The Seventh Asian-Pacific Symposium on Structural Reliability and Its Applications (APSSRA2020)
October 4–7 2020, Tokyo, Japan
T. Takada, I. Yoshida & T. Itoi (editors)

Bottom-Up Approach to Building Functionality

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Abstract: Building functionality is defined as the set of essential support services required for occupant safety and wellness. Traditionally these services have been designed using a top-down (owner) rather than bottom-up (occupant) based approach. A framework for performance-based criteria is suggested for a set of bottom-up indoor environmental quality indicators. The required levels of performance used in the framework combine aspects of existing prescriptive and adaptive criteria. Monte Carlo simulation using probability distributions from case studies and the literature are used to demonstrate the feasibility of the framework.

Keywords: Functionality; Occupant Comfort; Indoor Environmental Quality; Performance-based Design, Energy Resilience.

1. Introduction and Background

several fields, such as architecture, civil engineering, mechanical engineering, public policy, and public health. Broadly speaking, a building is designed for an architectural function or purpose, which is related to its mission. Buildings are intended to “shelter humans in an environment conducive to health and well-being,” e.g. Ozkan, Kesik, Yilmaz, & O'Brien (2019). Civil engineering researchers Mieler & Mitrani-Reiser (2017) are succinct in their definition of functionality as “the availability of a building or facility to be used for its intended purpose.” The building may have a single purpose or mission to fulfill such as serving as an office, residence, factory, school, etc., or it may be multi-mission and combine these functions. Mieler & Mitrani-Reiser (2017) *imply* in their definition that the conditions conducive to occupants fulfilling the intended purpose are available, but the specifics of the conditions are not provided. In this paper, the needs of the occupants and community inhabitants are *explicitly* considered, because these people are the driving force behind the mission of the building or shelter. “Functionality” is defined here as “the ability of an individual building to support its occupants and community inhabitants with the services essential for their safety and well-being”. Well-being is used here in the quality of life or “well building” sense e.g. USGBC (2014); WELL Institute (2017).

Not only are people the primary concern behind the design of buildings, they also spend a considerable amount of time in them. In the US, it is estimated that people spend 90% of their time in buildings e.g. Klepeis et al. (2001). Therefore, the inhabitant quality of life is strongly connected to the indoor experience. The ability of occupants to go about their daily activities within buildings relies upon support services such as lighting, heating and cooling, and potable water. Because these support services rely heavily on electricity and other sources of energy such as natural gas, it is not surprising that buildings comprise about 40% of the entire US energy budget. A breakdown of this energy budget shows that 65-70% of the electricity consumed in the US is in buildings e.g.US DOE (2008). In addition, suggested reductions in fossil fuel consumption as a means of influencing climate change may have a major impact on energy usage in buildings. In order to reduce the carbon footprint, use of renewable energy sources will be increased while reductions in energy consumption will be sought. One means to reduce consumption is through greater energy efficiency of mechanical systems for heating and cooling. Energy management specialists have developed procedures to reduce energy consumption.

The link between occupant demand and energy consumption has been widely documented e.g. Smith & Parmenter (2017). Behavioral methods have been developed primarily by social psychologists to provide occupants with tools and techniques to reduce consumption, such as shutting off lights when leaving a room. The acceptance of behavior modification is partly influenced by the attitudes of the individuals within a community. That is, some individuals within a community are very supportive of lifestyle changes to create greener communities and see the reduction of the carbon footprint as a social good. Others do not embrace these attitudes. In sum, the ability of a building to support occupants in their activities is dependent upon the active and passive means available to provide needed services. At present, the design of the support services in an engineered structure is conducted in a top-down multi-disciplinary manner under the general supervision of an architect.

The objective of this paper is to introduce a probability-based framework for building functionality performance using a bottom-up occupant-based approach rather than one imposed by building owners in a top-down approach. In the development of the framework, indicators and related metrics are identified for implementation in the framework. Indicators are defined as “physical attributes that can be observed or measured”, as discussed in Ozkan et al. (2019). These indicators will be appropriate for risk management and decision-making regarding buildings, particularly energy usage. Commonly referred to in sustainable construction practice, these indicators are based on indoor environmental quality (IEQ) metrics e.g. Kilbert (2013). IEQ metrics have been developed by governmental agencies, such as the U.S. Environmental Protection Agency (1991), public health organizations such as WHO (Burton (2010)), and others involved in architectural design. Each indicator in the framework is comprised of multiple metrics, and the values of these metrics over time provide evidence of whether adequate services are provided.

The IEQ-based indicators used in the proposed framework include thermal comfort, indoor air quality, lighting, water supply, wastewater treatment, and egress and movement. Each of these indicators has associated objective measurements such as air temperature, relative humidity, light intensity, and concentrations of various gases and particulate matter. There are also established subjective measurements derived through survey instruments and reflect the degree of satisfaction with the (objectively) measured values e.g. (CBE) (ISO, 2005).

2. Proposed criteria using IEQ

Functionality analysis employs indicators for thermal comfort, indoor air quality, water supply, wastewater management, and egress and movement. Each of these is related to target values, or limits of acceptance. Table 1 provides an example of the performance criteria and the levels of acceptability associated with them. Under “thermal comfort”, it is acceptable for the indoor temperature to be in the range of 20-23°C for 90% of the time or 7884 hours of the year, if the building is occupied 24 hours a day. From psychrometric analysis, it is known that the accompanying indoor relative humidity should also be within the range of 30 to 40%, e.g. ASHRAE (2010,2011). For a given building type and location, the probability distributions of independent and possibly joint peak outdoor temperature and relative humidity can be identified, and used in a Monte Carlo simulation scheme, to identify how many times the indoor target values are exceeded. The frequency (how often) and amount of exceedance (how much) can be assessed in this manner for the building. Monte Carlo simulation methods require probability distributions for the variables used.

3. Results for an example building

3.1 Thermal comfort

In this section, the results of the application of a thermal comfort analysis are shown for an example building on the University of Washington campus. The outdoor temperature was simulated by a Normal distribution with a mean of 24°C, which was obtained from the online Weather Underground site for August 2017, and a coefficient of variation of 0.10. The total number of observations was 100,000. The indoor temperature T_{indoor} was calculated as the black globe operative temperature based on the empirically derived adaptive relationship for the summer:

$$T_{indoor} = 16.01+0.366T_{outdoor} \quad (1)$$

It is noted that the R^2 value for the fit of 2796 observations was 76.6%. The resulting values from Eq. 1 were compared with the values in Table 1. It was found that for 100,000 simulations, 2% of the indoor temperature values were in the acceptable range; 72.9% were in the tolerable range; 0.58% were in the discomfort range; and 10^{-4} values (essentially zero) were in the intolerable range. Fig. 1 shows the histogram of the indoor temperature where the ranges of the simulated values are evident. The upper and lower mean values determined using the ASHRAE (2010, 2011) standards are also shown.

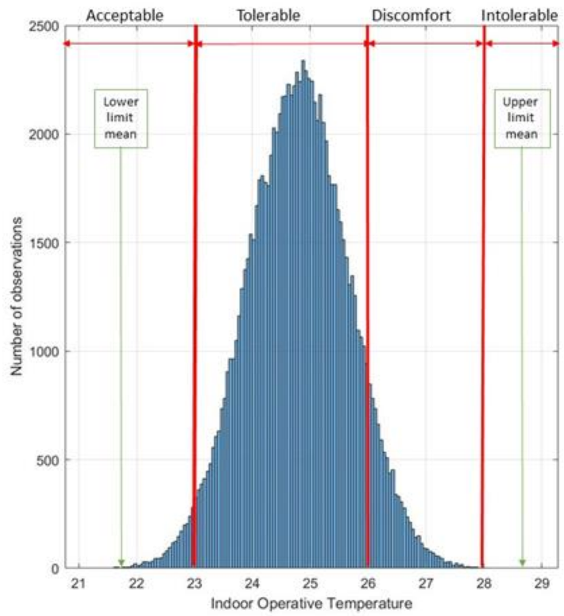

Figure 1. Histogram of the simulated indoor temperature.

Coley, Herrera, Fosas, Liu, & Vellei (2017) employed a probability approach to thermal comfort by investigating the temperature changes over a 30-year period for five major climate classifications. Through a time series analysis of the upper and lower adaptive bounds given in ASHRAE, they derived probability factors to better characterize the variability in temperatures. The factors were derived using a Normal distribution and the approach requires probability distributions or statistical data for the building locale. The simulation shows that the majority of the values fall into the “tolerable” range and cooling through better ventilation, window shading, and fans should be investigated. These values coincide with what was experienced during August in the office where measurements were taken. For comparison with the ASHRAE bounds, the mean T_{upper} = 28.7°C and the mean T_{lower} = 21.7°C, were determined. These values suggest that the bulk of the simulations should be acceptable to 80% of the occupants. This discrepancy suggests that the present guidelines are too broad to be applicable to all climate zones.

One benefit of the Monte Carlo simulation approach is that it allows for numerical testing of guidelines for specific building sites. The selection of the probability distributions for the indicators is not straightforward. While the ASHRAE adaptive thermal comfort guidelines have been based upon the thermal comfort database ASHRAE RP-884, significant extensions have been made, such as the smart controls and thermal comfort *SCATs* for European offices e.g. Humphreys et al. (2013). Humphreys et al.(2013) provide a database of thermal comfort summary statistics. Although the general pattern of indoor thermal comfort being directly related to outdoor temperatures as illustrated through the implementation of ASHRAE RP-884, consensus of the appropriate outdoor temperature data is not yet available. Further collection of data for various climate zones will be useful in this regard.

3.2 Indoor temperature, CO_2 and RH

The description of the indoor conditions is captured primarily by measurements in databases for select buildings, such as offices. However, the data are challenging to compare because the conditions within a building will vary and occupant preferences may not be equivalent in different regions or cultures. Time series data for the building described in Figure 1 were examined for their probability distribution formats. In the University of Washington dataset, indoor and outdoor temperatures, indoor and outdoor relative humidity, and indoor carbon dioxide levels were recorded for 9 months (summer, autumn and winter) as described in detail in Kim,Wang & Reed (2015). The seasons are identified through the solstice and equinox calendar dates.

Figure 2 provides the 5-minute average values recorded during Winter 2015 for the University of Washington office location. The upper and lower bounds were determined using outdoor data values recorded on a nearby campus building. The recorded indoor temperature was acceptable for most of the time according to the framework, but there are overlaps with discomfort due to heat and cold. This analysis suggests that the ASHRAE bounds may not be applicable to the climate zone for Seattle. The bounds are much broader than the suggested performance framework values. Preliminary investigations suggest that the indoor temperature may be lognormally distributed.

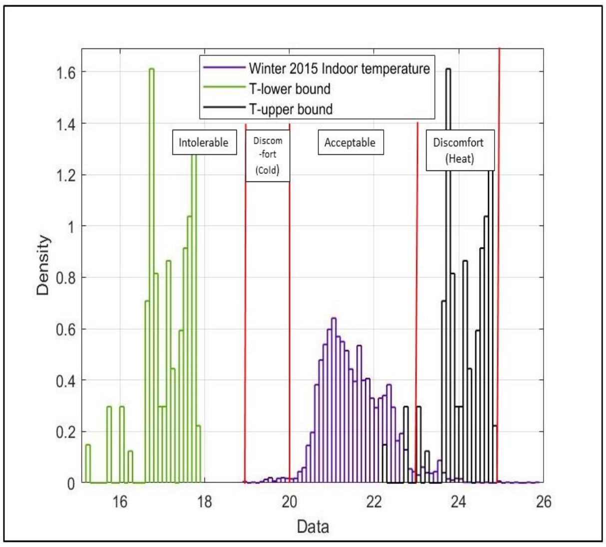

Figure 2. Indoor temperature analysis for example building (HUB) during Winter 2015.

The CO_2 values for the autumn were found to be very high compared to the summer months. The highly skewed histogram of these data appears in Figure 3, with the performance scores identified. Preliminary analysis suggests that the data are best fit with a lognormal distribution. Figure 4 provides a similar analysis for relative humidity *RH* in percent for Autumn 2014. The indoor *RH* distribution is also highly skewed and preliminary analysis suggests that the Gumbel distribution is appropriate. The performance scores suggest that the *RH* is high for most of the autumn months, which reflects the “rainy” season of the year. However, exceptionally dry conditions were recorded, most likely when heating systems were turned on.

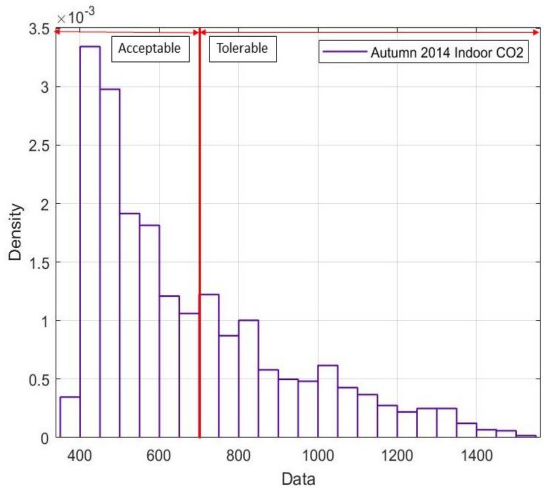

Figure 3. Indoor CO_2 analysis for the HUB during Autumn 2014.

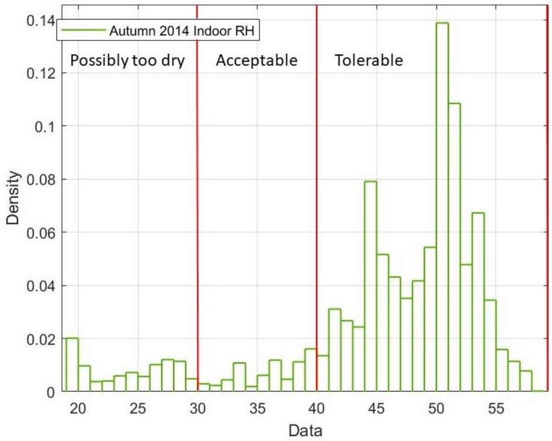

Figure 4. Indoor CO_2 analysis for the HUB during Autumn 2014

The examples here are used to illustrate their possible use in the framework. It is anticipated that the input distributions for the framework will need to be thoughtfully considered before implementation.

4. Discussion

The performance-based framework for building functionality has been derived using indicators and metrics from the field of indoor environmental quality (IEQ). The levels of performance for each indicator have been suggested using the results of occupant safety and comfort analyses available in the literature as well as those obtained by the writers on the University of Washington campus in Seattle. These are recommended for the framework formulation and may require multiple iterations from the research and professional practice communities. The Monte Carlo simulation using probability distributions allows for a risk-based functionality analysis. Risk refers here to the consequences of a particular indicator exceeding its limit. For example, the damaging consequences and losses associated with public health, occupant comfort and safety are the most common functionality risks. It has been well-documented that indoor air quality and thermal comfort have a significant influence on occupant behavior and wellness e.g. Frontczak et al. (2011); MacNaughton et al. (2017); Seppänen & Fisk (2002); *Standards for Thermal Comfort* (1995); Wargocki & Wyon (2017).

Risks associated with climate change include those associated with cooling and heating as well as air quality. Functionality includes thermal comfort, which is related to climate change through temperature changes. However, increased use of active power systems to better control indoor thermal comfort may add to the carbon footprint of the building. The international research community focused on thermal comfort has discussed how people in different cultures have adapted to changes in building temperatures e.g. (*Standards for Thermal Comfort* (1995). Yet adaptation culturally as well as physiologically to air-conditioned buildings is not well understood. It appears that more research into the rising demand for air conditioning in regions where temperatures are climbing, as well as the use of passive means for indoor comfort, is warranted.

One of the benefits of using the probability-based outcomes derived in Table 1 is the ability to assess the uncertainty that propagates through the modeling process. Uncertainty in individual indicators such as adaptive thermal comfort has been investigated e.g. Coley et al. (2017). As mentioned previously, Coley et al. (2017) investigated the influence of uncertainties in the long-term temperature patterns on indoor conditions for several separate climate zones. Other uncertainty investigations have focused on individual building scenario simulations involving occupancy patterns, temperature set points, plug loads, etc., to evaluate the robustness of the building for energy performance, e.g. Kotireddy et al. (2019). All approaches to uncertainty assessment for buildings indicate that the occupant-derived comfort scores have perhaps the greatest degree of subjectivity and uncertainty. In this respect, perhaps a range of preferred outcome values for all indicators according to climate zone and locale is best. Investigation into the uncertainty aspects of the proposed functionality framework is currently underway.

5. Conclusions

Building functionality is a critically important aspect of contemporary society. In this investigation, functionality has been defined as the ability of a building to provide essential support services for the occupants and community inhabitants. This definition differs from others because it employs indicators and metrics based upon occupant safety and well-being, in a bottom-up approach to design. Most performance metrics within the larger research community rely on specific energy demand and consumption behaviors of individual building types. The approach here has been chosen because it is estimated that people in the US spend 90% of their time indoors. The use of indoor environmental quality indicators and metrics allows for the assessment of the indoor conditions conducive to occupant safety and well-being. The framework assumes that outdoor weather conditions for such variables as temperature, wind speed, and relative humidity, can be characterized by probability distributions that may then be used to estimate corresponding indoor conditions. The Monte Carlo simulation techniques can be used to evaluate the degree of uncertainty involved in identifying the frequency and amount of exceedance of various metrics. In this manner, decision makers will have more information on which to base new functionality designs or retrofits of existing buildings.

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Table 1. Example of proposed functionality PBD framework

Performance Indicator	Metric for criterion	Acceptable: 90% of time	Tolerable: 1 or 2 days per year	Discomfort: 5 hours per year	Intolerable: Less than one hour per year
Thermal Comfort	Indoor Temperature [ºC] Summer & Spring	20-23	24-26; 19-20	26-28; <20	>28
	Indoor Relative Humidity RH [%]	30-40	40-60	60-70	>70
Air Quality	CO_2 [ppm]	350-700	700-2000	2000-10000	>10000
Lighting	Lumens/m^2	As needed for all tasks	Limited for common areas	Inability to undertake tasks	No lighting
Water systems	Water supply [m^3/s] (quality is considered separately)	Clean cold & hot water in bathrooms; potable water adequate	Clean cold water available	Limited clean cold water	No water
	Wastewater management[m^3/s]	Toilets flushing	Toilets slow	Toilets do not flush	Toilets back-up & overflow