Power Performance Assessment of Building Energy Systems

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Abstract

Buildings are the main consumers of electricity. However, the focus of building domain has been on energy efficiency measurement and evaluation and we lack adequate measures to quantify and assess performance of building energy systems in terms of their power consumption. The significance of this issue is growing in parallel with the advancements of the smart power grid. This paper presents methods and measures needed to study and assess performance of buildings in the electricity system. To achieve this, a set of quantitative power performance indicators (PIs) is first defined. These PIs are consequently applied to a variety of building control strategies in the context of demand response (DR) scenarios to quantify, assess, and compare their performance.

Introduction

Electricity production is the leading source of greenhouse gas emissions in the U.S. (EPA, 2013). According to the recent statistics published by the U.S. Energy Information Administration (EIA), buildings are the main consumers of electricity (EIA, 2016). As shown in Figure 1, residential and commercial building sectors used 38% and 36% of the electricity sold in the United States in 2011, respectively. The high electricity consumption of buildings, the diversity of end-users, and the variability in their daily, monthly, and yearly load profiles all affect the power grid performance.

The significance of understanding buildings' electricity demand is bi-fold in both achieving building energy and cost reduction goals and also the power grid planning and management especially in the emerging modern grid with 'smart' features. Grid-centric building control strategies such as demand response (DR) strategies have grown in the number and size to manage load and reduce peak demand. However, the focus of building energy studies has been on energy performance assessment whereas the instantaneous power consumption of building energy systems and aggregated load profiles have received less attention. Today, we lack methods and commonly accepted performance measures (e.g., energy use intensity) that support building-grid interaction assessments.

The objective of this paper is to enhance understanding of building systems with respect to the electricity system by elucidating the underlying principles of a power performance framework that identifies how building systems respond to certain "power" performance criteria and develop a set of performance indicators (PIs) to measure power performance of building systems in conjunction with their control strategies. In doing so we aim to support the trade-off decisions between energy efficiency and investments in power management at the building site.

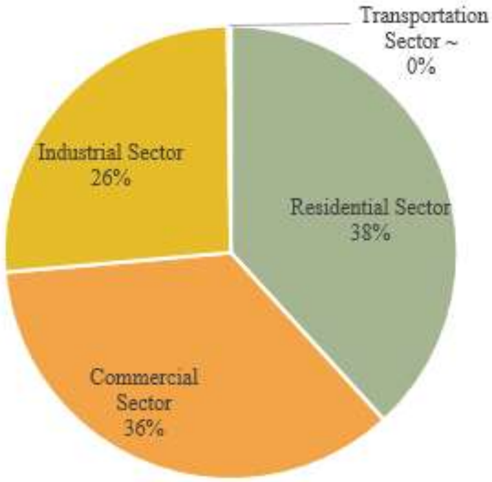

Figure 1: 2011 Electricity Retail Sales in the U.S. (EIA, 2016)

Approach

The approach adopted here is based on the contemporary methodology for performance measurement and assessment. Following the engineering perspective and approach adopted for performance-based building design and operation, the objectives of this work are achieved by identifying systems and interactions within and between them that determine how a set of functions that we define at the outset is achieved. The level at which these functions are achieved is usually expressed as a set of criteria that are quantifiable. In our case, this boils down to defining the criteria by which we express these requirements and then measure (through real or virtual experiments) how well the expected functions are achieved or fulfilled. The new criterion or multiple criteria that we intend to define are chosen such that they

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collectively define "power performance". The next step is then to formulate quantifiable performance indicators and their measurement methods that express how well a defined function is achieved. This process conforms to a conceptual framework that systematically situates power demand and capacity in the context of building performance assessment.

In engineering and manufacturing, a performance approach is mainly applied to facilitate the 'design' process. Decision science and value-focused thinking in engineering e.g., Hazelrigg (2012) and performance based building in architecture, e.g., Augenbroe (2011), have been established around the effective design of an artifact. However, the work presented here is more concerned with performance-based operation of a building while concepts can be applied during building design process as well.

In both design and operation process, expectations of clients, building owners and occupants can be expressed in form of performance requirements. This requires careful formulation of statements of performance requirements and effective management of a well-defined and tested procedure that enables and assures their fulfilment. The main goal of designers and facility managers is to fulfil requirements of their clients. This is a challenging task to accomplish without a systematic framework for the definition of performance measures and quantification methods. The dialogue among different stakeholders will lack continuity and rationality without establishing such systematic approach. It has been well understood that "a performance based approach is a key enabler of rational decision-making across many stakeholders and based on a large set of performance criteria" (Augenbroe, 2011). Quantification of these performance criteria identified (through simulation experiments or other proper methods) is the only way to have a consistent and apple-to-apple metric to inform decisions.

Augenbroe (2011) defined a compulsory performance based framework and a systematic approach to structure it for building domain decisions. This performance approach offers a step-by-step method to design an application or case specific performance tree for categorization of functionality and their mapping into sets of performance criteria with well-defined measures. In the context of building design, the high level steps in this process are: 1) agreement on performance criteria to satisfy functions identified, 2) agreement about ways to quantify them in order to quantify required and fulfilled levels of performance, and 3) making rational multi-objective design or operation decisions considering preferences of the client, occupant, or building's owner. Here, we expand this framework to facility management and operation decisions in the context of grid centric control applications.

To achieve this, it is critical to first categorize building functions to enable mapping of those onto a set of performance criteria that can be used to quantify building performance in terms of power and capacity efficiency.

To define quantifiable expressions of performance to objectively compare and evaluate design and operation alternatives, the initial task is to decompose the main function into smaller manageable functional units, and the technical system into smaller manageable technical systems. The knowledge of the system level characteristics and interactions can then be utilized to formulate methods to quantify performance indicators found. By performing the top-down functional decomposition and bottom-up technical system aggregation approach (shown in Figure 2), one will arrive at functional criteria that can be expressed as explicit performance requirements.

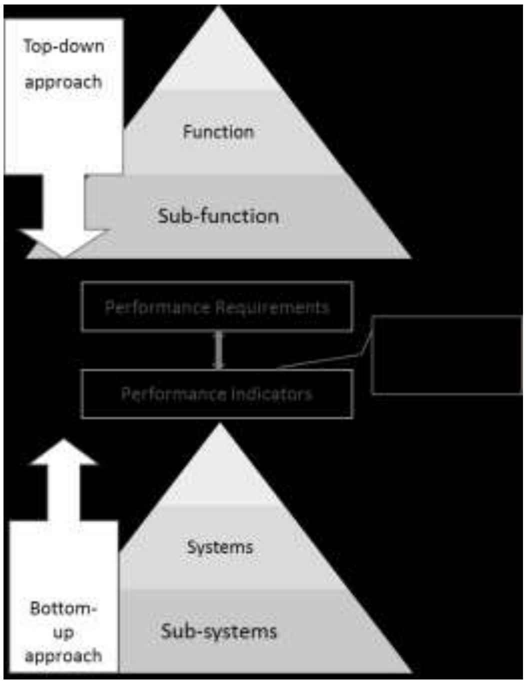

Figure 2: Top-down functional decomposition and bottom-up technical system aggregation approach to capture quantifiable performance indicators

This work explores performance requirements of building systems as sub-systems of the power grid through identification of performance criteria in this domain, and proposes metrics that can be used to quantify the criteria-associated performance indicators. Although this framework is generic at the top level (i.e., functional hierarchy), it is constructed to show how building power (i.e., electric energy) performance can be quantified. Therefore, only those properties of the building and its systems that determine power behavior need to be considered in the formulation of performance criteria and PIs. Consequently, in the bottom half, systems, sub-systems, and their components are specifically discussed in terms of their power characteristics. Because of the complexity and scale of the problem, this performance framework is for now defined for a specific building case and focuses on one building system, the air handling unit (AHU). All relationships of a centrifugal supply fan element in an AHU system influencing power behavior of the building energy system in the grid are classified and described.

The following sections describe different layers of the top-down and bottom-up performance framework developed in this order:

1. Identification of functional requirements.
2. Classification of systems and elements that play a role in achieving the functions identified.
3. Formulation of statements (criteria) of performance requirements and PI names/descriptions.
4. Discussion of quantification method for each criterion, leading to PI valuation.

Function Identification and Performance Requirements

Building primary functions have conventionally been formalized and understood according to the qualitative expectations of user(s). The 'user' class or type defines the scope for performance framework formulation. The direct 'users' of a building are its occupant(s) but there are other stakeholders impacted by how a building performs as a result of its design, construction, and operation. Examples of these are the building owner and the society. Here, we assume that other stakeholders involved, such as designers, builders or contractors, facility managers, and the local and federal government intend to support and satisfy expectations of users impacted (occupants, owner, and the society) by how building is operated during its life-cycle.

It is well understood that different users involved have different expectations which are reflected in how they want a building to perform. For instance, following the main function of a building, which is providing shelter and satisfying the main activity and service of the building (e.g., school, hospital, office, etc.), occupants expect a building to be a comfortable, safe (including structural safety, fire safety, accident safety, and security), and healthy (characterized by indoor air quality, moisture and mold safety, acoustics, visual comfort, hygiene, and water quality) environment (Becker, 2008). Satisfying these functions at a sufficient level of achievement would ensure the occupant's well-being and productivity. Yet, the building owner expects the building to satisfy occupants' expectations while minimizing operating cost and environmental impacts.

Historically, the main function of a building has been to provide a comfortable shelter and the electricity system was expected to provide service to buildings. The main performance criteria of the power grid have traditionally been stability, reliability, and affordability. However, the power grid is evolving and going through major changes to satisfy the requirements of the modern grid. Today, the grid has further performance requirements. It should be sustainable (i.e., energy efficient) and even more reliable (i.e., resilient) in addition to its traditional objectives. This is one of the main reasons behind the need for building-grid integrated assessment and the need for buildings to provide ancillary services to the power system. The society and the government expect the built environment to have high performance design and be operated considering current global concerns such as sustainability, climate change, and power resiliency.

Although the main objective of this study is to formulate a framework for performance assessment of 'buildings' in the context of the modern grid, the new expectations of the electricity generation, transmission and distribution system force us to consider functions and performance considerations of the power grid. By considering certain performance requirements of the power system, we ensure development of methods and techniques that support rational decision making about the design and operation of buildings because they enable quantification of the trade-offs between building energy efficiency and investments in power management at the building site.

Following the general discussion about building functions and the grid requirements, the top section of the performance framework is defined using the top-down functional decomposition method. The top layers of this performance framework as shown in Figure 3 are strictly selected based on the scope of this work and they do not represent the broader performance requirements traditionally considered in building design such as IAQ and safety. Performance requirements of sustainability, power resiliency and thermal comfort are those that will be considered in the definition and formulation of the performance indicators that support rating a building in terms of power efficiency.

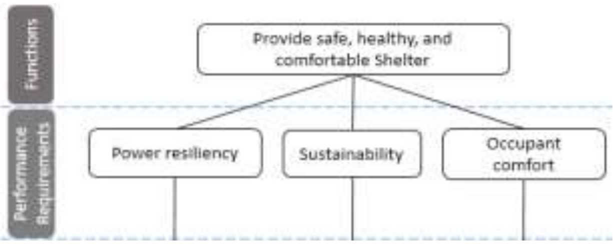

Figure 3: The top layers of the top-down functional decomposition of the performance framework.

Classification of Systems and Elements

The second half of performance approach, the bottom-up assembly of building systems, involves definition of building systems, sub-systems, elements, their relationships, interactions, and constraints that are employed to fulfil building functions while addressing performance requirements. These are first identified and discussed in this section; their relationships are then presented in the performance framework.

Research and studies in the area of demand side management (DSM) have identified HVAC as a flexible load among other building systems (e.g., plug load and lighting) that has potentials for DR, load following, and regulation purposes. This is because of several reasons: 1) HVAC systems consume a large amount of electricity in commercial buildings, 2) the thermal mass of buildings reduces the impact of zone temperature adjustment on occupants thus offering considerable flexibility and elasticity in regard to power demands, and 3) most HVAC systems are controlled automatically using building automation systems (BAS) nowadays, which can be used to implement a variety of advanced control strategies for power reduction (Watson et al., 2006 and Wang et al., 2014).

Because of the complexity of HVAC and different types of systems available, here, the focus is on electricity consumers of the air distribution system (i.e., AHU system). The supply fan is the largest electricity consumer with an electric motor in an AHU. Hence, that is the main component considered in this work for further discussion and analysis. Electric motors consist of a "mechanical drive," an "electrical system," and a "control system." The properties and interactions among decomposed elements of each of these systems are discussed in detail in the following sections to carefully select the performance indicators that can measure how a system fulfils functions identified.

Figure 4 depicts the lower half of the performance framework concerned with electric power consumption of supply fan in an air distribution system, i.e., AHU as derived by the mechanical and electrical elements and attributes of the system. This bottom half contains the 'electrical and mechanical system.' Fan electric power consumption depends on: 1) fan air power, which is a function of the airflow and pressure difference across the fan, 2) mechanical efficiencies, including fan and belt characteristics, 3) and electrical efficiencies consisting of motor and drive properties electrical characteristics e.g., voltage and current (DOE, 2016).

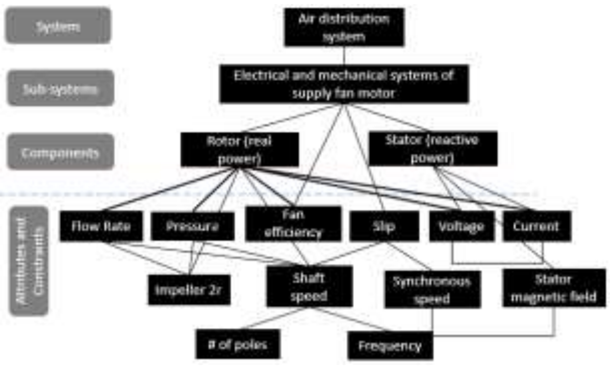

Figure 4: Mechanical and electrical components and attributes affecting power use of supply fan in AHU.

The bottom half of the performance framework also contains the 'thermal system' in addition to the mechanical and electrical system. This thermal module is defined by building characteristics such as window and wall types, material, and building layout. These building characteristics affect building energy demand (i.e., zone thermal load) calculations. The cooling or heating load of a thermal zone is defined as the rate at which heat must be removed or added to a space to maintain a constant temperature. The standard method used for calculating zone loads is the heat balance method using conduction, convection, and radiation. Variations in zone load resulted by changes in the building envelope and layout affect the energy performance, air flow rate and subsequently the power consumption of the AHU fan. This thermal module of the performance framework is illustrated in Figure 5.

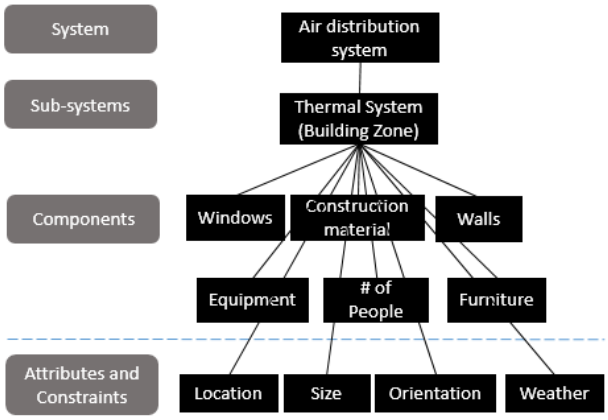

Figure 5: Thermal system components and attributes.

The third system or sub-system of the air distribution system is the 'control system.' Beside the type of the controller and functions used, there are three basic elements in any basic or complex HVAC control system. These are the sensor, controller (including the actuator), and the controlled device. Sensors measure the actual and current value of controlled variables such as temperature, humidity or flow and provide this information to the controller encompassing the control function and logic. A controller receives input from the sensor(s), processes the input based on its logic and then produces intelligent output signal for the controlled device. Figure 6 illustrates the control system of the air distribution system as described for the bottom half of the performance framework.

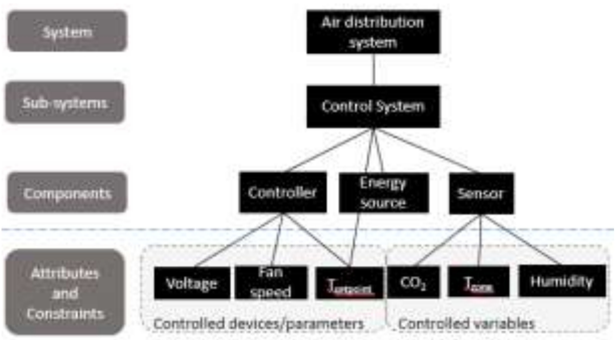

Figure 6: Control system components and attributes.

The forth system in the bottom half of the performance framework is the 'occupant behavioral system.' This system involves parameters, elements, and attributes affecting human sensation of thermal comfort. There are other internal, external, and psychological factors and elements affecting thermal comfort of occupants in a building beside indoor air temperature. These include outdoor air temperature, mean radiant temperature, air movement, relative humidity, clothing, activity levels, individuals' metabolic rate and their internal core temperature, in addition to psychological aspects. Although these are important factors, they are not considered in this work because a lot of assumptions should have been taken into account to estimate them making it difficult to have reliable results. Hence, thermal comfort is only derived as a function of indoor air temperature and thermostat setpoint.

Performance Criteria and Quantifiable Performance Indicators

The previous section elaborated on the top and bottom parts of the top-down functional decomposition and bottom-up technical system aggregation approach used to define AHU power performance framework. Up to here, we identified, classified, and formulated functional requirements of a building in relation to the power grid. Now, we should transform these into performance criteria and quantitative PIs. The discussions in the previous sections regarding identification of functions and classification of systems lead us to the identification of performance criteria or formulation of statements of performance requirements. The selected performance criteria are derived from those higher level objectives of the energy system (more specifically, the electricity system) that are defined here as power performance requirements of buildings. These performance criteria can be supported by efficient design and flexible operation of buildings and facilities. These performance criteria are defined, measured, and assessed based on building functions. Building simulation engines have been developed in order to generate results that support related decisions. According to Augenbroe (2011), the performance criterion under study is at the heart of the experimental set-up. This section covers the middle part of the top-down functional decomposition and bottom-up assembly of building systems approach, where 'functions' meet 'systems' as functional or 'Aspect' Systems to enable selection of the right measures to be used in ultimate experiments.

Performance of motors, their controller, and DR strategy employed should be evaluated in terms of combined performance of all of them. This can only be achieved by understanding interactions among components of a system and finding meaningful methods from physics of that system to support translation of performance requirements into quantifiable performance indicators.

It has been a challenging task in DR studies to even define performance requirements. Some studies have introduced meaningful factors that could be taken as performance criteria, however, they have failed in giving a standard method to measure them. For instance, Mathieu et al. (2011) presented load shape parameters such as near-base load, near-peak load, high-load duration, rise time, and fall time as illustrated in Figure 7 to describe load shape. These parameters can also support performance assessment of building systems in terms of demand capacity. Although rise-time, high load duration and fall-time seem to be meaningful parameters to describe load, authors state "it is difficult to find definitions of these time intervals that yield consistent, easily interpretable results" and they work only if load shape looks similar to Figure 7 (Mathieu et al., 2011). Therefore, we need PIs defined as functions of a set of 'quantifiable' and 'controllable' parameters and attributes, such as flow rate. Quantifiability of these parameters enable us to systematically define a range or distribution for each parameter to be used in calculation of the PI. PIs should also be defined so that they can support evaluation of power performance under different DR scenarios.

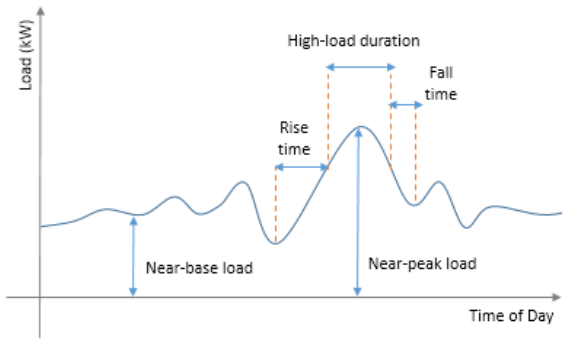

Figure 7: Parameters of load shape (based on Mathieu, 2011).

In the process of defining PIs for power related performance requirements, it should also be considered that assessment of power performance is different from energy performance. This is mostly because of different characteristics and behavior of power. Power changes over time in shorter time intervals and parameters affecting it vary at a much faster rate compared to parameters and factors influencing energy consumption. Therefore, we cannot only rely on one quantifiable PI, such as Energy Use Intensity (EUI) measured in $kWh/m^2/yr$ as used to assess energy performance. Load has multiple characteristics as illustrated in Figure 7 that should be taken into account when evaluating performance of power. As a result, more than one PI will be defined to assess load performance; these PIs are functions of power and independent of how power itself is calculated.

There are a number of measures such as demand factor, load factor, and diversity factor used mostly by utilities to estimate and evaluate load (Fink and Beaty, 2013). Demand factor is the ratio of maximum demand to the amount of total load (i.e., sum of all loads) connected. The demand factor is always less than or equal to one. The lower the demand factor, the less system capacity is required to serve the connected load. Load factor is the ratio of average consumption (i.e., actual kWhs used in a given period of time) to possible kWhs that could have been used during that time. The potential kWhs are calculated by multiplying the peak power use (kW) in that period of time by the number of days multiplied by the number of hours in a day. A high load factor is considered to be 'good' although it means higher energy consumption. A low load factor means inefficient use of electricity. Load factor is also used to determine demand limit (i.e., how much load can be curtailed) by considering an ideal load factor. Diversity factor is the ratio of installed load to the running load and it is always greater than or equal to one. Although these measures were considered in definition of PIs developed in this work, they are not directly utilized. The most applicable measure to assessment of building load for DR applications is load factor. However, the issue with this factor is that it evaluates peak inseparable from energy consumption. In other words, a high load factor is considered to be good even if it is achieved by increasing energy consumption. This is not ideal at the building level so other PIs are defined to assess peak independent of energy use. Also, not using load factor avoids confusion with the power factor which is the ratio of real power to apparent power.

PI1: Max-to-average power ratio (MAPR)

The first PI defined is based on power characterization and quantification of minimum, maximum, and average power demand in a given time period (e.g., one day). Characterizing power in terms of its minimum, maximum, and average provides the basic measures for analyzing the behavior of the power demand of a system, building or community of buildings at any point in time. It also supports comparing the load profile of one system, building, or DR strategy against another one. To be more specific, the first PI is defined as the ratio of maximum power demand to the average demand. Max-to-average power ratio (MAPR) is also used in power studies (more commonly referred to as peak-to-average power ratio) and hence relevant to be utilized here. This PI is used to assess load performance in terms of power 'peaking' and 'rebound.'

$$MAPR = \frac{Max(P_i)}{\frac{1}{n}\sum_{i=1}^{n} P_i} \qquad (1)$$

In Equation 1, $\boldsymbol{P_i}$ is the instantaneous power consumption at time i and $\boldsymbol{n}$ is the total number of data points included in the time period (e.g., day) considered.

PI2: Demand Flexibility (Intensity)

The next PI should be capable of measuring power elasticity or flexibility, which is an important factor when evaluating power performance in the area of demand side management. Flexible load or demand means an energy consuming system that is capable of ramping its power demand up or down as a response to the DR signal received. Therefore, demand flexibility can be broken down into both 'demand reduction' and 'excess absorption' depending on the requirement. Demand flexibility can be measured by demand intensity, which is defined as power consumption per unit of time per unit of space, i.e., $(W/min)/m^2$. Assuming 97.5th percentile of daily load is near-peak load in kW (Mathieu et al., 2011), we can calculate near-peak load per unit of space and compare that with load intensity to assess flexibility in terms of its potential for demand reduction. On the other hand, assuming 2.5th percentile of daily load is near-base load in kW (Mathieu et al., 2011), we can determine near-base load per m^2 and evaluate demand flexibility by its potential for absorbing excess generation.

PI3: Demand Disparity

The third PI defined to measure power performance is demand disparity. Demand disparity can be determined by calculating a coefficient of variation for a period of time e.g., daily, monthly, or annually as described in Equation 2. The higher the demand disparity, the more power demand is deviating from the average power consumption in a given time period. The demand disparity also indicates the length of a peak or rebound. Flexibility of load in terms of both demand reduction and excess absorption can also be realized from the demand disparity. To minimize the length of rebound, the demand disparity should be low during after DR hours i.e., after applying any advanced energy or demand saving strategy. The lower the demand disparity, the closer it is to average power use and hence not flexible. However, the demand disparity does not represent the exact time of deviation and hence not possible to use it for taking an action about the next operational decision. Figure 8 represents what the demand disparity coefficient mean in terms of power performance and how it can be interpreted to detect flexible load or rebound.

$$\text{Demand disparity} = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}{n-1}}}{\frac{1}{n}\sum_{i=1}^{n} P_i} \qquad (2)$$

In Equation 2, $\boldsymbol{P_i}$ is the instantaneous power consumption at time i , $\overline{\boldsymbol{P}}$ is the average power, and $\boldsymbol{n}$ is the total number of data points included in the time period (e.g., day) considered.

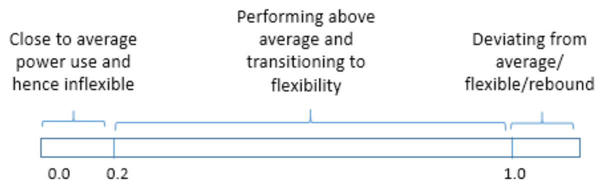

Figure 8: Demand disparity coefficient

PI4: Power Performance Coefficient (PPC)

The fourth measure defined to evaluate power performance is load variation in time. This PI, power performance coefficient (PPC) can assess performance of load at certain point in time. Load factor is a measure typically used in the power grid to represent the level of peak loads over a specified period of time (Wang et al., 2014). It is defined as the average load divided by the peak load in a time period. At the building level, similar concept could be used to quantify the performance of power at each time step by dividing the average power calculated for a time period (e.g., daily) under normal operation by power at each time step after the implementation of a control strategy. Equation 3 represents quantification of this PI. Nominal power use of the system could also be used instead of the average.

$$Time_{variant}\ power\ performance\ coef\ (PPC) = \frac{\frac{1}{n}\sum_{i=1}^{n} P_i}{P_i} \quad (3)$$

In Equation 3, $\boldsymbol{P_i}$ is the instantaneous power consumption at time i and $\boldsymbol{n}$ is the total number of data points included in the time period (e.g., day) considered.

The closer this ratio is to 1, the better the system is performing in terms of power consumption to reduce peak. Basically a PPC = 1 means a balanced power consumption. If PPC<1, the power consumption is below average and if PPC>1, the power use is above average. As PPC approaches zero, it indicates a larger power peak. Determination of the time interval is also important. For instance, if we find PPC within 10 minutes, the peak point (the lowest PPC found at each time step during that time interval) may or may not represent the daily peak. PPC works well for detecting or determining power dips. Figure 9 depicts how this concept works.

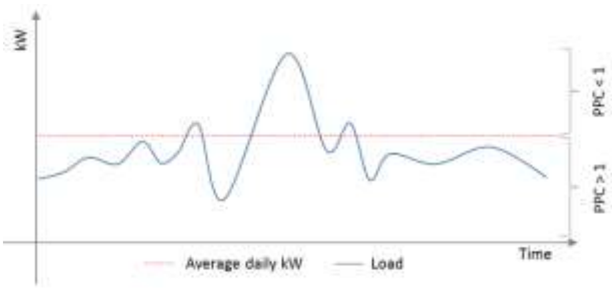

Figure 9: Power performance illustration

PIs 5 and 6

Other PIs used here are energy performance and thermal comfort. Load responsiveness and granularity, fan performance, and indoor air quality can also be considered, but they are out of scope of this work. Table 1 shows a summary of selected performance criteria identified, their PIs and quantification methods defined in this work. These criteria as listed in Table 1 include power performance, energy performance, and thermal comfort.

Figure 10 provides the overall top-down and bottom-up performance framework explained.

Table 1 Performance Criteria, Indicators, and Quantitative Methods

Performance criteria	*PI #*	*PI Name*	*Quantitative Method*
Electric energy (power) performance	1	Peak or rebound formation	Peaks or rebound formation are quantified by calculating the ratio of maximum demand to average power demand.
	2	Demand intensity	Power consumed in a given time interval normalized by the area of thermal zone served.
	3	Demand disparity	Demand disparity coefficient
	4	Power performance coefficient	Time-variant load coefficient
Energy performance	5	Energy consumption	E+ or normative methods
Thermal comfort	6	Deviation from setpoint and its duration	Quantification of space temperature deviation from setpoint and its duration.

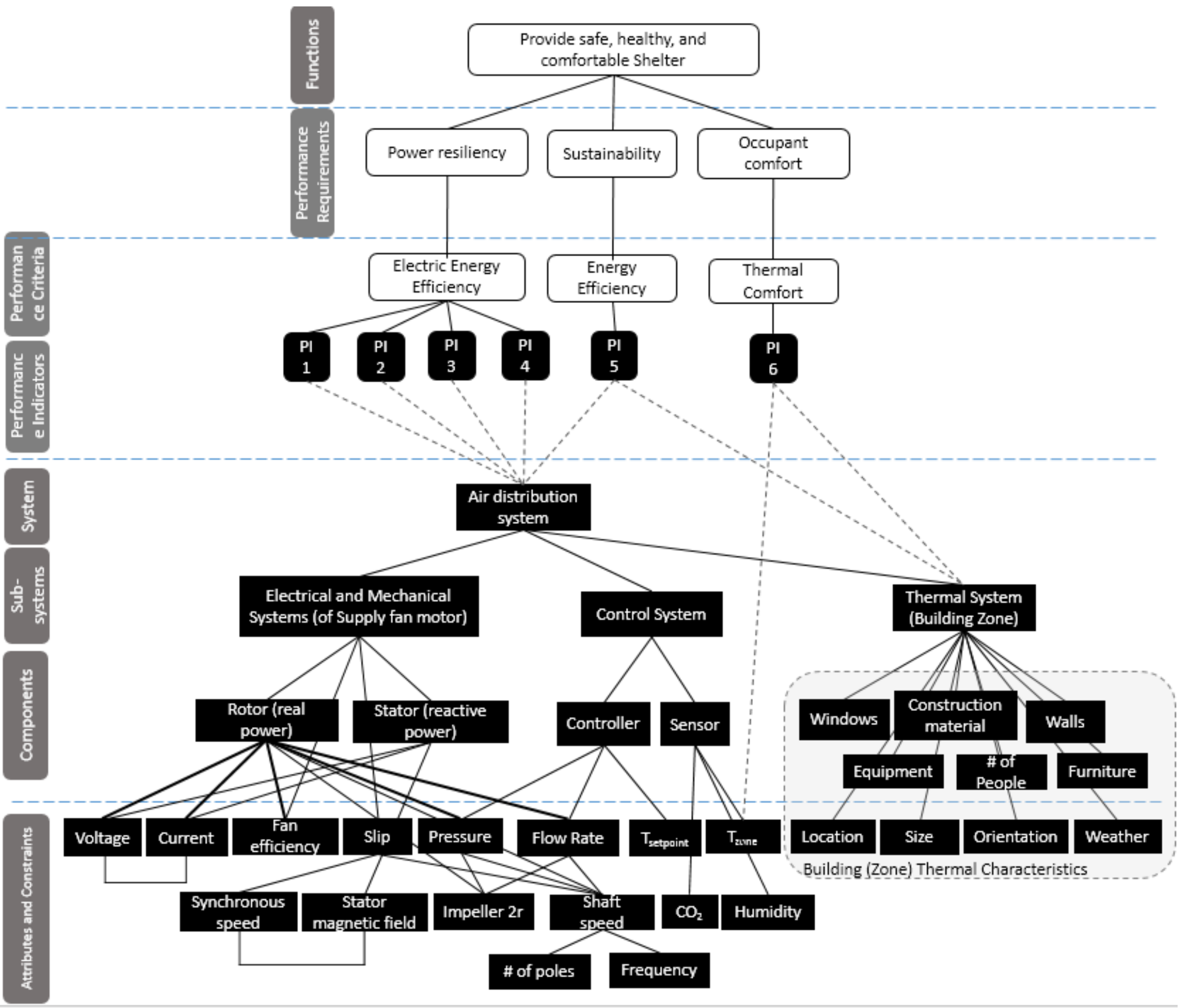

Figure 10: Performance framework with a focus on electric energy performance.

PIs Validity and Evaluation

In this section a brief summary of PI quantification and performance assessment results are included to illustrate how PIs identified work and what is their application. Each PI identified is calculated by subjecting the chosen (fixed) system to a set of normative scenarios. These scenarios are defined and modelled in a controlled simulation environment to understand how well they capture and quantify the performance criterion they are supposed to measure. The numerical outcomes obtained are used to rank different control solutions.

Several studies (e.g., Motegi et al., 2007; Wang et al., 2014; and Watson et al., 2006) have identified HVAC as flexible and controllable load for DSM and DR applications. To assess HVAC performance for these applications using PIs identified, different HVAC control strategies are modelled in a single story building. The building, system type, and weather conditions have been kept constant in this study (i.e., one building type, one system type, and one day) in order to evaluate performance of different control strategies. By keeping the building, system, and weather conditions the same, we can ensure a consistent and robust assessment and comparison across the performance of different control strategies implemented. This shall yield to identification and selection of the most effective mechanism for a given scenario. Furthermore, comparison of different control strategies for the same building under different scenarios indicates applicability and potential use of PIs developed for automated building energy management systems.

The building used in this case study is a 2,120 square meter single story building constructed in 2015 providing both office and laboratory spaces. This building is located in Richland, WA. In addition to office spaces, there are three control rooms, laboratories, outdoor testing pads, EV charging stations, data storage and computing capability. The lighting intensity in the building is 3.28 W/m^2, the number of people (m^2/person) varies between 4.6 to 18.5 m^2/person from zone to zone with an average of 14.8 m^2/person. Plug and process has a minimum of 1

W/m^2 and maximum of 53 W/m^2 with an average of 13.6 W/m^2. Building is modelled using EnergyPlus™ modelling and simulation engine as shown in Figure 11.

Figure 11: EnergyPlus™ model of the building.

The control strategies considered and implemented in this case study are: 1) setpoint increase, 2) setpoint reduction, i.e., pre-cooling, 3) fan shut-down, 4) reducing fan flow rate, 5) demand control ventilation (DCV), and 6) combined strategy. Each control strategy has a definition (e.g., changing setpoint) and a degree of variation (e.g., -4°C to +4°C) that can be assigned to it. Figure 12 shows how the combinations were generated. Each control strategy combined with a DR specification (hour and duration) results in a scenario. More than 100 scenarios were defined and modelled in this study.

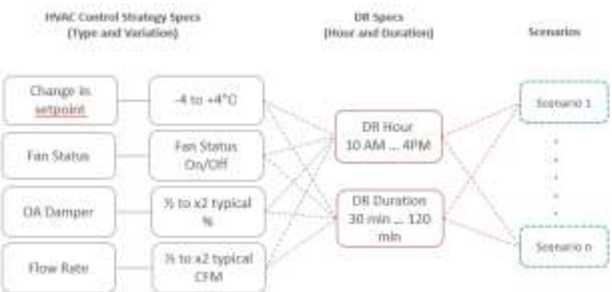

Figure 12 shows a sample of results obtained.

DR specifications were modeled by modifying the schedules for each scenario defined. Scenarios implemented were simulated at 5-minute timestamps for a few days in July. Results were extracted from EnergyPlus^{TM} output files for one day (July 6th) for post processing to analyze data using performance metrics described. Using the outcomes of the simulations, the different PIs defined previously were calculated. These PIs were quantified and ranked per control strategy to conclude which PI's determine how a certain DR control strategy performs against another one.

A summary of normalized outcomes is included to present effectiveness of each PI in measuring different criterion. Figure 13 depicts a summary of normalized PI results obtained for each control strategy modelled.

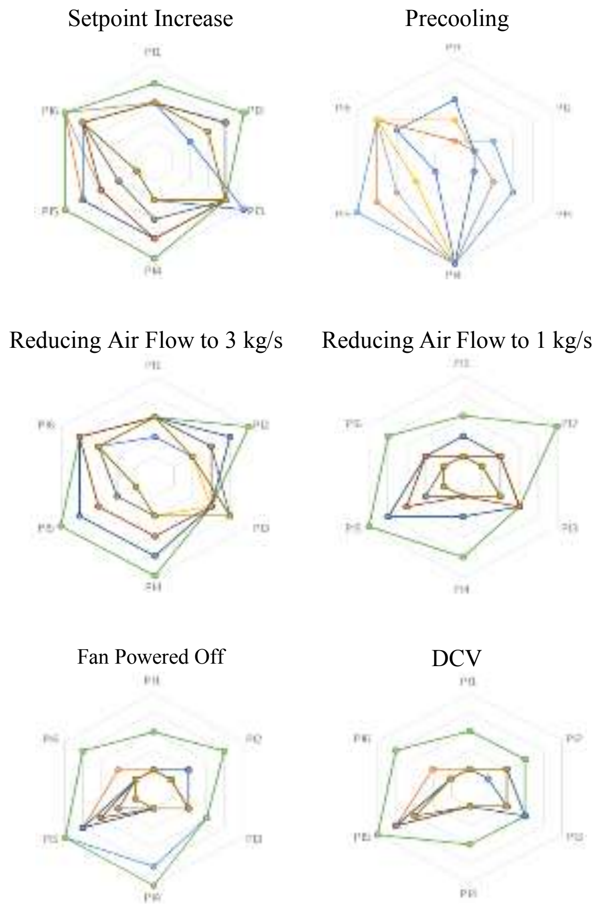

Figure 13: Summary of Normalized Results.

In Figure 13, each line represents a scenario in the category of control strategy mentioned above each radar chart. PIs are:

PI1: MAPR
PI2: Disparity
PI3: PPC
PI4: Energy use
PI5: Thermal comfort (duration of uncomfortable minutes)
PI6: Thermal comfort (intensity of uncomfortable temperature)

Outcomes indicate that performances of mechanisms vary and some perform better in terms of some PIs. There is clearly no winner and the context of the decision and preferences of decision makers are important in order to add weights to results.

Conclusion

The objective of this study was to develop methods needed to evaluate building load profiles and instantaneous power consumption of building energy systems to aid DR decisions at building scale. The top-down functional decomposition and bottom-up technical system aggregation approach is adopted to structure a performance tree that supports identification of these performance criteria and their associated quantifiable measures. Quantification methods are then carefully selected and introduced for each quantifiable PI to measure the effectiveness of an HVAC control alternative in the context of DR to fulfil performance requirements and criteria defined for each function identified. It should be mentioned that, the number of PIs mentioned and discussed are more comprehensive than those actually selected for further analysis in this work.

Discussing functions, understanding physics of the problem, system types, interactions among systems and elements, their characteristics, controller scheme, and other aspects mentioned in this work intend to support identifying parameters that affect a fan motor performance. This is significant for formulation of effective performance quantification methods to rate power performance of building systems. Having a systematic approach to quantify performance of power in a building leads us to better coupling and integration of energy efficiency measures with power performance measures (e.g., DR).

The measureable PIs are necessary to construct a framework that can be used to control the negative effects of the integration of buildings in the power system. Furthermore, the set of quantifiable PIs as defined in this work enable development of a multi-scale decision making framework to calculate the trade-off between different choices in the presence of multiple objectives. In the case of building-grid interactions, these objectives are maximizing service provided to the grid (e.g., reducing peak) while minimizing energy consumption of buildings.

In addition to the state of knowledge, this work also contributes to the state of practice. Peak demand reduction and DR are key parts of energy policies in different states in the U.S. However, customers and facility managers have limited knowledge of how to operate their buildings to reduce their electricity costs. Lack of knowledge about how to develop and implement control strategies to respond to DR programs is certainly a challenge and limitation. In addition to that, the lack of automation in evaluating control strategies to respond to a DR signal is another restriction. PIs developed are an essential part of dashboards necessary to automate evaluation of building control strategies to respond to grid-centric signals to reduce load.

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