Indoor Environmental Quality in Public Schools: Repositioning Health at the Nexus of Design and Operation

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In the past two decades, a number of school districts have constructed new, or renovated existing schools to meet energy and environmental targets yet, few studies have examined the actual impact of green building measures on IEQ or on the health or academic performance of students and staff. This paper reports on the first phase of study entitled Environmental Quality and Learning in Schools (EQUALS). In the US Midwest, 37 schools constructed within the last 15 years, were visited and include a mix of conventional, LEED or EnergyStar-certified facilities. Walkthrough assessments, teacher surveys, HVAC system inspections, and comprehensive IEQ analyses in each classroom were undertaken. The paper discusses observations recorded and raises questions regarding relationships between design intent, operational practices and occupant behaviors as a means to advance related aspects of dialog surrounding design and health..

INTRODUCTION

Indoor environmental quality (IEQ) in America's 98,500 public schools affects the health and performance of over 50 million students, 3 million teachers, and millions more staff and administrators in the U.S.[3] A typical American student spends over 1200 hours in school each year; for them, schools are the most frequented indoor environment after their homes. School IEQ—encompassing ventilation, particulate, biological and chemical exposures, temperature, humidity, lighting, and acoustics—is key to ensuring the health of the next generation of Americans.

In addition to improving health, good IEQ in schools may also improve learning. Recent studies have found that better ventilation may raise student attendance, [4,5] boost work speed and accuracy, [6,7,8,9], and improve academic achievement on standardized tests. [10,11] Other studies have attempted to link air filtration and student performance, but with less conclusive results. [12,13,14,15] But, while IEQ is increasingly recognized as important for both health and learning in schools, many American schools still perform poorly. [16, 17, 18, 19]

THE PROMISE OF HIGH PERFORMANCE BUILDINGS

What makes a school building 'high-performance'? The imperative and desire for 'green', 'sustainable', and 'efficient' buildings, and the popularization of performance standards such as LEED and EnergyStar have led many school districts and state policymakers to mandate more 'high-performance' facilities, instead of conventional facilities designed to meet minimum building code requirements. For example, Ohio's Green Schools Program requires all school buildings receiving state funding to pursue minimum LEED Silver certification; Ohio now leads the nation in LEED schools, with 273.[20] As more states and districts adopt a high-performance mindset, there is an opportunity to advance a new healthy schools agenda which promotes occupant health and superior indoor environmental quality as defining characteristics of high-performance schools, together with the already established goals of environmental and operational sustainability.

Unfortunately, there is a lack of guidance for designing, operating, and assessing *health* in high-performance schools. Holistic performance standards such as the WELL Building Standard [21] or Living Building Challenge [22] include significant health-related components within their respective frameworks, but are not yet widely adopted. On the other hand, EPA's widely-used EnergyStar framework [23] prioritizes energy efficiency and does not consider health or IEQ (though in practice, prioritizing energy efficiency alone may impact the design and operation of a building's HVAC systems, with potentially adverse implications for ventilation, IEQ, and health). LEED falls in between: it includes IEQ criteria, though they are optional and comprise a small portion of the total available certification credits. The standard most used by schools in this study, LEED BD+C v3,[24] includes one credit each for monitoring ventilation, increasing ventilation above the ASHRAE Standard 62.1 minimum, and mold prevention; five credits for reducing chemicals and material emissions; but no credits for improved filtration. The schools in this study predate LEED v4, [25] which includes a maximum of two credits for "enhanced IAQ strategies" including high-efficiency filtration, increased ventilation, and CO_2 monitoring; however, the standard reduces the number of credits for low-emitting materials and eliminates the credits for indoor chemical and pollutant controls and mold prevention. LEED O+M,[26] a separate rating system not used by any schools in the present study, promotes sustainable operation and maintenance; it includes IEQ practices such as ongoing commissioning, IAQ monitoring, occupant surveys, green cleaning plans, and IAQ maintenance plans. However, LEED BD+C is more widely used and does not incorporate measures to ensure that healthy IEQ is maintained after construction.

Finally, little research has investigated IEQ, health, and learning in high-performance versus conventional schools. Studies of other building typologies either represent simulated conditions[27] or are limited to self-reported, survey-based perception studies.[28, 29, 30, 31] These studies do not address operational performance or objective IEQ parameters of school buildings currently in use. There is also insufficient objective analysis of ongoing building performance, for example life-cycle studies of energy use, and durability of systems and materials. And last, not enough attention is given to the human elements of building performance: more research is needed to understand the relationship between design and behavior, and their effects on the operation and maintenance of healthy, high-performance schools.

REGIONAL CHALLENGES

Best practices for IEQ and building performance are region-specific, determined by the climate and sociopolitical context in which a school is designed, built, and operated. In the U.S. Midwest, where the present study is based, public schools face unique challenges that affect their ability to deliver and maintain good IEQ. Cold, dry winters and hot, humid summers complicate the task of balancing energy efficiency, ventilation, and comfort throughout the year. Mechanical ventilation is a must: tight envelopes reduce outdoor air infiltration and entrap pollutants, and there are limited options for year-round natural ventilation. Recent economic and demographic trends in the 'Rust Belt' have limited school districts' ability to build, improve, and maintain facilities. Aging infrastructure, budget and staffing cuts, local politics, and other pressures may lead schools to sacrifice IEQ in favor of other operational needs. As a result, many Midwestern schools—even recently-built and high-performance buildings—have poor IEQ, indicated by low ventilation rates and high CO_2 concentrations.[32] Other regional studies have revealed inadequate school IEQ in America's Northeast,[33] West Coast,[34] Southwest,[35] and Northwest,[36] as well as in the UK,[37] and Europe.[38, 39] Each region has its own unique challenges pertaining to school design, management and operation, and therefore require region-specific IEQ strategies.

Given the importance of school environments for affecting health and learning outcomes, it is imperative to design, teach, and implement practical, region-sensitive IEQ best-practices that account for the complex contexts surrounding the design and operation of public schools. Healthy, high-performance school design must aim to improve health among students and teachers, but must also support schools' goals of improving learning achievement and work performance, streamlining operational costs, and environmental sustainability. Designers, researchers, school administrators, teachers, and operations personnel should ask:

• How can high-performance school design better prioritize IEQ, student and teacher health, learning and working performance, and sustainable operation?

• How do other performance metrics—for example, energy efficiency—impact IEQ and occupant health, performance, and well-being? How can school design and operational protocols be refined to achieve which balance of these issues?

• What tools will enable design practitioners, administrators, teachers, operations personnel, and other school stakeholders to better understand the benefits and tradeoffs associated with improving IEQ in school buildings?

• How might we design school facilities where health and IEQ are not optional add-ons, but rather integral parts of the building's normal, everyday operation?

Ideally, this conversation should also include broader life-cycle aspects and sustainability implications of schools like: site selection, transportation and infrastructure, and holistic assessment of student health and learning. The present analysis, however, is limited to the immediate school environment, architectural design, and operational and behavioral factors.

THE EQUALS STUDY

Environmental Quality, Health, and Learning in Schools (EQUALS) is a 3-year study funded by the U.S. EPA which aims to:

• Increase understanding of the relationship between environmental factors in schools and the health and performance of students, teachers, and staff;

• Compare the use and effectiveness of IEQ measures in "high-performance" and conventional school buildings; and

• Promote understanding of the importance of IEQ in schools, develop guidance for IEQ targets in school buildings, and inform the next generation of design, construction, and operational standards for healthy, high-performance schools.

During the first phase of EQUALS, between October 2015 and May 2016, architecture and public health researchers conducted IEQ measurements, HVAC inspections, walkthrough observations, and teacher surveys in 147 classrooms at 37 elementary and K-8 schools built in Michigan, Indiana, Ohio, and Illinois after 2000. The sample included 10 conventional schools, 15 EnergyStar schools, and 12 LEED schools.

IEQ sampling equipment was deployed for two full school days in four classrooms and one outdoor location per school. The

Variable and unit		Mean ± SD or Count	Min/Max or %
School-Wide Information (n = 37)			
Enrollment	Children	468±192	176/1060
No. classrooms	-	26±9	8/51
No. teachers	-	24±9	8/45
Floor area	1000 ft^2	81.4±38.4	10.7/203.5
Floor area per student	ft^2	176.3±56.8	57.9/354.3
Construction year	1920-2000	11	29.7
	2001-2005	10	27.0
	>=2006	14	37.8
Typology*	Bar	11	29.7
	Grouped	11	29.7
	Wing	13	35.1
	Courtyard	5	13.5
	Pod	1	2.7
Neighborhood	Residential	21	56.8
	Commercial	4	10.8
	Industrial	8	21.6
	Agricultural	12	32.4
Potential hazards	Highway	9	24.3
	Major road	6	16.2
	Fly path	2	5.4
	Railway	6	16.2
	Factory	8	21.6
	Warehouse	4	10.8
	Brownfield	1	2.7
	Plowed field	12	32.4
	Livestock	1	2.7
Visited Classrooms (n = 147)			
Classroom floor area	ft^2	991±156	758/1638
No. children		23±6	0/43
No. adults		1.5±0.8	1.0/4.5

*Building Typology: Bar = classrooms and other areas are generally arranged along a single straight corridor; Grouped = classrooms and other areas are generally arranged in a single large group with interior corridors and no protruding wings; Wing = classrooms and other areas are arranged in multiple wings connected by a central hub; Courtyard = classrooms and other areas are arranged in a ring around a central courtyard; Pod = classrooms and other areas are arranged in small groups or pods, linked by corridors to a central hub.

Table 1. Characteristics of study schools (from Batterman 2016)

samplers collected data on CO2 concentrations, coarse and fine airborne particulate matter (PM), volatile organic compounds (VOC), formaldehyde, sound pressure levels (SPL), temperature, and relative humidity (RH). Walkthrough inspections were conducted in each of the four classrooms to observe physical characteristics that might impact IEQ, including classroom size, occupancy patterns, construction type, material finishes, maintenance issues, windows and lighting, and potential sources of PM and VOC. Inspections and construction document reviews were conducted for HVAC components serving the sample classrooms. Observations included air handler (AHU) type and capacity, filter type and condition, maintenance issues, and potential sources of PM and VOC. Finally, overall building and site walkthroughs were conducted at each school. These included characterizations of typology, construction type, building condition, and siting, with a focus on conditions that could affect IEQ, such as damage to building envelope and source proximity to highways, industrial sites, or farms.

OBSERVATIONS

The main intent of these school visits was to collect baseline data on IEQ and document building characteristics which could affect IEQ. However, walkthrough observations, teacher surveys, and informal conversations with teachers, staff, and administrators, revealed how human behavior—the everyday use and operation of the school—can also profoundly affect IEQ. The relationships between schools' original design schemes, as-built conditions, operational regimes, and actual performance are complex. In better-performing schools, good design and operation tended to reinforce each other, which helps the building perform as designed. In schools with worse IEQ, there was often a mismatch—for example, poor design limiting IEQ performance despite conscientious operations; poor operational practices diminishing IEQ performance below the designed levels; or a conflict between design and operations, where school design actually hinders IEQ best practices. Several of these cases are described below.

VENTILATION

Meeting ASHRAE 62.1-2007 ventilation standards is mandatory for LEED schools; it is also the accepted IAQ standard in many local building codes, and is required by state law in Indiana (the location of 46% of schools sampled). However, many classrooms observed had high median and peak concentrations of CO2 over 2000 ppm, and most had ventilation rates (VR) below ASHRAE standards. A number of LEED-certified schools had significantly higher peak CO2 concentrations than EnergyStar or conventional schools, and comparable median and average levels. While all schools should be designed to meet minimum ventilation standards, many—even newand 'high-performance' schools—fall short when actually occupied.

School and district operational practices can have effects on ventilation that override well-intentioned design. In many schools, operation of ventilation systems appeared to prioritize the minimization of heating demand load and energy use, rather than meeting fresh air requirements. HVAC systems were typically activated just early enough to heat the school by the start of class, and were commonly shut down at the final bell—even while the building was still occupied. These practices are meant to reduce energy consumption, but adversely affect IEQ. In one district, four EnergyStar schools recirculated 100% indoor air during the day to reduce heating costs; Outdoor air (OA) dampers were closed, and two schools reported sealing OA intakes with plastic on the coldest days. There were also reports that HVAC systems were not run during the summer, saving energy but causing discomfort for occupants, humidity and condensation problems, and noxious conditions during maintenance activities like floor stripping and re-finishing. These four schools included some of the highest observed CO2 concentrations and lowest VRs; however, a fifth school in the district with similar design but a properly running HVAC system had VRs much closer to the study average.

Figure 1: Field Observations (left to right): Delivery truck in a "no-idling" zone adjacent to classroom OA intake vents visible on second floor. Classroom chemicals are a significant concern exacerbated by teachers' autonomy in operating individual classrooms. Energy saving imperatives often inflect operational logics, example of plastic sheeting applied over OA intake during winter months to reduce energy demand loads. (images courtesy of authors)

Teachers' actions also affect ventilation in individual classrooms. For example, two teachers on opposite sides of a conventional school disabled their classrooms' unit ventilators (UV)—one due to excessive noise, the other due to outdoor pollutants. The first teacher kept windows and doors closed, also due to noise; the second teacher opened them for fresh air whenever possible. As a result, the first classroom exhibited high CO2 and low VR, while the room with open windows was comparable to classrooms with normally operating UV. Most classrooms in this study had operable windows; though many teachers stated a desire to open windows for fresh air, few actually did. Teachers cited outside noise and distractions, difficulty of use, and school policy as reasons for keeping windows closed. These examples demonstrate the importance of holistic consideration of ventilation measures in classrooms: simply providing ventilation equipment or operable windows does not guarantee good ventilation or IEQ if other factors like noise or impractical design discourage proper use.

Even in newly constructed schools with advanced HVAC systems, ventilation and IEQ can be compromised by operational practices and teacher behavior. In contrast, one of the best-ventilated schools in the study, a LEED school with a dedicated outdoor air system (DOAS), had a ventilation system that was both designed and operated to high-performance standards. Both the building engineer and principal were knowledgeable about the system, had well-developed energy and ventilation strategies, and were proactive in reminding teachers how to maximize IEQ in their classrooms. High-performance schools should be designed with ventilation systems—mechanical and natural—that provide superior ventilation, are energy efficient, and are practical to use. Schools should also monitor performance and undergo periodic recommissioning to ensure that ventilation systems are meeting designed specifications throughout their life-cycle. And, school administrators, teachers, and staff should receive training on the importance of ventilation, how their school's system works, and how school policies and personal actions can affect ventilation and IEQ.

FILTRATION

In addition to poor ventilation, many schools also lacked proper air filtration. Most schools (59%) used only minimal filtration—typically 2-inch disposable filters with a MERV-8 efficiency rating. Fewer schools (41%) used more advanced filtration, typically a MERV-8 prefilter followed by a higher-efficiency main filter; four schools used MERV-11 main filters and eight had high-efficiency MERV-13 main filters. However, simply installing air filters is not enough—to be effective, filters must also be monitored and replaced regularly. Dirty filters needing replacement were observed at 15 schools (41%), including six with advanced filter systems. One LEED-certified school had prefilters so dirty they had deflected from air pressure buildup. Another LEED school's dirty filters had completely blown out and were heaped at the bottom of a running AHU. We also suspect that poor filtration had clogged coils and ERU desiccant wheels in several schools, tremendously reducing airflow.

Perceived cost is a major reason why schools do not replace air filters as often as necessary. Districts with limited budgets may try to cut costs by reusing dirty filters; one district facilities worker stated that replacing only slightly soiled filters was "throwing away money." This sentiment grows in schools using high-efficiency filters; these more expensive filters were typically replaced once annually or less, even at schools that were diligent in replacing cheaper prefilters. Misinformation about filter performance often reinforces this habit: for example, more expensive filters last longer, dirty filters are more efficient, or filters only need to be replaced when they are visibly clogged or obstruct airflow. Some staff reported that even obviously dirty filters were used until a third-party energy management service instructed a change, or until lack of airflow triggered alarms. These practices ignore the fact that replacing filters is inexpensive compared to the high cost of cleaning and repairing dirty HVAC systems, in addition to the human costs of breathing higher concentrations of PM.

Training facilities personnel about the importance of regular filter replacement, and how to recognize and correct problems is an easy way to improve school IEQ through better filtration; but design can also play an important role. HVAC system designers can address cost concerns by including slots for a variety filter

Figure 2: Filter replacement was a consistent concern across school types. In some instances, cost or lack of knowledge regarding replacement protocols was a contributing factor, however ease of access and in some instances access perceived to be dangerous in overhead or rooftop locations was a mitigating factor. (images courtesy of authors)

types—a low-cost solution that would enable schools to test and adopt different types of filters according to budget and preference. Designers of high-performance schools can also encourage health and IEQ by considering the human factors—such as labor cost and accessibility—associated with HVAC systems. Many schools have complicated HVAC systems with air-handling and filtration components scattered throughout the building. Monitoring and replacing filters can be time-consuming, difficult, and disruptive, especially in schools with classroom-based units, or components in hard-to-access locations like ceiling plenums or rooftops. At many such schools, filter changes were so disruptive that they could only occur when school was not in session. One LEED-designed school had roof-mounted AHUs accessible only by ladders and hatches; the school used high-efficiency filters, but carrying dozens of bulky 12-inch filters to and from the roof was laborious and dangerous. Furthermore, the roof membrane was slippery when wet, and facilities personnel avoided the roof altogether in rainy, windy, snowy, or cold conditions. As a result, dirty filters were rarely replaced, and the rooftop was strewn with spent filters which could not be carried down the ladder. In contrast, schools with the best filter-changing practices all had HVAC components that were centralized, easily accessible, had ample space for filter storage and disposal, were isolated from student areas, and could be checked and maintained by few staff with minimal effort. In general, healthy school design should encourage and simplify—rather than hinder—best practices in facilities operations and maintenance.

CHEMICAL PRESENCE

Chemicals used in schools and classrooms also affect IEQ and health by introducing VOCs and other pollutants into the indoor environment. Teachers play an important role in limiting potentially harmful chemicals in their own classrooms. Although many districts visited had chemical policies, many teachers were observed using unauthorized products in their classrooms; it is likely that many more cases went unobserved during classroom visits. Cleaning products like disinfectant sprays or wipes, whiteboard cleaners, and bathroom cleaners were found in 39% of classrooms. Air fresheners, including plug-ins, sprays, candles, and oil warmers were observed in 24% of classrooms. Teachers often justified using these products by citing frequent messes and odors caused by their students. Families may also donate prohibited products to their child's classroom, unaware of official chemical policies and IEQ best practices.

Teachers and parents should receive clear instruction about safe products allowed in school, and should be informed of the health hazards associated with air fresheners and other products commonly found in classrooms. Healthy classrooms should also be designed with sufficient ventilation and exhaust to dispel odors and refresh classroom air without the use of chemicals and air fresheners; exhaust is particularly important in science and art rooms where chemical are used. Classrooms could also be designed to give teachers greater control over ventilation; for example, incorporating digital overrides, exhaust fans, and operable windows. But above all, classrooms must use low-emitting materials: controlling IEQ by ventilation alone is unlikely to suffice if even moderately strong VOC sources are present in the classroom.

In addition to classrooms, rooms containing HVAC equipment must also be kept clean and free of hazardous substances in order to avoid potential contamination of supply air. However, schools were often observed storing hazardous chemicals, including concentrated cleaners, floor finishing products, refrigerants, paints, adhesives, lubricants, and solvents in rooms containing HVAC equipment. HVAC areas were also used to store cleaning equipment, trash, furniture, and spare building materials like carpet, vinyl flooring, insulation, and ceiling tiles. Healthy schools should be designed with sufficient dedicated storage space for hazardous chemicals and supplies, to prevent sensitive HVAC areas from being misused as storage.

DAYLIGHTING

Daylighting is a common strategy high-performance schools use to improve IEQ and reduce energy costs; LEED awards up to three credits for daylighting, plus an additional credit for outdoor views. In both high-performance and conventional schools visited, most classrooms had large windows with ample daylight and views—however, many teachers kept windows covered with blinds, curtains, or posters throughout the day. Many classrooms now feature smartboards and digital projectors which require a darkened room for visibility. Teachers with unshaded east, west, or south-facing windows frequently blocked them to prevent excess sun penetration, which can cause thermal discomfort and glare—especially in rooms with whiteboards, glossy desktops, and other reflective surfaces. Teachers with windows facing play areas, bus zones, and other high-traffic areas covered windows to keep students from getting distracted. Finally, a large number of teachers kept built-in blinds or shades closed simply because they were broken, hard to reach, or difficult to operate.

While many teachers liked the idea of daylight and outdoor views, the above examples demonstrate that daylighting strategies are not always well-integrated with actual classroom practices. Designers of healthy, high-performance schools must consider evolving occupant preferences—such as teaching methods and technologies—as well as usability, durability, and adaptability over time. Designers should be wary of "cookie-cutter" buildings; daylighting is context-specific, and appropriate strategies vary depending on the building's region, climate, site, and orientation. Daylight design must make good use of high-performance glazing and external and internal shading strategies, or else windows may reduce, rather than improve classroom IEQ. Healthy, high-performance schools must be careful to implement daylighting strategies that are sensitive to the needs and preferences of students and teachers; as our visits showed, poorly-planned or counter-productive IEQ strategies are likely to be rejected once the school is in operation.

CONCLUSION(S)

School building performance goes beyond energy efficiency and 'green' design; designing a truly high-performance school also means holistic consideration of health, academic performance, practicality, operating costs, and the building life-cycle. High-performance schools should be healthy, pleasant, environmentally friendly, economically sustainable, and—above all—conducive to learning. To these ends, a new healthy school agenda should be incorporated into the current sustainable schools campaign. This would address both health and sustainability at the nexus of design and operation, and would include a broad range of school stakeholders involved in both school design and operation. Healthy school guidelines should be developed to help:

• Design practitioners—including architects, HVAC engineers, lighting consultants, and interior designers—to incorporate healthy and sustainable features into the architecture of the school in ways that are sensitive to the building's climate and siting, initial and long-term costs, and occupants' present and future needs.

• School administrators, to weigh the full costs and benefits of implementing healthy, high-performance design and operational practices in their facilities, and to select strategies that match their district's unique goals and circumstances.

• Facilities personnel, to understand the importance of their role with respect to student health and learning, and to identify best practices which they can easily incorporate into their standard operational routines.

• Teachers, to understand how their classroom environment affects students' health and performance as well as their own, and to be aware of what steps they can take to make their classroom healthier and potentially better for learning.

A new 'healthy schools' agenda might also encourage a 'healthy design vocabulary' that gives more architectural prominence to IEQ and health-related building elements such as HVAC systems—similar to the way many buildings intentionally draw attention to their 'green' features, both in terms of legibility, but also through curricular integration. While multiple challenges exist in establishing new guidance for IEQ,[40] new emphasis could be placed on the commissioning process; developing IEQ capacity and expertise among school facilities, operations, and inspections personnel; and staging regular reviews of HVAC and IEQ performance throughout the building's lifespan. Finally, this agenda should recommend that the entire school community—not just facilities and operations personnel—share responsibility for maintaining healthy environments in their schools. There is a growing body of research linking health and learning with school IEQ; most teachers already believe that classroom IEQ affects their students' ability to learn, and future phases of the EQUALS study will quantify the impact of IEQ on student health and learning. Architects, engineers, and other designers must also recognize the links between school design, operation, and the health and performance of students, teachers, and staff. These efforts would aim to contribute to new evidence-based guidelines to enable the widespread adoption of healthy, high-performance standards for the next generation of schools.

ACKNOWLEDGEMENTS

The authors appreciate and acknowledge the engagement and assistance of the teachers and staff at each school participating in the EQUALS study. We thank our research associates and staff, including Andrew Wald, Christopher Godwin, Floyd Watkins, Lexuan Zhong, Feng-Chiao Su, Julien Heidt, An Nguyen and Kallie Strenburgh for their assistance. This publication was developed under Assistance Agreement No. 83563701-0 awarded by the U.S. Environmental Protection Agency to the University of Michigan. This text has not been formally reviewed by EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products, recommendations or commercial services mentioned in this publication.

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