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The Well-Being of Children in Nurseries Does Not Have to Be Expensive: The Real Costs of Maintaining Low Carbon Dioxide Concentrations in Nurseries

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Abstract: There are different standards and regulations outlining the requirements regarding building air quality as well as in nurseries. These requirements specify air stream supplies and carbon dioxide concentration levels, both of which ensure proper indoor air quality. Mechanical ventilation should be used to maintain acceptable carbon dioxide levels. This article analyses the use of ventilation equipped with decentralized units, which helps secure the well-being of children. This paper proposes and evaluates economically affordable ventilation units. An algorithm for selecting the size of the devices is described by the supplied air stream depending on the number of children present at the nursery. A method of transferring the investment costs related to the assembly of the given units to the parents is proposed. Air quality in terms of CO_2 concentrations was based on the following levels: 750 ppm, 1000 ppm, 1500 ppm. This assessment also includes the investment costs resulting from device usage and the costs of electricity consumed by the fans. These results showed the additional costs that assure the air quality improvement do not have to be high (45 PLN/month, ~10 EUR/month) per child attending the nursery. A 3% tuition increase returns the investment costs on mechanical ventilation within four years.

Keywords: indoor air quality; IAQ; nursery; economic costs; ecological costs; decentralized ventilation; façade ventilation

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1. Introduction

The population of Poland was 38,479,000 at the end of 2014 and included 2,801,000 children from 0–7 years of age, which comprised 7.3% of the total Polish population [1]. Half of the children in Poland live in the cities, which forces their working parents to pay for child care. Approximately 12.4% of parents send their children to public or non-public nurseries due to the lower costs. According to data provided by the Central Statistical Office, the number of institutional care places for children up to age 3 in 2019 has increased by 15.4% compared to 2018. There were 4400 nurseries, children clubs and nursery branches which operated that year and provided 159,900 places for children. The indicator of pupil numbers per 1000 children up to age 3 increased from 105 in 2018 to 124 in 2019. As the parents care for the health of their children they should pay particular attention to the quality of in the rooms in which their children are staying [2]. One of the key aspects connected to a healthy and comfortable environment dedicated to people is its physical quality.

The quality of indoor air can be described by several indicators such as the [3–5] carbon dioxide (CO_2) concentration of the volatile organic compounds (VOC), the concentration of particulate matter (PM) [6] or the presence of the bio-aerosols (biologic aerosols). Carbon dioxide is not hazardous in and of itself, but its increased concentration in the room may cause problems with focusing, learning, general feeling unwell, somnolence and even death at extreme concentrations [7–12].

Volatile organic compounds (VOC) are toxic, airborne substances, which volatilize and people inhale. Sources of VOCs in the room come from all manner of chemical substances used for finishing works in the rooms (paints, glues, gypsum) and cleaning (rinse aids, fresheners, insect repellents). Higher concentrations of particulate matter and long environmental stays with high concentrations of PM may cause respiratory and cardiovascular diseases [12–15].

Most biological particles do not create serious health dangers; however, some may contain pathogenic properties as well as allergenic or toxic ones. Higher indoor concentrations of bacteria and fungi may cause severe medical conditions such as fever, headache, cough or respiratory failure. [16,17]. Several papers have described the increased concentrations of CO_2, VOCs, dust, bacteria and/or fungi in educational purpose buildings with a particular focus on schools. The main reason for poor air quality stems from insufficient room ventilation [6,7,18–20]. School or nursery buildings are usually ventilated via airing when the natural ventilation ducts are occluded. That way is particularly troublesome when the external environment contains larger concentrations of hazardous substances [3,7,8] such as during the winter which lasts from October until May in Poland. Airing as the only method for air quality improvement very often brings an opposite effect because an uncontrolled volume of polluted air enters the building and exacerbates the already polluted indoor air. Children who stay in rooms with poor air quality get sick more often [4]. Cleaning the outside air before it is introduced inside or by cleaning the indoor air helps alleviate this problem [6,7,21]; however, the latter option is quite often ineffective [6]. The location of the building is very important. If the building is located in an industrial area or close to intensive road traffic, the indoor air quality, connected to the external air quality, will be worse [3,4,15].

1.1. Air Quality Standards

There are different standards and regulations regarding building air quality and those standards extend to nurseries as well. These requirements specify air stream supplies or carbon dioxide concentration levels that ensure proper indoor air quality. Table 1 shows requirements regarding carbon dioxide levels following different guidelines.

Table 1. Requirements regarding maximum CO_2 concentrations in different guidelines.

Air Quality	Guideline	CO_2 Concentration [ppm]
Very good	EN 13779 [22]	750 (350 + concentration in the outdoor air)
	EN 13779 [22]	900 (500 + concentration in the outdoor air)
Good	ASHRAE [23], BR10 [24]	1000
	EN 13779 [22]	1200 (800 + concentration in the outdoor air)
Acceptable	DIN [25], BB101 [26]	1500
Low	EN 13779 [22]	1600 (120 + concentration in outdoor air)

Concentration standards vary from 750–1600 ppm depending on the level of indoor air carbon dioxide or relative to outdoor air. Lower carbon dioxide concentrations correspond to better air quality conditions in the room. It has to be remembered that high room population densities make it more difficult to achieve low CO_2 concentration levels.

In order to improve indoor air quality, it would be necessary to supply more external air to the room. Another more technically demanding solution involves the application of a controlled supply—exhaust or exhaust ventilation [18]. The air quality in the room is temporarily improved by the direct supply of the outside air. However, this involves an increase in costs due to heating this air. Each of these solutions improves the air quality, but increases operating costs. These costs might be reduced by the use or air circulation. To maintain the required carbon dioxide concentration levels, it is advisable to examine guidelines regarding the required supply air streams. Table 2 presents a comparison of guidelines valid in five European countries. The outdoor air stream values supplied to rooms that contain 3, 5, 8 or 10 children are shown.

Table 2. Air stream of external (outdoor) air in relation to the number of children according to the guidelines valid in different countries.

Number of Children		3	5	8	10
Air Stream per Child		Air Stream per Room [m^3/h]			
Denmark [24]	11	32	54	86	108
Poland [27]	15	45	75	120	150
England [26]	18	54	90	144	180
Finland [28]	22	65	108	173	216
Portugal [17]	30	90	150	240	300

Mechanical ventilation applied in the building forces an air stream utilizing fans. The electricity costs of the fans increased building operating costs [29–31] and the electricity consumption by the fans depends largely on the volume of air delivered to the building and the extent of the ventilation system. For large central systems (vast or with huge airstreams) often presented as solutions to air quality problems [19], the static pressure of a fan has to be big and results in significant energy consumption.

Usage of such a type of ventilation demands an additional space for its installation [32,33]. The installed elements include ducts, intakes, exhausts and air handling units. Larger buildings require more involved installations and additional space for the larger elements. Problems with space designed for ventilation systems in new buildings are relatively simple to solve—it needs only the agreement of the designer, who should make provisions for ducts and ventilation unit spaces. However, existing buildings may pose problems during their modernisations or if the building uses change. A partial solution for lack of space involves use of a decentralised system consisting of the local ventilation unit dedicated to a limited number of rooms [32,34–37].

As requirements regarding energy savings or zero-energy buildings have constantly increased, mechanical ventilation with heat recovery is a common, required standard [38]. It is impossible to construct a building having low overall energy consumption without heat recovery coming from the exhaust air or without a rational approach to the volume of air stream delivered to the buildings and the fan compression connected to it. Since 2018, heat recovery efficiencies in ventilation devices must equal or exceed 73% [39] in Poland. In cases of building thermo-modernisations, the most popular activities consist of either improving external wall heat insulation or changing heating systems (including regulation and change of heat source). However, the issue of building ventilation system improvement goes largely ignored [40–46], due to a lack of space or a lack of technical possibilities to install exhaust or supply-exhaust ventilation. However, it is strongly recommended to assume an application of mechanical and controlled ventilation, which will provide proper air quality conditions during building modernisation [18,47,48].

The solutions for the issues mentioned above have ensured delivery of air to the limited space in a controlled way. One such solution features a one-pipe system of ventilation units with a ceramic exchanger for heat recovery [18,34].

It is also important to remember that the best solution for ventilation system control, both central or decentralised, is regulation of the air stream, which follows the number of people present in the room [49]. The control based on the actual number of people in the room, so-called demand control ventilation, is the most effective and also the cheapest [19,29].

1.2. Economic Costs of Air Quality

The costs of a ventilation system in the building include both the investment and operating costs. Investment costs include all expenditures for the expensive devices supplying air, cleaning the air, ventilation ducts, intake—exhaust elements in case of central ventilation and ventilation units in case of local ventilation as well as labour costs [50,51].

The investment costs borne by the owner of the building (investor, nursery owner) vary depending on the size of the building.

The operating costs are related to the energy consumption for driving the fans, eventual heating of the external air, changing air filters and periodical repairs [52]. The nursery owner covers the operating costs, though ultimately the parents pay for those costs in tuition fees. The tuition for children staying in the nursery/ kindergarten has covered all operating costs, employee payments, cleaning costs, costs of toys, hygiene products and all elements used or replaced in a given nursery. Part of the monthly tuition paid by parents is also dedicated to modernisation and repairs. Tuition also covers the building rent, media charge and provides income for the owner. Parents pay agreed to monthly tuition when enrolling a child in the nursery.

Installation and usage of a mechanical ventilation system incur additional investment, which appears unnecessary if airing ventilates the building. But an important question is: how can one assess the health costs for children staying in buildings with poor air quality?

1.3. Purpose of the Research

Schools are already well recognised and diagnosed in terms of indoor air quality. Sundell et al. [53] indicated that nurseries and daycare centres need some research due to a dearth of studies at these facilities. The main reason for poor air quality at nurseries is a high population density of children in a small area and insufficient air exchange. Nursery owners, initially opening in existing buildings, do not invest in ventilation system improvements; however, controlled and mechanical ventilation is needed there, as indicated by Campano-Laborda et al. [7] or Basińska et al. [18]. In general, owners do not want to sacrifice additional financial means for ventilation systems. Secondly, they suspect that operating pressure supply-exhaust ventilation is costly. The quality of air in the educational building is poor due to a lack of improvements. The authors of this paper feel the ventilation system installation economic costs should be treated as a secondary issue and assuring good air quality as the primary issue [54]. First of all, the indoor environment of a building should be healthy because children remain in this closed area, and those children get sick less often when the air quality is good [55]. Seppanen et al. [52] recommended searching for solutions that supply external airflow to the room in a controlled way while simultaneously assuring low operating costs.

Literature reports have suggested that examining air quality in nurseries is necessary as well as ensuring that the costs connected to installation of controlled ventilation in such buildings are low. This paper presents research regarding the economic costs of securing proper air quality using a decentralised ventilation system equipped with reversible fans and heat recovery exchangers. The analyses presented refer to the assumption of different values of supply air streams to ventilate nurseries based on guidelines from different countries. The ventilation air stream was assumed to keep concentrations of carbon dioxide at an acceptable level (1500 ppm) as had been recommended by Franco and Schito [29], Calama-Gonzales et al. [19] or Griffiths and Eftekhari [56]. The analyses took into account the real number of children in the building that functioned as a nursery, applying the conclusions of Calama-Gonzales et al. [19] and Inaniello [28], that regulation of the ventilation system depended on the number of persons was more effective. The investment and operating costs connected to the application of a mechanical ventilation system were analysed for the applied system in the existing building and secured hygienic safety.

Bartyzel et al. [6] concluded that investment into air quality should be a duty of (educational) building management, as management is responsible for providing the proper conditions for learning. Settimo [8] has drawn attention to the necessity of investing in solutions that improve indoor air quality as it is very important for health. Also, Wargocki [57] showed that ventilation investments quickly pay for themselves, so any trepidation at the upfront costs can be overlooked.

Following the indications of other authors, an economic analysis was conducted for operations that provide the given air quality based on the simple payback time assessment

(SPBT). How nursery tuition will increase if the investment costs were transferred to the parents was analysed because such an approach may convince nursery owners to undertake the investments.

1.4. Research Goal

The main goal of this article was an economic analysis for operations that provided given air quality based on a simple payback time assessment (SPBT) conducted in nurseries. The article analyses the use of ventilation equipped with decentralized units, which secures the well-being of the children. An assessment of how nursery tuition would increase if the investment costs for additional equipment were transferred to parents was conducted.

2. Materials and Methods

As a ventilation system securing acceptable air quality, a solution allowing installation in the existing building was adopted. Reversible fans installed on the wall were chosen. A SPBT indicator was proposed as an assessment indicator for the proposed solution.

2.1. Properties of the Proposed Ventilation System

The proposed ventilation unit is shown in Figure 1.

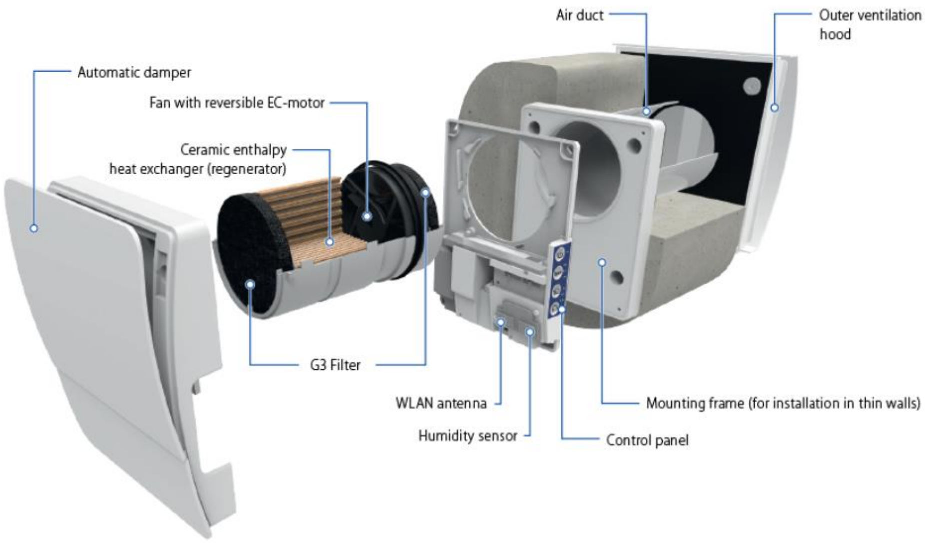

Figure 1. Wall-type ventilation unit used in the analysis [58].

Reversible fans work according to the following principles (Figure 2):

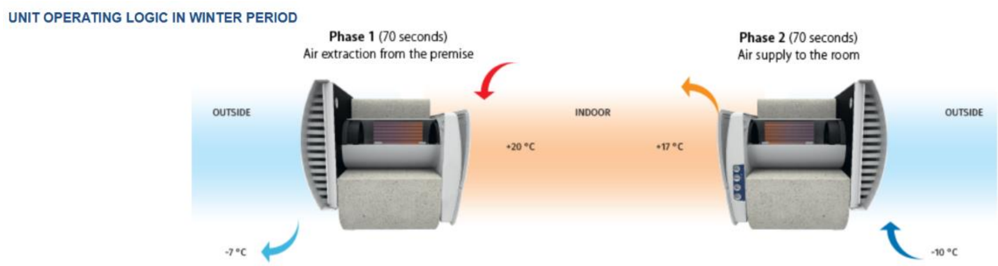

Figure 2. Principle of how the wall-type ventilation unit works [58].

(1) warm air is exhausted from the room and heats the ceramic filling inside the unit. The operation time for this mode is 70 s,

(2) the airflow is reversed and external air is supplied to the room for 70 s. Contact with ceramic filling heats the air and filters G3 or G4 purifies the air,

(3) the whole cycle repeats itself.

The advantages of a decentralised ventilation system equipped with reversible fans are as follows:

- Installation of the devices directly to the external wall of the building, which means low ventilator pressure and energy consumption,
- Fan installation does not demand a lot of time, as installation requires only a 200 mm diameter hole drilled in the wall for the opening,
- Fans are equipped with ceramic exchangers and because the fans are reversible, they effectively recover heat. As a result, the initial air supply is heated,
- The efficiency of fans was controlled; they can work in three modes so their efficiency can be regulated depending on actual demand,
- Filters—using readily changed G3 or G4 filters, the device provides pre-cleaned air (filters are supplied by the device manufacturer and their form varies depending on the manufacturer),
- Independent work of individual unit provides superior regulation of air stream supplied to the room.
- Table 3 presents the device characteristics.

Table 3. Device characteristics [58].

	Speed I	Speed II	Speed III
Air stream, [m^3/h]	10	20	30
Power consumption, [W]	2.0	3.7	6.0
Heat recovery, [%]		up to 80	

2.2. *Assessment of Room Carbon Dioxide Concentration*

Carbon dioxide concentration increases in closed rooms where people stay come from carbon dioxide emission connected to breathing. The dynamics of CO_2 concentration growth depends on several factors. To calculate carbon dioxide concentration when people occupy a room over time τ [h], the following shall be taken into account: value of emission rate $m_{CO_2}\left[\frac{dm^3}{h}\right]$, supply air stream $V_{SU}\left[\frac{m^3}{h}\right]$, times of air exchange in the room $n\left[h^{-}\right]$, initial concentration $c_{int}\left[\frac{dm^3}{m^3}\right]$, and CO_2 concentration in the air supplied to the room C_{ex} $\left[\frac{dm^3}{m^3}\right]$. Equation (1) presents the relationship between these factors [35]:

$$c = \left(\frac{m_{CO_2}}{V_{SU}} + c_{ex}\right)\cdot\left(1 - e^{-n\cdot\tau}\right) + c_{ini}\cdot e^{-n\cdot\tau}\left[\frac{dm^3}{m^3}\right] \tag{1}$$

Equation (2) gives the way to calculate the CO_2 concentration increase Δc as a function of time, τ, in a closed room with no mechanical ventilation system and considers: size of emission of carbon dioxide m_{CO_2}, cubic capacity of the room V $\left[m^3\right]$ and time τ:

$$\Delta c = \frac{m_{CO2}}{V}\cdot\tau\left[\frac{dm^3}{m^3}\right] \tag{2}$$

Equation (1) was used to calculate the influence of the room size change where the children stay on the CO_2 concentration change, including the forced flow, while Equation (2) refers to situations when external air is not mechanically supplied.

2.3. *Energy Consumptions by the Fans—Final Energy*

The fan working modes have been adjusted in such a way to minimise energy consumption. Table 4 compares the working modes of the fan relative to the number of children staying in a room. The air stream required to provide an indoor air quality defined as a maximum carbon dioxide concentration i.e., 1500 ppm was calculated. When the required air stream was defined, the air stream provided by mechanical ventilation was determined as well as the number of ventilation units and their power. When selecting the fans, a maximum 10% reduction in the supply air stream was assumed. Additionally, the power consumption for the fans working in the given mode is presented.

Table 4. Working modes of fans in relations to the number of children.

Number of Children	Required Air Stream	Air Stream Supplied by Ventilation	WORKING FANS	Power Consumption $E_{el,m}$		Working Modes m
[Children]	[m^3/h]	[m^3/h]	[Mode of Each Unit]	[W/Every Unit]	[W]	
3	19.8	20	II	3,7	3.7	1
4	26.4	30	III	6.0	6.0	2
5	33.0	30	III	6.0	6.0	3
6	39.6	40	II + II	3.7 + 3.7	7.4	4
7	46.2	50	II + III	3.7 + 6.0	9.7	5
8	52.8	50	II + III	3.7 + 6.0	9.7	6
9	59.4	60	III + III	6.0 + 6.0	12.0	7
10	66.0	60	III + III	6.0 + 6.0	12.0	8

Calculation of the additional final energy for the proposed ventilation unit was conducted assuming a given profile of nursery operation, for which the number of children present, time of ventilation operation (number of hours children are staying in the nursery each day) and power consumption by the ventilation units (Equation (3)) were assumed. Each number of children present corresponds to an appropriate working mode of a fan that allows the ventilation system to provide the required stream of external air (Table 4).

$$E_{el} = \sum_{i=1}^{n} \frac{E_{el,m}}{1000} \cdot \tau_i \left[\frac{kWh}{year}\right] \quad (3)$$

where $E_{el,m}$—power consumption in a given working mode m [W/mode], τ_i—time of work in a given mode, 8 h/day, number of days of work in a given mode, [h/year] and I—working mode [1–8]

2.4. Economic and Environmental Analysis

2.4.1. Operating Costs

The economic assessment of the proposed technical solution utilised knowledge regarding the final energy described by utilizing Formula (3). To determine the operating cost, the electricity price was assumed as the mean value from prices valid in Poland during 2020 for different tariffs [59]. The mean value level was assumed as follows c_{el} = 0.65 PLN/kWh (0.14 EUR/kWh). Value of 1 EUR was assumed as 4.5 PLN.

The incurred operating costs have been designated following Equation (4):

$$C_o = E_{el} \cdot c_{el} \left[\frac{PLN(EUR)}{month}\right] \quad (4)$$

where c_{el}—costs of electricity, [PLN(EUR)/kWh].

Assuming that after device installation in the room, N children will use it within 12 months, the operating costs borne by the owner can be charged to the parents of children in the nursery following the equation below (5):

$$\Delta C_{m,e} = \frac{C_o}{N \cdot 12} \left[\frac{PLN(EUR)}{month}\right] \quad (5)$$

where N—number of children using the installed device that improves room air quality, [–].

2.4.2. Investment Costs

The investment costs (C_I) of the proposed ventilation system included the costs of both the ventilation units and installation. The device costs were assumed as 3000 PLN/unit (667 EUR/unit) and the price of installation of one ventilation unit as 1000 PLN/unit (222 EUR/unit) [60]. Tuition increases due to the installation of decentralised ventilation utilised SPBT, a method of static evaluation of thermo-modernisation. The timeline for the profitability of the investment improving air quality was assumed at four years. Such a short payback time may serve as a significant impetus for a nursery owner to invest in a given solution. However, the parents who ultimately pay these costs might view them as unjust. However, they should support such initiatives because these improvements ultimately benefit their children. Parents of children attending the nursery in the years following the payback period will return to paying the lower monthly tuition. It was assumed that during the first years of ventilation system work, tuition will increase in such a way as to allow a four year payback period. Based on those assumptions, Equation (6) gives the formula used to calculate the tuition increase for a group of N children:

$$\Delta C_{m,i} = \frac{C_I}{SPBT}\left[\frac{PLN(EUR)}{month}\right] \tag{6}$$

As an economic analysis, the investment costs necessary to provide very high air quality (750 ppm) or high quality (1000 ppm) were also calculated as well as the additional costs transferred to tuition paid by the parents of the children in the nursery. All calculations connected to the additional costs included in tuition were related to the average tuition cost in the analysed city, which was ~1000 PLN/month (222 EUR/month).

3. Case Study

The demand for nursery care in every big city is high. In Poznań, a city of >500,000 people), 3154 children attend the nurseries. There are 15 nurseries run by the city and 88 non-public nurseries financially supported by the city [61].

3.1. Description of Building

The nursery building, being a subject of assessment, is placed in one part of the semi-detached building. It had previously served as a residential building. Many modernisation improvements were introduced to bring the building to the requirements associated with a child-care facility. However, the ventilation system had not been modernised and the building was ventilated naturally.

An air quality assessment was conducted in two rooms dedicated to the youngest children. All analyses of the chosen ventilation system parameters and cost analyses were conducted referencing this group of children. All indicators were referred to and calculated for one child.

3.2. Description of the Rooms in the Building

Children up to 1.5 years stayed in a separate part of the building, which consisted of a few rooms. There were kitchen and dining rooms, toilet, hall, main room (MR), and sleeping room (SR).

The total area of the rooms mentioned above is 65 m^2 and the area of the nap room is 18 m^2 (54 m^3). During the day, children stay in the open space that consists of the kitchen and dining rooms, hall and main room (total area, 42 m^2; 100 m^3). The toilet and sleeping room are closed. In general, children remain in the main room for six hours per day and one hour per day outside, except during winter. Figure 3 shows pictures of the sleeping room (a) and main room (b).

Children stay in the analysed rooms from 08:00 a.m. to 04:00 p.m. The sleeping room is occupied for 2–3 h per day, in mid-day. Airing the rooms took place four times a day for 10 min, following the ordinance of the Minister of Health [62] valid in Poland. The time of airing differed depending on weather conditions. During the winter, it lasts as long as

10 min, but in the summer the windows are not closed unless the temperature outside is low. From June to September the windows in the rooms remain open at all times while periodic airing takes from October till May.

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

Figure 3. Rooms analysed: (**a**) Sleeping room; (**b**) Main room.

3.3. Attendance

The nursery operated Monday thru Friday, except for national holidays. There are 13 children in the group. During the period analysed, attendance varied from 3–10 children present, as some children were absent due to health problems. The frequency of each day was recorded in a journal. Table 5 presents the number of children present in a given day within 12 weeks the measurements had been taken. Depending on the number of children present, there was between 6.5–21.7 m^2 per child.

Table 5. Number of children present during the 12 weeks of measurement.

	Number of Children Present at Nursery											
	Week 1	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**	**Week 9**	**Week 10**	**Week 11**	**Week 12**
Monday	8	7	5	7	5	8	10	10	9	7	10	10
Tuesday	9	6	5	8	5	7	10	9	7	8	9	9
Wednesday	9	3	6	7	5	10	10	10	7	8	7	10
Thursday	8	3	7	6	6	10	9	9	7	0	8	9
Friday	8	3	7	6	7	10	9	8	3	0	9	8
Average	8	4	6	6	5	9	9	9	6	4	8	9

3.4. Supply Air Stream

Proper air quality may be provided by supplying unpolluted external air, in a given volume. The average daily concentration of carbon dioxide in the outside air was 380 ppm. Most often, the volume of the air supplied to the room was defined by the stream unit value per child present in the room. CO_2 emission was assumed as 7.5 $dm^3/h/child$, assuming the emission from one child is 70–80% of adult, which is 12 $dm^3/h/person$ [29].

Table 2 shows a large range of calculated streams allocated to a given number of children. Three levels of air quality were assumed during these analyses described by carbon dioxide concentration, assuring good air quality and corresponding to the air streams. The values of 1500, 1000, 750 ppm were chosen. Those values followed the guidelines established or recommended in different countries (Table 2). The air streams at the given CO_2 concentration in Table 6 are shown.

Assuming a CO_2 concentration of 1500 ppm, i.e., good air quality, 6.6 m^3/h of external air per child must be supplied to the room. This value is definitely lower than standards established by different countries (Table 2). Very often, streams smaller than required by legal regulations suffice for obtaining satisfactory air quality.

Table 6. Air stream assuring good air quality.

Air Quality	Max CO_2 Concentration [ppm]	Air Stream per Child [m^3/h/Child]
Sufficient (DIN)	1500	6.6
Good (ASHRAE, BR10)	1000	11.9
Very good (EN13779)	750	19.7

Considering that during the summer the nursery windows are open continuously and provide external air, maintaining air quality was relatively simple. The analyses refer to the time of mechanical ventilation work, (October–May) was the focus of these analyses. For the sake of these analyses, it was assumed that nursery work 162 days from October to May. The time of children present in the sleeping room was assumed as 2.5 h and 5.5 h in the main room. This totalled 405 h/year in the sleeping room and 891 h/year in the main room. An air stream of 60 m^3/h supplied to the rooms during the entire time children stayed in the nursery was assumed; however, it could be less, depending on frequency. The fans can work in three modes so supply and exhaust at the same time are possible for volumes of 10, 20, 30, 40, 50, or 60 m^3/hour, and creates a large range of possibilities for adopting the air stream to the nursery needs. As shown in Table 5, the number of children staying in the rooms and subject to these analyses varied daily (from 3 to 10). Based on data obtained over 12 weeks (three months) that covered the period of mechanical ventilation work, the number of days was designated during the period when mechanical ventilation was working (October–May) with a defined number of children. In order to determine the frequency, the data covering three months was expanded to coincide with the eight months from October to May. The frequency, the number of days with a given number of children, is shown in Figure 4.

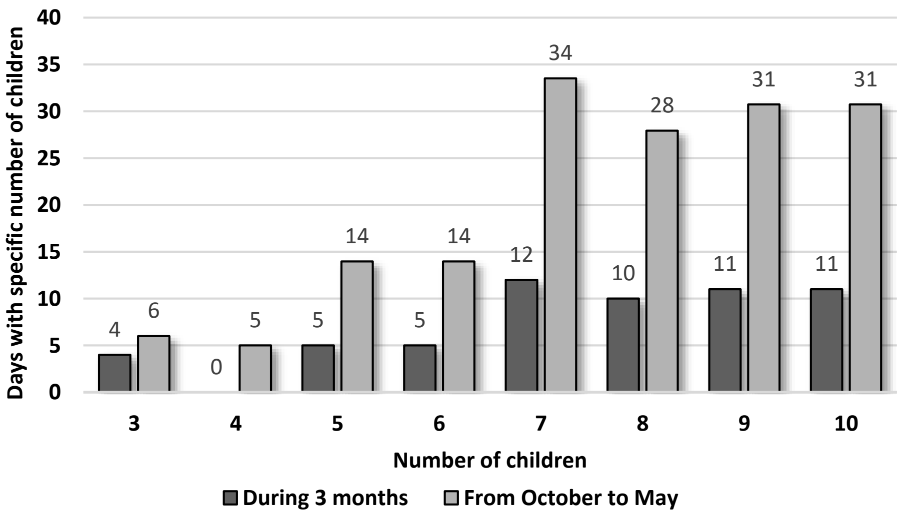

Figure 4. Assumed number of days with a defined number of children (3–10) during the work of ventilation, during 8 months (October–May).

3.5. Applied Technical Solutions

This paper presents an analysis of two connected devices working in one room, both devices can work together or separately as is common when a building changes its purpose from residential into a nursery, little space exists for installation of additional devices. This solution allows adjustment of ventilation levels to the number of children present in the room. Four Vento Duo units, two units in each room, were chosen with the assumption that during nap time, two fans will work in the sleeping room and the other two fans (in the main room) will work the rest of the time.

4. Results

4.1. Air Streams and CO_2 Concentration

An external air stream supplied to the room removes the pollution emitted in the room. Depending on the air stream supply volume and the children group size, the distribution of the CO_2 concentration growth curve will vary. If external air is not supplied to the room, the pollution concentration grows. The concentration increase dynamics vary depending on CO_2 emission time and volume. The distribution of pollution increase also depends on the room volume; larger volumes slow CO_2 concentration growth.

The sleeping room, with a cubic area of 54 m^3, was subject to situational analysis when the average time of children present in the room was 2.5 h. Figure 3a,b show the curves generated using Equations (1) and (2) and depict CO_2 concentration increases when there is no supply of external air ("no ventilation") and when air is supplied (CO_2 concentration of 370 ppm) at 6.6, 11.9, 19.7 m^3/h/child, which corresponded to the levels of air quality presented in Table 2. Figure 5a presents analyses assuming five children present while Figure 5b corresponds to 10 children.

(**a**)

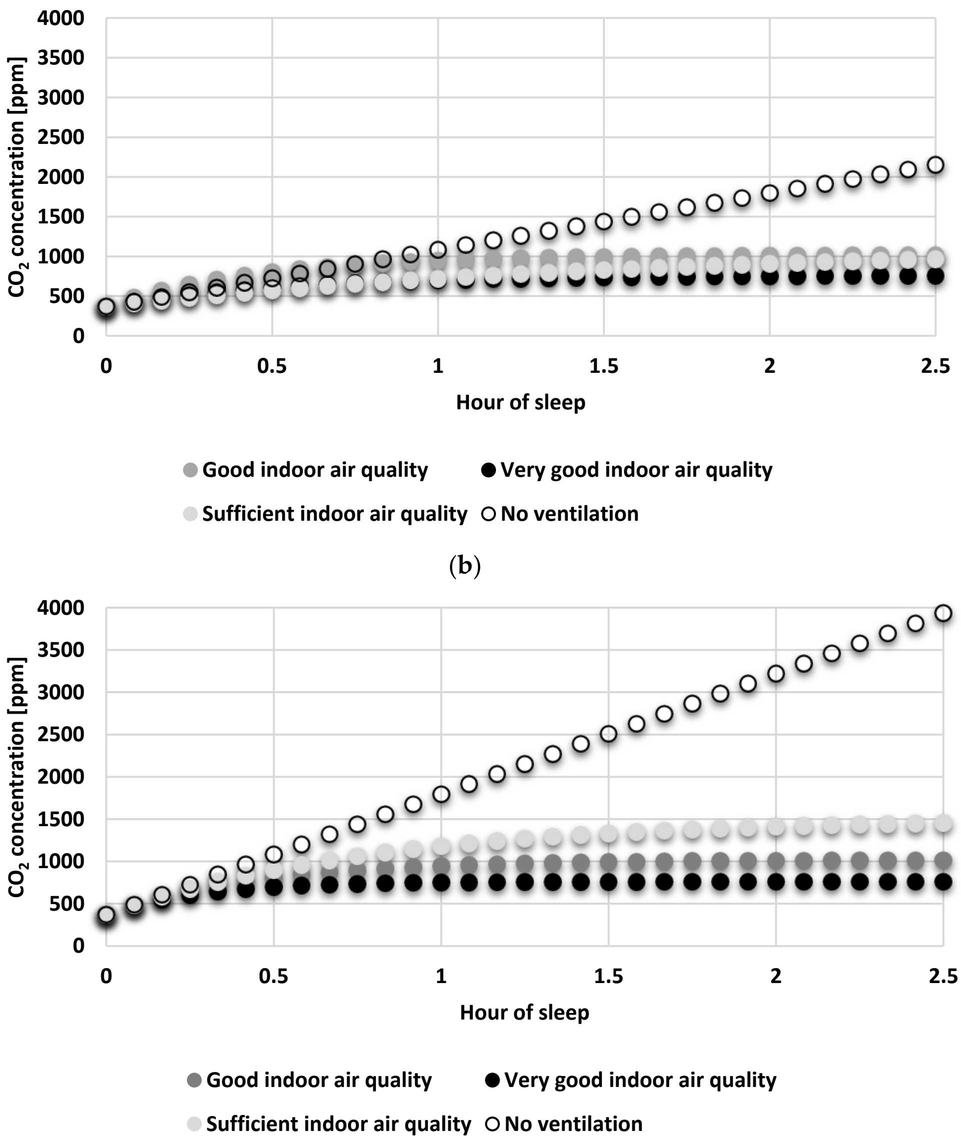

Figure 5. Assumed number of children during operation of the fans over eight months, (**a**) for five children in the room, (**b**) for 10 children in the room

Figure 5a,b show how the concentration in the room increased with five or 10 children. Fewer children slow the increase of CO_2 concentration. For five children sleeping for 2.5 h, the CO_2 concentration can reach 2200 ppm and approximately 4000 ppm for ten children. Those values are definitely out of the recommended range. Data shown in Figure 5a,b indicate the room volume per child is of key importance for the rate of increase in CO_2 concentration. A larger room volume per child increases the time it takes before the CO_2 concentration exceeds the proper air quality limit.

Supplying fresh external air removes carbon dioxide from the room. Once the fans begin working, the CO_2 concentration stabilises and remains at the specified level.

If expected air quality level is 1500 ppm (an air stream supply of 6.6 m^3/h/child), assuming different emissions caused by different numbers of children, the maximum concentration will be obtained just after 45 min. If fewer children are present, but the air stream maintained at the same level per child, the maximum concentration would be achieved after 90 min.

Referring to the values shown in Figure 5a,b in the absence of mechanical ventilation in the rooms, a nap for children in terms of good air quality could only last for 30 min if 10 children slept in this room, or 60 min for five children. This time is definitely too short; they need to sleep much longer for their well-being, so it would be necessary to provide larger rooms or to use forced ventilation.

4.2. Annual Energy Consumption during Fan Operation–Final Energy

The technical possibilities of ventilation control should be considered when using mechanical ventilation. The ventilation devices work in several few modes and can be adjusted if necessary.

For this analysis, it was assumed the devices work in different arrangements that depend on the planned efficiency. Each room was covered by two ventilation units and each unit can operate at one of three speeds. Each gear consumes a different amount of electricity (Table 4). Moreover, it was also assumed that ventilation control was conducted when children enter the room. The working mode for the ventilation units was chosen by the babysitter and depended on the number of children. It could be possible to install an automatic control, but due to the increased costs, this analysis did not consider that option. Figure 6 shows how energy consumption changes by the fans depending on the number of children, for three weeks selected based on the average number of children staying in the room. The difference in energy consumption resulted from fan operation in a given mode and was related to the number of children in the room (week 1, eight children; week 2, four children; week 5, six children), which varied on different days of the week.

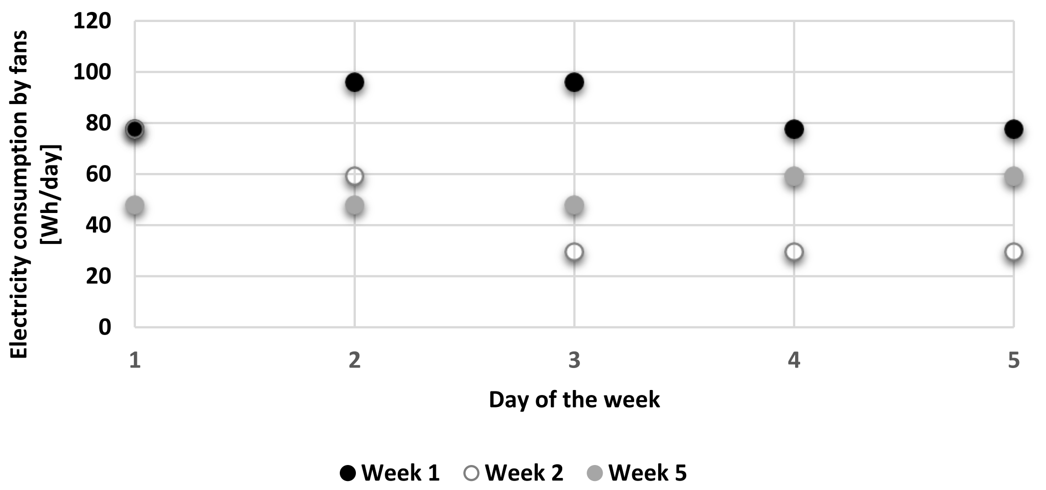

Figure 6. Weekly work of ventilation based on usage profile (three selected weeks).

The total energy consumption by fans (Table 7) is relatively small and amounts to 13 kWh/year because single-pipe fans do not consume much electricity. When operated in an on-demand manner only for a certain amount of time and adapting their use based on the number of children present, the total electricity consumption is small and establishes the economic viability of mechanical ventilation.

Table 7. Annual consumption of final energy for purpose of mechanical ventilation.

Number of Children	Number of Days	Operating Mode	Electricity Consumption	Electricity Consumption Per Day (Ventilation Works 163 Days for 8 h a Day)
[Kids]	[Days]	[−]	[W]	[Wh/day]
3	6	1	3.7	178
4	5	2	6.0	240
5	14	3	6.0	670
6	14	4	8.0	894
7	34	5	9.7	2601
8	28	6	9.7	2173
9	31	7	12.0	2950
10	31	8	12.0	2950
Total electricity consumption [kWh/year]				12.7

4.3. Economic Results Analysis

The investment costs of introducing the fans to the building are related to the purchase costs of the ventilation units and the cost of their installation and totalled 16,000 PLN (3556 EUR).

The operating costs of the ventilation are related to the fee for electricity necessary to operate the reversible fans. The low level of electricity consumption stems from the low static pressure of such ventilation units (the fan needs to break the resistance of a short section of duct, an intake-exhaust louvre, a supply-exhaust louvre and a ceramic heat exchanger; the system does not consist of long ventilation ducts). Small compress translates into low fan power. The final energy for fan operation, considering the number of children present in the nursery was 12.7 kWh/year; an insignificant part of the total energy consumption. So, it can be assumed the operating costs of the analysed system are negligible.

Even if the fans worked around the clock and they supplied the maximum air stream, the energy consumption would still only be 105 kWh/year. Based on an energy price of 0.62 PLN/kWh (0.14 EUR/kWh), the maximum operating costs in such a case would be 65 PLN/year (14 EUR/year).

4.4. Tuition Increase Connected with Fan Installation

An entrepreneur running his/her business usually transfers additional costs to their clients. Nursery owners follow those same rules. The investment costs borne are included in the monthly tuition. If the investment costs are passed to parents whose children attend the nursery (10 children in the room) and spread throughout the year, each parent would have to pay an additional 130 PLN/month (29 EUR/month) based on Equation (7):

$$\Delta C_{m,e} = \frac{16000}{10 \cdot 12} = 130 \frac{\text{PLN}}{\text{month}} = 30 \frac{\text{EUR}}{\text{month}} \tag{7}$$

Assuming a tuition of 1000 PLN/month (222 EUR/month), the monthly cost of child care would increase by 13%, and may not necessarily be approved. The average time a child spends in the nursery in the analysed group was approximately one year so if the owner chose a smaller tuition increase, he/she would need to recover the investment costs from the parents of children subsequently attending the nursery. A compromise sum for each parent could raise tuition by 50 PLN/month or ~11 EUR/month.

It is also possible to calculate the tuition increase if an owner spread the investment costs over a four year period, which seems reasonable considering these long-running devices will require replacement after some time. If the assumed simple payback period (SPBT) was four years, the monthly fee increase would be given by Equation (8):

$$\Delta C_{m,i} = \frac{16000}{4} = 4000\frac{\text{PLN}}{\text{year}} = 30\frac{\text{PLN}}{\text{month}}\text{per child} = 7\frac{\text{EUR}}{\text{month}}\text{per child} \quad (8)$$

Assuming above causes a 3% tuition increase, and could be acceptable for the parents, especially if it is connected to a healthier nursery environment for their children.

4.5. Provisional Costs for Air Quality <1500 ppm CO_2

Based on improving nursery air quality to maintain CO_2 concentrations at 1000 ppm, it would be advisable to install additional ventilation units; however, such an installation could be an issue in the existing building. The chosen ventilation units operate economically but the investment costs are borne by the owner to provide the air quality defined by the appropriate concentration of CO_2 and have been compared.

As better air quality requires a larger ventilation air stream to lower the CO_2 concentration to 750 ppm (very good IAQ), seven ventilation units should be installed in one room (14 units for two rooms). The investment costs would total 42,000 PLN (9333 EUR). Assuming a maximum concentration of 1000 ppm, those would cost approximately 24,000 PLN (5333 EUR) and include four units in each room. To make this installation profitable for a nursery owner, the investment payback time was chosen at the SPBT equal to 4 years, with the ventilation installation costs transferred to the parents by way of tuition increases. Figure 7 shows the tuition increases necessary to secure better air quality depending on the acceptable level of carbon dioxide concentration.

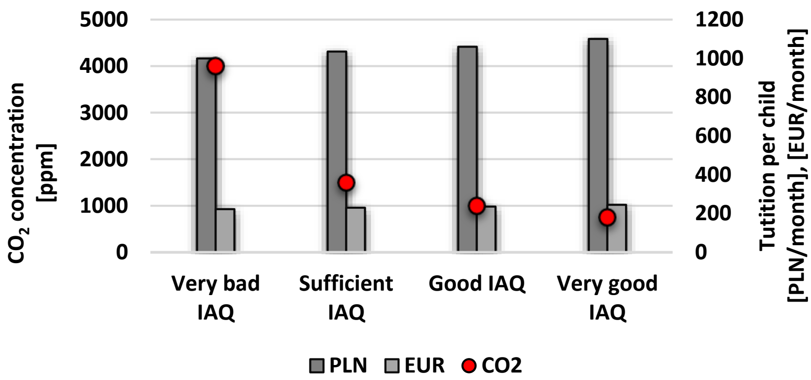

Figure 7. Annual costs of maintaining a given level of carbon dioxide concentration based on the number of children.

Achieving a simple payback time of four years would result in tuition increases of 10% or 6% for air qualities of 750 ppm or 1000 ppm CO_2 concentrations, respectively.

5. Discussion

Poor indoor air quality might have adverse health effects, particularly for children who remain permanently in environments with elevated CO_2 concentrations. This results in nursery absences as well as absences of their parents at work. A similar situation was observed in schools where the pupils remained in classrooms with elevated concentrations of air quality parameters [63].

Polish regulations have stipulated that the absence of a parent at work due to the necessity of personal care upon his/her child affords this parent an allowance of 80% of their normal remuneration. Assuming an average monthly remuneration of 3900 PLN per month (867 EUR per month), the sicknesses of children can create real material damage, which amounts to 780 PLN per month (173 EUR per month). To limit absences of children in the nurseries due to illness, the improvement of air quality will help limit these so-called avoidable costs. Another significant factor, in particular during a recession, is secured continuity of work.

Depending on the requirements in a given country, different indoor air quality outcomes might be achieved via the supply of the defined external air stream. Without it, using only periodical airing, air quality in the rooms with high population densities, will suffer [7].

The analyses showed the degree of air quality improvement (smaller CO_2 concentration) depended on the cubic area of the room. Małecka-Adamowicz et al. [64] concluded the same thing regarding bio-aerosols. Larger per child cubic areas led to slower CO_2 concentration increases. Therefore, it is necessary to ensure that rooms intended for more people have the largest cubic area possible. It has to be noted that during the analysis of cubic area influence on CO_2 concentration, the same air stream value per child was used during the calculations. Nonetheless, the increase in CO_2 concentration was characterised with different dynamics. A CO_2 concentration of 1500 ppm occurred just after 45 min; however, when the cubic area was twice as large, the same concentration occurred after 90 min. When assuming a larger cubic area, the concentration in it remains lower for a longer period.

These results showed that adjusting the ventilation efficiency to the actual number of people was key and in accord with results reported by Calama-Gonzalez et al. [19] and Inaniello [29]. Satisfactory air quality was achieved with air streams lower than required in the legal regulations. Similar achievements have also been reported [6,18,29]. Optimal system work occurred with a ventilation efficiency adjustment and led to low operating costs.

Decentralised ventilation, regardless of the building type, does not have to be expensive. Based on these analyses, the operating costs of decentralised ventilation are insignificantly small. It is connected to the applied solution, i.e., installation of the fans with a small compress, where the energy consumption is low. It represents a very good solution for existing buildings in particular. As nurseries normally open in such buildings, the ventilation with wall mounted units mounted should be obligatory. Theoretically, mechanical ventilation should be installed in nurseries, kindergartens and schools; as only mechanical ventilation can provide the appropriate air quality contributing to better well-being of children and improved perceptual abilities. If it is not possible to install in the traditional central duct ventilation of an existing building, spot solutions available on the market should be considered.

An unquestionable benefit of mechanical ventilation is the control of air delivered to the room. Filters applied in ventilation units are limited to pollution existing in the external environment (dusts, PM_{10}, PM_5, $PM_{2.5}$). Air quality improvement due to dust control should also improve the micro-biological situation of air, because dusts carry bacteria and fungi, including pathogens as noted by Małecka-Adamowicz et al. [64]. It is also worth noting the suggestions of Bryzel et al. [6] that air purification in the room is ineffective and should be purified before being delivered inside.

A dilution of pollutants through a supply of outdoor air has been connected with introducing outside air to a building. Warm outside air generally does not pose problems, but cold air can. The air temperature inside drops when the room is airing. To return to the air temperature before airing, a heating system must deliver the energy. If air is delivered to the building using a heat exchanger, the ventilation system does not need to heat the air. If the ventilation units are equipped with heat exchangers, the air coming into the room is pre-heated. As noted by Zender-Świercz [32], this is why ventilation units with heat exchangers are worth using. Also, when children enter a room, the temperature increases (heat gains from the people). A small amount of colder air offsets those gains and maintains the air temperature at a defined level, with no need for heating.

Airing a room, recommended if there is no mechanical ventilation, may cause a temperature drop in a room, particularly in winter. The volume of air can be too big temporarily, which requires additional heating power [7]. That effect disappears if the system is equipped with ceramic heat exchangers. So, it can be assumed that the installation of reversible fans with ceramic inserts does not increase heating costs. It can even have a positive effect on maintaining the temperature in the room without heating caused by the presence of people.

These analyses demonstrate a compromise between sufficient air quality, technical possibilities of installation of ventilation units and the investment costs may bring some very good results. These results address the demands of Sappanen et al. [52] to seek the solutions, which allow for supplying the room such an air stream volume to provide a good indoor air quality without raising maintenance costs. The cost analysis includes the assumption regarding investment payback time and transfer the costs to the parents of the children attending the nursery, and provides a full range of available solutions. The investment costs into a ventilation system are not huge thanks to the use of the system maintaining a CO_2 concentration of 1500 ppm, which is required in the UK or Germany. The simple payback time of the investment will be four years with a small tuition increase of 3% and will allow for additional air quality investments. The parents of the children will surely accept the small raise of monthly tuition if their children will spend 1/3 of a day in an environment with good air quality. Quick investment payback time was demonstrated by conclusions reported by Wargocki [57]. Results from this paper illustrate the investment costs are recovered in the form of higher employee productivity, who work in an environment with higher air quality generated higher company profits. In the case of children, the investment in better air quality will be connected with better perception during lessons as shown in [7–12], CO_2 concentration has a huge impact on perception. As a result, children receive a better education and will more productive in future work.

6. Conclusions

As it is necessary to provide proper air quality in rooms where small children are staying, it is important to equip those rooms with a ventilation system that ensures a constant external air supply or provides appropriate space in the rooms. These recommendations should always apply, but it is especially important during the COVID-19 pandemic. Recommendations valid all over the world indicate the need to reduce the density of people in rooms and to ventilate rooms. The results of this research showed that the use of such principles in rooms dedicated to small children should be common.

The decentralised ventilation for one room is not an expensive solution in terms of investment and operation. Temporarily raising tuition by 3%, the investment pays for itself after four years. As it is not a significant cost, owners could consideration no tuition increases, but by advertising a nursery as certified in terms of air quality, an owner obtains new clients.

Parents should be inclined to pay higher tuition in buildings where good internal environment parameters are provided. Proper management of educational buildings shall invest in the solutions improving air quality in buildings dedicated to children, as it is an investment in their health and their futures. At the same time, these solutions do not have to be expensive; however, they should be quite effective.

The theoretical work of the fans was assumed in the analyses. In real conditions, depending on the number of used ventilation units, the indoor air quality may be different than that presented in the analyses. When more units would be engaged (a greater air stream supply), the indoor air quality will be better, but also the energy consumption will be higher. However, the intake air stream shall be adjusted to the needs. The groundless increase of air stream is connected to the needless costs. Bearing such costs does not lead directly to an improvement of the air quality. A main goal of the conducted analyses was to determine if there is a way to find not expensive solution for the improvement of the air quality. Further research should be focused on comparison between the operation costs of decentralized ventilation and central ventilation, and then a continuation of the studies in real buildings.

Summary:

(1) The use of decentralized ventilation units improves indoor air quality in existing buildings.
(2) Depending on the size of the supply air stream, the concentration of carbon dioxide can be kept at acceptable levels.
(3) The costs related to the use of such devices turn out to be acceptable for the parents of children enrolled in nurseries.
(4) A provision of bigger room volume contributes to lesser dynamics of CO_2 concentration increases, so there are better conditions in terms of air quality in the rooms.
(5) If a larger cubic area per child is not possible, a forced supply of external air should be provided.
(6) The decentralisation of the ventilation system, via the installation of devices designed for one room, gives control over devices and adjusts their efficiencies.

The algorithm for selecting the device size described by the supplied air stream that depends on the number of children allows for the assessment of additional costs that may be incurred by parents to ensure that their child occupies a clean internal environment.

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