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Indoor environmental quality (IEQ) in Slovenian children daycare centres. Part II: The interrelationship between building characteristics and IEQ

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ABSTRACT

In the process of building design it is important to consider the interconnected impact of occupants' behaviour and building characteristics on the quality of indoor environment. Moreover, it is necessary to identify how potential energy renovation measures may influence the indoor environmental quality. For this reason, this paper, as Part II of the larger study "Indoor environmental quality (IEQ) in Slovenian children daycare centres", further investigates the results of in-situ measurements, presented in Part I. Additionally, comparative study of the potential impacts of building renovations on IEQ was performed. The IEQ was identified as poorer in renovated (i.e. where windows were replaced) and newly constructed low-energy buildings. Furthermore, the most significant connection was identified between indoor air quality and outdoor temperature, which is most likely the consequence of occupant's behaviour (opening of windows). The results of the study should raise the awareness regarding possible adverse health effects of indoor environment on occupants' health, as well as to serve as recommendations for building designers.

Key words: indoor environmental quality, holistic approach, comfort, public buildings, daycare centres

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The presented paper further extends the analysis of the results to the study of interrelationships between IEQ parameters, environmental conditions and building characteristics of the analysed DCCs.

INTRODUCTION

This is the second part of the larger study "Indoor environmental quality (IEQ) in Slovenian children daycare centres". The first part (Part I: Results of in-situ measurements) of this study presented the data, acquired by in-situ measurements of the selected comfort parameters in randomly selected 17 Slovenian children daycare centres (DCCs). The study compared the collected measured data and thus the conditions in DCC facilities with the policy requirements and recommendations. Furthermore, the IEQ conditions of Slovenian DCCs were compared to the conditions of DCC facilities in other countries, where similar studies had been made. However, the presented paper further extends the analysis of the results to the study of interrelationships between IEQ parameters, environmental conditions and building characteristics of the analysed DCCs. In other words, it was of further interest if building (e.g. age of buildings) or environmental (e.g. outdoor air temperature) characteristics influence any of the considered IEQ parameters. The authors kindly suggest the readers to firstly consider the first part of this study (i.e. Indoor environmental quality (IEQ) in Slovenian children daycare centres. Part I: Results of in-situ measurements) in order to better understand the background of the research presented in this paper.

According to statistical data [1, 2], the number of children enrolled in Early Childhood Education and Care (ECEC) is growing every year. Because the number of children registered in ECEC is increasing, even greater attention must be paid to comfortable conditions in indoor environment of DCCs. The latter must be provided at all times, including the elimination of adverse health effects [3–9]. Increasing number of children enrolled in DCCs results in the shortage of building stock designed specifically for educational purpose. In Europe, only Denmark, Finland, Sweden and Norway do not report any significant imbalances between the demand and supply for the entire ECEC age range [10]. The problem of overcrowded DCCs is usually solved by altering the existing norms for class sizes, or with repurposing of alternative facilities (e.g. remodelling of residential buildings). In Slovenia the government authorities amended the main ECEC legislation in 2010 to allow buildings originally constructed for purposes other than ECEC (e.g. residential, administrative or office buildings) to be used as ECEC settings. During the same year, 118 buildings of this type were brought into use. Several buildings were repurposed and renovated due to their age and increasingly stringent energy saving demands (e.g. modifications of building envelope or Heating, Ventilation and Air Conditioning – HVAC systems, replacement of windows, etc.). Although the executed renovations are ideal opportunities to improve energy performance and at the same time also indoor comfort, this is mostly not the case, as in general only the energy efficiency aspects of the building renovation are addressed [11]. Even more, the aspects of healthy and comfortable living environment are often disregarded, as they represent a "collateral" damage on the path to higher energy efficiency [12]. Thus, some fundamental decisions in building construction design, for example the choice of glazing characteristics, are essential for later behaviour of a building,

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which affects indoor environmental quality [11, 13, 14].The above described situation can in the end unintentionally result in poor indoor environmental conditions and may cause sick building syndrome and/or building related illnesses [15, 16]. Wargocki and Wyon [17] warned that impulsive and oblivious attempts to reduce energy use in buildings could lower a child's learning abilities by 30%. In the last three decades, an increasing number of studies have reported uncomfortable and unhealthy conditions in educational institutions. All the indoor environmental quality (IEQ) fields were more or less investigated with a similar proportion, with most studied definitely being indoor air quality (IAQ). Although IEQ has become a growing concern over time, very few holistic studies have been carried out in DCCs, as most of them considered each field of living or working environmental quality separately, i.e. noise, thermal comfort and indoor air quality, one or two at a time. Nevertheless, De Giuli et al. [18] investigated several indoor environmental quality fields in Italian schools simultaneously. The focus was on measuring indoor environment conditions, which included thermal comfort, IAQ and illuminance measurements.

In the last three decades, an increasing number of studies have reported uncomfortable and unhealthy conditions in educational institutions.

Throughout the process of ensuring and providing comfortable and healthy indoor environment for children, a holistic and multidisciplinary approach is essential. Consequently, the objective of our study was to holistically assess all of the IEQ fields. This was executed on the basis of in-situ measurement results, presented in the first part of this article Indoor environmental quality (IEQ) in Slovenian children daycare centres. Part I: Results of in-situ measurements. The measurement data consisted of parameters of visual, thermal and acoustic comfort, as well as indoor air quality. For a holistic and multidisciplinary study on indoor environmental issues, the objective of our research was to determine the environmental or building related characteristics that influence IEQ on a sample of 24 playrooms in 17 DCCs in Slovenia. The study took place from March to June 2013. The main goal was to get better understanding of the indoor environment conditions in DCCs, which are public facilities and where a lot of building renovations, primarily focused on energy performance, have been or will be conducted in the near future. The stated is of great importance, since DCCs represent an environment that may have a decisive influence on children's physical and mental development. In the first place, the acquired knowledge would enable designers to have better control over potentially negative effects in future building renovations. Finally, the results of the study should serve as a basis for recommendations to building designers for the minimisation and prevention of possible adverse health effects of IEQ on building occupants.

METHODS

The research was carried out in 17 randomly selected children daycare centres (anonymised and denominated by letters A–R) located in Slovenia, which included 24 playrooms intended for children aged 3 to 5. The research took place at the targeted DCCs from March to June 2013.

In the first place, the acquired knowledge would enable designers to have better control over potentially negative effects in future building renovations.

The methodology of the performed measurements and data preparation is presented in the first part of this study: Indoor environmental quality (IEQ) in Slovenian children daycare centres. Part I: Results of in-situ measurements. For the purpose of better interpretation of results, basic building characteristics of the analysed facilities are once more presented in Table 1. Buildings A, C and E were three out of 118 buildings in Slovenia originally constructed for purposes other than ECEC (residential buildings) and later adapted and used as DCCs. All other buildings included in the analysis were purposely designed and built as DCCs between 1963 and 2013. Among the analysed facilities, two were constructed in the last 10 years (i.e. P and R, 2012 and 2013, respectively) and were designed as low energy buildings. All other DCCs were constructed before the 1963.

Table 1: Basic information and building characteristics of selected DCCs

Daycare centre	Year of construction	Recent renovation[b]	Playroom No.	Playroom occupation (children + staff)	Floor area [m^2]	Floor area per occupant [m^2/occ]	Volume [m^3]	Area of windows [m^2]	Orientation of majority of windows, azimuth [°]
A	1952	Yes	A1	14 + 2	35.7	2.2	102.2	7.3	W, 290
			A2	20 + 2	35.8	1.6	112.2	10.3	W, 290
B	1979	Yes	B1	19 + 2	52.7	2.5	155.5	16.8	W, 292
C	1899	Yes	C1	14 + 2	35.2	2.2	131.5	11.5	E, 100
D	1963	No	D1	18 + 2	44.6	2.2	161.1	20.8	NW, 310
			D2	16 + 3	37.2	2.0	116.8	15.5	S, 178
			D3	16 + 1	46.9	2.8	142.6	13.8	SE, 130
E	1906	No	E1	14 + 2	36.3	2.3	127.4	3.3	W, 275
F	1979	No	F1	19 + 3	39.0	1.8	116.5	14.8	E, 100
G	1979	Yes	G1	14 + 2	41.9	2.6	151.7	10.0	S, 160
			G2	14 + 2	36.0	2.3	164.2	13.1	SE, 150
H	1976	Yes	H1	16 + 2	44.6	2.5	133.8	16.7	SW, 210
I	1973	Yes	I1	18 + 2	43.7	2.2	128.6	15.0	SE, 142
J	1982	No	J1	20 + 2	33.8	1.5	113.3	11.5	SE, 128
			J2	15 + 2	32.9	1.9	111.0	11.8	S, 149
K	1976	Yes	K1	18 + 2	38.2	1.9	99.4	10.7	E, 80
			K2	21 + 2	46.8	2.0	145.9	13.4	SE, 128
L	1976	No	L1	20 + 2	41.0	1.9	132.8	18.4	S, 172
M	1979	No	M1	14 + 3	42.4	2.5	122.1	9.9	SW, 220
N	1971	No	N1	17 + 2	50.3	2.6	174.5	21.5	S, 180
O	1972	Yes	O1	13 + 2	44.7	3.0	134.1	11.6	S, 200
			O2	17 + 2	49.1	2.6	146.3	13.2	S, 158
P[a]	2013	No	P1	21 + 2	39.2	1.7	118.0	17.3	S, 178
R[a]	2012	No	R1	17 + 2	43.6	2.3	132.2	15.4	S, 164

[a] Low-energy DCCs; [b] Energy retrofit: replacement of windows.

All the required data were then collected and prepared for further investigation. The data were directly transferred to MS Excel software environment, where a database was made and prepared for additional processing.

The main purpose of the study was to analyse the interrelationships among the selected boundary conditions and IEQ parameters. In general, the selected boundary conditions of interest can be divided into two groups, namely building characteristics and environmental characteristics.

The investigated boundary conditions of building characteristics were as following: the year of construction of building, playroom volume, playroom volume/occupant, ventilation mode (natural or mechanical), window orientation and window to flor ratio (WFR), and whether the DCC has been energy retrofitted or not. Comparatively, the investigated boundary conditions of environmental characteristics were the number of playroom occupants and outdoor air temperature. In addition, it was investigated whether the replacement of windows, as an energy renovation measure, has any impact on IAQ (i.e. concentration of CO_2) or not. Beside the studied correlations between the selected boundary conditions and IEQ parameters, the potential correlation between different IEQ parameters was investigated as well.

RESULTS AND DISCUSSION

Although many of the possible correlations between the selected boundary conditions and IEQ parameters were investigated, the following subsections represent only several selected results. In the majority of cases the selected results represent the most significant findings, where potential correlation between studied IEQ parameters and boundary conditions can be drawn. Every field of IEQ is presented separately.

Thermal comfort

Observing Figure 1, a weak correlation can be identified, showing that poorer thermal comfort conditions (higher percentage of people dissatisfied with thermal comfort, i.e. PPD) can be recognised in newer DCC facilities. In this case, high PPD values were mostly the consequence of high indoor air temperatures in comparison to prescribed values. However, this may be the result of higher outdoor air temperatures during the measurements in these facilities (Figure 2). The latter is even more apparent in the case of the two low-energy DCCs. Thus, it cannot be presumed that thermal discomfort in the investigated playrooms was necessarily a result of older building age. Similarly, in their study in Latvian DCCs Stankeviča and Lešinskis [19] reported that the temperatures were the highest in two newly-built DCCs that both had an underfloor heating system and a mechanical ventilation system, which is the same situation as for both low-energy DCCs (i.e. P and R) in the presented paper. Nevertheless, Ruotsalainen et al. [20] reported the opposite trend in Finish DCCs, where indoor air temperatures and the corresponding thermal comfort were on average significantly lower in older buildings, which were, however, mechanically ventilated.

The findings presented in Figure 2 show that PPD values grow with the increase in outdoor air temperature, which indicates a presence of correlation between PPD and outdoor air temperature. This may be the result of non-existent cooling system in the selected facilities, which operate in a free run mode during cooling season. Furthermore, thermal comfort in mechanically ventilated facilities strongly deviated from that in facilities with natural ventilation, especially in playroom R1 with PPD value of 29%. Inappropriate design or use of mechanical ventilation

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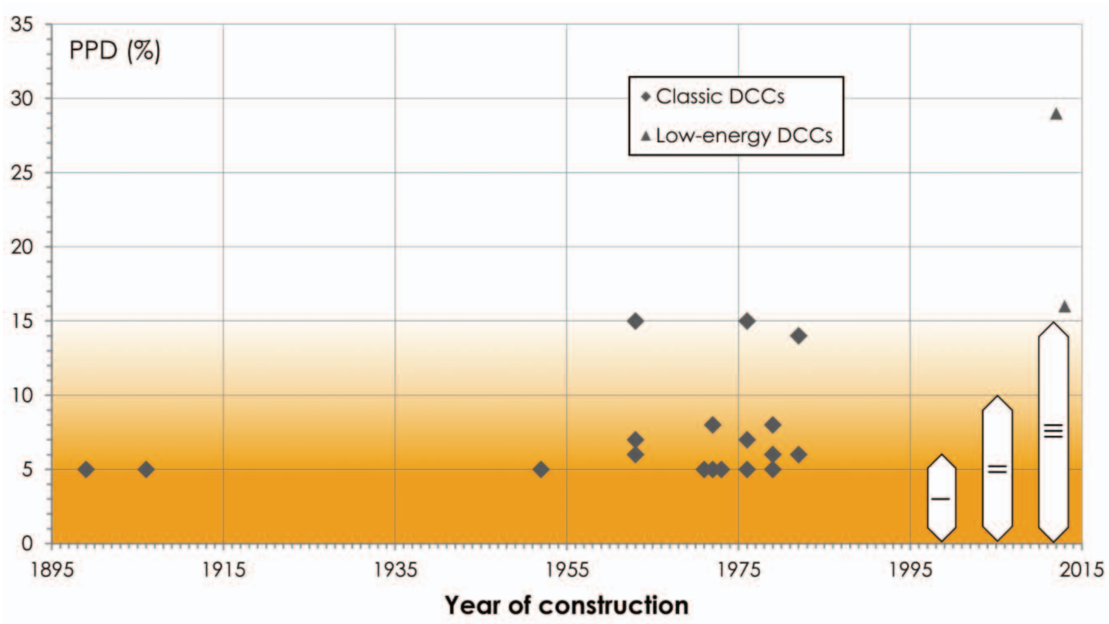

Figure 1: Percentage of people dissatisfied with thermal comfort (PPD) in all the considered playrooms compared with the building's year of construction. Roman numbers I, II and III represent classes of thermal comfort defined in EN 15251:2007.

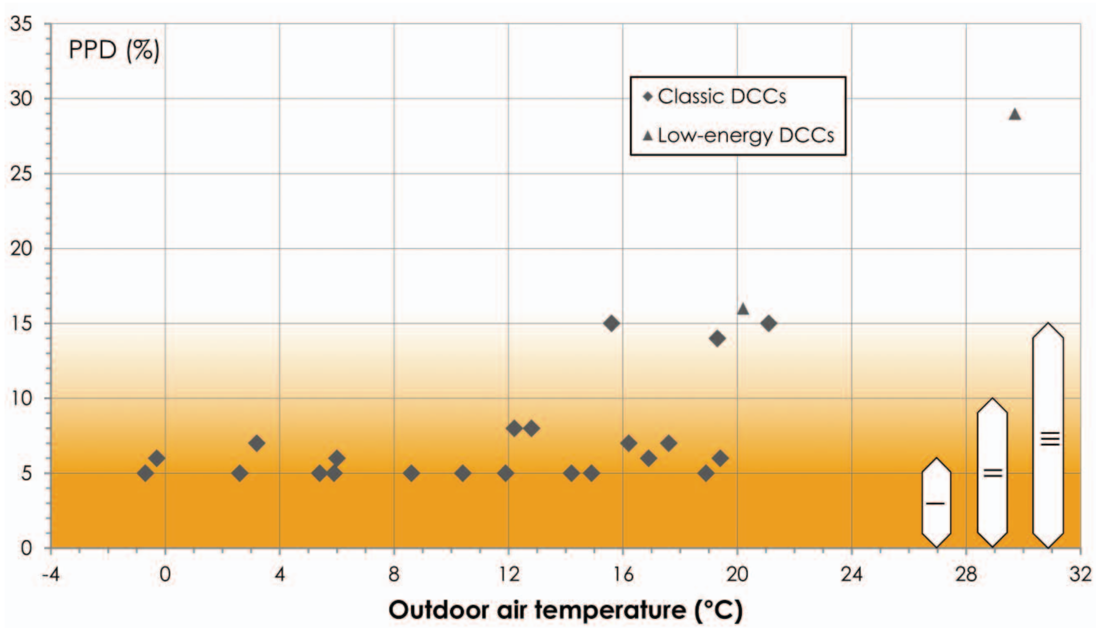

Figure 2: Percentage of people dissatisfied with thermal comfort (PPD) in all the considered playrooms compared with the average outdoor air temperature during measurements. Roman numbers I, II and III represent classes of thermal comfort defined in EN 15251:2007.

system could be one of the possible causes for thermal discomfort. As mentioned in Part I of the study, the highest CO_2 concentrations were also identified in playroom R1, which has an above average floor area per occupant ratio (Table 1). Therefore, high CO_2 concentrations are probably related to building characteristics or building use.

Indoor air quality (IAQ)

In the context of indoor air quality, the first correlation investigated was the correlation between the percentage of people dissatisfied with indoor air quality (PPD_{IAQ}) and the volume of playroom per occupant. The latter has in general a considerable impact on IAQ, since greater volume of air means that there is more breathing air available per occupant. The volume of playroom per occupant varied between 4.97 m^3/occ in playroom K1 and 10.26 m^3/occ in playroom G2, which had the greatest ratio, while the average value is 7.22 m^3/occ. However, playroom G2 was among playrooms with the worst IAQ (highest concentrations of CO_2 were measured). The results in Figure 3 show that, surprisingly, there is no obvious correlation between the volume of playroom per occupant and the predicted percentage of dissatisfied with indoor air quality. Therefore, because indoor concentration of CO_2 is also directly connected to the volume of indoor air, it can be said that other influential parameters have much greater effect on IAQ than the volume/occupant ratio. One of such parameters is definitely occupants' behaviour. In this study, the latter is investigated through a search for the correlation between PPD_{IAQ}, temperature of outdoor air and teachers' behaviour (i.e. decision to open a window or not) in Figure 4.

Similar to the interpretation of PPD values in Figure 2, PPD_{IAQ} values in the investigated DCCs (Figure 4) show a probable dependence on outdoor air temperature as well. The trend is evident for the playrooms with natural ventilation, since the teachers in these playrooms opened windows or doors towards the outside (i.e. they naturally ventilated the playroom) more often, when the outdoor air temperatures were higher. No evident connection can be identified in the cases with mechanical ventilation system, as such systems are usually programed to ventilate rooms at a constant rate. However, it can be concluded that naturally ventilated playrooms had better IAQ than the ones with mechanical ventilation (low-energy DCCs). This is more apparent when observing the PPD_{IAQ} value in the case with mechanical ventilation in relation to the other naturally ventilated playrooms with the same outdoor temperature (about 20°C) (Figure 4). In this instance, the PPD_{IAQ} of mechanically ventilated DCCs was approximately 10 percentage points higher than in the case of naturally ventilated ones. The trend line in Figure 4 presents the connection between PPD_{IAQ} and external air temperatures for naturally ventilated playrooms. It was generated according to the conducted measurements, but excluding the values for playrooms D1, I1 and J1 (marked with doted ellipse). The measured values for the stated playrooms greatly diverge from the trend evident in other naturally ventilated playrooms, due to external causes connected to the use of the rooms. Comparison of playrooms in the same DCC facilities (i.e. D2 to D1 and D3 as well as J1 to J2) shows

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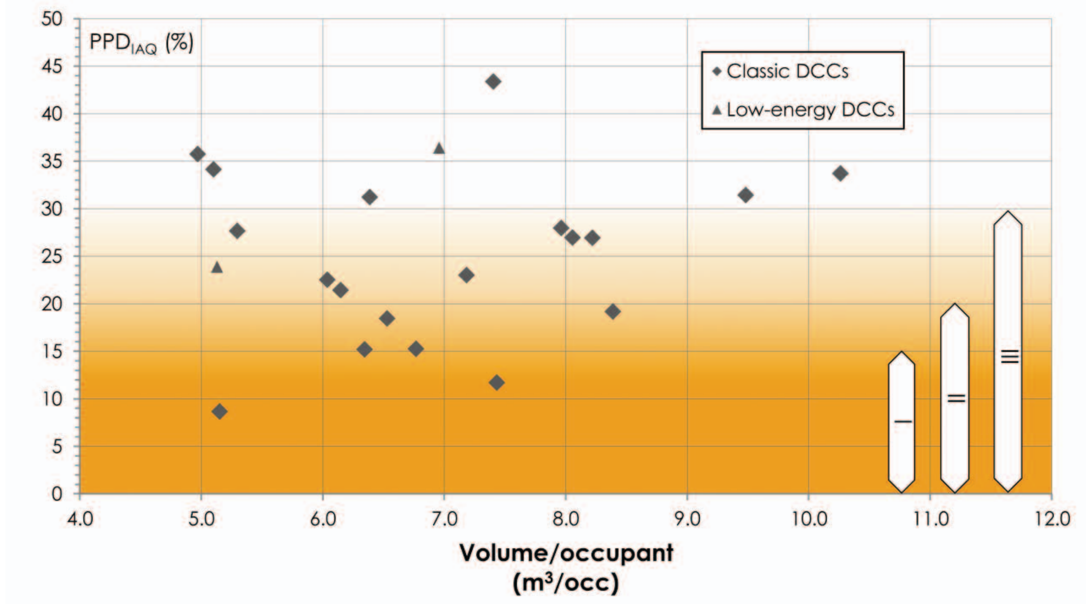

Figure 3: Percentage of people dissatisfied with indoor air quality (PPD_{IAQ}) in all the considered playrooms compared with the volume of playroom per occupant. Roman numbers I, II and III represent classes of indoor air quality defined in EN 15251:2007.

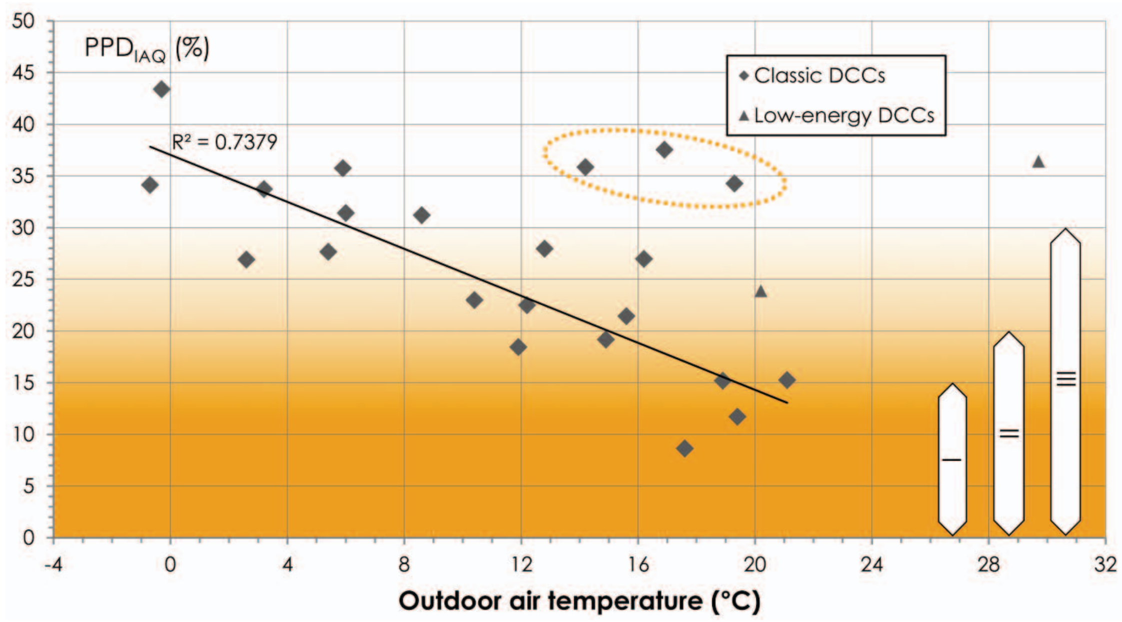

Figure 4: Percentage of people dissatisfied with indoor air quality (PPD_{IAQ}) in all the considered playrooms compared with the average outdoor air temperature during measurements. Roman numbers I, II and III represent classes of indoor air quality defined in EN 15251:2007. Trend line was calculated only for playrooms with natural ventilation, excluding playrooms D2, I1 and J1, marked with dots.

that the high values of PPD_{IAQ} are probably the cause of occupant interaction with the built environment (e.g. teachers opening windows only when the children left the playroom due to the institutional internal rules as in the case of playroom I1). In other cases the reason why the playrooms were inadequately ventilated by teachers was in the external environment, as in the case of D2 when due to the mowing of the lawn the windows were kept shut during the conducted measurements in order to block high levels of external noise (L_{eqe} = 75 dB).

Although the majority of the playrooms used natural ventilation as a ventilation mode, poor IAQ was still identified in several such cases. Teachers were reluctant to open windows or doors to naturally ventilate playrooms when outdoor temperatures were low or precipitations were present. Similarly, Cano et al. [21] noticed that teachers seldom open windows when outdoor temperatures are low, while Andersen et al. [22] and Dubrul [23] showed that occupants in general open windows more often and for longer periods during sunny weather. Correspondingly, since opening of windows in such situations cannot provide the optimal indoor conditions, Stankeviča and Lešinskis [19] recommended the use of a more efficient ventilation system (i.e. mechanical). Nevertheless, in order to ensure the highest level of hygienic conditions, regular maintenance and supervision of such systems is necessary.

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However, since mechanical ventilation can have its benefits (i.e. is occupant independent), a number of parameters influence its functioning as well. The latter can again result in poor IAQ, if the ventilation regime is not properly designed or its continuous maintenance is not performed. Hence, it was of further interest, if there are any differences in the IAQ of old, renovated or mechanically ventilated facilities. On the basis of Figure 5 it can be assumed that energy renovation of DCC facilities (i.e. replacement of windows) that were naturally ventilated had a negative impact on IAQ. The higher CO_2 concentrations in renovated DCCs are probably the

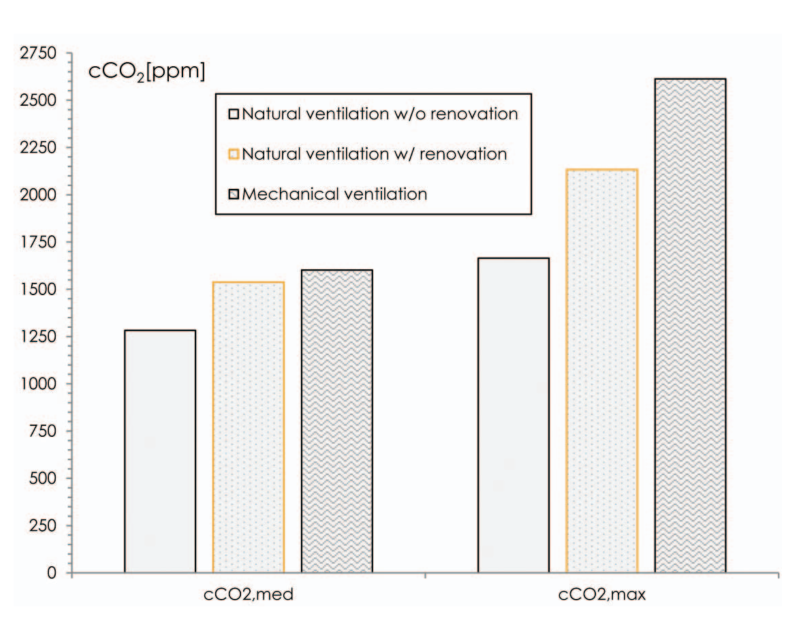

Figure 5:
Median values and mean maximal values of CO_2 concentrations, measured in the considered playrooms, divided in three different categories: playrooms with natural ventilation w/ (N=12) or w/o (N=10) recent renovation (i.e. replacement of windows) and playrooms with mechanical ventilation (N=2).

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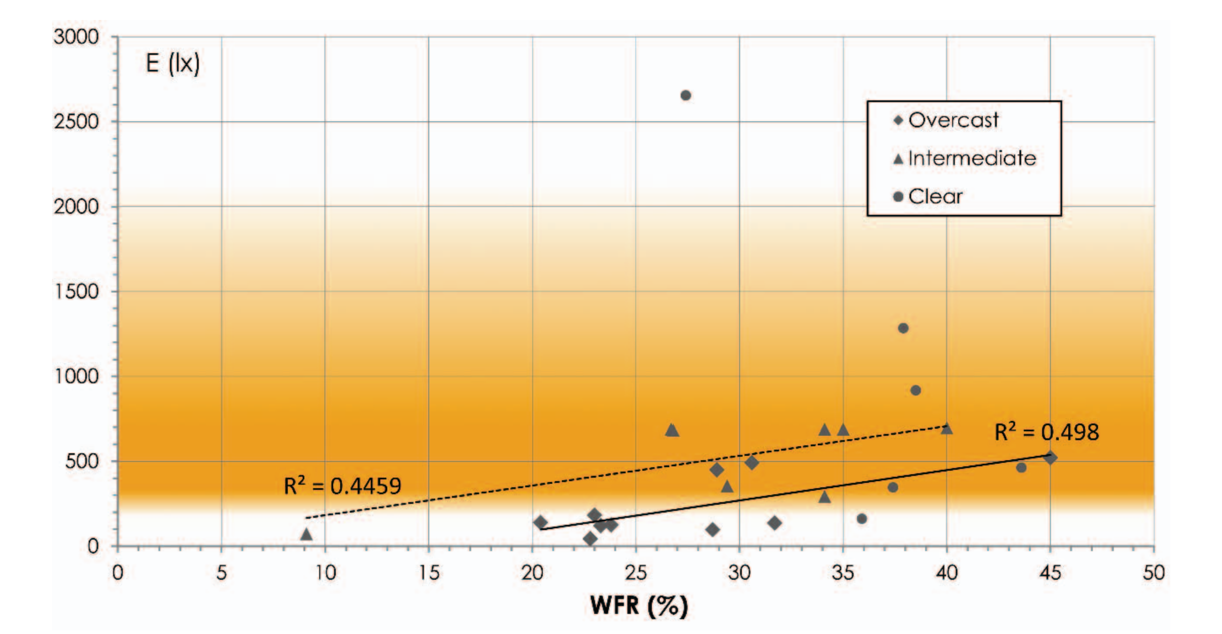
result of new windows, which are better sealed and thus the uncontrolled infiltration of external air is lower. Nevertheless, the occupants' air ventilation habits remain the same as before the renovation. Therefore, it is essential to assess the potential impact of the performed energy renovation measures on indoor environmental quality in DCC facilities. Moreover, the staff (e.g. teachers, managers, janitors) should be informed and educated about the consequences of executed energy renovations in order to adjust their behaviour appropriately. Unexpectedly, the measured CO_2 concentrations in new low-energy DCCs with mechanical ventilation systems were also quite high. This is probably the result of inappropriately designed ventilation system and of thoughtless wish to achieve greater energy savings of building, ignoring IEQ at the same time. Nonetheless, in some investigated playrooms the teachers noticed poor IAQ conditions by themselves as well.

Visual comfort

The trend of the insufficiently naturally lit playrooms can be to some degree related to the external weather conditions, as insufficient illuminance of the work plane was mostly recorded during overcast sky conditions (Figure 6). Overcast sky conditions were present in 77% of measurements in the analysed playrooms where the average work plane illuminance was below the 300 lx threshold. On the other hand, as expected, the playrooms with larger areas of transparent elements (i.e. windows) exhibited higher levels of indoor illuminance. This can be seen from the trend lines generated for overcast and intermediate sky condition measurements presented in Figure 6.

However, this relationship between indoor illuminance and building envelope configuration is also dependent on the orientation of the windows, as it can be observed from the results measured during clear sky conditions (Figure 6), where larger windows do not necessarily mean

Figure 6:
Mean daylight illuminance of working plane (E) in all the considered playrooms compared to the WFR. Playrooms are classified by the sky condition in three classes: overcast, intermediate and clear sky. The solid trend line is calculated for playrooms with overcast sky conditions, the dashed trend line for those with intermediate sky conditions.

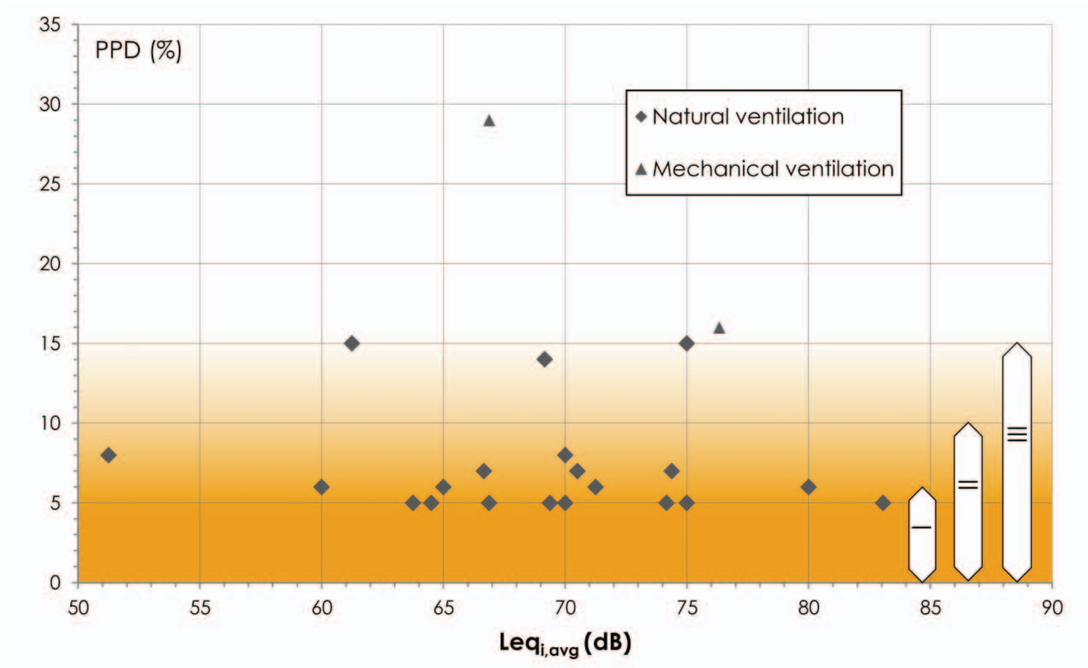


better indoor visual comfort [24, 25]. High values of indoor illuminance can also cause occupant discomfort. Therefore, they represent a source of dissatisfaction with indoor visual environment, mainly due to the occurrence of glare. An upper limit of 2000 lx (Figure 6) for average indoor illuminance was set in the conducted analysis on the basis of Useful Daylight Illuminance metrics proposed by Nabil & Mardaljević [26, 27], where horizontal illuminance levels above this value indicate higher level of glare occurrence [28]. Only one case (i.e. R1) exhibited average values above 2000 lx during the time of conducted measurements. However, this does not mean that in other cases localized parts of the playrooms were not illuminated above the upper threshold.

Acoustic comfort

Although potential links between noise level and building characteristics were investigated, no specific correlations were found. Thus, the number of children in playrooms or the volume of playroom per occupant had no evident effect on the measured noise levels. Moreover, no clear association was detected between the noise level in the playrooms and other types of discomfort. Specifically, no correlation was identified between the measured equivalent noise level and PPD (Figure 7) or PPD_{IAQ}, where it was speculated that children would make more noise when dissatisfied with the thermal comfort or the quality of indoor air. Notably, Figure 7 clearly illustrates that for the selected sample of playrooms, no evident correlation between noise level and PPD can be identified, since playrooms with the worst PPD (e.g. playroom R1), were not necessarily also the noisiest. However, no correlation between the parameters of acoustic comfort and other investigated parameters was identified during the conducted analysis. Although this may be the case, the phenomenon is worth of further investigation in order to identify whether the connection exists or not.

Figure 7:
Percentage of people dissatisfied with thermal comfort (PPD) in all the considered playrooms compared with the average measured noise level. Roman numbers I, II and III represent classes of indoor air quality defined in EN 15251:2007.



Even though some of the presented results probably do point to a trend connecting certain studied parameters, they should still be used with caution due to a small sample of buildings and varied environmental conditions encountered during the conducted measurements.

STUDY LIMITATIONS

Although this research was carefully prepared, we are aware of its limitations. One of the greatest limitations is the sample size of the analysed children daycare centres. Because the sample of 24 playrooms is relatively small, no certain statistical correlation can be determined. However, the identified relationship between the studied IEQ parameters and environmental boundary conditions was in some cases weak or even non-existent (e.g. acoustic comfort), while in other instances it was strong (e.g. relationship between PPD_{IAQ} and external air temperatures). Even though some of the presented results probably do point to a trend connecting certain studied parameters, they should still be used with caution due to a small sample of buildings and varied environmental conditions encountered during the conducted measurements. Furthermore, in order to get more accurate results, IEQ parameters should be monitored and measured through a longer time span. For instance, monitoring of IEQ parameters should be conducted during several months, preferably including both heating and cooling season and for the entire period of occupied hours of DCC.

Another limitation of the study is that there is not enough prior research available in the field of indoor environmental quality in Slovenian children daycare centres. Consequently, there are no or very few available data to, for example, compare IEQ in the same facility before and after the executed energy renovation. Therefore, further research in this field is highly encouraged.

CONCLUSIONS

Occupants play a key role in the design of buildings and their indoor environment, especially if they are a vulnerable population (e.g. children). However, initial design decisions on the level of building envelope largely influence further response of a building, as shown by Hudobivnik et al. [13] and Pajek et al. [29]. Therefore, thoughtful design decisions should be encouraged, because designers rarely holistically analyse the building behaviour before it is put into use. In addition, the potential negative impacts of energy renovation of buildings on IEQ have to be taken into account, where the wish for smaller energy use in buildings in most cases dominates over other design criteria [11]. Similar conclusions were shown by Perino et al. [30] for residential buildings, where energy renovations had a negative impact on IAQ. Consequentially, it can be assumed that in DCC facilities this problem could be even more pronounced (Figure 5) due to higher occupant density. Thus, it is on one hand necessary to understand how the energy renovation measures will influence the indoor environment and on the other to educate the occupants how to use the renovated building, as higher levels of building envelope's air tightness will result in lower air changes and consequentially lower IAQ. This was already identified by Langer and Bekö [31], reporting that newer buildings were characterised by lower air change rates and therefore higher levels of indoor pollutants. Nevertheless, outdoor air quality also has an evident impact on indoor envi-

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ronment and should be considered as well [32]. In the case of buildings with mechanical ventilation system applied, the design and use of the system should be occupant-requirement based and not influenced only by the energy-saving potential of lower ventilation rates. This is very important, because mechanical systems are more user independent than natural ventilation, which can be manually regulated by the occupants according to their needs and wishes.

Acknowledgements

This study was conducted in collaboration with the selected children daycare centres in Slovenia. The children daycare centres included in the research were randomly selected and were given free choice to participate or not in the research. The authors gratefully acknowledge co-operation of the managers and educators of the participating day care centres, field technicians and other project collaborators.

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