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Air Pressure Differences over External Walls in New and Retrofitted Schools and Daycare Centers

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Abstract: Air pressure differences are a key factor in the behavior of building ventilation and air leakages through the building envelope. Field measurements of the air pressure differences over the building envelope were conducted in 24 Finnish municipal service buildings. The measured buildings were mainly schools and daycare centers, of which half were new buildings and half recently retrofitted. All buildings had mechanical ventilation. The measurements were conducted during 2016–2018. The total number of measurement points was 100, and the duration of individual time series varied. According to the results, the mean air pressure difference was within the range of national recommendations (small underpressure indoors) in 81–89% of measurement points, but some cases experienced either strong underpressure or overpressure conditions. In some cases, the air pressure difference showed a clear stepwise constant behavior, while other cases showed larger temporal variation. The conditions varied between different operating situations and the time of year. The study also supports the current recommendation that air pressure difference measurements should be done as continuous measurements of at least one week duration.

Keywords: air pressure difference; indoor air conditions; overpressure; underpressure; school; daycare center

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1. Introduction

1.1. General

Air flows in buildings have an impact on the indoor environment, hygrothermal behavior of the building envelope, and building energy consumption. Generally speaking, air flows depend on two factors: air pressure differences and air flow resistances. This article focuses on the former.

The attention to building airtightness started to increase around 1990s and has resulted in relatively airtight building envelope structures for new and retrofitted buildings. Concurrently, there has also been a shift from natural to mechanical exhaust ventilation, and eventually to mechanical supply and exhaust ventilation with heat recovery. Well-functioning buildings have both airtightness and ventilation systems in good order, while maintaining modest air pressure difference levels.

The overarching purpose of this article is to present results from an air pressure difference field measurements that were conducted in Finnish schools and daycare centers. First a short literature review is given on topics related to air pressure differences. Then, the research methods are explained, and the measured buildings are described. Finally, the measurement results are presented, and recommendations and future research needs are given.

1.2. Literature Review

The weight of the atmospheric air creates an air pressure that has a reference value of 101,325 Pa at sea level [1]. The actual air pressure P_e [Pa] depends, e.g., on the elevation from the reference level and the atmospheric temperature. The air pressure indoors P_i [Pa] is affected by temperature differences (stack effect), wind, and mechanical ventilation [2–4]. The air pressure difference ΔP [Pa] is defined here according to Equation (1).

$$P_i = P_e + \Delta P, \quad (1)$$

The two absolute air pressures have the same elevation. The air pressure difference is positive when air is flowing from indoors towards outdoors. The time scales of air pressure differences vary from short to long time scales (wind gusts, operation of HVAC systems, outdoor air temperature, fouling of the ventilation filters). Air pressure also varies within a building.

The two main categories for the building air pressure and air flow simulation models are: (i) macroscopic methods, which use control volumes and ordinary differential equations to model multizone situations [5–13]; and (ii) microscopic methods, which use continuum assumption with partial differential equations for modelling the conditions inside a single zone or outside the building [14–17]. For the continuum approach, the Computational Fluid Dynamics (CFD) with Reynolds-averaged Navier-Stokes (RANS) turbulence models has been the main approach [18], but others have also been proposed, such as the coupling of Fast Fluid Dynamics (FFD) with multizone airflow models [19], and the Lattice-Boltzmann method [20].

Field measurements were conducted in 15 high-rise buildings with a height of 44–150 m in four US cities during winter. The air pressure difference at ground floor was between −94.7 Pa and −12.7 Pa, the average being −38.1 Pa (the coldest outdoor air temperature was −12 °C). [21]

At a 60-story commercial high-rise building in Korea with the temperature of −5.2 °C outdoors, 22 °C indoors and the wind speed of less than 1 m/s, the air pressure difference over the elevator doors was between −50 Pa and +25 Pa, −20 Pa and +40 Pa, and −10 Pa and +45 Pa at the low-rise, mid-rise, and high-rise elevator zones, respectively. When the air pressure difference was at record value −121 Pa across first-floor elevator doors, the doors did not close properly [22]. In high-rise buildings, airflow noise and drafts have been identified as the main source of user complaints [23].

According to instantaneous measurements from 26 Finnish apartment buildings with mechanical exhaust ventilation, the air pressure difference was in the range −95.0 Pa and +10.1 Pa (average −18.6 Pa). Data from nine buildings after renovations showed an average air pressure difference of −19.1 Pa. The air change rate and air pressure difference typically increased in Finnish buildings during energy efficiency retrofit, whereas they decreased in Lithuanian buildings. [24,25]

Measurements from a two-story detached house with mechanical supply and exhaust ventilation showed an air pressure difference of −5 Pa < ΔP < 0 Pa at the first floor, and it was similar but of the opposite sign at the second floor. Measurements from a five-story apartment building showed ΔP = −11 Pa at the first floor and ΔP = −2 Pa at the fourth floor, on average [26]. A subsequent study with three two-story detached houses and the same apartment building concluded that at least ±10 Pa should be used as design value for detached buildings and up to ±30 Pa in cases with highly airtight building envelope with unbalanced ventilation [27]. Other examples are approximately −20 Pa in the first floor of five-story apartment buildings during cold weather [28], −17 Pa to −5 Pa between indoor air and crawlspace at a four-story apartment building [29], and almost constantly negative air pressure difference with the maximum measured underpressure being −38 Pa in a school building [30].

Adjustment of ventilation rates and even overpressurization can prevent transport of impurities to indoor air [31–36]. In cold climates, exfiltration can increase moisture loads into the envelope structures [37], but the risk increase has been considered small, if the indoor vapor excess is small [38,39]. An overpressure of 5–7 Pa indicated positive impacts to the indoor air quality at a studied school building, but a strong confirmation of the results was difficult due to small sample size, large number of factors and only partly reaching the target conditions [40].

A follow-up study of seven buildings with airtightness retrofit concluded that the envelope structures and the sealant materials had stayed in good condition, but the ventilation system required adjustments in 20–30% of the areas [41].

The previous Finnish guidelines have stated that buildings should be designed to have a small underpressure over the envelope, but no more than −30 Pa [42–44]. The current regulations demand that exfiltration must not cause degradation or harmful accumulation of moisture into the structures, and infiltration must not transport harmful impurities to indoor air [45,46]. An average air pressure difference of larger than −15 Pa should be investigated and made smaller [47]. A stricter guideline also exists that for the design of new and maintenance of existing buildings should not be more than −5 Pa [48]. One to two weeks long continuous measurements are recommended for the purposes of indoor air quality condition investigations [49]. The airflows and whole ventilation system must be also taken into account to balance various performance requirements [50].

1.3. Goals of the Study

The aim of this paper is to present results from air pressure difference measurements of 22 Finnish schools and daycare centers and two assisted living facilities all with mechanical ventilation. The research questions were:

(a) What was the general behavior of air pressure differences?
(b) Was there a difference between new and retrofitted buildings?
(c) How well did the conditions comply with the national guidelines?

This paper is related to the project: "Comprehensive Development of Municipal Service Buildings (COMBI)". There exist previous publications in the form of two M.Sc. theses [51,52] and two Finnish Building Physics Symposium papers [53,54], all in Finnish. Initial measurement results are reported in [55].

2. Materials and Methods

2.1. Studied Case Buildings and Measurement Locations

Field measurements were conducted in 12 new and 12 comprehensively retrofitted municipal service buildings in the Pirkanmaa and Helsinki regions in Finland (Tables A1 and A2). The monitored zones in those buildings are listed in Table A3. The buildings considered as new in this study were on average five years old during the field measurements. The retrofitted buildings were on average 58 years old but had gone through an extensive retrofitting work on average four years prior to the field measurements. Most of the buildings were schools and daycare centers, while two of the buildings were assisted living facilities. One of the new and retrofitted buildings belonged to the same complex and were connected to each other through a passageway.

The case buildings were owned and managed by the research project partner cities and municipalities. The criteria for choosing new case buildings were as follows: (a) a building having a small air tightness number n_{50} or q_{50} and (b) a building belonging to other studies in COMBI research project.

The criteria for choosing retrofitted case buildings were as follows: (a) large air pressure differences between indoor and outdoor air discovered in a condition survey; (b) pre-reported user complaints about inadequate indoor air quality; (c) findings of exceptionally large energy consumption, (d) special attention had been put to improve the energy efficiency of the building during retrofitting, including measures such as improved ventilation with heat recovery and/or supplementary thermal insulation of the envelope structures; and (e) buildings belonging to other studies in the COMBI research project. The criteria for selecting case buildings are relatively shortly described, but the selection process also included the evaluation of several other possible criteria, such as the type of building envelope structures; the number, type, and zoning of ventilation equipment; and the details of building use. These latter criteria were not eventually used because either the necessary data were not readily available and gathering them would have required unreasonably high resources, or it was considered that although the data would have been available, there would not have been enough a prior information to properly differentiate between different situations.

Air pressure differences were measured in rooms describing the typical function of the building. In schools and daycare centers, the measuring units were located mainly in classrooms and playrooms, respectively. In assisted living facilities, the measuring units were located in rooms for occupants and in corridors.

The measurements included 24 buildings in total, of which 12 were new and 12 were retrofitted. Two of the buildings (one new, one retrofitted) were extensions, but were considered as separate buildings because of the differences when compared with the other parts of the building complex. The number of measured rooms was 28 for new buildings and 25 for retrofitted buildings, so that the number of measured rooms per building was mostly one to three. In most of the cases, two measurement units were used per room, and the total number of measurement points was 53 in new buildings and 47 in retrofitted buildings. The measured buildings and rooms are listed in Appendix A.

Two measurement units per room were installed on the inner side of the exterior wall on the same vertical line. The vertical distance of the bottom unit from the floor surface was between 0.08 and 1.50 m (mainly 0.1–0.4 m, mean 0.24 m). The other unit measuring the conditions at the top part of the wall was above the bottom one and was at distance 1.90–5.35 m (mainly 2.10–3.50 m, mean 2.7 m) from the floor surface. One measurement point in a school sports hall was located only at the higher level (2.4 m) to protect it from physical contact. The units were installed to the first floor above ground (at ground floor).

The details of the ventilation systems varied, but all studied case buildings had either mechanical exhaust or supply-and-exhaust ventilation. Typically, the case buildings contained multiple ventilation zones with one or multiple units managing each zone. The ventilation units were controlled either by pre-set time schedules, demand-control based on CO_2 concentration, boosted ventilation by user-adjustable timers, or a combination of the previous. Some of the zones had cooling but not all (19% of the confirmed cases). The daycare centers were mostly single-story buildings and overall smaller in size, whereas the school buildings were multi-story buildings with a larger floor area. The location of the measurement points also varied with respect to the orientation of the building and local microclimatic conditions.

2.2. Measurement Equipment

The process for selecting suitable measurement equipment for field monitoring included a preliminary survey, laboratory comparisons of different systems, and eventually the design and manufacturing of custom measurement equipment.

The preliminary survey of air pressure difference monitoring equipment was done by first tabulating the specifications, capabilities, and prices of different systems based on the information from the manufacturer's websites and by direct contacts with the companies. Based on this, a list of 12 possible differential pressure transmitters and the accompanying utilities was formed. Then, a short list of three differential pressure transmitters/sensors (Vaisala PDT101, Beck 984A (3-wire) and Honeywell HSCDRRN001ND2A3) were chosen for further laboratory testing. The first two were available with complete field measurement capabilities, whereas the third one was included as an in-house development project over a Raspberry Pi platform.

Three transmitters were compared with each other using Additel 901A low-pressure test pump for creating adjustable stationary air pressure conditions. A comparison was also done against measurement results from a calibrated Furness Controls FCO16 Digital Manometer. Besides room-temperature stationary conditions, three transmitters were also tested by installing one of each to measure the air pressure difference over the laboratory building's exterior wall. All the tested systems gave similar results in the preliminary laboratory testing.

The final decision on the equipment type was made based on the type (analog or digital), measurement range, accuracy, stability, and total investment costs. It was eventually chosen to use the Honeywell pressure sensors connected to Raspberry Pi computers. Important reasons for this were the relatively low cost of equipment and the possibilities to extend the system in the future. The total number of measurement units was 120 and the setup is presented in Figure 1.

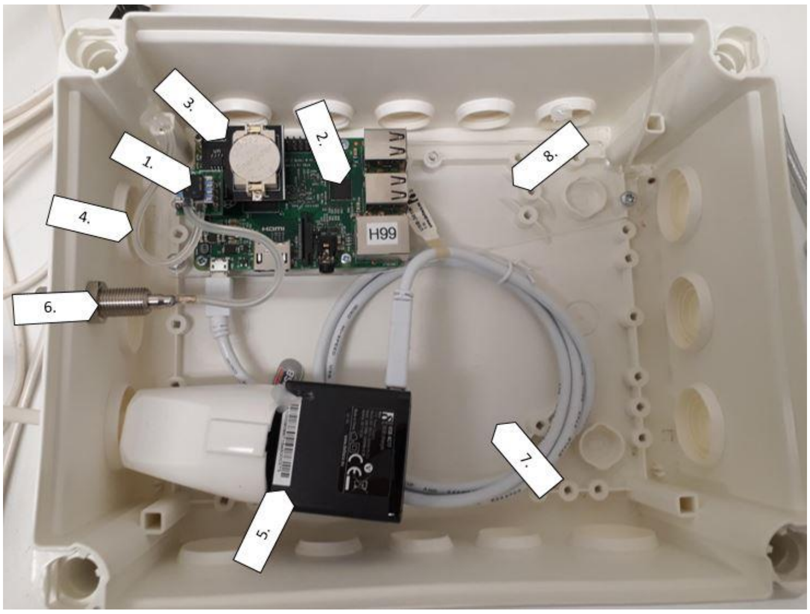


Figure 1. The air pressure difference measurement unit inside an installation box. 1. Differential pressure transmitter (Honeywell TruStability). 2. Raspberry Pi 2 model B. 3. Clock timer. 4. Flexible tube for differential pressure transmitter (indoor air conditions). 5. Power adapter for Raspberry Pi. 6. A coupler for different diameter tubes (outdoor air conditions). 7. Protective casing for the device. 8. Connection board (transparent plastic) to fix the equipment to the casing.

The chosen type of differential pressure transmitter (No. 1 in Figure 1) used I2C digital communication protocol to communicate with Raspberry Pi (2 in Figure 1). Cloud services and mobile (GSM) modems were originally installed to allow for data to be gathered without on-site visits. The system was set to boot automatically into measurement protocol when the power was turned on. The measurement interval was five minutes, and the data were written to weekly csv files, which were then uploaded into the server. A linear correction (calibration) was determined separately for each of the measurement units and applied to measurement results before further data analysis. The calibration was done using the Additel low-pressure pump and the Furness Controls pressure manometer.

In most of the studied buildings, the measuring tubes were led straight through the drilled holes in the external wall. The air gaps in drillholes of the external walls were carefully sealed in indoor and outdoor faces in the external walls to keep the building as airtight as before. Curved tubes via window frame were applied in one case study building, where drilling through the external walls was not allowed due to the airtightness requirements of a new building. The external head of the outdoor air measuring tube was sheltered with a ventilated plastic cover box to protect it from rain and other direct exposure to outdoor climatic conditions.

Despite the initial testing, a large part of the modems experienced malfunctions during the measurement campaign, and in large part, the data were not properly uploaded into the server. Malfunctions in the modem also contributed to a situation, where some of the units lost the correct time when doing an intentional reboot or when the unit was detached from the electricity socket and attached back. There were also malfunctions in the Secure Digital (SD) card durability, likely because the number of writes to the SD card started to exceed the card specifications.

Because of the data transfer and storage malfunctions, the modems were removed, dedicated clock timers (3 in Figure 1) were added, and SD cards were replaced with more durable ones during the measurement campaign. The equipment malfunctions caused several gaps into the measurement results, and the data files also had to be manually checked against pen-and-paper journals to identify the correct time stamps in the data. If the measurement results were not possible to allocate to a certain time period with confidence, then those parts of the data were removed from the studies presented in this paper.

2.3. Measurement Times and Data Analysis

The total duration of field measurements, i.e., the measurement units being in the studied buildings was about 19.5 months, lasting from 21 November 2016 to 8 July 2018. The duration of individual time series varied within these limits due to differences in installation/removal dates and possible equipment malfunctions.

The first task of the data analysis was to identify reliable time stamps, align the data sets according to them and remove the sections of the data where the correctness of the time stamps was uncertain. This was done largely manually. After that, each of the data sets were plotted in whole and in parts with Python code to visually inspect the overall behavior of the data.

A base-case scenario was formed by keeping each individual time series at its maximum length. It was, however, also of interest to study variations within the whole measurement campaign, such as due to differences between summer and winter, and between working weeks and holiday weeks. Because of this, the data were divided into winter season 2016–2017 and spring/summer season 2018, and then for work/holiday weeks as follows: 12–18 December 2016 (work week), 26 December 2016–1 January 2017 (holiday week), 14–20 May 2018 (work week), 4–10 June 2018 (holiday week), and 2–8 July 2018 (holiday week). These individual calendar weeks were selected based on the regional time schedules for schools and daycare centers, the representation of different times of the year, and the availability of measurement data with correct time stamps. It was required that a time series needed to have at least 1500 readings (~5 days and 5 h out of 7 days) for it to be included into the analysis.

The calendar weeks were then further divided into four operating situations (OS). This was done because of the distinctive patterns in how the studied schools and daycare centers and their ventilation systems were being used. The most common use was the normal school and daycare activities during the day, while some of the buildings had additional evening activities, such as hobby groups. The four different operating situations used (OS) for this study are presented in Table 1.

Table 1. The different operating situations (OS) used in the study. The daytime/night-time hours were selected as a little bit shorter compared to full working day to include only times of full/no occupancy.

Operating Situation	Symbol	Days of the Week	Time
Whole week	OS 0	Mon-Sun	00:00–24:00
Daytime during working days (weekdays)	OS 1	Mon-Fri	10:00–14:00
Night-time between Monday evening and Friday morning (weeknights)	OS 2	Mon-Fri	23:00–04:00
Weekends	OS 3	Sat-Sun	00:00–24:00

Descriptive statistics were calculated for each of the data sets. The statistics were related to the time of air pressure difference being in certain range or to the air pressure differences corresponding to certain cumulative distribution function (cdf) percentages.

The descriptive statistics were: (i) the number of readings, (ii) percentage of time of underpressure ($\Delta P < 0$ Pa), (iii) percentage of time of overpressure ($\Delta P > 0$ Pa), and (iv) percentage of time air pressure difference in the range –15...0 Pa; (v) the 0% cdf value (minimum), (vi) 2.5% cdf value, (vii) 50% cdf value (median), (viii) 97.5% cdf value, (ix) 100% cdf value (maximum), and (x) the arithmetic mean.

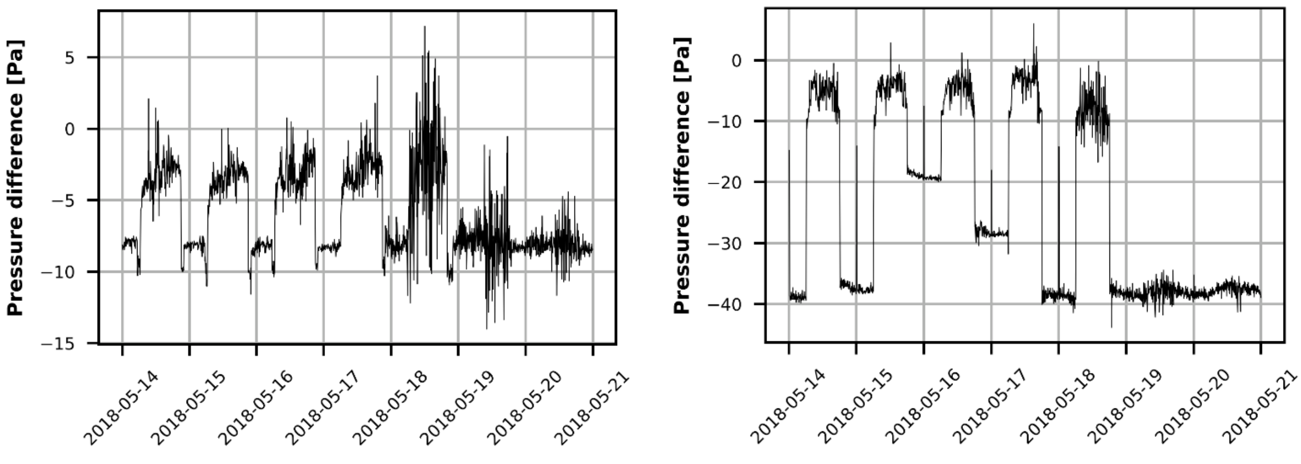
Statistical tests were used to compare new and retrofitted buildings to each other. The *t*-test for two independent samples with unequal variances tests the null hypothesis that the sample means are equal. The Mann–Whitney U-test was used to test if two independent samples came from the same population. The U-test assumes the homogeneity of the variances for the background population but is less strict for the violation of this than the *t*-test for two independent samples (not the previous test). The two-sample Kolmogorov–Smirnov (KS) was used to test if the two samples came from the same distribution [56]. The two-tailed *p*-values were calculated with the scipy.stats package [57]. The alpha level was set to 0.05.

Besides air pressure difference measurements, additional information was also gathered from the studied buildings, such as type and service areas of mechanical ventilation systems, short questionnaires to building users on indoor air conditions, and measurements on indoor and outdoor air conditions. This material was utilized as a background material when studying the air pressure difference conditions but could also be further studied in future projects.

3. Results and Discussion

3.1. General Description of Air Pressure Difference Behaviour

One of the first noticeable things in the data were the regular behavior of air pressure difference in certain measurement points. This was due to the mechanical ventilation commonly used in the studied schools and daycare centers and which was typically scheduled to run with higher airflow rate during the weekdays and lower airflow rate during other times. Examples of typical air pressure difference behavior are shown in Figure 2.



(**a**) (**b**)

Figure 2. Examples of regularly varying air pressure differences between 14 and 21 May 2018. Air pressure differences were strongly controlled by the mechanical ventilation. Typically, the air pressure difference was smaller (closer to zero) during daytime and larger during weeknights and weekends. (**a**) Small underpressure with steady pattern; (**b**) large underpressure during weeknights and weekends with changing pattern during weeknights.

In Figure 2a, the air pressure difference was approximately −8 Pa during weeknights and weekends (OS2, OS3) and −3 Pa during the weekdays (OS1). These values can be considered good from the perspective of the Finnish guidelines. In Figure 2b, the air pressure difference was approximately −20...−40 Pa during weeknights and weekends and −5 Pa during weekdays. In this case, the weekday values were within the recommended range, but the weeknight and weekend values were larger compared with the recommendations in guidelines. For both examples, the air pressure difference was mostly negative, which is in line with the national guidelines.

In the previous examples, the air pressure difference behaved in a regular way, but this was not always the case. In some measurement points, the air pressure difference had greater variance within each operating situation (OS), and the data might not show as clear patterns as in Figure 2. Two more examples of air pressure difference from individual measurement points are shown in Figure 3.

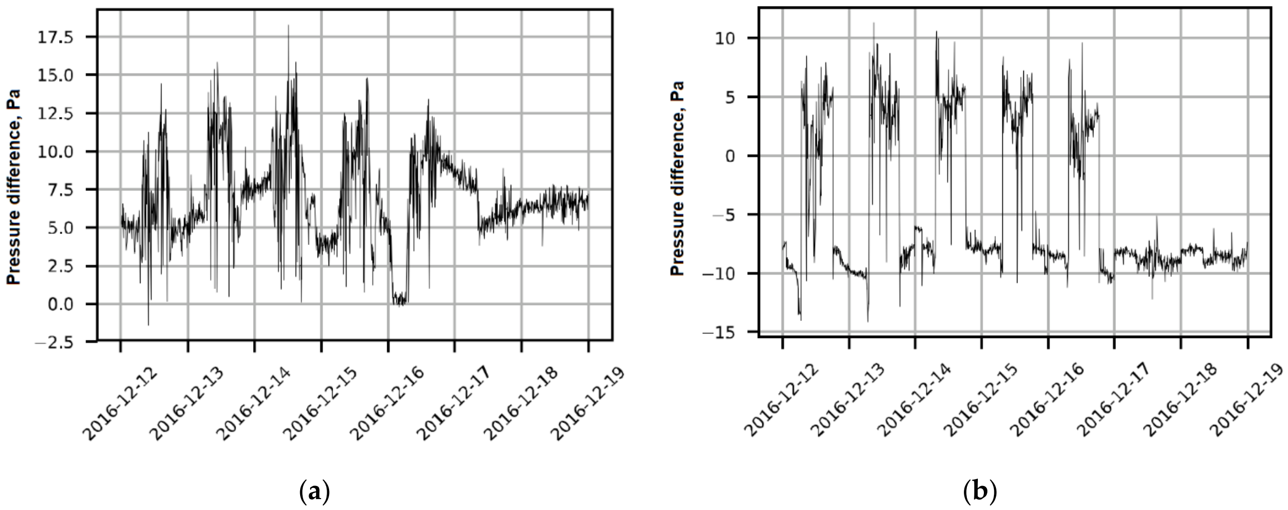


Figure 3. Air pressure difference over the exterior wall. (**a**) Measurements showing overpressure conditions with higher values during weekdays; (**b**) fluctuation between under- and overpressure.

Figure 3a shows continuous overpressure conditions with higher values during weekdays, compared to weeknights. The figure shows also varying weeknight air pressure conditions, when comparing successive nights. This kind of behavior was a clearer step-change type in Figure 2b, whereas in Figure 3a, it is more gradual. Some of the measurement points also experienced fluctuation between under- and overpressure conditions, as is shown in Figure 3b.

Some of the measurement results showed strong ($|\Delta P| > 100$ Pa) peaks, which could be either positive or negative. When they occurred, it was typically during afternoon hours and lasted for approximately 5–20 min. The reason for these peaks was not certain, but they could have been created by multiple ventilation units operating at little bit different schedules. One-day irregularities were also noticed from the data, when the air pressure level differed a certain day and then returned to the original level. The likely cause for these differences were the various events held in the measured buildings, such as open house days, ceremonies, and parties.

Overall, the air pressure conditions showed multiple kinds of patterns and ranges, although the basic functionality of the buildings was somewhat similar (schools and daycare centers), and the measurements were done from the first-floor level.

3.2. Comparison between New and Retrofitted Buildings

A comparison of air pressure differences for new and retrofitted buildings is presented in Figure 4. The cumulative distribution functions (cdf) represent the 2.5% cdf values, arithmetic means, and 97.5% cdf values calculated from all the measurement points and from the full final time series. The bold vertical lines in Figure 4 show the national guidelines for air pressure differences according to Ch. 1.2 (−15 Pa, −5 Pa, and 0 Pa).

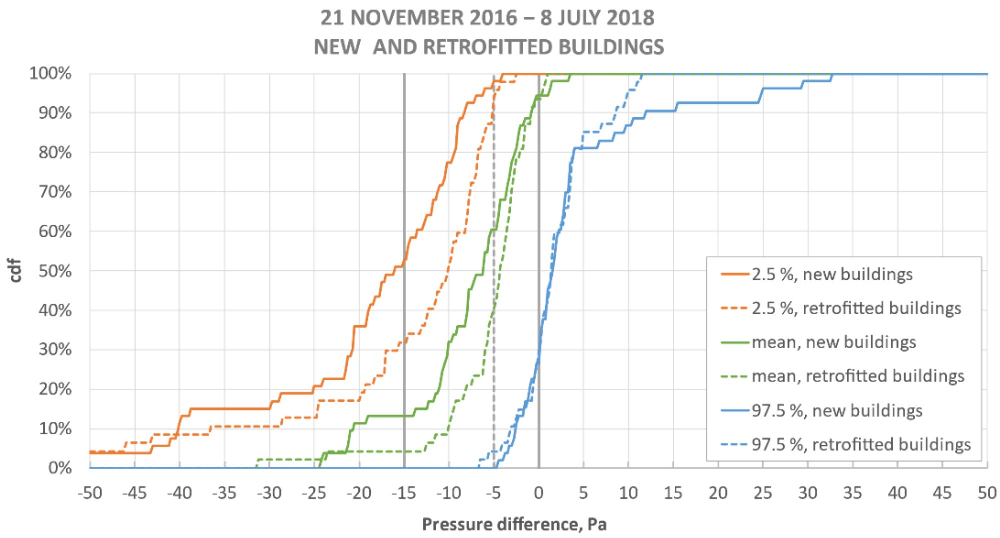


Figure 4. Cumulative distribution functions of 2.5% cdf values (**left**), mean (**center**), and 97.5% cdf values (**right**) of air pressure differences in all of the measurement points. The values for new (solid lines) and retrofitted buildings (dashed lines) are calculated from the whole measurement duration. Vertical lines describe the national guidelines for air pressure differences over the building envelope.

Based on Figure 4, the air pressure differences over the ground floor walls were generally smaller in retrofitted buildings, compared with new buildings. This is visible in curves for the 2.5% cdf values and means in Figure 4, where the dashed lines are closer to zero, compared with the solid lines. The upper-range values described by the 97.5% cdf values were similar between retrofitted and new buildings for approximately 80% of the measurement points (up to +4 Pa overpressure), but for the last 20% of measurement points, the new buildings experienced higher overpressures compared with the retrofitted buildings. In other words, the differences between new and retrofitted buildings were most visible in Figure 4 for the largest underpressures and largest overpressures.

The cdf curves in Figure 4 show smooth increase in the middle part of the curves, but also horizontal flat sections in the lower and upper ends of the curves. This means that there was ~5–15% of measurement points with higher-than-typical underpressure and ~10% of measurement points with higher-than-typical overpressure conditions. From the perspective of building maintenance, the ventilation systems related to these measurement points would be primary targets for further investigations and performance improvements.

Based on visual inspection of Figure 4, the value range between 97.5% cdf values and 2.5% cdf values was mostly between 10 Pa and 30 Pa, depending on the case and the specific cumulative distribution function percentile.

On the comparison of new and retrofitted buildings the two-tailed *p*-values from statistical tests were as follows: for the 2.5% cdf values, the *t*-test showed not significant ($p = 0.12$) results, while the U-test and KS test showed statistically significant difference ($p = 0.004$ and 0.012). For means, the *t*-test and KS test showed not significant results ($p = 0.064$ and 0.060), while the U-test showed statistically significant results ($p = 0.038$). For the 97.5% cdf values, none of three tests (*t*-test, U-test, and KS test) showed statistically significant results ($p = 0.15$, 0.80, and 0.86, respectively). These results are interpreted such that, although the proper adjustment of the ventilation system will likely reduce the largest underpressure conditions, the a priori difference between randomly selected new and recently retrofitted building is likely to be small. Further descriptive statistics are given in Table 2.

The mean air pressure difference was within −15 Pa and 0 Pa in 81% (new buildings, 43/53) and 89% (retrofitted buildings, 42/47) of measurement points, and within –5 Pa and 0 Pa in 34% (18/53) and 53% (25/47), respectively. The values correspond to a visual inspection of Figure 4.

Table 2. The number of measurement points belonging to different groups and the cumulative distribution function percentiles for air pressure differences in the groups.

Building	Value	Number of Measurement Points					Percentiles for Each of the Indicator					
		Total	<0 Pa	>0 Pa	−15...0 Pa	−5...0 Pa	0%	2.5%	50%	97.5%	100%	Mean
New	2.5%	53	53	0	26	1	−109.5	−55.2	−16.2	−5.4	−4.1	−20.4
	mean	53	50	3	43	18	−24.4	−23.3	−6.2	1.4	3.3	−7.8
	97.5%	53	14	39	14	14	−4.7	−3.8	1.6	28.1	32.6	3.8
Retrofitted	2.5%	47	47	0	32	3	−68.4	−61.9	−10.0	−4.5	−2.6	−15.4
	mean	47	44	3	42	25	−31.3	−21.9	−4.3	0.6	0.8	−5.5
	97.5%	47	14	34	13	11	−6.6	−5.5	1.4	10.9	11.4	2.0

The minimum mean air pressure differences were −24.4 Pa for new buildings and −31.3 Pa for retrofitted buildings, respectively. The order of these is different when compared with the mean-of-means, where the value for new buildings was further away from zero compared to retrofitted buildings. The minimum (single measurement points) 2.5% cdf value was −109.5 Pa for new buildings and −68.4 Pa for retrofitted buildings, both of which are quite strong underpressure conditions. The absolute minimum air pressure difference values were smaller than these. The maximum 97.5% cdf value was +32.6 Pa for new buildings and +11.4 Pa for retrofitted buildings.

3.3. Comparison between Different Operating Situations

Figure 5 shows the cumulative distributions functions for new and retrofitted buildings and for different operating situations OS 1–OS 3 (Table 1).

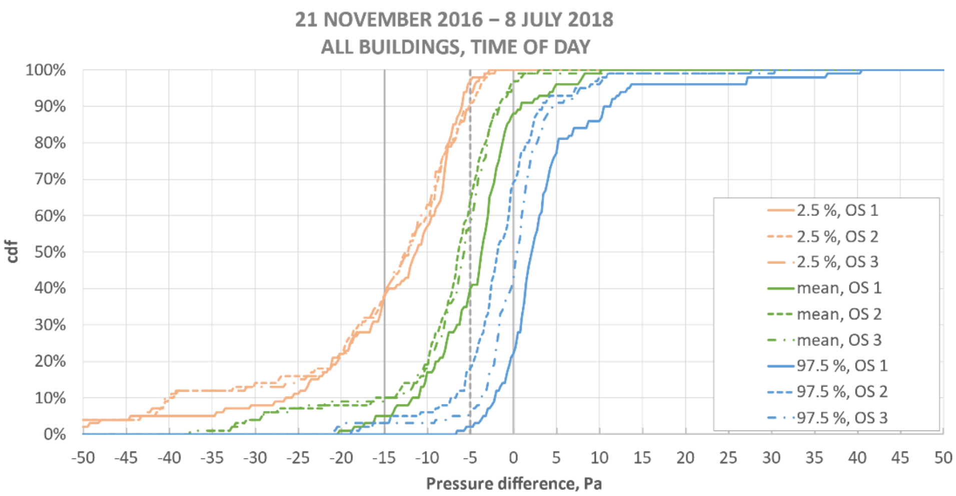


Figure 5. Cumulative distribution functions of 2.5% cdf values (**left**), means (**center**), and 97.5% cdf values (**right**) for three operating situations (OS). The bolded vertical lines indicate guideline values for air pressure differences.

The low-end values of air pressure differences (2.5% cdf values in Figure 5) were close to each other between different operating situations. The differences between operating situations were larger when compared using the means of the samples and largest when compared using the 97.5% cdf values.

To study the correlation between air flow rate and air pressure difference further, an equation was derived for the impact of a small, fixed-size change in volumetric airflow rate: First, the power-law equation is written as: $q_v = C\Delta P^n$, where q_v is the volumetric air flow rate (m^3/s) and ΔP is the air pressure difference (Pa). Flow coefficient C and flow exponent n are positive and determined by least-squares procedure [58]. Flow exponent n is assumed to be smaller than one ($n < 1$). Secondly, the formula is written as: $\Delta P = ((q_v + \Delta q_v)/C)^{1/n}$, where Δq_v (m^3/s) is a small positive fixed value that describes the inaccuracy in the airflow rate adjustment. Thirdly, the change to air pressure difference ΔP_{change} (Pa) from constant Δq_v is defined as: $\Delta P_{change} = \Delta P_{\Delta q_v} - \Delta P_{\Delta q_v = 0} = ((q_v + \Delta q_v)/C)^{1/n} - (q_v/C)^{1/n}$. From these equations it can be noticed, that because $n < 1$, then $1/n > 1$. This leads to the result, that for a fixed Δq_v, the change in air pressure difference ΔP_{change} increases, as the absolute airflow rate q_v increases. The results in Figure 5 contradicts this result, so it is concluded that the variation in air pressure difference conditions must also be affected by other variables than just the natural power-law-type behavior at different airflow rate levels.

If we look at the mean air pressure difference curves in Figure 5, then the weekdays (OS 1) had values closest to 0 Pa, when compared with OS 2 and OS 3. This result was in line with the Finnish indoor environmental guideline values being targeted primarily for occupied hours. Further details of different operating situations are given in Table 3.

Table 3. Descriptive statistics on the air pressure differences for different operating situations. The total number of measurement points was $n = 100$.

Operating Situation	Value	Under-Pressure, % of Time	Over-Pressure, % of Time	In Range −15...0 Pa, % of Time	Percentile					Mean
					0%	2.5%	50%	97.5%	100%	
OS 1 Mon-Fri 10–14	2.5%	100	0	62	−65.4	−48.7	−11.3	−5.0	−2.8	−15.0
	Mean	88	12	83	−20.3	−16.8	−3.7	7.8	10.2	−4.5
	97.5%	22	78	22	−6.5	−4.2	2.2	27.1	40.3	3.8
OS 2 Mon-Fri 23–04	2.5%	100	0	62	−66.3	−56.5	−12.5	−3.4	−2.0	−16.5
	Mean	97	3	87	−35.4	−31.7	−6.3	0.3	3.0	−8.0
	97.5%	69	31	66	−18.9	−15.5	−1.9	9.7	27.7	−1.6
OS 3 Sat-Sun 00–24	2.5%	100	0	63	−104.9	−62.8	−12.1	−4.1	−2.0	−17.0
	Mean	95	4	87	−37.6	−31.3	−5.8	0.4	11.8	−7.6
	97.5%	41	58	39	−21.0	−14.8	0.5	10.3	30.3	0.2

The medians of means in operating situations OS 1–OS 3 were −3.7 Pa, −6.3 Pa, and −5.8 Pa, which are relatively close to each other. However, a larger difference between weekdays and weeknights/weekends in the 2.5% cdf values could be noticed.

The differences between operating situations in an individual zone level are of further interest. Figure 6 gives an example of four buildings, where the air pressure difference conditions could be further improved.

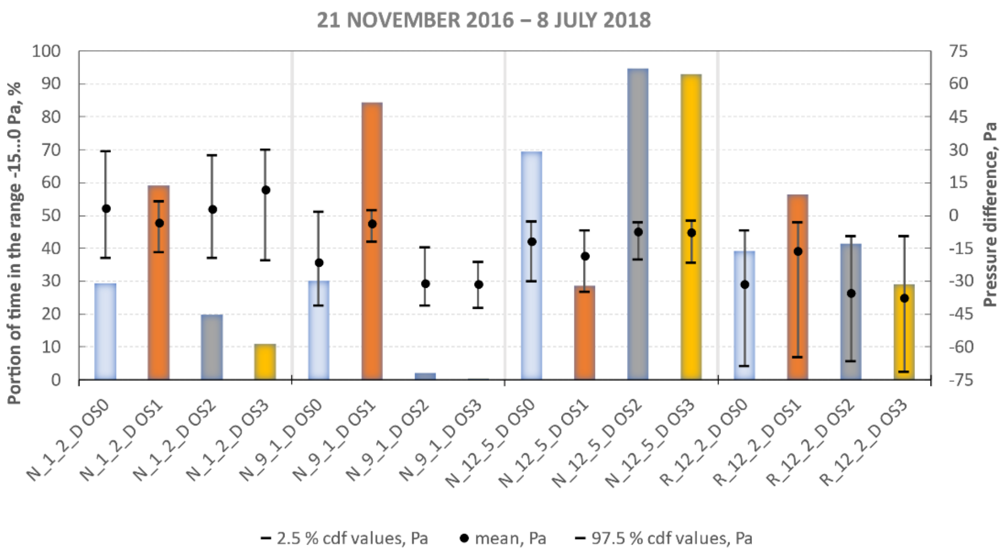


Figure 6. Example of air pressure difference conditions varying between different operating situations in four buildings. The vertical bars describe the relative portion of time that the air pressure difference was between −15 Pa and 0 Pa (left y-axis). The dot (mean) and whiskers (2.5% and 97.5% cdf values) describe the air pressure difference values (right y-axis).

The example shows that there were various combinations of air pressure difference conditions in the studied buildings. In the case of N_9_1_D, the air pressure difference at the bottom of the wall was about 84% of the time at the recommended range −15...0 Pa. However, during weeknights and weekends, there was strong underpressure beyond the recommended range. In the case of N_12_5_D, the situation was the other way around, i.e., there was strong underpressure during daytime, but the air pressure difference was closer to zero during weeknights and weekends.

In principle, the air pressure differences can be described using the variation between operating situations and variation within operating situations. As demonstrated in Figure 6, the variation between different operating situations can be large and should be accounted for. Figure 6 also shows an example of the variation within operating situation, by the range between 2.5% cdf values and 97.5% cdf values (described by the whiskers) being larger than the mean air pressure difference (described by the dot) for all the examples. This was checked for other measurement points and operating situations and the range between the two cdf values was almost always larger than the absolute mean air pressure difference for the same measurement point and operating situation. Additionally, in Figure 5, the range between 2.5% cdf values and 97.5% cdf values is much larger than the difference between different operating situations. This implies that the air pressure differences were better under control with respect to different operating situations than with respect to what happens within a specific operating situation. If the air pressure difference conditions would be improved by adjusting the mean air pressure difference per operating condition to be closer to 0 Pa, then there would still be a certain (inherent) variation in how the air pressure difference behaves during those situations. A large variation around the mean could still be harmful due to the alternating over- and underpressure, but this would require further studies. For a proper control of air pressure difference, both the variation between operating situations and within each operating situation should be addressed.

Figure 7 shows the difference in air pressure differences between the top and bottom parts of the wall.

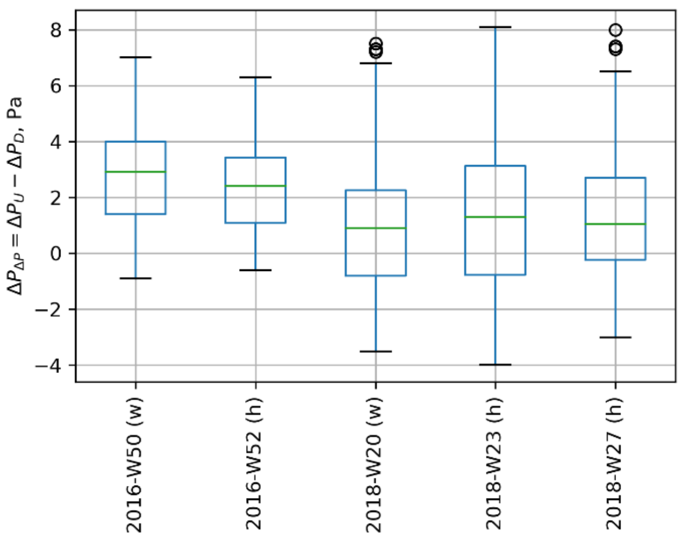


Figure 7. Difference in air pressure differences over the top and bottom parts of the wall. Each of the box-and-whiskers plots describe one week of data. (w) = work week, (h) = holiday week, (U) = upper part of the wall, (D) = lower part of the wall.

The mean (standard deviation) outdoor air temperature during weeks 2016-W50, 2016-W52, 2018-W20, 2018-W23, and 2018-W27 were as follows: −2.6 °C (3.0 °C), 1.4 °C (2.8 °C), 16.8 °C (5.3 °C), 11.7 °C (4.1 °C), and 16.3 °C (3.2 °C), respectively. The values are calculated from the stacked hourly outdoor air temperatures of The Finnish Meteorological Institute observation stations at Helsinki Kaisaniemi and Pirkkala Tampere-Pirkkala Airport [59].

The upper parts of the measured walls experienced an air pressure difference that was closer to zero (less negative) than the lower parts of the walls. For example, if the air pressure difference at the top part of the wall would be −9 Pa and at the bottom part of the wall −12 Pa, then the difference in air pressure differences would have been: (−9 Pa) – (−12 Pa) = 3 Pa. If we use an average vertical height difference of: 2.7 m – 0.24 m = 2.46 m between the measurement units, then the air pressure difference would have decreased approximately by: 3 Pa/2.46 m = 1.2 Pa/m during winter conditions. For more accurate results the averaging should be done last and is left for future studies. Figure 7 also shows negative values especially in summer conditions, which might have been caused by solar radiation and surface heating on the exterior side of the wall structure and/or measurement uncertainties. The influence from work or holiday week was considered minor.

4. Conclusions

This paper presented field measurement results of air pressure difference over the building envelope from 22 Finnish schools and daycare centers and two elderly housing units. The measurement points were located at the ground floor. All studied buildings had mechanical ventilation. The measurement units (n = 100) were built around Raspberry Pi computers with Honeywell pressure sensors. The equipment experienced malfunctions in the internet connection, SD card durability, and internal clock, which were later fixed, but caused interruptions to the measurement data. Data with uncertain time stamps were removed from the analysis.

Certain measurement points showed strong stepwise air pressure differences caused by the time schedules of the mechanical ventilation. There were also situations where the air pressure difference had some rough average level, but had higher temporal variation, likely caused by the variable air volume (VAV) system, wind, and user behavior. On average, the air pressure difference was between −15 Pa and 0 Pa in 81% of measurement points in new buildings (mean −7.8 Pa) and 89% of measurement points in retrofitted buildings (mean −5.5 Pa). Visual inspection and statistical tests of the results implied that the recently retrofitted buildings had the largest underpressure conditions that were better in line with the Finnish guidelines when compared with the new buildings. The difference was, however, small when compared to the overall variation in the results.

Although the average air pressure differences were quite well within the recommended range, the overall conditions could be improved. The top ~10% of measurement points at both high underpressure and overpressure conditions should be brought within the recommended range and the overall temporal variation could be reduced. The conditions also varied between operating situations, creating multiple combinations of values being in or out of the recommended range. Due to the variation between operating situations, it is recommended to use continuous measurements of at least one week when studying the air pressure difference conditions of a building (as is instructed in current Finnish condition investigation guidelines). The time resolution for successive measurements should be short, e.g., a few minutes. The time of year and outdoor air temperature affect the magnitude of stack effect in the building, and the evaluation process of the air pressure difference conditions should take this into account.

Comparison to earlier literature is not straightforward because earlier results have been primarily reported for single buildings or for point-like (not continuous) measurements. Nevertheless, previous studies have shown underpressure at the ground floor, and the same behavior was present in this study.

From the viewpoint of this study, it would be reasonable to first ensure that largest air pressure differences are decreased to be within the guideline values. After that, the optimum mean air pressure difference should be set by taking into account the size of the indoor moisture excess, amount of impurities in the building envelope, and the safety margin related to the variance in air pressure difference. This would improve the accuracy of building performance evaluation.

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Appendix A

The next tables give additional information on the measured buildings and zones. The measurements were conducted during 2016–2018, and there was variation in the length of the measurement period corresponding to individual measurement units.

Table A1. The new case study buildings. The city of Helsinki is located in Southern Finland and the Pirkanmaa region in the southwest part of Finland. (*): Building has a new and retrofitted part.

Case	Area	Building Use	Construction Year	Number of Studied Zones (28 in Total)
N 1	Helsinki	School and daycare center	2015	2
N 2	Pirkanmaa	Daycare center	2014	1
N 3	Helsinki	School and daycare center	2012	3
N 4	Pirkanmaa	Assisted living facility	2013	1
N 5 *	Pirkanmaa	School	2006	2
N 6	Helsinki	School and daycare center	2013	2
N 7	Pirkanmaa	Daycare center	2014	1
N 8	Helsinki	Daycare center	2013	2
N 9	Helsinki	Daycare center	2015	3
N 10	Pirkanmaa	Daycare center	2012	3
N 11 *	Pirkanmaa	School	2012	2
N 12	Pirkanmaa	School and daycare center	2013	6

Table A2. The retrofitted case study buildings. The city of Helsinki is located in Southern Finland and the Pirkanmaa region in the southwest part of Finland. (*) Building has a new and retrofitted part.

Case	Area	Building Use	Construction Year	Retrofitting Year	Number of Studied Zones (25 in Total)
R 1	Pirkanmaa	Daycare center	1983	2015	2
R 2	Pirkanmaa	Daycare center	1980	2014	2
R 3	Pirkanmaa	Assisted living facility	1955	2013	3
R 4	Pirkanmaa	Daycare center	1906	2013	1
R 5 *	Pirkanmaa	School	1950	2016	1
R 6	Helsinki	Daycare center	1981	2013	2
R 7	Helsinki	Daycare center	1971	2012	2
R 8	Helsinki	Daycare center	1976	2015	2
R 9	Helsinki	School	1966	2013	3
R 10	Pirkanmaa	Daycare center	1929	2012	1
R 11 *	Pirkanmaa	School	1958	2012	2
R 12	Helsinki	School	1965	2014	4

Table A3. A listing of the zones that were monitored in the measurement campaign. N = New building, R = Retrofitted building. Zone id is of the format <building number>_<zone number>. (*) N_3_7 Gym was not included in the calculations on the difference of air pressure differences between top and bottom part of the wall (Figure 7).

New Buildings			Retrofitted Buildings		
Building Type	**Zone Id**	**Description**	**Building Type**	**Zone Id**	**Description**
N	1_1	Lunchroom	R	1_1	Staff room
N	1_2	School class	R	1_2	Playroom
N	2_1	Playroom	R	2_1	Shower/WC-room
N	3_1	School class	R	2_2	Playroom
N	3_2	Rest room	R	3_1	Hall
N	3_7	Gym (*)	R	3_2	Hall
N	4_1	Habitable room	R	3_8	Habitable room
N	5_1	School class	R	4_1	Playroom
N	5_3	School class	R	5_1	Staircase
N	6_1	Storeroom	R	6_1	Playroom
N	6_2	Playroom	R	6_2	Playroom
N	7_1	Playroom	R	7_1	Playroom
N	8_1	Playroom	R	7_2	Playroom
N	8_2	Playroom	R	8_1	Playroom
N	9_1	Playroom	R	8_2	Playroom
N	9_2	Office room	R	9_1	School class
N	9_3	Office room	R	9_2	School class
N	10_1	Playroom	R	9_5	School class
N	10_2	Playroom	R	10_1	Playroom
N	10_3	Kitchen	R	11_1	Hall
N	11_1	School class	R	11_2	School class
N	11_2	Gym	R	12_1	School class
N	12_1	Office room of the kitchen	R	12_2	Lunchroom
N	12_2	Hall	R	12_3	School class
N	12_3	Staff room	R	12_5	Gym
N	12_4	Playroom			
N	12_5	Consulting room			
N	12_6	Utility services room			

References

1. CGPM. Resolution 4 of the 10th CGPM. Definition of the standard atmosphere. In Proceedings of the 10th CGPM (1954), Paris, France, 5 October 1954; Available online: https://www.bipm.org/en/committees/cg/cgpm/10-1954/resolution-4 (accessed on 29 April 2022).
2. ASHRAE. ASHRAE Fundamentals, Atlanta, GA. 2017. Available online: www.ashrae.org (accessed on 29 April 2022).
3. Hagentoft, C.-E. *Introduction to Building Physics*; Studentlitteratur: Lund, Sweden, 2001.
4. Lstiburek, J.W. Toward and Understanding and Prediction of Air Flow in Buildings. Ph.D. Thesis, University of Toronto, Toronto, Canada, 2000.
5. Axley, J. Multizone Airflow Modeling in Buildings: History and Theory. *HVACR Res.* **2007**, *13*, 907–928. [CrossRef]
6. Annex 23, Multizone Air Flow modelling (COMIS), Technical Synthesis Report, IEA ECBCS, 1996. Available online: https://www.iea-ebc.org/projects/project?AnnexID=23 (accessed on 29 April 2022).
7. Khoukhi, M.; Yoshino, H.; Liu, J. The effect of the wind speed velocity on the stack pressure in medium-rise buildings in cold region of China. *Build. Environ.* **2007**, *42*, 1081–1088. [CrossRef]
8. Khoukhi, M.; Al-Maqbali, A. Stack Pressure and Airflow Movement in High and Medium Rise buildings. *Energy Procedia* **2011**, *6*, 422–431. [CrossRef]
9. Jokisalo, J.; Kalamees, T.; Kurnitski, J.; Eskola, L.; Jokiranta, K.; Vinha, J. A Comparison of Measured and Simulated Air Pressure Conditions of a Detached House in a Cold Climate. *J. Build. Phys.* **2008**, *32*, 67–89. [CrossRef]
10. Ng, L.; Musser, A.; Persily, A.; Emmerich, S. Multizone airflow models for calculating infiltration rates in commercial reference buildings. *Energy Build.* **2013**, *58*, 11–18. [CrossRef]
11. Domhagen, F.; Wahlgren, P.; Hagentoft, C.-E. Pressure distribution around the thermal envelope—A parametric study of the impact from wind and temperature on contaminant transport within building. *E3S Web Conf.* **2020**, *172*, 11004. [CrossRef]

12. Kosonen, R.; Jokisalo, J.; Ranta-aho, I.; Koikkalainen, E.-P. Methods to Reduce Stack Effect and Improve Energy Efficiency in a Nordic High Rise Residential Building. *Procedia Eng.* **2017**, *205*, 2311–2317.
13. Gimenez, J.; Bre, F. Optimization of RANS turbulence models using genetic algorithms to improve the prediction of wind pressure coefficients on low-rise buildings. *J. Wind. Eng. Ind. Aerodyn.* **2019**, *193*, 103978. [CrossRef]
14. Srebric, J. *Ventilation Performance Prediction from: Building Performance Simulation for Design and Operation*; Routledge: London, UK, 2019.
15. Ayata, T. Investigation of building height and roof effect on the air velocityand pressure distribution around the detached houses in Turkey. *Appl. Therm. Eng.* **2009**, *29*, 1752–1758. [CrossRef]
16. Jaffe, A.; Kopp, G. Internal pressure modelling for low-rise buildings in tornadoes. *J. Wind. Eng. Ind. Aerodyn.* **2021**, *209*, 104454. [CrossRef]
17. Blocken, B. Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Build. Environ.* **2015**, *91*, 219–245. [CrossRef]
18. Toja-Silva, F.; Kono, T.; Peralta, C.; Lopez-Garcia, O.; Chen, J. A review of computational fluid dynamics (CFD) simulations of the wind flow around buildings for urban wind energy exploitation. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *180*, 66–87. [CrossRef]
19. Tian, W.; Sevilla, T.A.; Zuo, W.; Sohn, M. Coupling fast fluid dynamics and multizone airflow models in Modelica Buildings library to simulate the dynamics of HVAC systems. *Build. Environ.* **2017**, *122*, 269–286. [CrossRef]
20. King, M.-F.; Khan, A.; Delbosc, N.; Gough, H.L.; Halios, C.; Barlow, J.F.; Noakes, C.J. Modelling urban airflow and natural ventilation using a GPU-based lattice-Boltzmann method. *Build. Environ.* **2017**, *125*, 273–284. [CrossRef]
21. Strege, S.; Ferreira, M. Characterization of Stack Effect in High-Rise Buildings Under Winter Conditions, Including the Impact of Stairwell Pressurization. *Fire Technol.* **2017**, *53*, 211–226. [CrossRef]
22. Yu, J.-Y.; Song, K.-D.; Cho, D.-W. Resolving Stack Effect Problems in a High-Rise Office Building by Mechanical Pressurization. *Sustainability* **2017**, *9*, 1731. [CrossRef]
23. Yoon, S.; Song, D.; Kim, J.; Kim, J.; Koo, H.L.J. Identifying stack-driven indoor environmental problems and associated pressure difference in high-rise residential buildings: Airflow noise and draft. *Build. Environ.* **2020**, *168*, 106483. [CrossRef]
24. Leivo, V.; Kiviste, M.; Aaltonen, A.; Turunen, M.; Haverinen-Shaugnessy, U. Air Pressure Difference between Indoor and Outdoor or Staircase in Multi-family Buildings with Exhaust Ventilation System in Finland. *Energy Procedia* **2015**, *78*, 1218–1223. [CrossRef]
25. Leivo, V.; Prasauskas, T.; Turunen, M.; Kiviste, M.; Aaltonen, A.; Dainius, M.; Haverinen-Shaugnessy, U. Comparison of air pressure difference, air change rates, and CO_2 concentrations in apartment buildings before and after energy retrofits. *Build. Environ.* **2017**, *120*, 85–92. [CrossRef]
26. Kalamees, T.; Kurnitski, J.; Jokisalo, J.; Eskola, L.; Jokiranta, K.; Vinha, J. Air pressure conditions in Finnish residences. In Proceedings of the Clima 2007 WellBeing Indoors, Helsinki, Finland, 10–14 June 2007; Available online: https://www.researchgate.net/publication/228860304_Air_pressure_conditions_in_Finnish_residences (accessed on 29 April 2022).
27. Kalamees, T.; Kurnitski, J.; Jokisalo, J.; Eskola, L.; Jokiranta, K.; Vinha, J. Measured and simulated air pressure conditions in Finnish residential buildings. *Build. Serv. Eng. Res. Technol.* **2010**, *31*, 177–190. [CrossRef]
28. Mikola, A.; Simson, R.; Kurnitski, J. The Impact of Air Pressure Conditions on the Performance of Single Room Ventilation Units in Multi-Story Buildings. *Energies* **2019**, *12*, 2633. [CrossRef]
29. Kurnitski, J. Crawl space air change, heat and moisture behaviour. *Energy Build.* **2000**, *32*, 19–39. [CrossRef]
30. Uotila, U.; Saari, A.; Junnonen, J.-M.; Eskola, L. Assessing ventilation strategies in a school with observed indoor air problems. *Facilities* **2022**, *40*, 1–16. [CrossRef]
31. ASHRAE. ASHRAE Handbook—HVAC Applications, Ch. 4.2. 2015. Available online: www.ashrae.org (accessed on 29 April 2022).
32. Cooper, L. Design, implementation, and control of building pressurization to protect occupants from arbitrarily hazardous environments. *Sci. Technol. Built Environ.* **2018**, *24*, 1114–1140. [CrossRef]
33. Shi, Y.; Li, X.; Sadatiseyedmahalleh, S. Influence of building envelope type on the minimum mechanical ventilation rate to achieve a positive indoor air pressure. *E3S Web Conf.* **2020**, *172*, 05002. [CrossRef]
34. Mäkeläinen, I.; Arvela, H.; Voutilainen, A. Correlations between radon concentration and indoor gamma dose rate, soil permeability and dwelling substructure and ventilation. *Sci. Total Environ.* **2001**, *272*, 283–289. [CrossRef]
35. Arvela, H.; Bergman, J.; Yrjölä, R.; Kurnitski, J.; Matilainen, M.; Järvinen, P. Developments in radon-safe building in Finland. *Radioact. Environ.* **2005**, *7*, 618–623.
36. Choi, D.H.; Kang, D.H. Indoor/Outdoor Relationships of Airborne Particles under Controlled Pressure Difference across the Building Envelope in Korean Multifamily Apartments. *Sustainability* **2018**, *10*, 4074. [CrossRef]
37. Laukkarinen, A.; Jokela, T.; Moistio, T.; Vinha, J. Hygrothermal simulations of timber-framed walls with air leakages. In Proceedings of the 8th International Building Physics Conference, IBPC 2021, Copenhagen, Denmark, 25–27August 2021.
38. Vornanen-Winqvist, C.; Toomla, S.; Ahmed, S.; Kurnitski, J.; Mikkola, R.; Salonen, H. The effect of positive pressure on indoor air quality in a deeply renovated school building—A case study. *Energy Procedia* **2017**, *132*, 165–170. [CrossRef]
39. Ferrantelli, A.; Vornanen-Winqvist, C.; Mattila, M.; Salonen, H.; Kurnitski, J. Positive pressure effect on moisture performance in a school building. *J. Build. Phys.* **2019**, *49*, 121–142. [CrossRef]
40. Vornanen-Winqvist, C.; Järvi, K.; Toomla, S.; Ahmed, K.; Andersson, M.; Mikkola, R.; Marik, T.; Kredics, L.; Salonen, H.; Kurnitski, J. Ventilation Positive Pressure Intervention Effect on Indoor Air Quality in a School Building with Moisture Problems. *Int. J. Environ. Res. Public Health* **2018**, *15*, 230. [CrossRef]

41. Laine, K. Pressure difference in buildings with good air-tightness: Control measurements after IAQ renovations. *E3S Web Conf.* **2020**, *172*, 05001. [CrossRef]
42. RakMK D2. The National Building Code of Finland. The Indoor Environment and Ventilation of Buildings. The Ministry of Environment, 1987. Available online: https://ym.fi/rakentamismaaraykset (accessed on 29 April 2022). (In Finnish)
43. RakMK D2. The National Building Code of Finland. The Indoor Environment and Ventilation of Buildings. The Ministry of Environment, 2003. Available online: https://ym.fi/rakentamismaaraykset (accessed on 29 April 2022). (In Finnish)
44. RakMK D2. The National Building Code of Finland. The Indoor Environment and Ventilation of Buildings. The Ministry of Environment, 2010. Available online: https://ym.fi/rakentamismaaraykset (accessed on 29 April 2022). (In Finnish)
45. Ministry of Environment. 1009/2017 Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New Buildings. 2017. Available online: https://www.finlex.fi (accessed on 29 April 2022). (In Finnish)
46. Ministry of Environment. 782/2017 Decree of the Ministry of Environment on Humidity. 2017. Available online: https://www.finlex.fi (accessed on 29 April 2022). (In Finnish)
47. Valvira, Application Guideline 8/2016 for the Decree 545/2015 from the Ministry of Social Affairs. National Supervisory Authority for Welfare and Health (Valvira). 2016. Available online: https://www.valvira.fi (accessed on 29 April 2022). (In Finnish)
48. RIL 107-2012. Guideline on the Water and Moisture Proofing of Buildings. Finnish Association of Civil Engineers RIL. 2012. Available online: https://www.ril.fi (accessed on 29 April 2022). (In Finnish)
49. Pitkäranta, M. (Ed.) *Ympäristöopas 2016. Condition Investigations for Moisture Behavior and Indoor Air Conditions of Buildings*; Ympäristöministeriö: Helsinki, Finland, 2016; Available online: http://urn.fi/URN:ISBN:978-952-11-4626-8 (accessed on 29 April 2022). (In Finnish)
50. A-Insinöörit. Measurement of Air Pressure Differences in Buildings. Final Project Report. 14.10.2019. Available online: https://ym.fi/rakentamismaaraykset (accessed on 29 April 2022). (In Finnish)
51. Pirhonen, J. Sisäilman Olosuhdemittaukset Uusissa ja Korjatuissa Palvelurakennuksissa. (Indoor Air Measurements in New and Retrofitted Service Building). Tampere University of Technology. Master's Degree Programme in Civil Engineering. 2017. Available online: https://urn.fi/URN:NBN:fi:tty-201704261344 (accessed on 29 April 2022). (In Finnish)
52. Kauppinen, A. Air Pressure Difference over the Building Envelope in New and Retrofitted Service Building. Tampere University of Technology. Master's Degree Programme in civil Engineering. 102 Pages with 228 Appendix Pages. Available online: https://urn.fi/URN:NBN:fi:tty-201811292781 (accessed on 29 April 2022). (In Finnish)
53. Kauppinen, A.; Kiviste, M.; Pirhonen, J.; Vinha, J. Air Pressure Differences at Municipal Service Buildings in Pirkanmaa and Helsinki Regions. Published at: The Finnish Building Physics Symposium 2017. 24–26 October 2017. Seminar Publication 5, Part 1. pp. 215–222. Available online: http://urn.fi/URN:ISBN:978-952-15-4022-6 (accessed on 29 April 2022). (In Finnish)
54. Tuominen, E.; Laukkarinen, A.; Kauppinen, A.; Raunima, T.; Vinha, J. Conclusions from the Air Pressure Difference Measurements in the COMBI-Project. The Finnish Building Physics Symposium 2019. 28–30 October 2019. Seminar publication 6, Part 1. pp. 139–144. Available online: https://urn.fi/URN:ISBN:978-952-03-1309-8 (accessed on 29 April 2022). (In Finnish)
55. Kiviste, M.; Vinha, J. Air pressure difference measurements in Finnish municipal service buildings. *Energy Procedia* **2017**, *132*, 879–884. [CrossRef]
56. Sheskin, D.J. *Handbook of Parametric and Nonparametric Statistical Procedures*, 2nd ed.; Chapman Hall/CRC: Boca Raton, FL, USA, 2000.
57. Virtanen, P.; Gommers, R.; Oliphant, T.; Haberland, M.; Reddy, T.; Cournapeau, D.; Burovski, E.; Peterson, P.; Weckesser, W.; Bright, J.; et al. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nat. Methods* **2020**, *17*, 261–272. [CrossRef]
58. *SFS-EN ISO 9972*; Thermal Performance of Buildings. Determination of Air Permeability of Buildings. Fan Pressurization Method. Finnish Standards Association SFS: Helsinki, Finland, 2015.
59. The Finnish Meteorological Institute, FMI Open Data. Download Observations, The Finnish Meteorological Institute. Available online: https://en.ilmatieteenlaitos.fi/download-observations (accessed on 29 April 2022).