A Graphical Approach to Evaluating High- Performing Buildings: Indoor Air Quality, Energy, Water, and Waste

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ABSTRACT

In this paper, we describe a graphical approach to illustrating the performance of high-performing buildings. Our approach enables building designers, owners, operators, and occupants to evaluate the performance of a building as designed and as operated with respect to four key attributes: indoor air quality, energy use, water consumption, and waste generation. Drawing upon both simulated and measured data, graphical representations of different buildings are presented that enable comparisons among these four attributes. Special attention is given to indoor concentrations of potential concern, on-site energy generation, water reuse, and the reduction of waste generated during construction.

INTRODUCTION

Defining a "high-performing building" is challenging given the multiple performance parameters that need to be considered including indoor air quality (IAQ), energy, water, and waste. Especially difficult is characterizing IAQ due to our current incomplete understanding of the impacts of indoor pollutant exposures on human health, comfort, and productivity. Nonetheless, the building community is currently being challenged to reduce the environmental impacts of buildings -- including energy consumption and associated greenhouse gas emissions, water use, and waste generation -- while maintaining, if not improving, indoor environments that are conducive to occupant health, comfort, and productivity.

This overarching goal is often addressed in discussions of green or sustainable buildings, and a number of programs, standards, codes, and other efforts are in place to promote, and in some cases require, the design and construction of green or sustainable buildings (ASHRAE, 2011; USGBC, 2009; GBI, 2010; ICC, 2012). More recently, there has been a focus on net-zero energy buildings, which are intended to be so energy efficient that the net energy they require can be provided on an annual basis by on-site renewable sources (NSTC, 2008). These efforts speak to the need for "high performance," which, in addition to energy, generally includes a range of non-energy performance attributes such as IAQ, water consumption, the use of recycled and/or regionally-manufactured materials, and the diversion of construction waste from landfills.

In this paper, we describe and demonstrate a graphical approach to illustrating the performance of high-performing buildings. Our approach enables building designers, owners, operators, and occupants to evaluate the performance of a building as designed and as operated with respect to four key attributes of high-performing buildings: indoor air quality, energy use, water consumption, and waste generation. Drawing upon both simulated and measured data, graphical representations of different buildings are presented that enable comparisons among these four attributes.

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THE NEED FOR AN IAQ METRIC

Ideally, an IAQ metric would be a parameter (or collection of parameters) that quantifies indoor contaminant levels and the health, comfort, and productivity of building occupants. The fact that indoor environments are defined by mixtures of indoor contaminants, and that the impacts of these mixtures on building occupants are not well understood, makes it difficult to quantify "acceptable" IAQ. Adding to this complexity, there is no set of universally agreed-upon health benchmarks or other reference values for many of these parameters. One reason for this lack is that there are several factors policy makers must consider when defining an acceptable health benchmark or reference value. These include: differences in the populations they are striving to protect (e.g., workers, susceptible groups, the general population); the nature of the exposure, i.e., the concentrations over time to which the populations are exposed (e.g., first responders to a hazardous situation and exposures to the general population); and the nature of the human health endpoint of concern (e.g., reversible or irreversible; morbidity and/or mortality).

Recently, Mouradian et al. (2012) proposed an IAQ metric based on four groups of pollutants representative of similar behavior, use, or effect. The four groupings are: CO_2 as a marker linked to human occupancy; NO_2 and sulfur dioxide (SO_2) in dwellings and ozone (O_3) in offices linked to occupant activities; CO and seven VOCs linked to materials, activities, and behavior; and particulate matter with diameter both 2.5 microns (μm) and smaller ($PM_{2.5}$) and 10 μm and smaller (PM_{10}) linked to activities.

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 62.1-2010 Ventilation for Acceptable Indoor Air Quality, contains a collection of such reference values, derived from other sources, in an informative (i.e., non-binding) appendix (ASHRAE, 2010a). While these values are not provided as a means of compliance with the standard, they are included along with a useful discussion of the challenges in developing and applying such reference values.

A GRAPHICAL APPROACH TO IAQ METRICS

Rather than trying to consolidate the many different dimensions of indoor air quality into a single metric, we propose to enable comparisons using multiple IAQ-related parameters. To facilitate making comparisons using our approach, we have limited ourselves to twelve parameters at a time, each of which is represented as an equal angular sector of a circle. The length of each sector represents the magnitude of the given parameter, e.g., the concentration of an indoor pollutant, and the circumference of the circle represents the upper limit for the parameter, e.g., an acceptable health benchmark or other appropriate reference value. If the parameter does not exceed its health benchmark, the length of the sector is proportionately shorter than the sector defined by the parameter's health benchmark. If the parameter exceeds its health benchmark, the length of the sector is proportionately longer than the sector defined by the parameter's health benchmark. For all of the parameters we use in this paper, the smaller the given parameter or associated sector, the better. In terms of our graphical representation, we currently assume all of the sectors are equally important.

Where a given pollutant has no health benchmark or reference value, an empty sector is displayed. To distinguish this situation from one in which the measured or modeled concentration is significantly lower than the reference value, we have chosen to graph the latter circumstance with a sector that is one quarter of the length of the reference value, thereby signifying the concentration is well below the reference value. Similarly, when a concentration significantly exceeds its corresponding reference value, we have chosen to represent this concentration as 1.5 times the length of the health benchmark, thereby signifying the concentration is well above the reference value.

The merits to this proposed approach are two-fold. First, rather than questionably and perhaps subjectively combining IAQ parameters into a single metric, our approach preserves the robustness of the available data and its ability to inform decision making relative to desired health benchmarks or other reference values. Second, it enables users to select the IAQ parameters (concentrations, locations, and populations) that are most relevant to the issues with which they are concerned.

APPLYING THE APPROACH TO EXISTING DATA

To demonstrate our approach, we have graphed the results from two existing datasets: (1) the Small and Medium Sized Commercial Buildings (SMCB) field study (CARB, 2011), and (2) a simulation study of residential IAQ control interventions (Emmerich et al., 2005).

Figure 1 plots twelve parameters from the SMCB study, including the 95th percentile concentrations of nine volatile organic compounds (VOCs) and the 75th percentile concentrations of carbon dioxide (CO_2), $PM_{2.5}$, and PM_{10}. The respective health benchmarks are: (a) for VOCs, the California (CA) chronic recommended exposure levels (RELs) for each pollutant (with the exception of formaldehyde (HCHO), which is an 8-hour REL) (Cal EPA, 2012); (b) for CO_2, 1800 mg/m^3 (930 parts per million (ppm)), which is commonly used as a reference value, despite its limitations as an indicator of IAQ, and (c) for $PM_{2.5}$ and PM_{10}, the EPA NAAQS (EPA, 2012b).

Figure 2 shows the impact of different interventions to address summertime concentrations of carbon monoxide (CO) and nitrogen dioxide (NO_2) in a kitchen in Boston with a maladjusted gas stove as modeled in Emmerich et al. (2005). The health benchmarks are the EPA one-hour NAAQS for CO and the EPA annual NAAQS for NO_2 (EPA, 2012b). This figure shows that not only does proper adjustment of the stove have the greatest impact on lowering both CO and NO_2 concentrations, it is the only intervention that reduces the NO_2 concentration below the health benchmark.

The preceding figures show how different pollutant parameters can be displayed to assess IAQ performance by comparing pollutant concentrations with respect to their health benchmarks in different building types, spaces, and locations. Therefore, it would be helpful to arrive at an accepted collection of contaminants to allow comparisons among datasets and buildings. For commercial buildings, a user may wish to use the parameters included in the EPA Building Assessment Survey and Evaluation (BASE) study (Girman et al., 1995), while for residential structures, the list of pollutants proposed by Logue et al. may be useful (Logue et al., 2010). (Note: The BASE study was a research effort to provide data on IAQ in existing, non-problem buildings. In contrast to the LEED rating system (USGBC,2007) and ASHRAE 189.1 (ASHRAE, 2011), the BASE study was not an effort to define IAQ design requirements or guidelines.)

BEYOND IAQ TO IEQ

Going beyond IAQ, Catalina and Iordache (2012) proposed an indoor environmental quality (IEQ) index model that was a function of four quality indices (air quality and thermal, acoustic, and visual comfort). It is only a short extension of our approach to include other IEQ parameters (e.g., temperature, humidity, noise, lighting). The application of our graphical approach in these cases is relatively straightforward, as most of these quantities have acceptable health and/or comfort benchmarks or at least ranges of acceptability. For example, rather than plot both building temperature and humidity in the context of thermal comfort, it would likely be more informative to plot the metric of predicted percentage of dissatisfied people as defined in ASHRAE Standard 55, where 20 % is considered an acceptable reference value (ASHRAE, 2010b).

ENERGY AND WATER

Whether or not they address IEQ, high-performing buildings (HPB) emphasize minimizing off-site sources of energy. Energy use intensity (EUI), expressed in terms of energy per square area or energy per person, is a common benchmark used to compare the energy performance of buildings of similar function in the same climatic zone (Peterson and Crowther, 2010). Data to do so in the United States can be found in the Commercial Building Energy Consumption Survey (EIA, 2008) and Residential Energy Consumption Survey (EIA, 2009).

In addition, energy performance can be simulated and compared to compliance with a given energy standard, e.g., ASHRAE Standard 90.1 or 90.2 (ASHRAE, 2010c and ASHRAE, 2007) or an energy rating system e.g., EPA's ENERGY STAR (2012a). Two other interesting energy comparisons for HPB are (a) the differentiation between the building EUI and the energy generated off-site (annual source energy), and (b) the portion of energy requirements met by renewable sources.

Equally valid, but much less commonly used, are metrics for water use. In addition to utilizing high-efficiency fixtures, HPB frequently include additional measures to conserve water, including gray water systems, collecting and using rainwater, utilizing low-water-use vegetation, constructing on-site bioswales and wetlands, installing permeable hard surfaces, and even performing on-site wastewater treatment. The goal of these measures is to minimize a building's need for off-site water supply (and disposal), just as the goal of energy efficiency measures is to reduce the need for off-site energy. Comparable to the EUI, we can define a water use intensity (WUI), expressed in water volume per square area of building or per person, as a parameter to use in our graphical approach. (Like the EUI, we would expect a WUI to be building-function dependent, but unlike the EUI to be less climate-dependent.)

One method to support such comparisons is to consider data from existing buildings. In an analysis of water use at Yale University, Iversen (2010) provides average consumption data per unit floor area for selected building categories. The types of buildings listed include academic; administrative; dormitory, apartment, and other housing; dining; and laboratory, among others. Similarly, the Department of Energy cites data from the American Water Works Association on gallons per person per day for commercial, recreational, and institutional buildings (DOE, 2012). In addition, data could be compared to building performance based on compliance with a given water standard, e.g., LEED baseline, EPA WaterSense, ASHRAE/IES/USGBC Standard 189.1 (USGBC, 2009; EPA, 2006; ASHRAE, 2011).

WASTE

Lastly, HPB usually handle waste minimization in one or more of three ways. The first way is how much construction waste was diverted from landfills. The second is how much of the construction materials were either reused from demolished buildings or derived from recycled materials. The third way is to quantify how much waste generated by the occupants and operator of a building is recycled. All three values can be important parameters for adding waste considerations to our approach, although none of the three is comprehensive or risk-based. Buildings, especially manufacturing facilities, not only generate solid waste, but also emit waste products into both air and water. In addition, the toxicity of the waste in addition to its mass is important to know if one is to assess the potential human health and environmental risks associated with the waste.

Until waste streams are better characterized, we suggest the following waste metrics be used in our graphical approach. With respect to construction waste generation, EPA estimates weighted averages of about 21.5 kilograms (kg) per square meter for both residential and nonresidential construction (EPA, 2009). Alternatively, one could include how much construction waste was sent to a landfill. (To be consistent with our convention to have smaller values (smaller sector lengths) be the desirable outcome, we suggest using waste sent to, as opposed to diverted from, landfills). In this case, a reference value of 25 % could be used based on the fact that the LEED rating system offers two points for sending 25 % or less of construction waste to landfills, i.e., 75 % of construction waste diverted (USGBC, 2009). Relatedly, ASHRAE Standard 189.1 requires total waste for new buildings nit exceed 5454 kg (12000 pounds) per 930 m^2 (10000 ft^2) of new building area, whether diverted, landfilled, incinerated or otherwise disposed of (ASHRAE, 2011).

Although many high-performing buildings are constructed in part from materials either reused from demolished buildings or derived from recycled materials, we have not yet found data robust enough to use as a reference value for the use of such materials. Therefore, we have arbitrarily set a reference value of 75 % for the use of virgin materials (i.e., equivalent to constructing a building using 25 % recycled/reused materials). Buildings that are constructed with more virgin materials would exceed the red line reference value, and correspondingly buildings constructed with less virgin materials would not reach the reference value (the more desirable situation). Since 92 % of all construction and demolition waste is from renovation and demolition (Resource Venture, 2005), such data are critically needed to properly assess the impact of reusing construction materials from demolished buildings to construct new ones.

With respect to waste generated during occupancy, we suggest considering the estimates of 1950 kg per unit per year for residential dwellings and the annual waste generation rates for different building types provided by Fairfax County, VA (Fairfax, 2012a and 2012b). Until better data are available, we are not able to factor appropriate credit for the use of salvaged materials when constructing a building or the reuse by others (recycling) of a building's generated waste.

GRAPHING A HIGH PERFORMING BUILDING

Table 1 shows twelve building attributes and a suggested reference value for each. These attributes and reference values are not presented as a recommendation for characterizing or rating high performance buildings, but rather as an illustrative example to show the flexibility and application of this approach. For example, the reference values for energy use and artificial lighting power density assume the building complies with ASHRAE Standard 90.1-2004 (ASHRAE, 2004). Similarly, other values that assume the building meets the EPA NAAQS for PM_{10} (averaged over 24 hours) and CO (averaged over eight hours); the CA REL for HCHO; the water use requirements specified in EPAct; and diverts 75 % of its construction waste away <u>from</u> landfills (i.e., takes 25 % of its construction waste <u>to</u> landfills).

Other reference values are based on either professional judgment (e.g., total VOC and CO_2 levels of 1000 µg/m³ and 1800 mg/m³ respectively) or were arbitrarily chosen (e.g., an ENERGY STAR rating of 75; 75 % use of recycled construction materials (25 % use of virgin materials); and renewable energy sources that account for 10 % of the building's annual energy requirement (90 % use of non-renewable energy sources) (EPA, 2012a).

Table 1 also includes published data from the Natural Resources Defense Council (NRDC) building for comparison with these reference values (Croxton, 2012). As can be seen, the high-performing NRDC building compares very favorably to the reference values. (Note: In the absence of published data on CO2 levels, an ENERGY STAR rating, and the use of recycled construction materials, we have assumed values for these parameters.) The NRDC building is well below all of the reference values except for the use of renewable energy sources, where such sources provide 4 % of the building's energy needs, below the arbitrarily set reference value of 10 % (i.e., 96 % non-renewables sources vs. 90 %).

Table 1 High Performing Building Parameters

Parameter	**Benchmark/Reference Value**	**NRDC**	**Hypothetical**
PM10	150 ug/m³ (24-hour)	7.1 ug/m³	34 ug/m³
HCHO	9 ug/m³ (CA REL)	4 ug/m³	32 ug/m³
Total VOC	1000 ug/m³	256 ug/m³	1030 ug/m³
Carbon dioxide	1800 mg/m³	1440 mg/m³ *	1470 mg/m³
Carbon monoxide	10 mg/m³ (8-hour)	0 mg/m³	3 mg/m³
Energy	100 %: 90.1-2004**	61 %	100 %
Non-Renewable	90 %*	96 %	100 %
ENERGY STAR	100 % : ENERGY STAR = 75	90*	50
Water Use	100 % : EPAct	54 %	100 %
Undiverted Construction Waste	25 %	4 %	50 %
Virgin Materials	25 %*	15*	33 %
Artificial Lighting Power Density	100 %: 90.1-2004	59.30 %	100 %

Notes: * indicates the value was assumed for illustrative purposes

** ASHRAE 90.1-2004 is included here, because this was the reference version used in the NRDC case study. Ideally, future articles will compare building performance to the latest version of all ASHRAE standards, including 90.1.

Table 1 also shows data from a hypothetical building comprised from multiple data sets, e.g., the BASE and SMCB studies (Girman et al., 1995; CARB, 2011). The data from our hypothetical building exceeds the reference values for six of our twelve parameters, specifically: HCHO, Total VOC, renewable energy sources, ENERGY STAR rating, diverted construction waste, and use of recycled construction materials. Figures 3 and 4 plot the data from the NRDC and our hypothetical building, respectively. It is clear from the graphical presentation that the "footprint" of the NRDC building is much smaller than that of our hypothetical building, indicating that the NRDC building is the much higher-performing building.

SUMMARY

In this paper, we:

- Presented a new, graphical approach to IAQ metrics that capture the robustness of indoor concentration data relative to health benchmarks and other reference values.
- Using existing data from field and simulation studies, used this approach to display IAQ performance both in a given building and among buildings.
- By combining spatial concentrations, activity patterns, and toxicological data, discussed how the approach could be used to characterize which populations are exposed to what air pollutant concentrations and where and the risks associated with those exposures.
- Extended our approach to developing an IEQ metric by including additional parameters, such as thermal comfort, lighting, and acoustics.
- Lastly, by including energy, water, and waste considerations, showed how the approach can be used to inform building design and assess the performance of high performing buildings.

To fully enable a comparison of the sustainability of different HPB requires the introduction of life-cycle performance in each of the four areas above (IAQ, energy, water, and waste), and their associated costs, over the life of the building (building design, the extraction and manufacturing of the raw materials or the use of recycled materials used to construct the building, their transportation to the building site, the construction of the building, its operation and maintenance, and its eventual demolition (hopefully reusing the building materials for a future building)). While performing life-cycle analysis poses challenges as well as opportunities, efforts are underway to collect this information, and the approach introduced here will be helpful in presenting that information in a useable way (Kneifel, 2011).

Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect those of the U.S. Environmental Protection Agency. In addition, the mention of any trade names or products does not imply endorsement.

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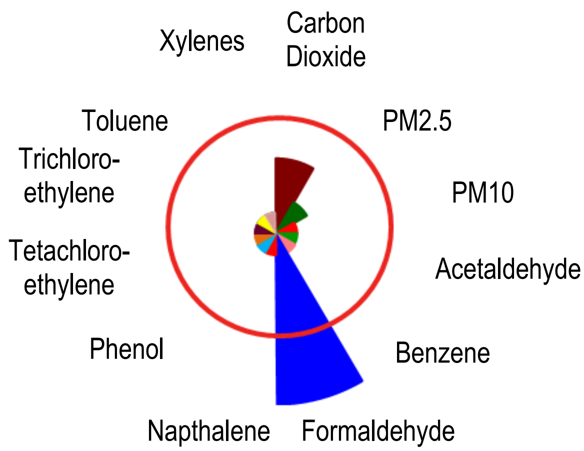

Figure 1 – SMCB Data (75th percentile, except for VOCs (95th), vs. CA Chronic REL(except HCHO, which is for 8 hours)

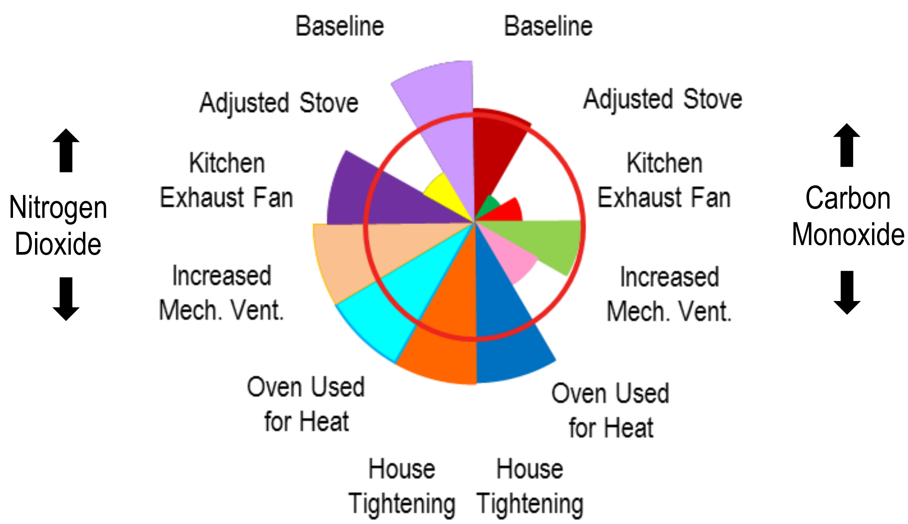

Figure 2 – NO2 and CO Concentrations in a Summertime Boston Kitchen with Different Gas Stove Interventions

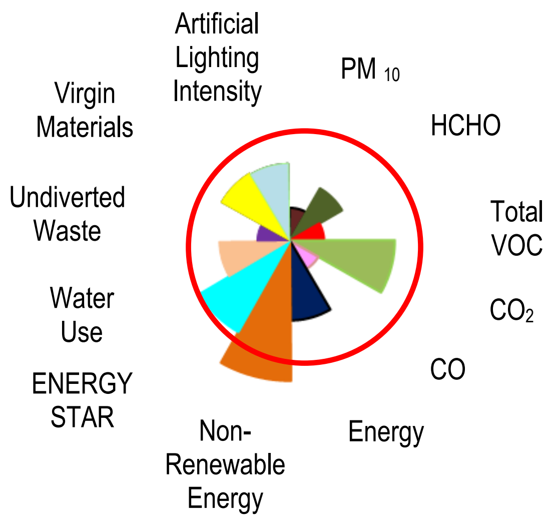

Figure 3 Twelve Building Parameters for the NRDC Building

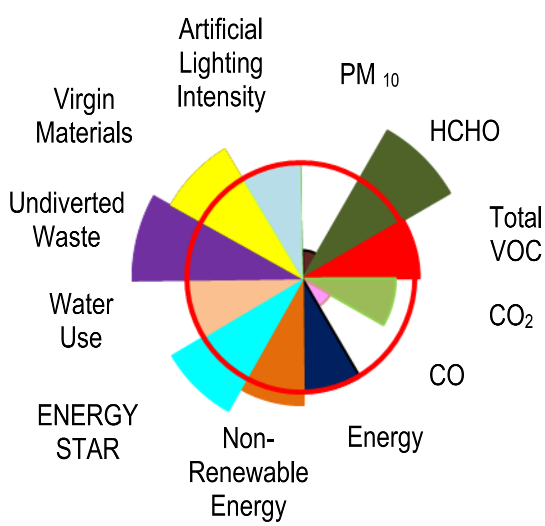

Figure 4 Twelve Building Parameters for a Hypothetical Building