RENOVAIR: Study of the evolution of airtightness, ventilation, comfort and indoor air quality in 7 energy renovation operations of social housing in France

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ABSTRACT

This article follows a first publication presented at the AIVC2022 conference (Handtschoewercker, 2022), with the preliminary results of the RENOVAIR project, that studies the impact of energy renovation works on social housing on the comfort and health of occupants when no requirements are given on IAQ, ventilation and airtightness performances.

In the frame of the eco-conditioned financial aid supported to the ERDF 2017-2022 operational program for the energy renovation of social housing building stocks, the eligibility conditions for financial aid concern requirements on energy consumption, thermal insulation performance and the energy efficiency of heating systems. Yet, the current specifications of this program do not condition any financial assistance on performance criteria relating to indoor air quality (IAQ), ventilation and airtightness of the building envelope. Thus, the RENOVAIR project studied the evolution of these performances, knowing that it is commonly admitted that these issues are essential for achieving comfortable low energy buildings.

RENOVAIR is based on 7 candidate operations for the ERDF program for the energy renovation of social housing in the Nouvelle-Aquitaine region (southwest of France). In this 3-year work, we sought to characterize the performances of IAQ, comfort, airtightness and ventilation, before and after the renovation work, through in situ measurement campaigns on 21 housing units, in order to assess the importance of such requirements in the implementation of public decarbonization policies.

This article presents the final results from the three measurement campaigns: before works, after works and one year after works. On each of the 7 pilot sites, measurements were carried out on 3 dwellings in order to characterize the evolution of performance following the energy renovation work:

i. Through air flowrates and pressure measurements, we determined whether the ventilation systems allowed sufficient air renewal in the renovated housing for each campaign.
ii. Airtightness measurements carried out according to the NF EN ISO 9972 standard highlighted the location of air leaks in homes during each of our visits and their evolution after each step.
iii. Dynamic measurements of temperature, relative humidity and CO_2 and passive VOC measurements characterized the impact of the work on the IAQ in each dwelling.
iv. The thermal comfort of the occupants was determined by commercial low-cost sensors in each accommodation for two weeks during the winter period

In light of the results of our work, which reveal in some cases a deterioration of performance, we discuss the need of explicit requirements regarding IAQ, ventilation and airtightness with the objective to reach low energy consumption renovated buildings. We also discuss the efficiency of the retrofits according to the associated cost, the energy gains and the discomfort problems that can arise.

KEYWORDS

Airtightness – Ventilation – Indoor Air Quality – Comfort – Energy Renovation

1 INTRODUCTION

For several decades, experts have admitted that efficient energy-efficient renovation of buildings requires extremely good management of air renewal, ventilation and airtightness. Moreover, the COVID-19 pandemic has accentuated the importance of indoor air quality (IAQ), becoming a major concern for building owners, in terms of occupant health and comfort. Studies show that poor IAQ can result in significant economic costs, including lost productivity and public health expenditure.

Public policies, notably through European programs such as the European Regional Development Fund Operational Program 2017-2022 (ERDF OP), offer financial aid for energy renovation, but these programs don't always take into account airtightness, ventilation or occupant comfort. Yet these elements are crucial to achieving low energy consumption.

From 2016 to 2023, Cerema assisted the Nouvelle-Aquitaine Region with the renovation of social housing, examining around 70 operations. The main objectives included verifying the quality of thermal studies, ensuring that works were consistent with energy diagnosis, and assisting with the analysis of environmental and social impacts of the ERDF OP. Cerema's assistance took place in three phases: the study of projects before construction, the verification during construction, and a final verification after construction. The main objectives of the assistance were:

- to ensure the quality of thermal studies and their consistency with actual implementation,
- to make sure that the planned work really does deliver sufficient energy savings to justify the financial assistance envisaged,
- to check the quality of the work and its consistency with diagnosis,
- to support the Nouvelle-Aquitaine region in analyzing the environmental and social impacts of the ERDF OP

2 OBJECTIVES AND METHODOLOGY

2.1 Objectives

The overall RENOVAIR project has three main objectives:

- To observe the effectiveness of the consideration given - or not given - to airtightness, ventilation and IAQ in the energy renovation of the 7 assisted projects monitored.
- Identify the conditions for improving the energy efficiency of renovations, in conjunction with the implementation of corrective solutions for airtightness, ventilation and IAQ, depending on the expected level of energy performance.
- Support public policies to define eco-conditionality criteria for airtightness of renovations, ventilation and IAQ, based on feedback from the field.

This article complements previous publications describing in detail the objectives and methodologies of our study (Handtschoewercker, 2022) (Handtschoewercker, 2023). We invite the reader to refer to it for more in-depth information.

2.2 General methodology

For this work, the analysis of an operation was broken down into three phases:

- Phase 1: Pre-engineering study of renovation projects (BW). This phase consisted in checking that the theoretical energy gains presented in the project corresponded to reality. First, we checked that the building's actual initial state was consistent with that of the thermal study. Secondly, we verified that the planned work would actually generate the expected energy savings.
- Phase 2: Verification of execution and compliance of renovation work during construction. This stage involved monitoring the quality of the work and the effective implementation of the project's features.
- Phase 3: Final post-work verification (AW). During this stage, the conformity of the work carried out with that planned, and its quality, was verified. A certificate of conformity or non-conformity was issued, and this conditioned the payment of the grant.

The sample selected for our study consists of 7 social housing operations, applying for ERDF OP funding, located in the Aquitaine region, in the south-west of France.

This sample represents approximately 10% of the total number of refurbishment operations that Cerema inspected for the ERDF PO until now.

The detailed presentation of the energy renovation work for each operation is presented in a technical report (Handtschoewercker 2023). All the refurbishment works included heavy work on the thermal insulation of the envelope, changing the joineries and the heating and ventilation systems. The specific costs of energy renovation works for appraised operations are between 100 €/m² and 300 €/m², which corresponds to the cost ratios observed at the national level for energy renovation for low-consumption buildings.

2.3 IAQ, comfort, ventilation and airtightness characterization

The study consists of carrying out a series of measurements on airtightness, ventilation, comfort and IAQ during the three phases "before works" (BW), "after works" (AW) and "one year after the works" (1yAW), established as follows, for three dwellings on each operation :

- Carrying out on-site measurements of the airtightness of the envelope of the dwellings studied to determine the airtightness level and identifying the location of the infiltration leakage locations in three dwellings.
- Diagnosis of the ventilation system on three dwellings
- Installation of measurement sensors to characterize comfort and IAQ in three dwellings of the operation.

- ***Airtightness test***

The airtightness of the dwellings was tested in accordance with NF EN ISO 9972 (AFNOR, 2015) and its application guide FD P50-784 (AFNOR, 2016) using a "blower door" device. The indicator used is $Q_{4PA\text{-}SURF}$ value (m³/h/m²), the air leakage rate related to the surface of envelope surfaces of the building under 4Pa expressed, as defined by the french Thermal Regulation RT2012 (MEEDDM, 2010). The corresponding regulatory requirements for new buildings are 0.60 m³/h/m² for single-family and 1.00 m³/h/m² for multi-family residential buildings. Test results were compared and trends in infiltration leakage were analyzed.

- ***Ventilation system diagnosis***

The diagnosis follows the PROMEVENT protocol (ADEME, 2016), applicable to new residential buildings, according to the new thermal regulation RE2020 (MTE, 2021). Measurements were carried out in three phases on three dwellings per renovated operation:

1) Visual diagnosis of the ventilation system before and after renovation,
2) User survey on the use of the ventilation system.
3) Pre- and post-retrofit ventilation measurements according to the PROMEVENT protocol for new residential buildings RE2020 (MTE, 2021).

- ***Comfort characterization***

Comfort is characterized by means of a questionnaire to occupants on their feelings, and by measurements with multisensory low cost commercial sensors (GreenMe®). These sensors, initially developed for office environments, measure eight parameters: i) Air temperature (°C); ii) Relative humidity (% RH); iii) Air quality (VOC and CO_2); iv) Average noise level; v) Maximum noise level (dBA); vi) Lighting level (Lux); vii) Flicker (%); viii) Color temperature (K). Three sensors were installed in each home (living room, kitchen, bathroom) for 15 days. They allowed us to characterize the indoor environment through physical measurements and occupants' votes on their comfort.

- ***Indoor air quality characterization***

The assessment of IAQ was carried out using passive tubes to measure VOCs (Benzene / Formaldehyde / Toluene / Ethylbenzene / Xylenes), CO_2 and Temperature and Humidity.

Three rooms were instrumented per dwelling (preferably living room) for passive tubes and 2 rooms per dwelling were instrumented with temperature, relative humidity and CO_2 sensors (living room + bedroom). This instrumentation was carried out for a period of one week. Benzene, toluene, ethylbenzene, xylenes (BTEX) were measured by passive samplers set up for 7 days and then analyzed in the laboratory, according to the standard NF EN ISO 16017-2 (AFNOR, 2003). Formaldehyde was measured by passive samplers set up for 7 days and then analysed in the laboratory, according to the standard NF ISO 16000-4 (AFNOR, 2012). Air renewal efficiency was assessed continuously using an infrared radiation-based CO_2 sensor.

3 RESULTS

The first BW measurement campaign was carried out between January and June 2021, the second AW between April and July 2022, and the third 1yAW between January and March 2023. Due to the significant delay in the works, operation #07 could not be monitored by the project. Only BW measurements could be carried out for operation #07.

3.1 Airtightness results

Comparing the results of the BW measurement campaign with the regulatory requirements for new residential buildings in France (MTE, 2021), we can see that airtightness levels were compliant with regulatory requirement in 6 out of 7 operations (see figure 3).

For these 6 residences equipped with self-regulating single-stream mechanical ventilation systems, $Q_{4Pa\text{-}Surf}$ measurements were below 1.0 m^3/h/m² (requirement for new multi-family buildings). Only one operation (#05) showed results with mediocre performance: this natural ventilation operation on shunt ducts showed $Q_{4Pa\text{-}Surf}$ values exceeding 1.60 m^3/h/m².

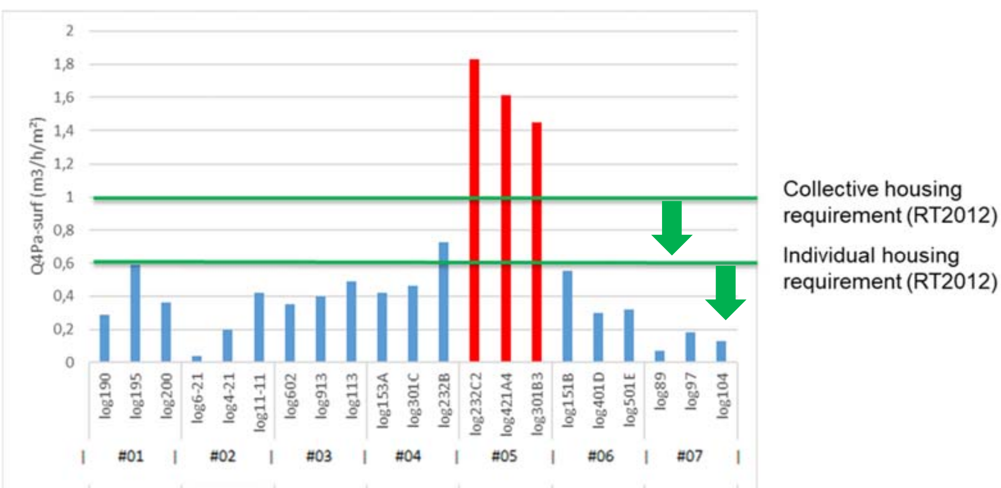


Figure 1 : Airtightness measurements prior to construction (BW)

We compared airtightness measurements from the BW, AW and 1yAW phases on 6 operations (see Figure 4). The results of the AW phase show a clear improvement in airtightness for 3 projects (#03, #05 and #06), particularly for the naturally ventilated residence which benefited from the installation of a single-flow mechanical ventilation system. On the other hand, one project (#01) suffered a significant deterioration in airtightness due to the installation of glass doors whose frames were warped on delivery. For the last 2 operations (#02 and #04), we found comparable levels of airtightness between the BW and AW phases.

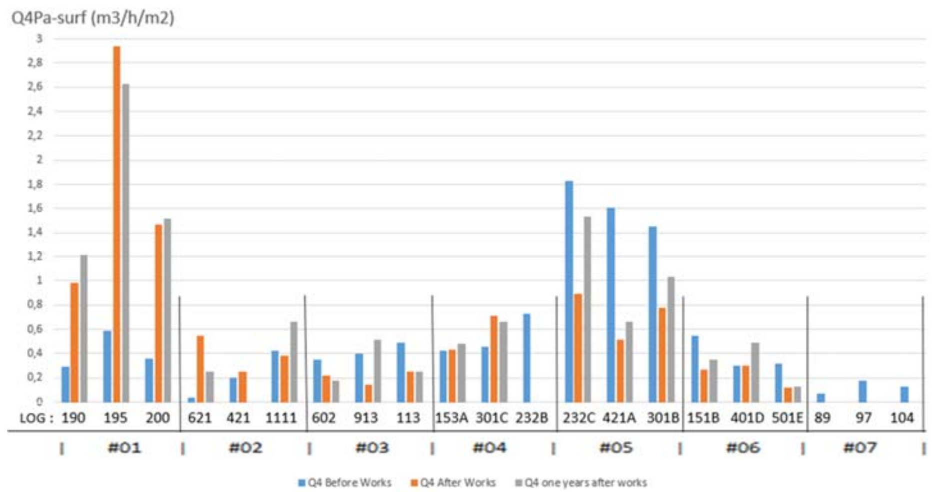


Figure 2 : Comparison of air leakage rates (m³/h/m²) BW (blue), AW (orange) and 1yAW (grey)

Measurements 1yAW, taken 1 year after completion of the work, show both an improvement and a deterioration compared with the AW measurements, taken at the time of delivery. There is no significant trend to be noted in the comparison of AW and 1yAW measurements.
A qualitative analysis of each dwelling was carried out to identify the points of air infiltration for each measurement. Overall, it was found that the works improved the leak correction on the service doors and on the exterior joineries by replacing them.
On the other hand, it regularly appeared that new joineries also leaked, either between sash and frame due to adjustment problems, or between new and old frame due to their installation during renovation. These new leaks appear either as soon as they are installed (AW), or one year after installation (1yAW). Other new leaks often encountered concern roller shutter housings (boxes or manoeuvring bars) replacing old shutters, new air inlets on joinery, exhaust ducts from replaced gas boilers and wall penetrations due to plumbing work in WCs - bathrooms.

3.2 Ventilation results

Ventilation rates were measured during the BW campaign, see Figure 5. The majority of dwellings had systems with significant imbalances that did not achieve the extracted airflow rates compliant with regulations for new dwellings (French Government, 1982). We found a compliance rate of less than 25 % on total flow rates per dwelling for the 21 dwellings studied. This ratio is significantly lower than published statistics on compliance with ventilation regulations in new residential buildings in France, with a rate above 40% (ADEME, 2016).

Pressure measurements on extract units after renovation (AW) comply with regulatory requirements for new-build homes in 4 cases (see Figure 6 left). The 2 non-compliant operations show results below 50 Pa on each of the extract units in each dwelling (regulatory requirements range from 80 to 160 Pa ±10%). Pressure measurements on extract units one year after completion of work (Figure 6 right), still comply with regulatory requirements for 4 operations. It should be noted that the results are significantly better for operation #01, but are still mostly below the regulatory threshold for new buildings. After discussions with the building manager, he reportedly contacted the company in charge of the lot to request adjustments to the installation.

A functional check of the systems was carried out in accordance with the PROMEVENT protocol (ADEME, 2016). The observed non-compliances, apart from the impossibility of accessing the ventilation units, were air inlets in poor condition or deliberately blocked by the occupants of the dwellings, clogged extractions, and the absence or non-functioning of a manoeuvring system enabling the kitchen extraction to be switched to nominal timed flow.

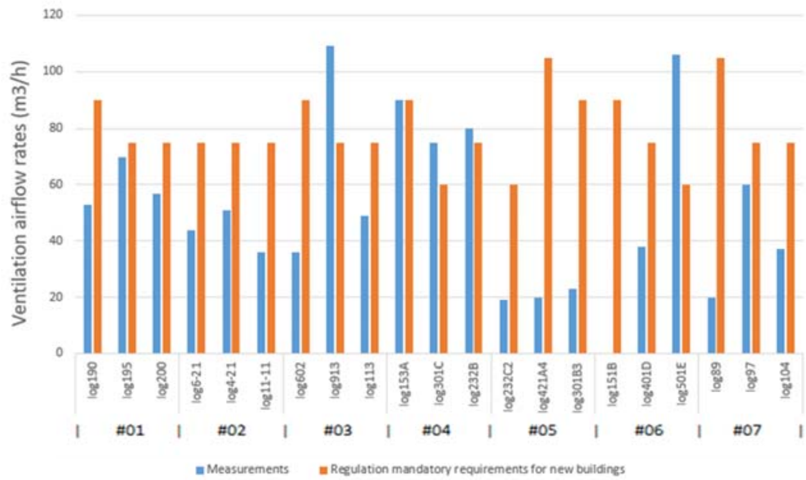


Figure 3 : Total ventilation airflow rates (m^3/h) in the BW phase.
Comparison between measurements (blue) and mandatory regulatory requirements for new buildings (orange)

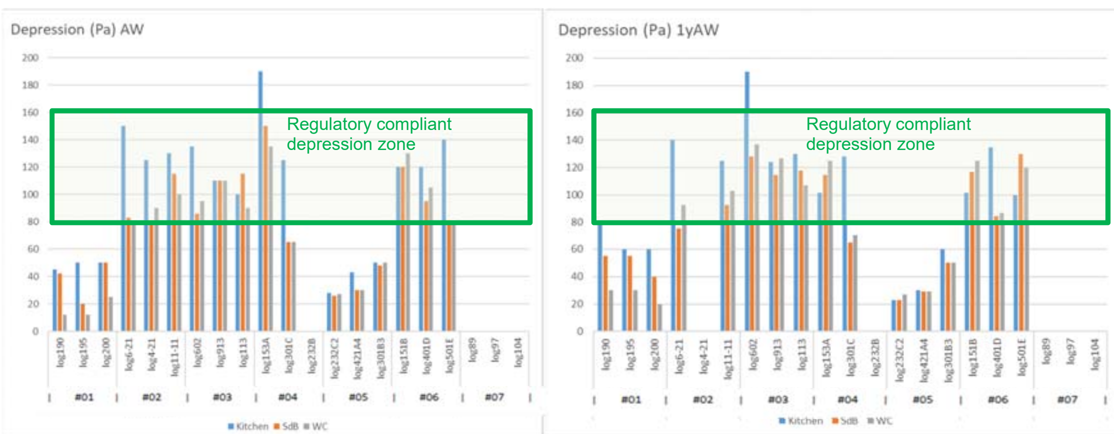


Figure 4 : Pressure measurements on extract units at AW Phase (left) and 1yAW Phase (right)

3.3 Comfort results

We assessed comfort in two different ways:

- Qualitative results: based on a questionnaire submitted to occupants,
- Quantitative results: based on an assessment of the percentage of time spent in comfort, deduced from temperature and relative humidity measurements.

With regard to comfort in the BW phase, the questionnaires given to occupants revealed a lack of thermal comfort in winter.

Comfort ratios derived from temperature and relative humidity measurements were evaluated for each operation according to the comfort ranges as defined in the standard EN 16798-1 (AFNOR, 2019) for category III (existing buildings), in three different locations in each of the three dwellings: living room, kitchen and bathroom. Due to the lack of seasonality for the post-work measurements (AW in spring), it was deemed more relevant to compare only the BW and 1yAW measurements in order to assess the impact of the work on the evolution of thermal comfort in the dwellings.

For the BW phase, the average comfort ratio per operation was calculated at between 25% and 86%, with an average for all operations of 56%. For operations with the lowest comfort levels, our measurements essentially reveal discomfort due to temperatures below 20°C, which corroborates the results of the comfort questionnaires (qualitative results).

BW (2021)	#01			#02			#03			#04			#05			#06		
	log195	log200	log190	log6-21	log4-21	log11-11	log602	log913	log113	log153A	log301C	log232B	log232C2	log421A4	log301B3	log151B	log501E	log401D
LIVING ROOM	99%	98%	43%	58%	89%	67%	21%	0%	63%	85%	86%	5%	65%	100%	99%		2%	96%
BATH ROOM	92%	99%	83%	1%	10%	71%	4%	0%	47%	99%	20%	46%	29%	97%	98%		0%	95%
KITCHEN	99%	90%	68%	14%	78%	85%	6%	0%	83%	75%	1%	1%	27%	95%	96%		0%	93%
Average per apartment	97%	96%	65%	24%	59%	74%	10%	0%	64%	86%	36%	17%	40%	97%	98%		1%	95%
Average per operation		**86%**			**53%**			**25%**			**46%**			**78%**			**48%**	
	13 - 27 January			1st - 12 March			8 - 22 March			15 - 29 March			26 Marchs - 9 April			31 March - 14 April		

1yAW (2023)	#01			#02			#03			#04			#05			#06		
	log195	log200	log190	log6-21	log4-21	log11-11	log602	log913	log113	log153A	log301C	log232B	log232C2	log421A4	log301B3	log211B	log501E	log401D
LIVING ROOM	**83%**	**99%**	**78%**		**60%**	**9%**	**47%**	**0%**	**20%**	**99%**	**19%**		**9%**	**100%**	**96%**	**55%**	**0%**	**0%**
BATH ROOM	**100%**	**99%**	**90%**		**45%**	**76%**	**1%**	**0%**	**0%**	**99%**	**1%**		**85%**	**99%**	**97%**	**36%**	**0%**	**0%**
KITCHEN	**62%**	**27%**	**0%**		**15%**	**20%**	**9%**	**0%**	**52%**	**95%**	**0%**		**96%**	**100%**	**84%**	**78%**	**0%**	**9%**
Average per apartment	82%	75%	56%		40%	35%	19%	0%	24%	98%	7%		63%	100%	92%	56%	0%	3%
Average per operation		**71%**			**38%**			**14%**			**52%**			**85%**			**20%**	
	10 - 24 January			16 - 30 January			25 January - 8 February			1st - 15 February			21 February - 7 March			28 February - 14 March		

Figure 7 : Comfort ratios assessed at BW and 1yAW phases, as the rate of time in comfort zone for instrumented rooms in each dwelling of each site, according to standard standard EN 16798-1

A comparison of BW and 1yAW comfort ratios was carried out on 6 operations (Figure 7). Overall, we noted a deterioration in comfort levels, with average rates per operation ranging from 14% to 85%, with an average for all operations of 47%. Indeed, we note a decrease in the comfort rate for 4 out of 6 operations. The other 2 operations showed a slight improvement in their comfort levels, notably operation #05, which showed a clear improvement in its AW airtightness level.

Before linking comfort to the renovation work carried out, it's worth recalling the economic context at the time the 1yAW measurements were taken. In the midst of a global energy crisis following Russia's invasion of Ukraine in March 2022, the occupants of the homes we visited were often very concerned about their energy bills. They explained that they had changed their behavior regarding the use of their heating system. Their choice was to lower their usual set temperature in favor of warmer clothes.

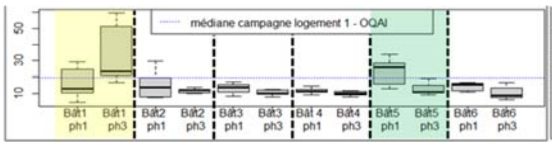
3.4 IAQ results

During the BW phase, instrumentation revealed that the building in operation #05, the only one with natural ventilation, had higher concentrations of formaldehyde and CO_2 (see Figure 8), compared with the other buildings and with the median of the OQAI's measurement campaign CNL1 (OQAI, 2007). Concentrations of these two pollutants decreased after the works and the installation of mechanical ventilation systems.

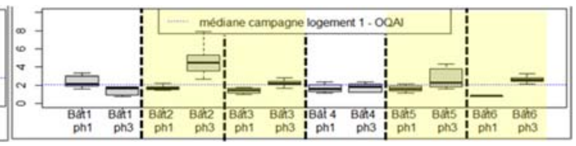
In operation #01, CO_2 concentrations increased after the 1yAW phase. The value of 1 500 ppm defined by the HCSP (High Council of Public Health) as unacceptable air confinement was exceeded in several dwellings, during all three measurement phases. Also, operation #03 shows a slight increase in CO_2 concentrations, but the median value remains within the above-mentioned threshold (see Figure 8).

Comparing the concentrations obtained BW and 1yAW phases, it appears that formaldehyde concentrations in operation #01 have risen sharply, to the point of exceeding in several dwellings the values recorded during the CNL1 and the threshold concentrations of the French mandatory regulation for indoor air quality in establishment open to the public, limit value of 30 µg/m3. However, concentrations remain below the limit value (100 µg/m3) for which the local authorities are required to be informed.

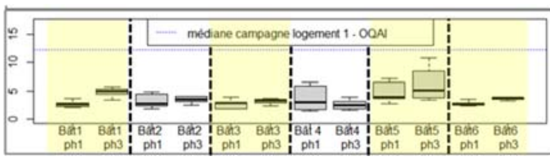
Concentrations of toluene and ethylbenzene also increased slightly in operation #01, but remained well below the Guide Value for Indoor Air (GVIA) from the Ministry of Health and Prevention (22 000 µg/m^3 for toluene; 22 000 µg/m^3 short-term and 1 500 µg/m^3 long-term for ethylbenzene). In operations #02, #03, #05 and #06, benzene concentrations have increased over the past 1 year, exceeding the values recorded at the CNL1 and the GVIA (long-term exposure) of 2 µg/m^3. Indeed, benzene concentrations are all below the limit value of 10 µg/m^3. These increases are also visible in toluene (operations #03, #05 and #06) and ethylbenzene (operation #03) concentrations. However, toluene and ethylbenzene concentrations remain well below GVIA. Finally, operation #04 shows an increase in xylenes 1yAW concentrations, exceeding the values recorded at CNL1.



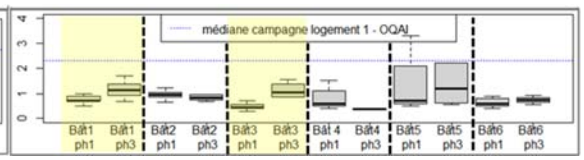
Formaldehyde concentration [µg/m^3]



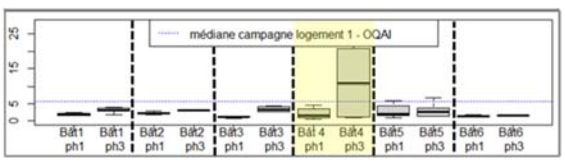
Benzene concentration [µg/m^3]



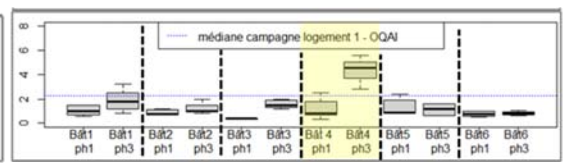
Toluene concentration [µg/m^3]



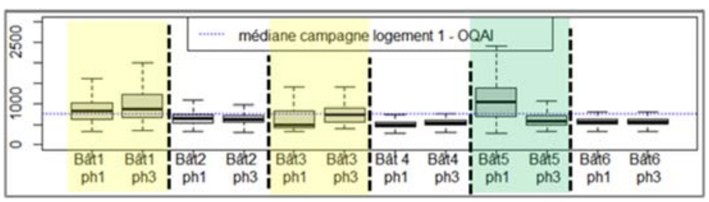
Ethylbenzene concentration [µg/m^3]



m+p-xylene concentration [µg/m^3]



o-xylene xylene concentration [µg/m^3]



Carbon dioxyde concentrations (ppm)

Figure 8: IAQ pollutants BW (ph1) and 1yAW (ph3), compared with the median of CNL1 (n=54)

As seasonality was not respected (higher temperatures and humidity) during the AW phase, compared with the BW and 1yAW phases, they are given for information only.

For several pollutants and buildings, higher concentrations are visible during the AW phase than during the BW and 1yAW phases. This may be explained by the fact that building materials installed just prior to the AW phase may have emitted a greater quantity of VOCs when they were new, then emissions decreased over time. It should be noted that temperatures were higher during the AW measurements, which may have resulted in greater VOC release. However, these warmer temperatures may also have resulted in better ventilation of the dwellings through more frequent opening of windows, and hence a reduction in actual VOC concentrations. The lower concentrations of AW carbon dioxide testify to better ventilation of dwellings during this period.

4 DISCUSSIONS

The study analyses the impact of renovation work on the airtightness, ventilation, thermal comfort, and indoor air quality (IAQ) of residential buildings. Before the renovations, air-permeability measurements indicated that most homes with mechanical ventilation were fairly airtight. The main air leaks were found in joinery, which were addressed by replacing them during the renovations, leading to significant improvements in airtightness post-renovation. Particularly notable improvements were seen in homes initially equipped with natural ventilation, which were upgraded to humidity-controlled mechanical ventilation (CMV). However, one project experienced a decline in airtightness due to the renovation activities.

Ventilation systems before the renovations were found to be inefficient across all monitored projects. AW measurements showed significant improvements due to the installation of humidity-controlled mechanical ventilation systems. Despite these improvements, two projects did not meet the regulatory requirements for new residential buildings. Efforts to obtain measurements from the responsible companies were largely unsuccessful, though one company did intervene to improve ventilation efficiency in one project, yet the results remained inadequate.

Regarding thermal comfort, the initial BW measurements showed varied results among the dwellings. The comparative analysis was complicated by the mismatch in seasonal conditions during the BW and AW measurements, with BW measurements taken during winter and AW measurements during spring. To address this, the 1yAW measurements were scheduled for the same time of year as the BW measurements to ensure a fair comparison. It was found that thermal comfort analysis should focus on living rooms rather than kitchens and bathrooms due to the specific and varied occupancy patterns of these spaces.

The energy crisis has significantly impacted household behavior towards heating systems, with many opting to reduce consumption at the expense of comfort, particularly in social housing where energy bills have a substantial impact.

In terms of IAQ, BW measurements indicated that natural ventilation was less effective compared to controlled mechanical ventilation, which provides more consistent air renewal and better pollutant extraction. Poor ventilation in one project led to higher-than-expected CO_2 concentrations, and renovation work introduced VOCs from new building materials, slightly degrading IAQ immediately post-renovation. However, VOC concentrations typically decreased over time, with 1yAW measurements generally showing lower levels than immediately post-renovation.

Despite these overall improvements, some dwellings showed an increase in VOC concentrations over the year, largely due to occupant behavior or the introduction of new furniture. Occupant activities such as smoking, using candles, and cleaning products contributed to this VOC pollution. The variability in occupant behavior between measurement periods complicates the assessment of renovation impacts on IAQ, suggesting that studies without occupants might better isolate building-related emissions.

5 CONCLUSIONS

The RENOVAIR project, conducted from 2016 to 2023 in the Nouvelle-Aquitaine Region, examined the impact of renovations on airtightness, ventilation, thermal comfort, and indoor air quality (IAQ) in 70 social housing operations. The project's primary goals included ensuring thermal study quality, verifying energy savings consistency with diagnosis, and analysing environmental and social impacts of renovations funded by the ERDF Operational Program.
Key findings include:

- Airtightness: Pre-renovation measurements indicated fair airtightness in most buildings with mechanical ventilation. Post-renovation improvements were significant, particularly in homes upgraded from natural to humidity-controlled mechanical ventilation (CMV). However, one project experienced a decline due to renovation activities.

- Ventilation: Pre-renovation systems were inefficient. Post-renovation improvements were noted due to the installation of mechanical ventilation systems, yet two projects did not meet regulatory requirements. Efforts to obtain additional measurements were largely unsuccessful.
- Thermal Comfort: Initial measurements showed varied comfort levels. Seasonal mismatches in data collection complicated comparative analyses, but adjustments ensured better comparison. Thermal comfort analysis should focus on living rooms due to specific occupancy patterns in kitchens and bathrooms.
- IAQ: Initial measurements revealed inefficient natural ventilation in one project. Post-renovation, IAQ generally improved, but new building materials temporarily increased VOC emissions. Over time, IAQ levels mostly returned to pre-renovation levels, with occupant behavior and new furniture contributing to VOC pollution in some cases.

The study underscores the importance of explicitly integrating airtightness, ventilation, and IAQ considerations into energy-efficient renovations to ensure occupant health and comfort.

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