the conditioned zone boundary is based on qualitative analysis. The results of the Morris sensitivity analyses emphasize the significant role of building depressurization on the air leakage's impact.

At low depressurization, the IHR effect is limited, i.e. only partially mitigating the air leakage's thermal load. However, at high depressurization, there is substantial IHR potential, which positively impacts energy-efficiency. To achieve significant energy savings at higher surface permeabilities, fan flowrates exceeding minimum ventilation requirements are necessary.

Nonetheless, at low depressurization, the warm loft configuration could exhibit minimal energy demand sensitivity to wall permeabilities (< 10%), suggesting surface permeability could potentially be preserved without sacrificing energy-efficiency – even without IHR.

RESULTS: EVALUATING ENVELOPE AND VENTILATION STRATEGIES

The NSGA-II analysis and subsequent multi-criteria decision analysis result in multiple sets of Pareto-optimal solutions ranked by their relative performance scores. The distribution of these scores is shown in Figure 4. For meaningful results, buildings with heritage-protected interiors are also compared against a non-insulated equivalent to the conventional retrofit.

The detailed results highlight that:

1. Non-insulated buildings could achieve up to 80% of improvements seen in fully-insulated conventional retrofits, under ventilation flowrate levels. Higher flowrates attain higher performances, indicating IHR's compensatory effect – although added insulation is necessary to match insulated conventional retrofits.

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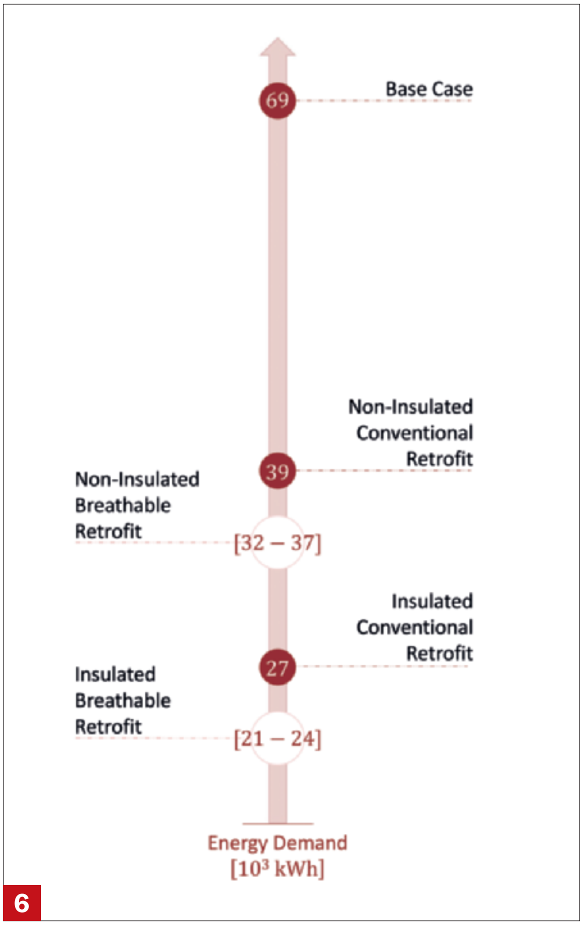

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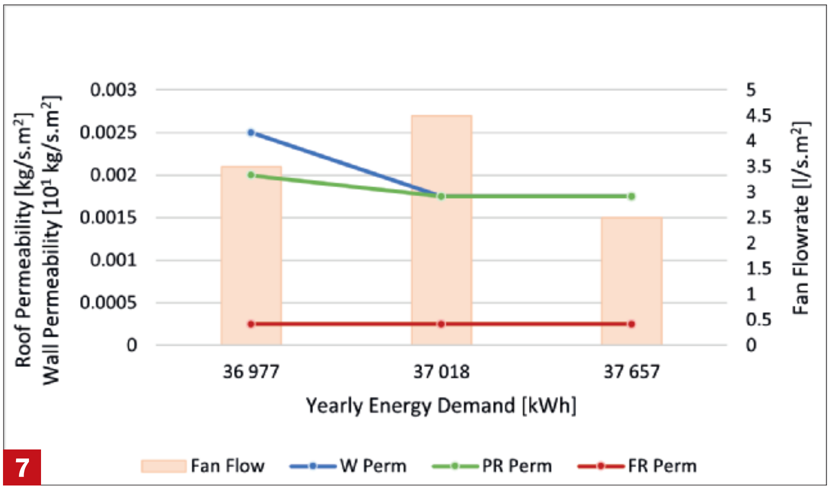
Achieved energy performances of the different retrofit approaches, relative to the base case.



7

Example of pareto-optimal solutions of the non-insulated scenario, revealing energy-savings through increased air infiltration (i.e. higher permeability and/or higher depressurization). Shown is each solution's yearly energy demand [kWh], exhaust fan flowrate [l/s.m2], and permeabilities of the pitched roofs (PR) and flat roofs (FR) [kg/s.m^2] and walls (W) [10-1 kg/s.m^2].

2. Oversized fan flowrates are essential for reliable building depressurization and effective IHR exploitation. IHR's significant impact on performance outcomes reveals the importance of its integration in building performance analyses.
3. Various ventilation regimes exhibit different IHR exploitation abilities, with fan-assisted depressurization necessary for effective performance.

Detailed examination of top-performing solutions revealed comparable indoor environmental quality, but varied permeability-energy demand relationships and levels of implementation intrusiveness. The "Exhaust ventilation with oversized fan flowrates" variant discerned itself with promising energy savings at high permeability levels and lower implementation intrusiveness.

Insulated or non-insulated, this retrofit variant outperformed conventional methods, though added insulation yielded substantial additional energy savings (of 40.8 kWh/year/m^2).

These findings culminate in tailored recommendations and application frameworks for traditional historic buildings, accommodating different baseline performances and heritage protection restrictions.

Ultimately, the choice of the retrofit approach depends on each project's specific characteristics and restrictions.

BUILDING PERFORMANCE AND AIR LEAKAGE FLOW: UNDERSTANDING THE CONNECTION

Post-retrofit performance analysis of all variants in the non-insulated case reveals energy improvements that may be attributed to changes in surface permeabilities and exhaust fan flowrates – in other words, to changes in the air leakage flow. The positive relationship between air leakage flow and energy savings in breathable buildings is then evident.

An example is shown in Figure 7. All else equal, increasing the exhaust fan flowrate from 2.5 to 4.5 l/s.m^2 reduces the energy demand by 640 kWh/year (2.6 kWh/year/m^2), with potential for higher energy savings of 679 kWh/year (2.8 kWh/year/m^2) when combined with increased surface permeabilities.

These findings challenge conventional views on air leakage and underscore the potential for heating energy savings through increased air infiltration. They demonstrate the impact of IHR and validating the retrofit strategy of converting traditional breathable constructions into dynamic insulations.

FINDINGS AND RECOMMENDATIONS: A BREATHABLE FUTURE

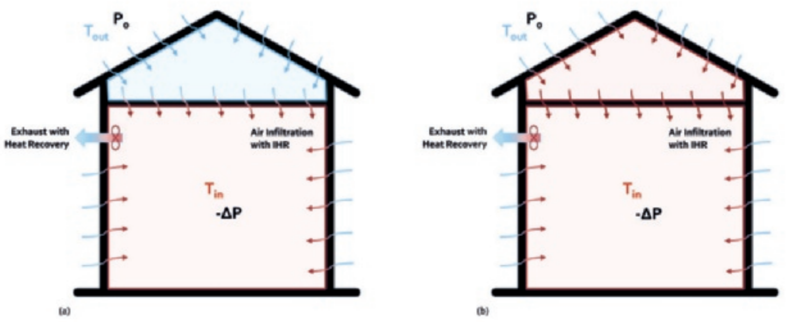
The analysis confirms the potential of enhancing building performances – energy-savings and indoor environment quality – by leveraging the building's air leakage in post-retrofit operations.

Challenging conventional assumptions, it demonstrates the significance of considering the Infiltration Heat Recovery (IHR) in building performance assessments for accurate outcomes and informed decision-making in the retrofit of breathable buildings.

The resulting recommended retrofit for traditional historic buildings is founded upon significant and well-distributed diffuse leakage, effective sealing of concentrated leakage pathways, and heat recovery on exhaust air. Effective performance of breathable buildings as dynamic insulations then calls for inherently well-insulating constructions and consistent building depressurization. The latter could be achieved by simply adjusting the exhaust flowrates beyond minimum ventilation requirements or, potentially, using alternative strategies such as the stack effect through chimneys or atriums, the wind effect through wind-driven ventilation and fans, or other novel approaches.

A simplified scheme of the proposed strategy is shown in Figure 8. Depending on the thermal boundary of the building, the surfaces involved in the IHR may differ. Adapted to buildings with heritage-protected exteriors or both exteriors and interiors, the recommendation primarily varies by the added insulation to enhance energy-efficiency.

While further development is needed, the study redefines retrofitting possibilities for traditional monumental buildings. It promotes the preservation of the building's breathability through simple non-invasive retrofit measures. By simply sealing concentrated leaks and establishing consistent building depressurization, some of the building's energy load could be mitigated, offering a step forward towards a more sustainable retrofitting approach. ■



8

Simplified scheme of the proposed retrofit strategy, highlighting simple and versatile nature of retrofit measures. Shown are the Cold Loft (a) and Warm Loft (b) configurations, common variants in building retrofits. Represented are the building's thermal boundaries, infiltrating air leakage, and the exhaust air. The temperatures, and consequently the heat recovery through the air flows, are color graded (red for heated, blue for non-heated).

SOURCES

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