OPERABLE WINDOWS, THERMAL COMFORT, AND INDOOR AIR QUALITY IN K-12 SCHOOLS: Identifying the Gap and Proposing Future Studies

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Abstract: Schools are the second most important environment in children's lives after homes (Baki-Biro et al. 2012; Mendell et al. 2013), illustrating the importance of school environments in students' learning performance, health, and comfort (Abramson et al. 2006; Madueira et al. 2009; Annesi-Maesano et al. 2013; Mendes et al. 2014; Almeida et al. 2016). Ventilation is one of the factors impacting student learning performance; ventilation can be provided through operable windows, exhaust fans, or mechanical ventilation systems (Gao et al. 2014). Additionally, different building elements such as air ventilation systems, HVAC systems, and building envelopes, can affect ventilation and occupant comfort (Catalina and Iordache 2012). ASHRAE Guideline 10P (2010) establishes four conditions for human comfort: thermal, visual, acoustic, and indoor air quality. Thermal comfort and indoor air quality are viewed as the most important of the four comfort conditions to improve occupant health and productivity (Pan et al. 2018). Several studies have focused on the relationship between operable windows, thermal comfort and/or indoor air quality, but no literature is found synthesizing these studies to establish a gap in research (Almeida et al. 2016; Dhaka et al. 2013; Jiang et al. 2018; Jindal 2018).

Through searching such keywords as operable windows, natural ventilation, open window, close window, temperature, thermal comfort, CO_2, indoor air quality, and IAQ, 136 articles were found on Web of Science, ScienceDirect, and Google Scholars. From these papers, only thirty-one had research conducted in schools. A synthesis shows that these thirty-one articles have been conducted largely through quantitative methods, including environmental monitoring, survey, and simulation. Also, only one of them was located in the U.S., with the rest located in Europe (15 out of 31), Asia (12 out of 31), South America (2 out of 31) and South Africa (2 out of 31). In addition, 54% of the total (thirty-one) papers focused only on thermal comfort, 25% focused on indoor air quality and only 21% addressed the relationship between operable windows and both thermal comfort and indoor air quality in K-12 classrooms. This synthesis of literature shows that the current research emphasized measurements in air temperature, relative humidity, and air velocity to address thermal comfort, and used CO_2 as the favored metric for measuring indoor air quality. This paper proposes future studies and methodologies to fill these identified gaps in the literature.

Keywords: Operable windows, thermal comfort, indoor air quality, K-12 schools, classroom

INTRODUCTION

Schools are historically important environments for communities, design professionals, and the general public for two primary reasons. First, schools often have environmental deficiencies due to funding shortages related to operation and facility maintenance (U.S. General Accounting Office 1995; Mendell et al. 2013). Second, classrooms are the second most important spaces for children, trailing only the home environment (Baki-Biro et al. 2012; Mendell et al. 2013). With students spending approximately one-third of their waking time at school, the importance of school environments on student health, well-being, and comfort is apparent (Abramson et al. 2006; Madueira et al. 2009; Annesi-Maesano et al. 2013; Mendes et al. 2014; Almeida et al. 2016). These impactful spaces represent a micro-environment for a vulnerable childhood population as they are still physically and mentally developing (Stabile et al. 2017; Peled 2011; Selgrade et al. 2008). Children are more vulnerable to environmental conditions, particularly pollutants (Suk et al. 2003); they breathe higher volumes of air relative to their weight, exposing them more to toxins compared to adults (Suk et al. 2003). In designing classrooms and schools, architects generally try to ensure that the environment improves student learning, performance and comfort. While these elements should be the priority in a school design, the literature shows that the energy analysis and cost effectiveness are also important in decision making processes (Catalina and Iodache 2012).

Ventilation may be a significant factor helping to improve students' learning performance and reducing the risk of health problems, (Gao et al. 2014). Inadequate ventilation can cause an increase in absenteeism, which has shown a negative consequence of impacting learning (Mendell et al. 2013). The literature shows that the current ventilation rates in classrooms are still inadequate and lower than in office and residential buildings (Daisey and Angel 2003; Santamouris et al. 2008; Gao et al. 2014). Some actions have been proposed for existing and future schools to increase classrooms indoor environment quality, such as: (i) adequate outdoor ventilation, (ii) control of moisture, and (iii) avoiding indoor exposures to pollutants (Bako-Biro et al. 2012). There are many ways to provide increased classroom ventilation including operable windows, exhaust fans, or mechanical ventilation systems. There is not a systematic data analysis on the impact of these different ventilation types on students' and teachers' comfort and health, or on student learning level in classrooms (Gao et al. 2014). Several elements, such as HVAC systems, building envelopes, occupant behavior, and air ventilation systems influence indoor environmental conditions (Catalina and Iordache 2012). Comfort has been studied in terms of four conditions: thermal (air velocity, temperature and humidity), visual (illuminance and reflection), indoor air quality (smells, irritants, outdoor air, and ventilation), and acoustics (control of unwanted noise, vibrations, and reverberations) (Ortiz et al. 2017; Bluyssen 2009). Thermal comfort and indoor air quality are two important comfort conditions that can improve both occupant's health and productivity (Pan et al. 2018). Since thermal discomfort may have a negative influence on students' learning performance, and classrooms have high densities compared to office spaces or residential buildings, providing appropriate comfort conditions in educational buildings has always been important and critical (Mendell and Heath 2005; Barrett et al. 2015).

Thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE Standard 55 2013). Individuals may feel differently in the same thermal condition, or different people may have the same levels of comfort in different thermal environments (ANSI/ASHRAE Standard 55 2017). Two models are commonly used internationally to discuss thermal comfort: (i) the "rational" model, and (ii) the "adaptive" model (Martinez-Molina et al. 2017). The "rational" model is the work of Fanger, who established the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). PMV is an index that predicts the votes of a large group on a 7-point thermal sensation scale, and PPD is an index that predicts the percentage of people who experience local discomfort (Fanger 1970). The main principle of the "adaptive" model focuses on human-building interaction, where people can improve their environment by interacting with both building controls (opening/closing windows/doors and turning on/off fans), and with personal conditions (changing their clothes or drinking hot or cold drinks). This model is the most realistic model for naturally ventilated buildings (Stazi et al. 2017).

Indoor air quality is also an important parameter for school environments, since it is related directly to occupants' health and comfort, indoor air quality should not be neglected in indoor environmental quality studies (Catalina and Iordache 2012). The definition of acceptable indoor air quality in terms of occupant satisfaction is a room where no contaminants reach a harmful concentration level and at least 80% of occupants do not express any dissatisfaction about the air (Lai et al. 2009).

The effect of natural ventilation on thermal comfort and indoor air quality is not easily predictable; it is important to further investigate this strategy (Stabile et al. 2017). Ventilation types in buildings might vary from completely natural to completely mechanical and can be categorized into three groups: (i) natural, (ii) mechanical, and (iii) mixed or hybrid. Many studies have been conducted on mechanically ventilated classrooms, while there is a lack of knowledge and information addressing naturally ventilated schools (Almeida et al. 2016). In places with mild outdoor climates, opening windows can reduce indoor cooling demands, and enhance indoor air quality (Pan et al. 2018).

When the building utilizes natural ventilation, opening windows can provide the interior with cool and fresh air from outside (Rackes and Warning 2013). In Portugal, like other mild climate countries, schools prefer natural ventilation instead of mechanical ventilation (Almeida and de Freitas 2014; Almeida et al. 2016). In naturally ventilated schools where temperature fluctuation is higher, students' adaptability is required to maintain an appropriate level of comfort (Almeida et al. 2016). Among the studies specifically on natural ventilation in school buildings, no agreement has been reached on the ventilation required to improve indoor air quality and thermal comfort (Dorizas et al. 2015); therefore, more studies are needed to understand various factors in this field.

Wargocki et al. (2002) state that having ventilation systems, either natural or mechanical, can impact people's health in buildings, particularly during cold seasons. The study also mentions that students have lower frequency of complaints in naturally ventilated schools. Meanwhile, some drawbacks of naturally ventilated schools, such as outdoor noise, air quality, safety parameters should be considered (Santamouris et al. 2008). Several studies regarding natural ventilation in schools and the relationships between operable windows and human comfort, especially addressing thermal comfort and indoor air quality, will be discussed in the following sections.

The influence of the indoor environment on occupant comfort and productivity, and the growing awareness of these issues, has led to an increase of efforts to obtain feedback from users of buildings via survey (Catalina and Iordache 2012; Lai et al. 2009; Andersen et al. 2009). Due to the importance of natural ventilation in classrooms and of thermal comfort and indoor air quality in providing human comfort, and considering the lack of the systematic literature review on this subject, this study synthesizes the literature on the relationship between operable windows, thermal comfort and indoor air quality in K-12 classrooms.

METHODOLOGY

The Web of Science, Google Scholar, and ScienceDirect databases were used to search for literature on operable windows, thermal comfort, and indoor air quality. The keywords used were *operable window*, *natural ventilation*, *open windows, close window*, *temperature*, *thermal comfort*, *CO_2*, *indoor air quality*, and *IAQ*. One hundred and thirty-six (136) papers were found through the initial search, with only thirty-one (31) were conducted in schools. This paper synthesizes this literature based on the study locations, targeted concepts of the study, methods, and the parameters of the measurements. This synthesis helps to understand the gap in the literature to aid in building future studies in a more efficient way.

RESULTS

Findings from the studies will be discussed in three parts: (i) thermal comfort and operable windows, (ii) indoor air quality and operable windows, and (iii) thermal comfort, indoor air quality and operable windows. A synthesis of the three will then be provided.

Therman Comfory and Operable Windows:

Operable windows impact both temperature and air velocity (Brager et al. 2004). Kumar et al. (2016) conducted a study to update the thermal boundaries in the psychrometric chart for naturally ventilated buildings. They used survey and environmental monitoring. The resulting proposed thermal comfort boundaries from this study have higher range compare to ASHRAE comfort zone which shows that people in naturally ventilated buildings have more thermal tolerance range, Mishra and Ramgopal (2015) state that students in naturally ventilated classrooms in tropical climates implement adaptive behaviors to improve their thermal comfort such as using fans, opening/closing windows, and changing clothes. They used survey and environmental monitoring in their study. Ogoli (2007) studied thermal comfort in naturally ventilated school buildings in Chicago based on a previous study of his done in Kenya, but since the sample of the Chicago study was very small, he indicated that it is a preparation for future studies in this field. They used survey and environmental monitoring in their study. Singh et al. (2018) studied thermal comfort during the summer season in naturally ventilated classrooms in composite climate in India, which is hot and dry, warm and humid as well as cold climate. They used survey and environmental monitoring. The results showed that there is a higher temperature fluctuation in naturally ventilated classrooms (79.9-96.8F) across different buildings. Also, around 80% of the participants responded to the thermal comfort question to be comfortable in the comfort band (+_1 thermal sensation) in all naturally ventilated classrooms. In most of the literature about thermal comfort and operable windows, they showed that students in classrooms with operable windows have more tolerance about higher and lower temperatures and make them more adaptable to their environment.

Indoor Air Quality and Operable Windows:

Griffiths and Eftekhari (2008) conducted a study on ventilation performance of the naturally ventilated classroom in the UK and their relationship with CO_2 concentration. They used environmental monitoring. The study shows that a 10-minutes opening windows in the break time between classes can help decrease CO_2 concentration in the classrooms around 1000ppm without compromising thermal comfort. The study also finds that to keep the CO_2 concentration in an acceptable range, more than two periods of this type of ventilation will be required. Heudorf et al. (2009) conducted a study on the relationship between ventilation, CO_2, and particulate matter in classrooms in Germany. They used environmental monitoring to measure CO_2 levels in two mechanically ventilated classrooms, for three weeks; in the last week, a protocol was used to engage operable windows between classes to improve ventilation rates. The results showed that during that third week, the mean value of the CO_2 concentration was reduced to 1000ppm.The literature shows that although using natural ventilation alone is not efficient for improving indoor air quality, combining it with mechanical ventilation systems can improve indoor air quality in an acceptable range.

Thermal Comfort, Indoor Air Quality and Operable Windows:

De Giuli et al. (2012) conducted a study on the relationship between indoor environmental quality and student perception of comfort in Venice, Italy. They used survey and environmental monitoring. They found that in naturally ventilated spaces, closed windows are the main cause of students' dissatisfaction about indoor air quality during class time. Similarly, Dias Pereira et al. (2014) studied the relationship between thermal sensation, thermal comfort, and indoor air quality in naturally ventilated secondary schools in Portugal. They used survey and environmental monitoring. Results show that students felt comfortable in both higher and lower temperatures beyond the limits of the standard ASHRAE comfort zone. On the other hand, the CO_2 concentration in these natural ventilated classrooms exceeded the standard ASHARE limits. To further address the possible benefits of operable windows, Stazi et al. (2017) conducted a study for developing an automatic system for operable windows and evaluated the effect of the automatic system on thermal comfort and indoor air quality in the classroom in Italy. They used survey and environmental monitoring. Results indicate that the priority of students for opening/closing windows is their thermal comfort (such as indoor and outdoor temperature) and CO_2 concentration is not a tangible factor for them. In the designed automatic system, there will be sensors to sense the CO_2 level so it will take CO_2 concentration into account, so that CO_2 level is usually below 1500ppm and users were thermally comfortable.

Liu et al. (2019) conducted a study to understand the relationship between thermal comfort and perceived indoor air quality in naturally ventilated classrooms in China. They used survey and environmental monitoring. The results show that CO_2 concentration did not have any relationship with the rate of dissatisfaction with indoor air quality, which was higher than 20%. Survey results indicate occupant density in the classrooms did not have any impact on the perceived thermal comfort, while density did influence perceived indoor air quality. The results show that the factor having the highest effect on occupants' acceptability of indoor air quality is thermal sensation. The literature shows that thermal comfort is more tangible than indoor air quality for the users of operable windows, that is why when they feel hot/cold they open/close windows. But they never open/close windows when the CO_2 concentration is high because they cannot sense it. One of the solutions is having automatic operable windows which have a CO_2 sensor to measure the CO_2 level and alarm the user when it is the time for open/close the windows.

Synthesis of the Literature:

This literature review and synthesis shows that all the previous research was conducted by using quantitative methods including environmental monitoring, survey data, and simulation. Also, most of the studies were completed in Europe and Asia; only one study was conducted in the United States. Figure 2 shows the percentage of studies in different areas.

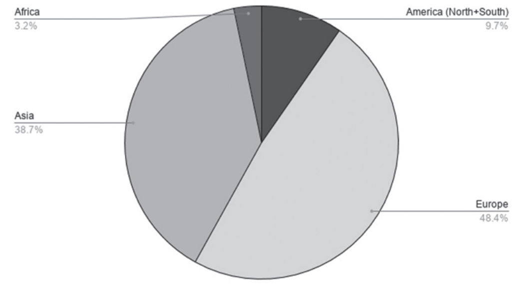

Figure 1: Percentage of studies in difference areas. (Author 2019)

Among the total of the thirty-one studies found, 54% (17 out of 31) focused only on thermal comfort and operable windows, 25% (8 out of 31) focused on indoor air quality and operable windows, and only 21% (6 out of 31) addressed operable windows and both thermal comfort and indoor air quality (Table 1). There is a gap in the location of the study and methodology of the research in this field.

To measure thermal comfort with environmental monitoring, all studies measured air temperature and relative humidity. Eleven of the studies also measured air velocity (table 1). For measuring indoor air quality, CO_2 levels were measured using indoor air quality sensors. In twenty-one of the thirty-one studies, survey was used to understand occupant thermal comfort and/or indoor air quality perceptions in classroom (table 1). All the twenty-one studies asked questions from students, despite the teachers having agency over the operable windows. The teachers' behaviors have not been addressed in these studies.

DISCUSSION

Schools are the second most important space in children's life after their home environment (Baki-Biro et al. 2012; Mendell et al. 2013), supporting the importance of the school environment in their health, well-being, and comfort (Abramson et al. 2006; Madueira et al. 2009; Annesi-Maesano et al. 2013; Mendes et al. 2014; Almeida et al. 2016). Children are more vulnerable to toxins as compared to adults, because they breathe in higher volumes of air relative to their weight.(Suk et al. 2003).

When designing classrooms, improving student learning, performance, and comfort should be prioritized by architects (Catalina and Iodache 2012). Ventilation is one factor that can improve students learning performance and health in classrooms and schools (Gao et al. 2014). There are many ways to provide increased and appropriate ventilation, such as operable windows, exhaust fans, or mechanical ventilation systems (Gao et al. 2014). In many schools, ventilation is expected to be provided by teachers or students

Author	Year	Location	Thermal	IAQ	Survey		Environmental Monitoring								Simula-tion
					Yes/No	Sample	Yes/No	Sample	Temp	RH	ACH	CO_2	VOC	Other	
Madrureira et al	2016	Portugal		x	No		Yes	73 classes				x	x		
Heudorf et al	2009	Germany		x	No		Yes					x			
Coley and Beisteiner	2002	UK		x	No		Yes	7 classes	x			x			
Giffith and Eftekhari	2008	UK		x	No		Yes					x			
Chithra and Nagendra	2012	India		x	No		Yes	1 school	x	x		x		CO,PMs	
Dorizas et al.	2015	Greece		x	Yes		Yes	9 schools			x	x	x	CO,PMs	
Fuoco et al.	2015	Italy		x	No		Yes	3 schools	x	x		x			
Krawczyk et al.	2016	Portland and Spain		x			Yes				x	x			
Almeida et al.	2016	Portugal	x		Yes	10 Schools	Yes	10 schools	x	x		x			
Buonocore et al.	2019	Brazil	x		Yes		Yes		x	x					
Djamila	2017	Malaysia	x		Yes										x
Ge et al.	2019	Singapore	x		No		No								
Zhang et al.	2007	China	x		Yes	25 classes	Yes		x	x				Air.Vel.	x
Huang and Hwang	2016	Taiwan	x		No		No								
Jinal	2018	India	x		Yes	130 students	Yes		x	x				Air.Vel	
Kumar et al.	2016	India	x		Yes	32 buildings	Yes		x	x		x		Air.Vel	
Liang et al.	2012	Taiwan	x		Yes										
Mishra and Ramgopal	2015	India	x		Yes		Yes		x	x				Air.Vel	
Nematchoua et al.	2014	Cameroon	x		Yes	2650 surveys	Yes		x	x		x			
Ogoli	2007	Chicago/US	x		Yes	120 students	Yes		x	x				Air.Vel	
Singh et al.	2018	India	x		Yes	30 classes, 3 uni	Yes		x	x				Air.Vel	
Teli et al.	2013	UK	x		Yes	230 students	Yes								
Tribilcock et al.	2017	Chile	x		Yes	440 studetns	Yes		x	x				Air.Vel	
Yang and Zhang	2008	China	x		Yes	11 Buildings	Yes		x	x				Air.Vel	
Papazoglou et al	2019	Greece	x		Yes		Yes		x	x				Air.Vel	
Dias Pereira et al.	2014	Portugal	x	x	Yes		Yes		x	x		x			
Stazi et al.	2017	Italy	x	x	Yes	68 people	Yes		x			x			
Almeida et al.	2017	Portugal	x	x	No		Yes	8 schools	x	x	x	x			
Liu et al.	2019	China	x	x	Yes	3 universities	Yes		x	x		x		Air.Vel	
De Guili et al.	2012	Italy	x	x	Yes		Yes		x	x		x		Air.Vel	
Gao et al.	2014	Denmark	x	x	Yes	4 classrooms	Yes		x	x		x			

Table 1: Classification of the Literature Review

via opening windows (Bako-Biro et al. 2012). Different elements such as air ventilation systems, HVAC systems, building envelopes, and occupant behavior influence the condition of the indoor environment (Catalina and Iordache 2012).

Comfort is another factor, which is influenced by these building elements. Human comfort can be broken down into four conditions: thermal, visual, indoor air quality, and acoustical (Ortiz et al. 2017; Bluyssen 2009). Thermal comfort and indoor air quality are the most important of these four comfort conditions to address in improving occupant health and productivity (Pan et al. 2018). Several studies focus on these two elements and their relationship with operable windows in K-12 schools.

This paper synthesizes a total of thirty-one papers focusing on this subject. Gaps were found in the consistency of their methodology, transferability across their locations, the factors addressed in each of the research studies, and the sample size of the studies. All the identified literature used quantitative methods, including environmental monitoring, survey, and simulation. Also, most of the studies were located in Europe or Asia, with only one being conducted in the United States. Besides, only 21% of total (thirty-one) papers were focused on the relationship between operable windows and both thermal comfort and indoor air quality in K-12 classrooms; the rest focused on either thermal comfort or indoor air quality and their relationship with operable windows in K-12 classrooms.

A synthesis of the sensor measurement parameters across the studies, show all thermal comfort studies measured air temperature and relative humidity. Almost half of the studies measured air velocity as the primary indicator of thermal condition, while all the indoor air quality studies measured CO_2 levels as their metric. Furthermore, all the literature reviewed that used surveys as one of their methods asked questions of students, while it is teachers and school administrators that are in charge of opening or closing windows and of making policies related to using operable windows. For example, Coley and Beusteiner (2002) state that some evidence shows that teachers and staffs are reluctant to open windows to improve ventilation and decrease CO_2 level because of: (i) a lack of awareness of the staff about the problem, and (ii) uneven natural ventilation drafts in the classroom. This literature review and synthesis establishes a gap in the samples showing that the teachers and school policy makers play an important role in using/not using operable windows in classrooms; these agents should be considered in the research design of future studies.

CONCLUSION

By synthesizing the literature review, several gaps were identified:

1. All the studies found addressing K-12 schools studied thermal comfort and indoor air quality from student's perspective, while teachers and school administrators oversee the use of windows.
2. All studies were conducted using quantitative methods. including environmental monitoring, survey, and simulation.
3. Only one study out of thirty-one was conducted in the U.S.
4. Only 21% of total papers addressing K-12 environments were focused on the relationship between operable windows and both thermal comfort and indoor air quality.

For future studies, mixed methods research is suggested to allow for more insight into the relationships between operable windows, thermal comfort, and indoor air quality in K-12 classrooms in the U.S. Interviews with teachers and school administrators are suggested for future research designs to better understand why they are or are not using windows, with environmental monitoring to measure temperature, relative humidity, air velocity, and CO_2 level. By implementing mixed methods studies in the U.S., a better understanding of these three considerations—operable windows, thermal comfort, and indoor air quality—can be harnessed to better support student health, wellbeing, and learning outcomes.

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