Refurbishing the Kampnagel Theatre in Hamburg

Improving environmental performance through building-specific assessment and minimal intervention in a listed industrial complex

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1. INTRODUCTION

Refurbishment of existing public buildings has become a central challenge in reducing institutional energy consumption. While technical standards and regulations increasingly demand high environmental performance, prevailing responses often rely on insulation, airtightness and extensive mechanical systems. In historic buildings in particular, such approaches tend to result in architecturally invasive interventions, high embodied and operational energy costs, and a progressive loss of the spatial and cultural qualities that motivated reuse in the first place.

In many cases, a careful analysis of existing conditions and patterns of use can demonstrate that the most effective strategies lie elsewhere than in the alteration of the building envelope. These may include modulating heating systems, adjusting occupancy and use patterns, or optimising window operation. Yet such strategies are often overlooked in refurbishment projects, as they require detailed fieldwork, monitoring campaigns and advanced simulation tools — an investment that is rarely built into conventional project workflows.

This paper presents the environmental study of the Kampnagel theatre in Hamburg, carried out by Atmos Lab in collaboration with Lacaton & Vassal, as a case study of a methodology in which environmental performance is not imposed onto a building through standardised systems, but instead emerges from a precise and holistic understanding of the existing structure, its climate and its modes of use. The study addresses three interconnected themes — heating demand reduction, summer comfort and indoor air quality — approached with the same logic: understand the building first, propose second.

The paper is organised as follows. Section 2 describes the building, its climate and the design approach. Section 3 presents the overall methodology. Sections 4 and 5 describe the building understanding and model calibration. Section 6 presents the refurbishment strategies developed for each theme. Section 7 discusses the wider implications, and Section 8 concludes.

2. BUILDING, ARCHITECTURE AND CLIMATE

2.1 The climate

Hamburg's temperate maritime climate is characterised by cold and overcast winters (average maximum temperatures around 5°C in December) and mild summers (average July maximum 23.4°C), though short heatwaves above 30°C do occur. Wind speed is considerable (annual average of 3.1m/s), which helps to moderate summer temperatures and offers favourable conditions for natural ventilation strategies. However, Kampnagel's urban context and proximity to residential areas impose acoustic limitations on window opening.

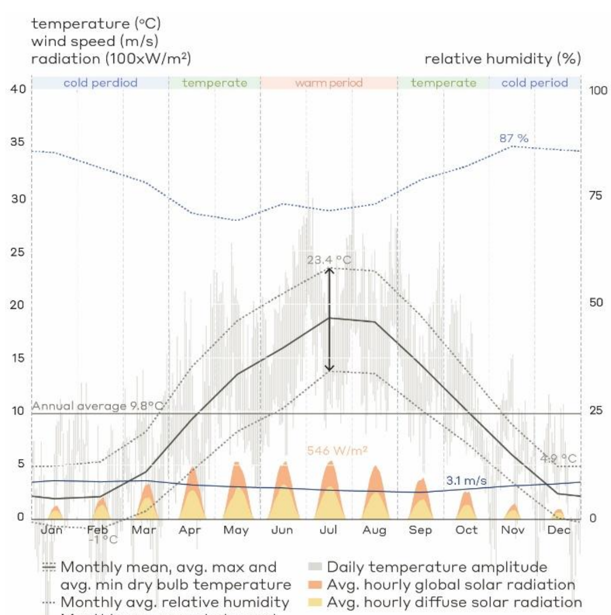

Figure 1: Hamburg TMY climate summary.

2.2 The building

Kampnagel is a former industrial complex in Hamburg, founded in 1865 as a crane and machinery factory, whose halls date back to the late 19th century and were expanded in stages over time. It has hosted independent theatre, dance, and music performances since the early 1980s, when the site was first adapted for cultural use following the shutdown of production in 1981. It started as a provisional substitute venue for the Schauspielhaus, but with time it became permanent, and no large intervention was planned until now. Its transformation was a progressive adaptation of the existing industrial structures, driven by limited resources and artistic needs. This process shaped a strong identity rooted in freedom, flexibility, and an "unfinished" character that allowed independent theatre to flourish.

Figure 2: External and internal photos of Kampnagel theatre.

The complex is made of former factory halls of different size and age, connected by shared circulation spaces. The industrial character is visible in the structure, with heavy steel frames, large-span roofs and exposed brick, and in the spatial quality of the venues, where the absence of conventional finishes is part of the architectural identity of the building.

Figure 3: Existing plan with performance venues highlighted.

Figure 4: Project plan with performance venues highlighted.

2.3 Architects approach and authors collaboration

Lacaton & Vassal have a long tradition of minimal intervention in cultural buildings, working under the principle of never demolishing what can be reused and preserving the character of the existing structure — as in their transformation of the Palais de Tokyo in Paris and the FRAC in Dunkirk [1,2,3]. Since 2017, they have worked in collaboration with Atmos Lab for all climatic and environmental studies [4]. The shared objective is to improve environmental performance while preserving the unique character of each building, through the least intervention possible. The strategies proposed follow a clear order of priority: operational adaptation first, followed by envelope adaptation through existing elements such as windows and doors, then architectural additions such as buffer spaces, and finally mechanical support.

The work methodology starts from field investigation and a detailed understanding of the specific building. Rather than working backwards from normative benchmarks to predetermined solutions, the process begins from observed reality: how the building actually behaves, under which conditions, and where are the real margins for improvement. This reversal of the conventional workflow — understanding first, proposing second — requires more time and investment at the early stages of a project, but produces a level of detail and precision in the final proposals that generic approaches cannot reach. Strategies are tested against the real behaviour of the building, and their expected impact is based on a calibrated model.

3. METHODOLOGY

The environmental study of Kampnagel was structured in three phases: (1) building understanding, to establish the existing thermal and operational baseline; (2) model development and calibration, to validate the simulation model against measured consumption and monitored data; and (3) strategy development, to test targeted interventions on heating, summer comfort and IAQ. Each phase is described in more detail in Sections 4 to 6.

Fieldwork combined three types of data collection. The envelope was surveyed in situ, recording materials, condition and types of openings across the full complex. Indoor environmental conditions were monitored using a COMET U3430 datalogger [5] for CO_2 concentration and Testo 174H dataloggers [6] for air temperature, over two campaigns of more than 20 days each, one at the end of summer 2022 and one in mid-winter 2023. Energy and operational data were provided by the building management team and comprised two years of annual district heating consumption from utility bills, one year of sub-hourly electricity metering data, and the theatre's calendar and events programme, which was used to reconstruct show schedules and average show lengths.

A multi-zone thermal model was developed using Ladybug Tools for Grasshopper [7]. Zone geometry was taken from the architectural drawings and checked on site. Internal electrical gain schedules were derived from the metered electricity data. Normative values from ASHRAE 90.1 [8] were used for the spaces not covered by the electricity analysis (restaurant and kitchen) and for the occupancy profiles of most spaces. The occupancy of the most contributing spaces — the venues, foyers and cinema — was instead reconstructed in detail from the electricity data cross-referenced with the events calendar, capturing realistic attendance and show durations. A fully normative model was also set up to allow a direct comparison between norm-based and calibrated assumptions.

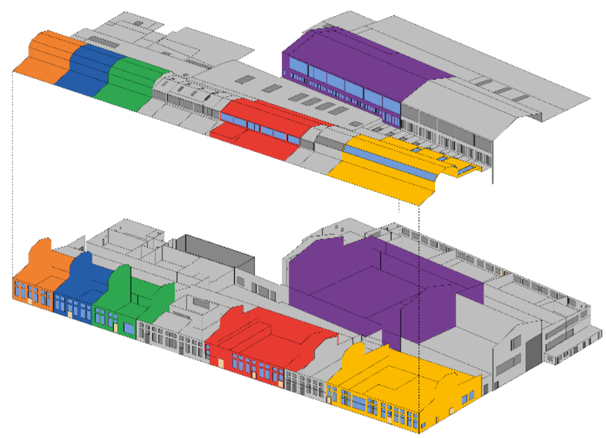

Figure 6: Kampnagel thermal model showing the venues.

CO_2 generation rates were taken from ASHRAE 62.1 [9] and Persily & de Jonge [10], with an outdoor concentration baseline of 450 ppm confirmed by on-site measurements. All simulations were run with EnergyPlus 22.0 [11], able to simulate both thermal performance and CO_2 concentration dynamics within the model. The model assumes well-mixed air conditions, evaluating average CO_2 concentration within each zone.

Model calibration and validation were performed in two steps. First, infiltration rates were calibrated by matching simulated CO_2 concentrations to measured data, verifying the temporal evolution during a performance and the subsequent decay. Second, other envelope parameters were fine-tuned and the model was validated against measured indoor air temperatures and annual heating energy consumption from utility bills for 2019 and 2021. Calibration runs used historical EPW weather files for Hamburg from White Box Technologies [12] to replicate actual conditions.

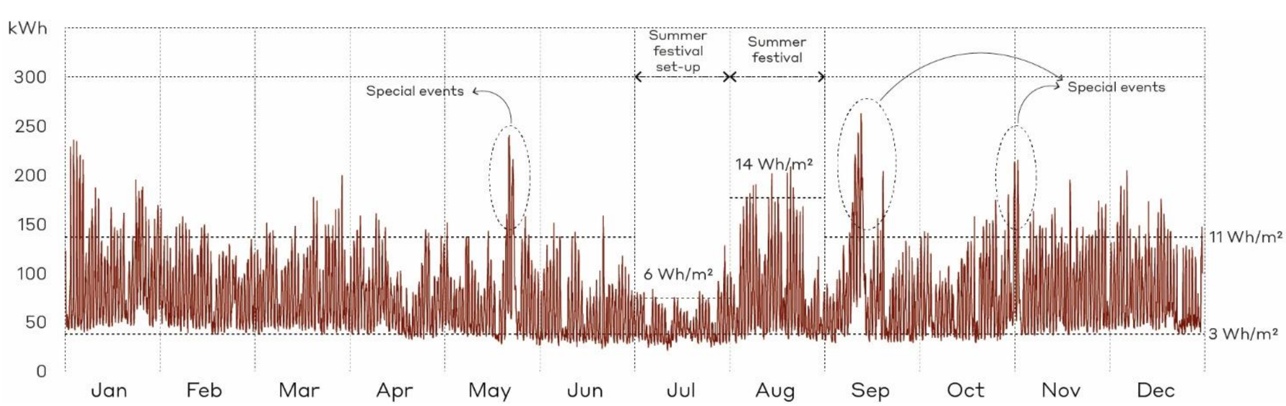

Figure 5: Hourly electricity consumption over 2019.

Once calibrated, the model was run under a Meteonorm 8.0 [13] typical meteorological year to simulate the building performance under typical conditions. The three main themes — heating demand reduction, summer comfort and indoor air quality — were approached with a similar logic: first establishing the current baseline, then testing interventions from least to most invasive, from operational strategies to architectural modifications and mechanical support.

For heating, the objective was to minimise annual thermal demand across the full complex, identifying the combination of operational and envelope measures capable of achieving the greatest reduction with the least intervention. For summer comfort, the target was to reduce degree-hours above 26°C below the 500 °Ch/year threshold defined by DIN 4108-2 [14], with particular attention to the spaces most exposed to overheating risk. For IAQ, the analysis was restricted to the performance venues, as these are the spaces where occupant density is highest and CO_2 accumulation most critical. Scenarios explored variations in audience size, show duration, presence of intermissions, window opening strategies, and use of mechanical support. Simulated CO_2 concentrations were assessed against EN 16798 [15] Category II and III limits of 1200 ppm and 1750 ppm respectively, corresponding to recommended conditions for new and refurbished buildings.

4. UNDERSTANDING THE BUILDING

This phase is the diagnosis of the existing building. Before any simulation or strategy work, a fieldwork programme was carried out to map the envelope conditions, thermal performance, use patterns and energy consumption. The programme combined two on-site monitoring campaigns, a full in-situ envelope survey and a thermal-imaging campaign to produce primary survey data. This was complemented by data gathered from the building management team: two years of annual district heating consumption, one year of hourly electricity metering data and the theatre's events calendar. Together, these inputs provided the basis for the thermal model developed in Section 5.

4.1 Envelope survey

The envelope survey was carried out in collaboration with the architects, covering every facade of the complex. For each facade, the materials and condition of opaque and glazed surfaces were analysed. The roofs were partially refurbished in 2008, with insulation added above most of the areas. The perimeter masonry walls, by contrast, are listed and remain uninsulated. A thermal-imaging campaign was used to identify the main thermal bridges, concentrated around the perimeter of the windows.

Estimated exterior wall U-values range between 1.0 and 3.8 W/m²K, interior walls between 2.4 and 4.2 W/m²K, and old floors between 1.8 and 3.5 W/m²K, while newer floors sit at around 0.7-0.8 W/m²K. Uninsulated roofs range between 1.8 and 3.4 W/m²K, while most insulated roofs are around 0.3 W/m²K.

The windows vary widely across the complex. Most of them are single-glazed and many are painted over or covered with graffiti, plywood or metal sheets to satisfy black-out requirements for the performance halls. Most windows are operable, making natural ventilation a viable option for passive ventilation strategies. Mechanical ventilation is limited to a few areas of the building where it was added during subsequent refurbishments: the restaurant area and the central foyer.

4.2 Electricity use and occupancy patterns

One year of hourly electricity data for 2019 was provided by the building management team. The dataset covers all electrical consumption without submetering, reflecting primarily lighting and show equipment. A typical weekly profile was extracted and assigned to each space using a scaling factor based on its use intensity, with peak values taken from ASHRAE 90.1 for three load categories: high load for venues (17.5 W/m²), medium load for workshops and rehearsal spaces (10 W/m²), and low load for circulation and storage areas (4.7 W/m²). July and August were treated separately to account for the annual maintenance shutdown in July and the summer festival programme in August.

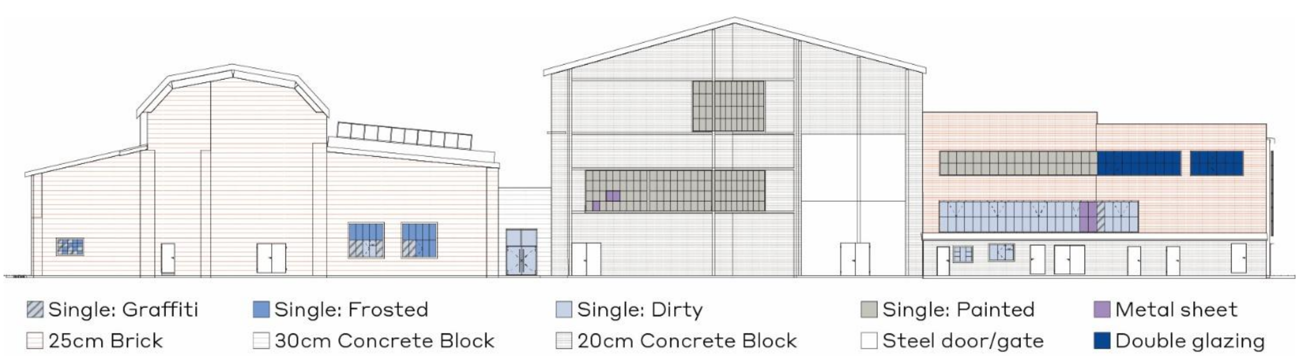

Figure 7: Envelope survey methodology, illustrated on the east façade.

The theatre's calendar of events was used to characterise show frequency, duration, and the extent to which performances ran consecutively or overlapped across venues — all key inputs for defining realistic occupancy schedules.

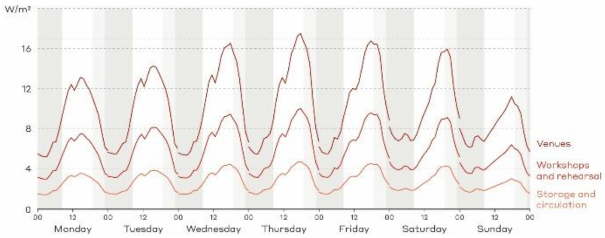

Figure 8: Typical weekly profile of electrical internal gains.

4.3 On-site measurements

Two on-site campaigns of more than 20 days each were carried out, one at the end of summer 2022 (August-September) and one in mid-winter 2023 (January-February). Air temperature sensors were installed across multiple spaces, and a CO_2 sensor was placed in one of the venues. An outdoor sensor recorded site-temperatures that correlate well with the closest official weather station.

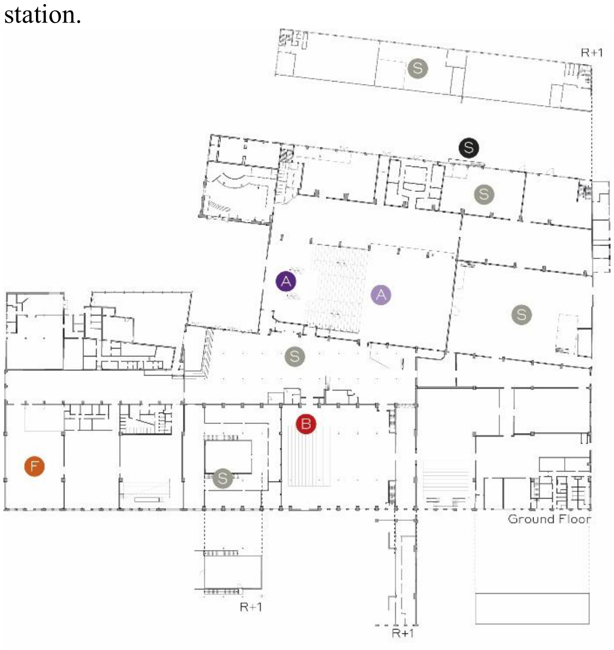

Figure 9: Monitoring locations on the existing plan. Venues are lettered (A,B,F), other monitored spaces are marked S.

In winter, all spaces in the building were heated uniformly to around 20°C at all times, regardless of occupancy — with no thermostatic regulation, no zoning and no night-time setbacks recorded. Temperatures in the venues rose to 22-26°C during shows due to internal heat gains. Storage and ancillary spaces were also being heated despite high envelope heat loss, contributing unnecessarily to overall demand.

In summer, outdoor temperatures during most of the campaign ranged between 15°C at night and 24°C during the day, with indoor temperatures in the performance halls remaining between 22 and 26°C. The absence of night ventilation meant that heat accumulated over the day was not discharged, keeping indoor temperatures persistently elevated even when outdoor conditions cooled. During the hottest days, when outdoor temperatures approached 30°C, indoor temperatures followed closely. The north-facing workshops maintained slightly lower temperatures throughout, benefiting from their orientation and reduced solar exposure.

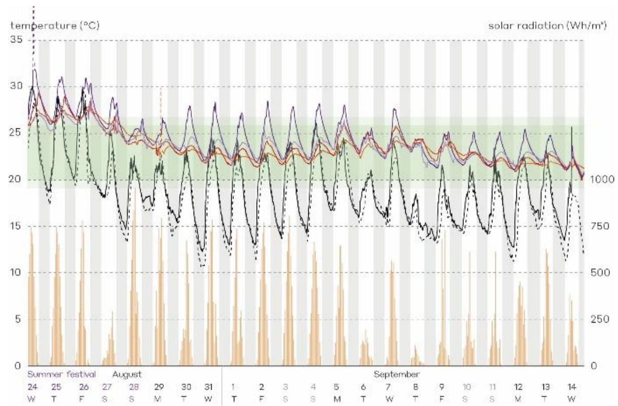

Figure 10: Temperature measurements during the summer campaign.

CO_2 monitoring in one of the venues provided a clear picture of accumulation dynamics during performances. With doors and windows closed, concentrations rose from the 450 ppm outdoor baseline to around 1,000 ppm after one hour, 1,200-1,300 ppm after two hours and approximately 1,700 ppm after three hours, before decaying overnight to roughly 500 ppm. On evenings with two consecutive shows the effect compounded: the second performance started at around 1,100 ppm and finished at roughly 2,100 ppm, above the EN 16798 Categories II and III threshold for its full duration. On the occasions where doors opening was observed, concentrations dropped by more than 1,000 ppm within the first hour, demonstrating the potential of short natural ventilation bursts to rapidly flush the space.

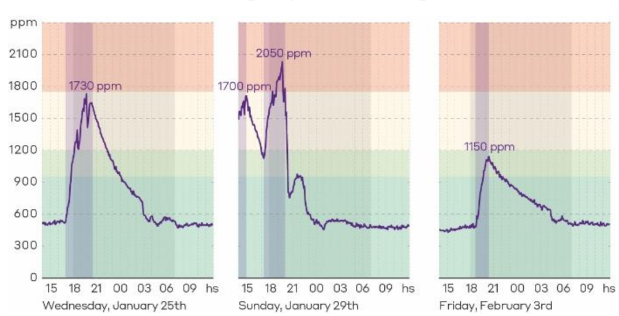

Figure 11: CO_2 measurements during the winter campaign.

5. MODEL DEVELOPMENT AND CALIBRATION

The thermal model was built from the envelope survey data and estimated inputs, with calibration performed by systematically adjusting the most uncertain parameters against three independent datasets: monitored CO_2 concentrations, measured indoor air temperatures, and annual heating energy consumption from utility bills for 2019 and 2021.

5.1 Importance of custom internal gains

One of the most important calibration findings concerned internal heat gains. The initial model used normative occupancy schedules from ASHRAE 90.1, which gave roughly 1,520 MWh/year of occupant heat gains and 569 MWh/year of electrical gains. When custom schedules derived from electricity use and the events calendar were used instead, occupancy gains dropped to about 458 MWh/year (-70%), while electrical gains moved in the opposite direction, increasing to 698 MWh/year (+52%).

The customised schedules for both types of gains significantly differ from those assumed in the standard: realistic occupancy profiles reflect alternating days of high attendance and short show durations lasting only a few hours, rather than the unrealistic constant peak occupancy throughout the entire day implied by the standard. For electrical gains, calibrated profiles show higher night-time gains and daily patterns that rise towards evening peaks.

Given the real patterns of use, occupancy-matched heating control becomes a critical strategy for reducing energy demand. For summer comfort, internal gains are lower during the day but more concentrated in the evening than norms would suggest, which shifts the overheating risk profile and points towards different mitigation strategies than a norm-based analysis would recommend.

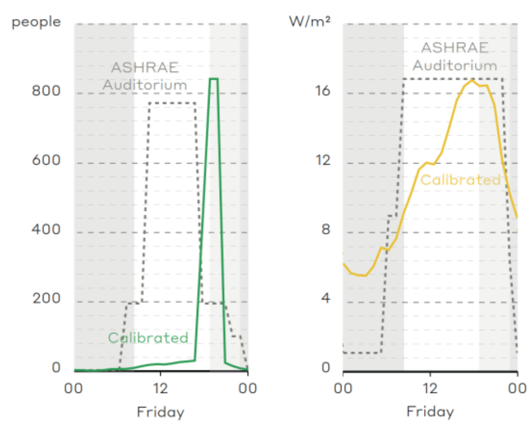

Figure 12: Comparison of norm-based and custom occupancy (left) and electrical gains (right) on a typical day in a venue.

5.2 Building airtightness

CO_2 monitoring during performances provided a direct calibration target for infiltration. By matching the measured rise and decay of CO_2 concentration to the simulated model, infiltration could be estimated with reasonable confidence. The calibrated infiltration rate was 1.08 m³/h per m² of exposed envelope, lower than would typically be assumed for an existing building. This finding has direct implications for both IAQ and heating: a tighter envelope means CO_2 accumulates faster during shows than norms would suggest, while heat losses from infiltration are correspondingly lower.

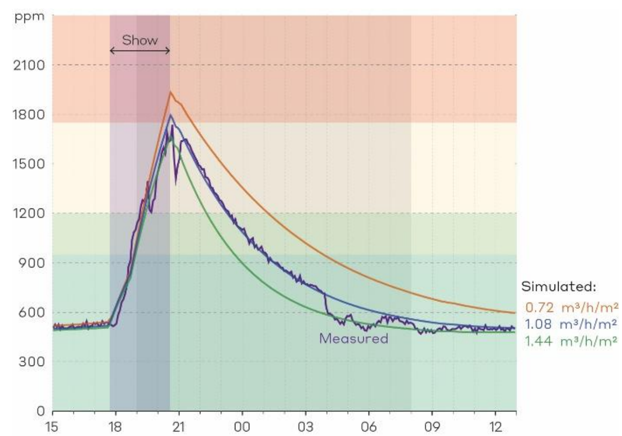

Figure 13: Measured and simulated CO_2 concentration at different infiltration rates for model calibration.

5.3 Validation against air temperatures and heating consumption

The model was calibrated against the summer campaign measurements and subsequently validated against two independent years of energy consumption data. Simulated indoor air temperatures were compared against on-site measurements, yielding R^2 values of 0.85-0.88 across most spaces. Accounting for a heat exchanger efficiency of 75.6% between the district heating network and the building system, simulated annual heating consumption fell within ±0.3% of the measured values for both 2019 and 2021 (Table 1). The close agreement across two years with markedly different weather conditions, combined with the independent validation against both CO_2 concentrations and indoor air temperatures, provides confidence that the model is well-calibrated and representative of the building's actual behaviour.

Table 1: Measured and simulated heating energy consumption.

	2019		2021	
	kWh/m²	MWh	kWh/m²	MWh
Measured	135	1,875.4	165	2,286.4
Simulated	135	1,869.8	165	2,293.7
Deviation	-0.3%		+0.3 %	

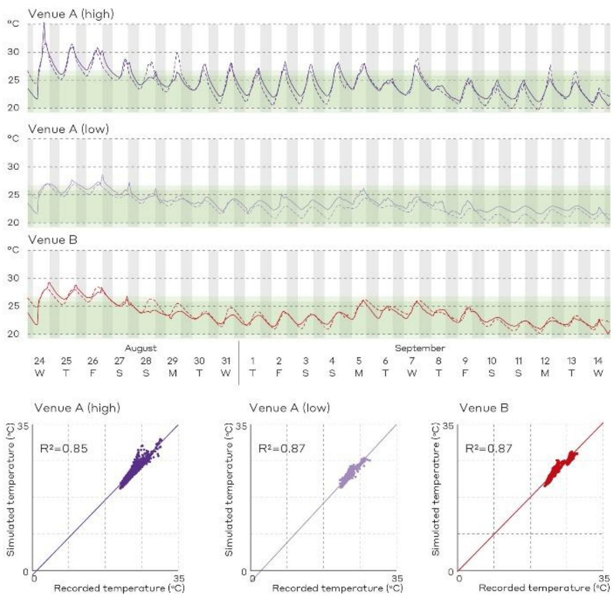

Figure 14: Measured and simulated indoor air temperatures over the summer monitoring campaign and their correlation.

6. TARGETED REFURBISHMENT STRATEGIES

With the validated model, the study moved to the development and testing of improvement strategies across three performance themes: heating demand reduction, summer comfort and indoor air quality. Measures were tested in order from least to most invasive: operational adjustments first, followed by architectural modifications and mechanical support only where necessary.

6.1 Heating demand

The on-site monitoring campaigns revealed that the dominant source of inefficiency was not the envelope itself, but the way the building was being operated — heated uniformly to 20°C at all times regardless of occupancy or use. This pointed clearly towards operational measures as the first and most effective line of intervention.

Heating setpoints were recalibrated by space according to actual occupancy patterns, and setback temperatures were introduced during unoccupied periods. These operational measures alone reduced average heating demand from 113 to 35 kWh/m² across the complex, without any physical change to the building.

Building on this, the project's changes to layout and internal programme were combined with targeted envelope measures. Non-listed partition walls between conditioned and unconditioned spaces were insulated with 10 cm of mineral wool, improving their U-value from 2.75 to 0.29 W/m²K. Roof insulation was added above the restaurant area, reducing the U-value from 3.40 to 0.30 W/m²K through the addition of 13 cm of mineral wool. Removable heavy thermal curtains were introduced along the listed masonry walls, modelled with a conductivity of 0.046 W/mK and a thickness of 10 mm, and applied during unoccupied night hours from autumn through spring. Glazing was refurbished across selected areas: double glazing (Ug = 1.4 W/m²K, g = 0.73, VT = 0.82) in spaces most exposed to thermal stress, and restored clear single glazing (Ug = 5.7 W/m²K, g = 0.70, VT = 0.90) elsewhere to improve winter solar gains.

Together, these additional measures brought the average heating demand down further to 31 kWh/m² — a total reduction of 72% from the baseline, achieved without any intervention on the listed walls.

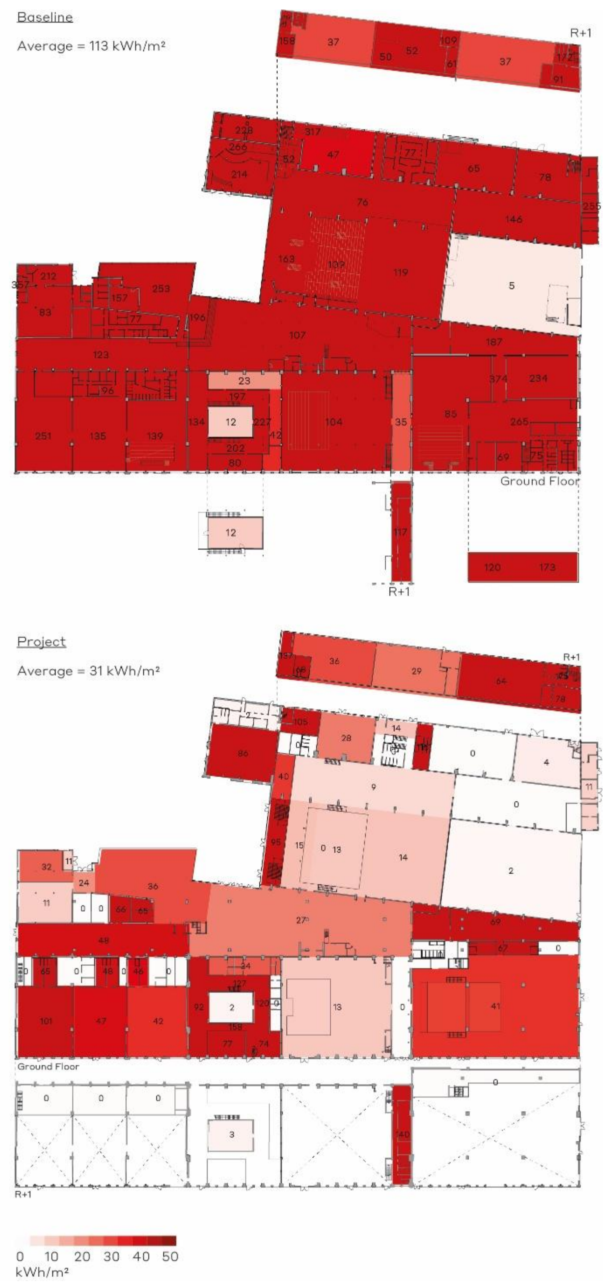

Figure 15: Heating demand by space: baseline and project.

6.2 Summer comfort

The baseline assessment identified a small number of spaces consistently exceeding the DIN 4108-2 threshold of 500 °Ch/year above 26°C. The spaces most prone to overheating were those combining high occupant density with significant solar exposure through west- and south-facing glazing, with the most critical reaching 1,354 °Ch/year — nearly three times the threshold. Across the complex, at least one space exceeded 26°C for approximately 15% of the year, with peaks coinciding with heat wave episodes. The performance venues were already operating in free-running mode, but with all openings closed and no ventilation strategy in place.

These findings pointed to two types of intervention: reducing solar gains in the most exposed spaces, and enabling natural ventilation when outdoor conditions are favourable — a strategy directly supported by the monitoring findings in Section 4.3, which showed that indoor temperatures remained persistently elevated due to the absence of any ventilation.

The proposed strategy combined operable windows for natural ventilation when outdoor conditions are favourable, summer curtains on the most exposed glazing, and the shading incidentally provided by the PV panels installed across most roofs for energy generation. The skylight refurbishment introduced as part of the heating strategy was also accounted for, as it increases summer solar gains in the spaces below. With these measures combined, overheating was reduced to within the 500 °Ch/year threshold across the complex, with the exception of one rehearsal room which remained marginally above at 516 °Ch.

6.3 Indoor Air Quality

Building on the monitoring findings of Section 4.3, simulations were run for all six performance venues across a range of scenarios varying audience size, show duration, intermission presence, window opening strategies and mechanical support. Results were assessed against the EN 16798 Category II and III thresholds introduced in Section 3 (1,200 and 1,750 ppm).

Three general findings emerged consistently across venues. First, the volume-to-occupant ratio is the dominant parameter: under average occupancy, all six venues can be managed without mechanical support, sitting within Category II or III depending on venue size and capacity. For longer performances, natural ventilation during intermissions is sufficient to maintain acceptable levels throughout. Second, intermissions are highly effective — a single 15-minute window-opening intermission reduces peak CO_2 concentrations by 200 to 400 ppm relative to an uninterrupted show, equivalent to an effective increase of 0.3 to 0.5 ACH, and in many cases determines whether Category II or III thresholds are met. Third, where mechanical support is needed, 4 l/s per person is sufficient — well below prescriptive standards for a new venue — and is only required during maximum occupancy events, estimated at around 10 per year per venue for a cumulative maximum of approximately 30 hours annually.

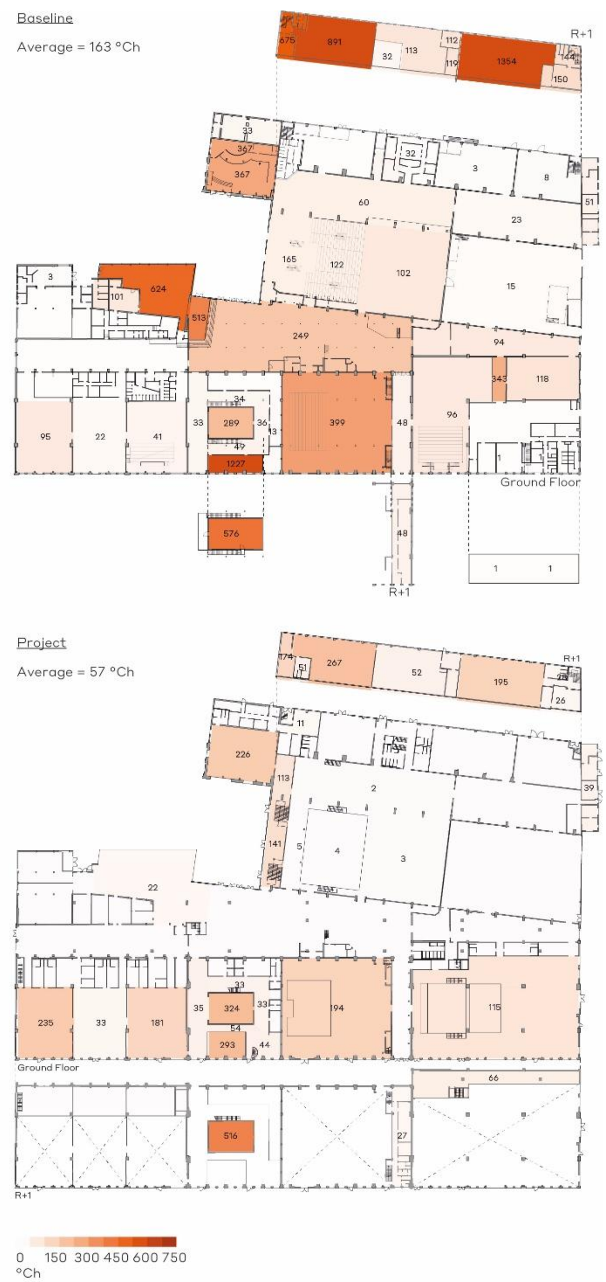

Figure 16: Degree hours >26°C by space: baseline and project.

At maximum occupancy, the picture differentiates across venues. Three venues require mechanical support to maintain acceptable CO_2 levels, while two can be managed through infiltration alone. One venue requires no mechanical support under any occupancy scenario, as its position facing quiet areas removes the acoustic constraints on window opening during shows, making continuous natural ventilation viable even at full capacity.

The simulated CO_2 profiles for all six venues are shown in Figures 17 to 22. Under average occupancy and 1h30 show durations, all venues remain within acceptable limits without mechanical support, with the larger venues sitting closer to the Category III threshold owing to their higher total capacity. For longer performances (2h30), intermissions with window opening maintain conditions within Category III throughout. Mechanical ventilation becomes necessary only under maximum occupancy in the venues where passive means are insufficient, where 4 l/s per person keeps CO_2 within or close to Category II for both show durations.

These results show that all six venues can be managed without mechanical support under typical operating conditions. Rather than installing mechanical ventilation across all venues by default, the findings translated into design recommendations. First, maximum audience sizes, show durations and intermission schedules should be defined as operational parameters calibrated to the environmental capacity of each venue. Second, mechanical ventilation should be introduced only where passive means and operational planning prove insufficient, reserved for the few venues and rare high-occupancy events that require it rather than for typical use.

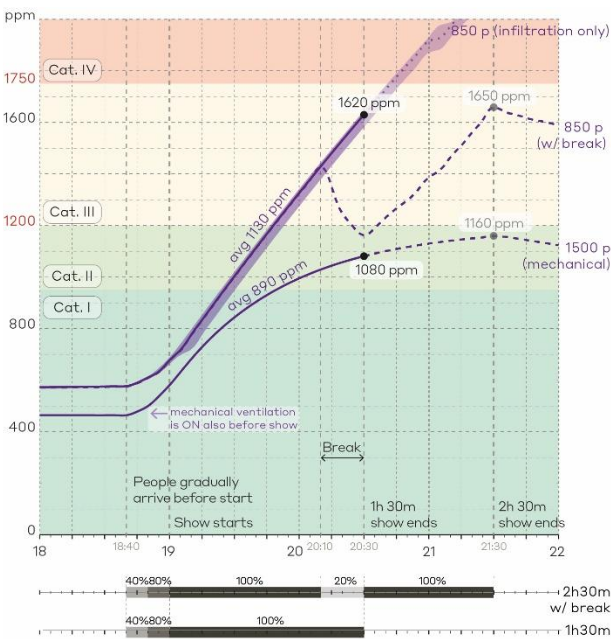

Figure 17: Simulated CO_2 concentration over time: Venue A.

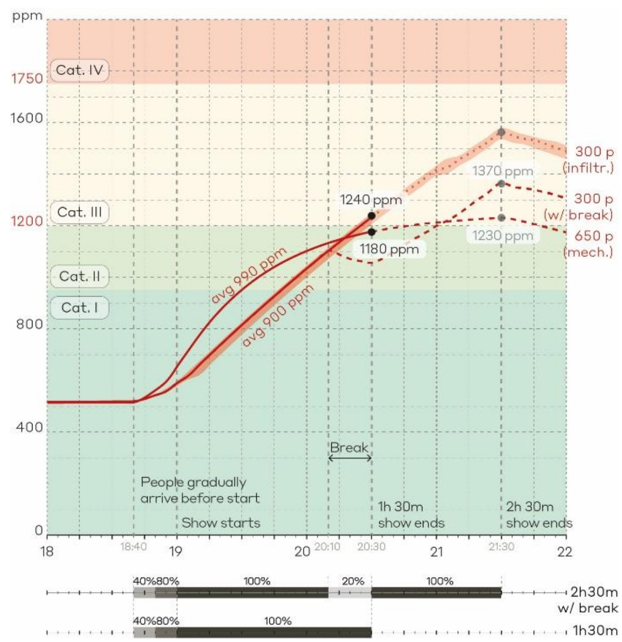

Figure 18: Simulated CO_2 concentration over time: Venue B.

Table 2: CO_2 performance and ventilation strategy per venue, by show duration and occupancy.

Venue	Number of spectators	Volume (m^3)	1h30 show			2h30 show		
			Strategy	**max ppm**	**max cat.**	**Strategy**	**max ppm**	**max cat.**
A (purple)	850 (avg)	23,750	Infiltration	1620	III	Infiltration + break	1650	III
	1500 (max)		Mechanical	1080	II	Mechanical	1160	II
B (red)	300 (avg)	7,670	Infiltration	1240	III	Infiltration + break	1370	III
	650 (max)		Mechanical	1180	II	Mechanical	1230	III
C (yellow)	300 (avg)	11,030	Infiltration	1000	II	Infiltration	1200	II
	800 (max)		Windows	1000	II	Windows	1050	II
D (green)	120 (avg)	3,610	Infiltration	1150	II	Infiltration + break	1230	III
	210 (max)		Infiltration	1500	III	Infiltration + break	1680	III
E (blue)	140 (avg)	3,180	Infiltration	1380	III	Infiltration + break	1480	III
	300 (max)		Mechanical	1040	II	Mechanical	1180	II
F (orange)	120 (avg)	3,350	Infiltration	1140	II	Infiltration + break	1210	III
	210 (max)		Infiltration	1450	III	Infiltration + break	1620	III

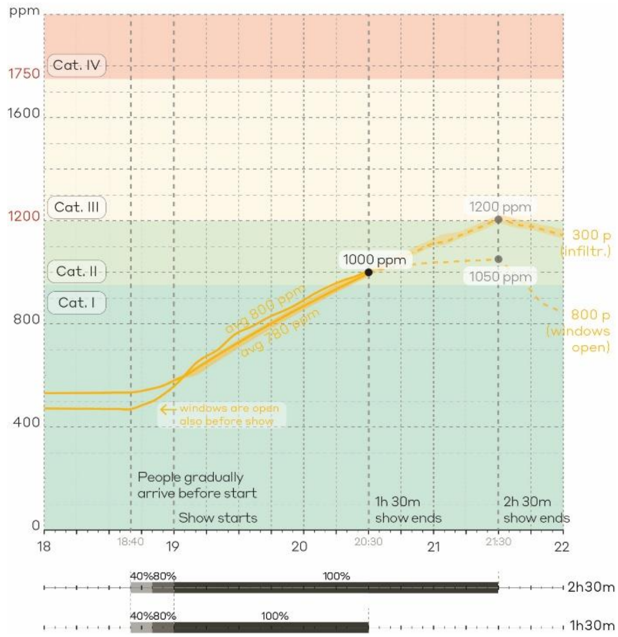

Figure 19: Simulated CO_2 concentration over time: Venue C.

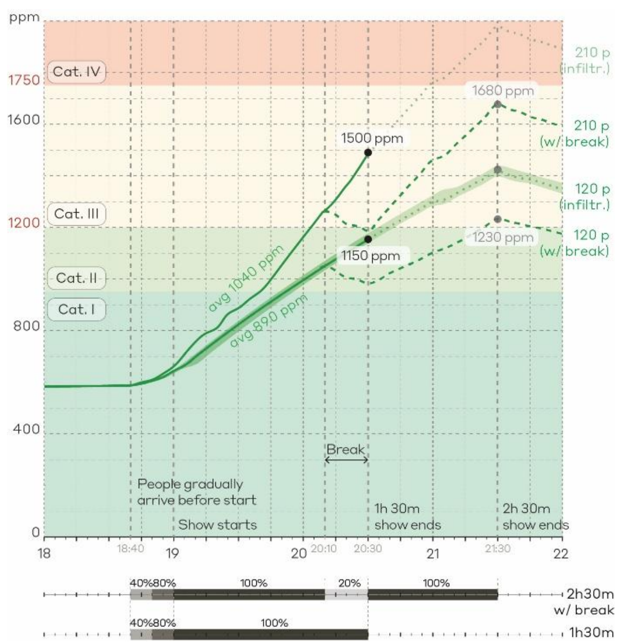

Figure 20: Simulated CO_2 concentration over time: Venue D.

The shift from a norm-driven to a building-specific design philosophy significantly reduces the extent of mechanical installation required, with direct consequences on cost, embodied carbon and the degree of architectural intervention needed in a listed building.

7. DISCUSSION

The environmental study of Kampnagel demonstrates a methodology that prioritises building understanding over normative prescription and conventional practice.

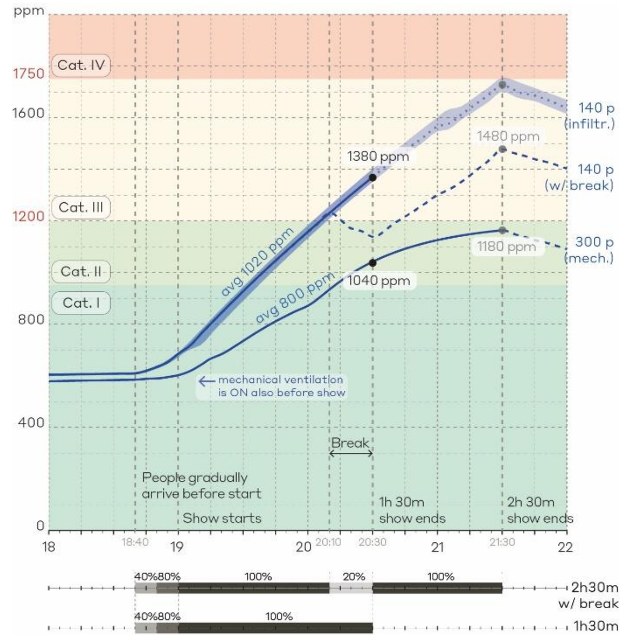

Figure 21: Simulated CO_2 concentration over time: Venue E.

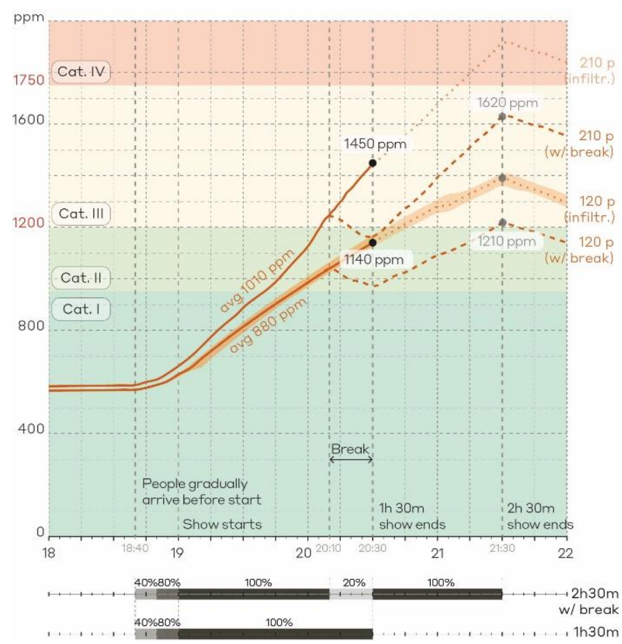

Figure 22: Simulated CO_2 concentration over time: Venue F.

Through fieldwork, monitoring and calibrated simulation, a precise understanding of the building's actual behaviour provided a stronger basis for refurbishment decisions than the application of generalised standards alone.

The study covered three performance themes — heating demand, summer comfort and indoor air quality — and in each case, the calibrated model consistently produced results that diverged from norm-based predictions and revealed margins that standard assumptions would have missed. For heating and summer comfort, the building proved more capable than standard assumptions would suggest, requiring less intervention to meet targets. For indoor air quality, the divergence ran in the opposite direction: the lower-than-assumed infiltration meant CO_2 accumulated faster than norms predict, but the intermittent, event-based occupancy — far below the continuous full-capacity use standards assume — kept real conditions within acceptable limits for most of the programme. In each case, the gap between assumed and actual behaviour was the decisive factor.

Two of the parameters with the greatest influence on the results — envelope airtightness and internal gains — are poorly represented in current standards. Yet they largely determined the heating demand, summer overheating risk and the rate of CO_2 accumulation. Measurement was therefore necessary to establish them accurately, and the development of more representative normative values would help close the gap between assumed and actual performance.

The main findings of the Kampnagel study are the following.

1. Building understanding pays off. Investing in monitoring and calibration before proposing solutions revealed performance margins that a norm-based approach would have overlooked, translating into a 72% reduction in heating demand, summer comfort maintained in free-running mode across most venues, and IAQ managed primarily through passive means and operational planning.

2. Operational strategies proved effective and least disruptive as a first line of intervention. Many of the improvements were achieved not through physical changes to the building, but through changes in how it is operated — heating schedules, show duration, intermission planning and window opening — measures that are reversible, low-cost and fully compatible with heritage constraints. The clearest example is heating: applied to the existing building, operational measures alone reduced demand from 113 to 35 kWh/m², before any physical change; the further reduction to 31 kWh/m² reflects the project as designed, combining the new layout and programme with targeted envelope measures.

3. When physical intervention is needed, building-specific understanding allows it to be precisely targeted — such as internal insulation between conditioned and unconditioned spaces, glazing improvement and selective roof insulation — rather than applying the same measures uniformly, limiting both the extent and the cost of the work required.

4. Mechanical support, when needed, can be limited to real use rather than worst-case assumptions. Mechanical ventilation for IAQ is required in only three venues, and exclusively for infrequent maximum occupancy events — with direct consequences on system sizing, embodied carbon and the degree of structural intervention required to accommodate it.

These findings are inherently tied to the building's current programme and patterns of use; should these change significantly over time, the model and its recommendations would need to be revisited accordingly.

8. CONCLUSION

Normative frameworks are, by design, conservative and generalised: calibrated to guarantee a minimum level of performance across a wide range of building types and future uses, they are not intended to capture the specific behaviour of any individual building. Applied to existing buildings, this generalisation risks overestimating the problem and producing over-intervention — larger mechanical systems, more extensive envelope modifications, and greater structural disruption than the building actually requires.

Kampnagel illustrates this directly. Before this study, the theatre management had been advised to insulate the walls and install substantial mechanical equipment — measures consistent with a norm-based approach, but in conflict with the preservation constraints and architectural identity of a building whose character depends precisely on its industrial heritage and deliberately unfinished quality. Starting instead from a precise understanding of how the building actually behaves, the methodology showed that heating demand could be reduced by 72% without touching the listed walls, and that acceptable IAQ and summer comfort could be maintained in most venues through passive means alone.

The approach developed here — fieldwork, monitoring, calibrated simulation and building-specific strategy development — is applicable to any existing building where the gap between normative assumptions and actual behaviour is likely to be significant. In these cases, investing in building understanding from the start produces proposals that are more effective and less invasive. By prioritising building understanding, operational planning and the selective use of natural means, acceptable environmental performance can be achieved while reducing costs, carbon impact and architectural disruption — allowing heritage buildings to evolve without sacrificing their cultural and spatial qualities, and challenging the assumption that sustainability necessarily requires extensive envelope modification and technological intensification.

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