10/9-20-96 JS ①

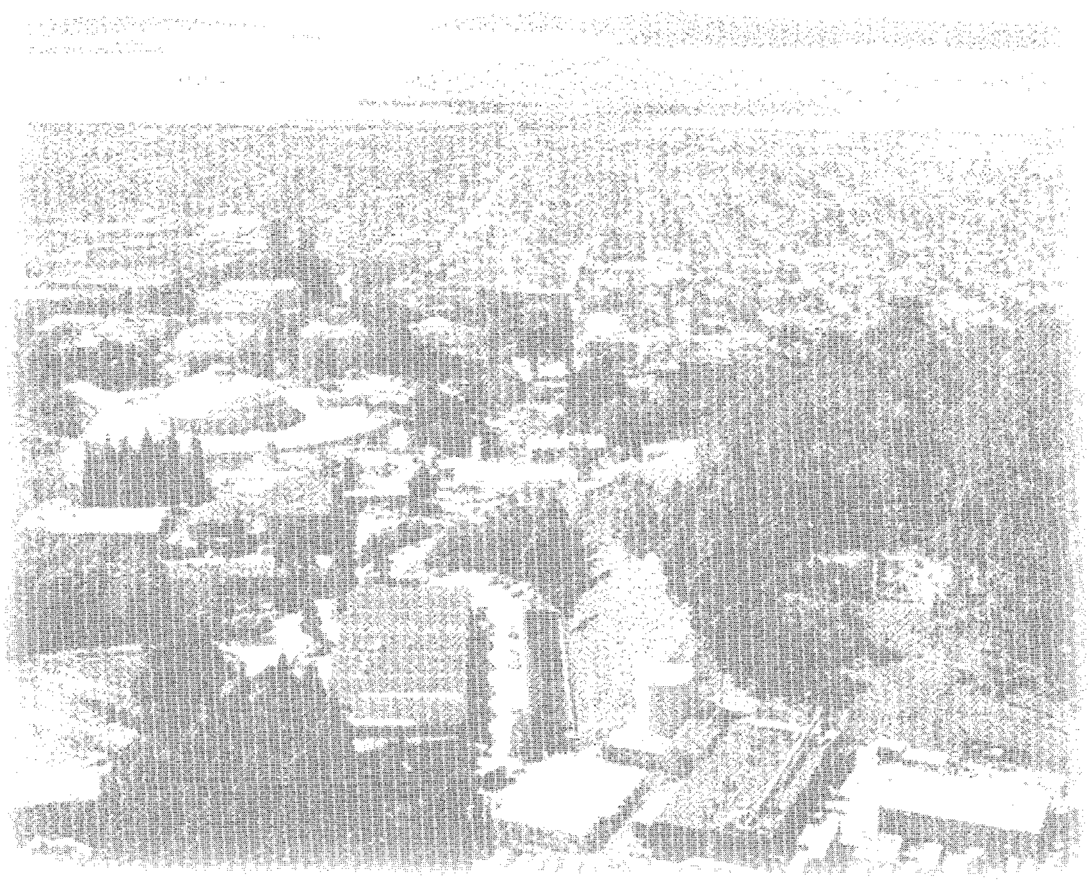
LBNL-39203
UC-1600

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

METRICS for Building Performance Assurance

G. Koles, R. Hitchcock, and M. Sherman
Energy and Environment Division

July 1996



LBNL-39203
UC-1600

METRICS

for Building Performance Assurance

Gretchen Koles

Rob Hitchcock

Max Sherman

Energy and Environment Division
Lawrence Berkeley National Laboratory
University of California

Berkeley, California

July 1996

This work was supported by the Assistant Secretary for Renewable Energy, Office of Building Technology, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Recycled Paper

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LBL-39203
UC-1600

METRICS
for Building Performance Assurance

Gretchen Koles

Rob Hitchcock

Max Sherman

Energy and Environment Division

Lawrence Berkeley National Laboratory

University of California

Berkeley, California

Keywords: Building Performance Assurance, Life-Cycle Metrics, Evaluation, Energy Tracking

This report documents part of the work performed in phase I of a Laboratory Directors Research and Development (LDRD) funded project entitled Building Performance Assurances (BPA). The focus of the BPA effort is to transform the way buildings are built and operated in order to improve building performance by facilitating or providing tools, infrastructure, and information.

The efforts described herein focus on the development of metrics with which to evaluate building performance and for which information and optimization tools need to be developed. The classes of building performance metrics reviewed are 1) Building Services 2) First Costs, 3) Operating Costs, 4) Maintenance Costs, and 5) Energy and Environmental Factors. The first category defines the direct benefits associated with buildings; the next three are different kinds of costs associated with providing those benefits; the last category includes concerns that are broader than direct costs and benefits to the building owner and building occupants.

The level of detail of the various issues reflect the current state of knowledge in those specific areas and the ability of the investigators to determine that state of knowledge, rather than directly reflecting the importance of these issues; it intentionally does not specifically focus on energy issues. The report describes work in progress and is intended as a resource and can be used to indicate the areas needing more investigation. Other reports on BPA activities are also available.

This work was supported by the Assistant Secretary for Renewable Energy, Office of Building Technology, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

FIGURES

INTRODUCTION

In the U.S. people spend most of their lives inside buildings: at work, at home and for recreational, commercial and social activities. These buildings consume a huge fraction of the nations resources, including over 30 percent of the energy use, and over 80 percent of the electricity use. Much of our economy is dependent upon the building sector and building performance. Unfortunately, buildings rarely perform to the level one might imagine from the importance of these statistics.

Lovins (1992) has well summarized most of the institutional barriers to better energy-efficiency in buildings. Most of these barriers stem from economic decisions based on setting short-term objectives rather than using any life-cycle analyses. These same barriers generally apply to broader measures of building performance. There are dozens of key actors in the process of designing, constructing and operating a building, each representing a different phase of the process; they rarely have much appreciation for the needs or intent of the others. This Babelic situation assures that important information will be lost during the process and that no one will be able to assure optimal performance outside of their own limited domain.

The short-term fixes that Lovins proposes (*i.e.,* restructuring fee arrangements) do not address the fundamental problems of building performance assurance: communication and information flow. Each of the individual decision makers (*i.e.,* owners, architects, designers, contractors, engineers, operators, employers, lessors, etc.) is unable to make use of much of the work that has come before them both for that particular building and in previous buildings of a similar nature. What is needed is an entire restructuring of the way buildings are designed, built and operated including new tools and new paradigms.

Such changes are neither easy, straight-forward, or quick. The Building Performance Assurance (*BPA*) project at the Berkeley National Laboratory is intended to help bring about this market transformation by the development of infrastructure (tools, protocols, etc.) and analyses (of potential, etc.) to facilitate the change. One necessary piece of this picture is the ability to quantify both the benefits (*i.e.,* building services) that buildings provide and the costs associated with providing those benefits.

This report classifies and attempts to quantitatively define the **metrics** that are appropriate for the economic optimization of building performance. By building performance we are referring to all of the services that the building provides to its owners, occupants, tenants, etc. Although many of the decision-makers in the lifecycle of a building do not explicitly use quantitative metrics to specify their objectives, each action taken ultimately affects these metrics and the building performance. Most metrics in use today are not quantitative and many of those that are quantitative are incommensurate. Ideally, we would like all metrics to be in the same (economic) unit, such as present value in dollars. However, some metrics are not appropriately expressed in dollar terms. For example, some metrics may simply be pass/fail criterion, and some may be sufficiently qualitative that only subjective judgments can be made.

It is easiest to understand these metrics from the point of view of the building owner, but often the real impact is shifted from the owner to those more intimately connected to the building, such as the renter, the occupants/employees, the building operator, the architecture and engineering (A&E) firm, etc. The owners sensitivity to some of these issues may be limited to rental income or complaints, which may not be significant considerations because of such things as market conditions. We will not attempt to address these institutional issues in this report, but limit ourselves to metrics more directly related to the building.

This report classifies metrics into five categories. The first of these is **Building Services.** This category includes all of the metrics that describe direct benefits to the owner, renter, or occupant. These benefits include health, comfort, safety, productivity, security, access to services, etc. In other words all the reasons to build a building in the first place. The boundary between a building service and services provided within the building can become a bit fuzzy. For example, in a large commercial building telecommunications or trash collection may be a building service, while in a smaller building it would not.

The second category is that of **First Costs**, often referred to as capital costs. These costs are the ones associated with the construction of a new building, a retrofit, a renovation, or any other major capital improvement. The costs are characterized by being *one-time* interventions and typically include design, construction and, the rarely done commissioning and are usually dominated by materials and equipment.

The third category is that of **Operating Costs.** These costs are the on-going expenses required to provide the building services from the extant building. These costs are typically dominated by electric and gas utility costs, but also involve some staff and supplies. These costs may also include the other internal utilities such as building security, waste collection, or communications.

The fourth category is that of **Maintenance Costs**. These are the costs required to keep the building in proper condition to provide the necessary building services and include servicing, repair and replacement, and preventative maintenance, including such tasks as cleaning. While operation costs are the direct costs to provide the building services, maintenance costs are those necessary to support the building so that it can continue to provide those services.

The fifth category is that of **Energy and Environmental Factors.** These metrics are for the factors that might be considered exogenous to the economic optimization of the building, but for which external decision makers (*i.e.,* State regulators, Energy Start programs, etc.) have some concerns. These factors include energy efficiency of the building and its components, siting, waste-stream production, peak power requirements, community planning issues, etc.

BACKGROUND OF BPA PROJECT

One of American industries critical objectives should be to maximize the performance of its buildings and their occupants to increase productivity. Today, that goal is rarely met if *performance* is defined by the productivity and satisfaction of its occupants and the lowest operating costs per service delivered by the building.

The focus of this report is to define the metrics by which one can measure building performance. To accomplish this, building performance was considered from the point of view of all the principle players in the life-cycle of a building. The interests of the building owner, operator, and occupants all contribute to identifying important services and features of buildings. Defining appropriate metrics is one task in a new LBL program entitled **Building Performance Assurance** (BPA). The BPA program as a whole is intended to transform the way buildings are built and used in order to optimize their life cycle utility. The general approach of BPA is to improve the information technologies and their use to provide the many decision makers with the information available about the building, its design intent, and its sub-systems. The building performance metrics tell which features of the building should be monitored and which information recorded.

The life-cycle of a building has distinct phases: design, construction (including commissioning), and operation, each with its own sub-phases and different organizations and individuals struggling to understand and cost-effectively manage the building and the enterprise within. Each of these organizations has a variety of skills and tools that are utilized over several years, such as in the design process, or on-going operations and maintenance. Effective storage and communication of information about the building among parties involved in the building life-cycle can greatly improve the performance and efficiency of a building.

Traditionally, communications during the building life-cycle are transmitted via voice, written documents, and annotated drawings. The development of computer-based analytical tools, such as those used for structural or energy analysis, has generated the need for a variety of distinct representations of the building. The cost and bulk of the building documentation, the difficulty of abstracting information for analyses and the difficulty of understanding engineering specifications have created costly barriers to further automation of the flow of building information throughout the life-cycle. Vast amounts of useful information, such as equipment specifications or design objectives, are lost in subsequent phases of building operation because decision-makers in each stage are different and disconnected from each other, and there is no effective archiving or transfer of critical information. For example, the owner may desire a certain feature in the building he is having designed and built. He communicates this to the architect. The architect then communicates this information to the contractor who is responsible for the building phase. As this piece of information is communicated from one party to another, it can easily become distorted or effectively lost altogether. One building manager gives the following account: We have cooling towers that are the wrong size. It is a common problem caused by bad design. We find the problem on hot days when we cannot satisfy the demand and get hot calls from the tenants. (DOE, 1994) Thus illustrating that the design intent was sufficiently obscured or changed that the cooling towers that were specified could not provide the heat rejections the building needed.

Most research on building technologies and processes to date have attempted to address the needs of isolated stages, missing the synergies of an integrated approach. The goal of this program is to address the problem of less-than-optimal communication of important building information by commencing the development and standardization of a set of integrated building life-cycle information systems. Such an information (super-)system would link together software tools to help assure the best possible building performance throughout the building life-cycle. Examples of the potential benefits include more comfortable buildings, increased occupant productivity, increased energy efficiency, lower operating costs, and improved indoor air quality.

Effective information flow should ensure that important engineering and economic information will be automatically and conspicuously available to the building decision makers in a form that will be easy, or even compelling, to use. Development of this information vehicle and the associated process of using the proposed system will require examination of institutional information systems and decision-making processes as well as traditional engineering and economic concepts. One critical success factor will be the careful consideration of the typical needs and problems of building decision makers leading to the development of a system that will be appreciated by these players as being invaluable in performing their jobs. The resulting institutional memory will then be embedded in the life-cycle of the building.

Creating an integrated Building Life-cycle Information Support System (BLISS) is a major effort that begins with the initial programming and design. BLISS would provide a repository for storing information about the building; a set of tools for building design, commissioning, operations and diagnosis and a distributed computing environment with standardized methods and procedures for connecting the various tools and subsystem software together. More specifically, it would include simple descriptive information about the building, such as product specifications and CAD drawings, plus less conventional items, including performance criteria and design intent, models representing the interaction of complex building systems, results from functional tests during start-up and distributed intelligence embedded in building systems.

The researchers developing these systems will build on the existing disconnected (and often incomplete) building data structures and software tools, adding to, integrating and restructuring these elements to meet performance objectives such as optimized energy efficiency and environmental quality throughout the building life-cycle. The fundamental solutions that this program seeks to address require a market transformation in the way buildings are built and used. Barriers to implementing the proposed information support system include technical, institutional, and behavioral factors that will be evaluated as the system is developed.

The use of building life-cycle information systems will dramatically improve the design of new buildings by furnishing the ability to compare, contrast, and assess existing designs. Better communications among the key participants will increase the rate of improvements to performance and serviceability (Ventre, 1990). Experience and data gained from operating actual equipment could be used to evaluate original design concepts.

METRICS IN BPA

To insure the effective operation of the collection of integrated tools that are developed to assure building performance, this collection must have an appropriate set of metrics with which to evaluate and optimize performance. Thus almost every use of the information stored within BLISS will have an implicit or explicit target metric. In the sections below we review this set of metrics and indicate how much can be quantified and what remains to be done.

Several of the metrics detailed below are subjective and difficult to quantify. For the metrics which are quantifiable, an evaluation metric is presented. This evaluation metric is meant to be optimized. For example, costs are frequently given as evaluation metrics. Owners and operators then try to optimize these metrics by lowering the costs as much as possible without sacrificing quality of service. In some cases, target operation variables are indicated. In the simplest case, these target operation variables are control parameters for specific components. It is important to note that they contribute to, and are derived from, the metrics, but they are not metrics themselves. For example, in the Thermal Comfort section, the evaluation metric given is Percent of Population Dissatisfied (PPD), which operators will then try to minimize. Target operation variables, specifying ranges of acceptable temperatures in a typical office situation, are also given. Operators will then know what they have to control in order to optimize the more abstract or derived evaluation metric.

BUILDING PERFORMANCE METRICS

In order to assess how well a building is performing, we must first define a building performance metric. That is, what do we care about when we consider a buildings performance? The answer will be different depending on the party asked. There are many people who care about what happens in a given building. Building owners, operators, occupants, employers of occupants, utility companies, and society at large all care about different aspects of a building. Many of their concerns will overlap. By considering all these points of view, we are able to develop with a list of parameters to examine how well a building is performing. In addition to identifying the relevant parameters, we would like to be able to quantify the effect that different levels of these parameters will have on building performance.

BUILDING SERVICES

Buildings are built to provide specific services either directly or indirectly to the building owner. In a typical arrangement, the owner rents the space to a tenant or tenants, who either are, or who employ the actual occupants. The building then provides services to these occupants. The owner in turn is reimbursed for the benefits that the tenants receive, by collecting rental income. Thus the owner, who may not be an occupant of the building, cares about building services since it is precisely these services for which the tenants pay.

HEALTH, SAFETY, AND SECURITY

The most basic function of a building is to provide the occupants with protection from the outdoor environment. The first building services metric, Health, Safety, and Security, is a measure of how well a building is performing in this area. While it is desirable that the building provide safety from a sometimes unpleasant or inclement environment and also offer security from unwanted individuals, a building should not add additional risks to the occupants or visitors. This factor can be judged by the number of accidents and adverse health effects that can be attributed to exposure to the building environment.

For the purposes of developing the performance metric, we differentiate health from comfort by defining health conditions to be those which present a health risk, and whose symptoms do not improve within twenty four hours after leaving the building. Examples are viruses spread by the HVAC system, asbestos in the insulation, lead in the water, elevated levels of radon, and accidents caused by unsafe conditions in the building. EPAs 1989 report on indoor air quality estimates that an average of 0.24 doctor visits per worker per year are attributable to poor indoor air quality (EPA, 1989). The evaluation metric in this case will be the number of building-related incidents of compromised health, safety, and security. It might be possible to translate this into dollar terms by considering the resultant loss of productivity, medical expenses, lawsuit expenses, and code violation fines. Operators working to minimize this metric should aim to fulfill all safety code requirements and ASHRAE recommendations, at the very least. Ensuring that the HVAC system is running safely and not spreading contaminants is also important to minimize health and safety risks.

SPACE REQUIREMENTS AND FUNCTIONALITY

The occupants of a building will have certain space requirements. One possible metric measures how well the building fulfills these needs. In an optimal situation, the space needs of the occupants are exactly met, with neither too little nor too much space. Too little space will lead to crowding, increased transmission of respiratory diseases, and possibly reduced productivity. Extra, unused space requires a larger than optimal energy use for the given occupants as well as rent for the leasee or loss of productivity. One evaluation metric for an office building would be floor space per occupant, though this does neglect space required by equipment. Ideally, one would compare a buildings space requirements to a similar buildings.

The quality of the space affects its functionality. The ability of the space to provide acceptable working conditions (*i.e.,* acceptable lighting levels or thermal conditions) is addressed below, but issues like the need for window space for windows to provide view is a space requirement. The ability of the space to access building services like electrical connections, communications and transport, or security is also part of its functionality. The more general topic of aesthetic appreciation of the space is discussed in a following section.

Another important, and often neglected, requirement is that of flexibility. Few buildings have the luxury of being designed with the knowledge of exactly how they will be used, or even who will be using them. The capability of being able to use a space for a variety of different purposes is a building service that may be taken for granted by the owner but is often very important and very expensive.

APPEARANCE, AESTHETICS, AND CONTEXT

People who work in or visit a building have an appreciation for the way the building and the building space looks. This appreciation may color their attitude both about the building directly and about what they are doing in the building. For workers their sense of the building environment may affect their satisfaction and productivity. For visitors, their sense of the building may affect their attitude and thus the reason they came to the building (*i.e.,* to conduct business). The owner may have aesthetic objectives independent of these. In any case, the appearance of the building, both internally and externally (often called curb appeal) may be an important building service. Ideally an appropriate metric also assesses such things as how well the building fits in with the architecture of the surrounding area, as well as whether the occupants and others like the way it looks.

Aesthetics is one the most subjective of performance metrics. This subjectivity makes it virtually impossible to measure algorithmically, and only slightly more possible to measure using other methods. It may in fact be meaningless as well as impossible to predict the aesthetics of a proposed building during the early design stages before a substantially detailed design exists to which human evaluators can react.

One attempt to systematize and record subjective reaction to atrium spaces in buildings can be found in an International Energy Agency (IEA) report (Aschehoug, *et al.*, 1990). This approach provides a means of recording occupant response to a number of characteristics of an atrium space by identifying opposing extremes for each characteristic, as shown in Figure 1. This approach is sometimes referred to as a semantic differential evaluation (Rittel *et al.*, 1966).

EXTREME	NEUTRAL	EXTREME
Usual		Unusual
Complex		Simple
Bright		Dark
Modern		Traditional
Noisy		Quiet
Small		Large
General Use		Specific Use
Open		Closed
Finished		Unfinished
Spacious		Tight
Friendly		Unfriendly
Urban		Rural
Public		Private
Safe		Unsafe
Masculine		Feminine
Varied		Monotonous

Figure 1. Atrium characteristic semantic differential chart.

INDOOR ENVIRONMENTAL QUALITY

The factor most apparent to the occupants of the building are the ones associated with their perception of the indoor environment. These factors include comfort, acceptability and satisfaction with the physical factors that affect their sensory organs: odor, irritation, sound, light, and thermal sensation. Whereas the aesthetics section above dealt with more cognitive perception, the indoor environmental quality metrics are more focused on physical effects which tend to be more quantifiable.

Indoor Air Quality: Odor and Irritation

Although it is definitely possible for the air quality in a building to be so poor that breathing the air presents a health risk, as mentioned above in Health, Safety, and Security, many indoor air quality problems will be considered irritations instead of health problems. Recall that health problems are defined as conditions which do not improve shortly upon leaving the building environment, whereas irritations are those conditions which clear up soon after leaving the environment and that do not present a serious health risk to the exposed individuals. This division means that most symptoms of Sick Building Syndrome, though they may be an impediment to productivity, will be considered comfort issues, not health problems. These symptoms include eye, nose, throat, and skin irritation, headache, lethargy, and sometimes nausea. However, these symptoms typically disappear upon leaving the building. Measurements to be taken include ventilation rate for outdoor air (minimum cfm), CO2 as a tracer for bioeffluents, formaldehyde, and possibly total volatile organic compounds (TVOC). The first two are measurements of fresh air while the second two provide information on the presence of known irritants in indoor air. The World Health Organization (WHO) guideline for formaldehyde in indoor air is 0.1 ppm; the state of California has recommended a somewhat lower concentration of 0.05 ppm. Although guidelines for TVOC are not as well developed, the generally accepted rule of thumb is that TVOC should be below 1-2 mg/m3.

So the metric for this section could be time that these compounds exceed their target concentrations. Designers would work to keep sources and ventilation within limits. Operators will work to minimize this time, provided the means of determining it are provided.

It is also helpful for operators to have a recommended ventilation rate to aim for that will insure that they reach the desired low concentrations of the pollutants listed above. ASHRAE standard 62-1989 gives ventilation rates for acceptable indoor air quality for different commercial facilities depending upon their use. These ventilation rates may be used as target operational variables. The amount of outside air required for ventilation varies from 15 cfm/person (8 L/person-sec) for facilities which do not generate a lot of indoor pollutant emissions, to 60 cfm/person (30 L/person-s) for smoking lounges.

Acoustic Comfort and Acceptability

This metric measures how well the building environment provides acoustic comfort to its occupants and visitors. Although it is difficult to quantify just what constitutes acoustic comfort, it must definitely be considered when designing a building. Complicating this metric is that buildings designed for different uses require different acoustics for peak performance. A building which is used for musical projects will require a much different acoustic environment than one which is used as an office. Acoustic comfort depends on the amount of outside noise which enters into a closed room or area, and how the noise originating in a given room reverberates throughout that space. Cubicles, though offering some visual isolation, are especially poor performers in providing acoustic isolation, allowing all the noises of the surrounding activities to reach the individual at her workstation. This metric is very subjective, however. In addition to the issue of different acoustics being required for different activities is the fact that even two individuals doing the same work may have very different ideas of what constitutes acoustic comfort. Certain individuals may find background noise very distracting, while others are stimulated by the sounds of other occupants and activities. The approach in this paper is to try to minimize annoyance caused by noise. Ideally we would present a formula similar to the Percent of Population Dissatisfied in Thermal Comfort, but one has yet to be developed. In the meantime, there are target value for background noise in order to minimize annoyance.

Stein and Reynolds report that tests have shown that, in general, annoyance as a result of noise is:

1. Proportional to the loudness of the noise.
2. Greater for high-frequency than low-frequency noise.
3. Greater for intermittent than continuous noise.
4. Greater for pure-tone than for broad-band noise.
5. Greater for moving or unlocatable (reverberant) noise than for a fixed-location sound.
6. Much greater for an information bearing noise (neighbors radio) than for a no-sense noise.

Since the authors wanted to establish criteria for acceptable background noise, that is, noise whose annoyance level is acceptable, they focused on the first two criteria only. They came up with the following criteria for suggested noise range for steady background noise:

Concert halls, opera houses, recital halls	20-30
Broadcast and recording studios	25-30(distant microphone)
	30-35(close microphone)
Large auditoriums	30-35
Small auditoriums	35-40
Bedrooms, hospitals, motels	35-45
Private offices, libraries, classrooms	40-45
Living rooms	45-55
Large offices, retail shops, restaurants	45-60
Lobbies, laboratories, secretarial areas	50-55
Office equipment rooms, kitchens, laundries	55-70
Shops, garages, power-plant control rooms	-

The unit used here is A-weighted decibels. The sound level in dBA is found by weighting the various components of the sound according to their frequency and sound level (dB). These A-weighted sound levels largely ignore low-frequency sound energy just as our ears do. Although two very different sounds can have the same dBA level, this at least gives us a way to predict community response to many kinds of environmental noise (Egan,1988).

In many building environments a major component of unwanted noise is generated from the provision of other building services. Elevators, air distribution systems, water pipes, etc. can all contribute to unsatisfactory noise levels.

Visual Comfort, Acceptability and Performance

Evaluating the performance of the visual environment created within a space requires a variety of metrics for measuring occupant comfort, performance of tasks, and the acceptability of the environment as a whole. Light intensity, distribution, and glare are all key considerations. While these factors can be considered independently of the source of lighting, it should also be noted that many people tend to prefer a combination of electric and natural lighting which when properly designed can have the added advantage of lessening the energy required to fulfill the lighting requirements. Also, improving the lighting in a space is claimed to increase productivity (Romm and Browning, 1994). The change in visible task orientation in today's office spaces from horizontal desk surfaces to vertical computer monitors requires special attention. Ideally, the lighting in a building will provide both the quantity of light and the quality of illumination that is appropriate for the task at hand and that promotes overall occupant satisfaction with the space.

There are a number of performance metrics related to lighting systems and visual comfort that have been developed by lighting experts. These metrics range from relatively straightforward measures of the quantity of visible light in a space, such as illuminance and luminance, to abstract derived measures of lighting quality such as visual comfort probability (VCP). This section is an attempt to concisely categorize and define this variety of metrics. It is beyond the scope of this paper to provide all details regarding the full spectrum of visual metrics. This section is certainly not a lighting design guide. For more complete information refer to the Lighting Handbook published by the Illuminating Engineering Society of North America (IESNA, 1993a) or the Advanced Lighting Guidelines: 1993 (DOE, 1993).

The quantity of visible light in a space is commonly quantified using two metrics, illuminance and luminance. Illuminance is the amount of light (measured in lumens) that falls on a given surface area and is measured in lux (SI units for lumens/m2) or foot-candles (lumens/ft2). Illuminance is the most commonly used metric for measuring the quantity of light in a space and as the basis for lighting system design standards. Table 1 shows current IESNA illuminance recommendations for a variety of types of activities. It should be noted that these recommendations have been set more by a process of consensus opinion of expert lighting practitioners than by a precise quantitative method. The fairly wide illuminance range associated with each activity type allows a lighting designer to take into account issues such as visual task target contrast and size, age of occupant, importance of speed and accuracy of visual performance, and room and task surface reflectance's. Despite the less than rigorous quantification of the association between illuminance and these issues of visual performance, most lighting system designs are based on this type of recommendation. Illuminance can easily be measured in an existing space using an inexpensive hand held meter. The IESNA has developed a uniform survey method for measuring and reporting interior illuminance data (IESNA, 1993b). There are also several computer programs available for predicting illuminance levels within simulated spaces (*i.e.,* see LBL, 1994).

Public spaces with dark surroundings	20-50
Simple orientation for short temporary visits	50-100
Working spaces where visual tasks are only occasionally performed	100-200
Performance of visual tasks of high contrast of large size	200-500
Performance of visual tasks of medium contrast or small size	500-1000
Performance of visual tasks of low contrast or very small size	1000-2000
Performance of visual tasks of low contrast and very small size over a prolonged period	2000-5000
Performance of very prolonged and exacting visual task	5000-10000
Performance of very special visual tasks of extremely low contrast and small size	10000-20000

[1] *10 lux is approximately equal to 1 foot-candle.*

Table 1. IESNA Recommended Illuminance Values for Generic Types of Activities in Interiors (IESNA, 1993a).

Luminance is a very important concept in lighting since it is luminance that the eye actually sees. It is defined to be the ratio of the intensity of light emitted by a surface in a given direction, to the projected area of the emitting surface. Luminance is measured in units of candelas/m^2 (SI) or candelas/ft^2. The IESNA has developed a uniform survey method for measuring and reporting interior luminance data (IESNA, 1993b). There are several computer programs available for predicting luminance levels seen from a specific location within simulated spaces (*i.e.,* see Ward, 1993). Luminance is such a fundamental measure of light that it can be used to derive many other lighting metrics.

While illuminance and luminance are the primary measures of light quantity, several other factors must be taken into account to derive metrics regarding the visual quality of a lighting system. These other factors include task type and orientation, task and room surface reflectances, lighting source photometry, angle and field of view, and occupant age. When these factors are properly taken into account much more accurate assessments of visual performance within a space can be accomplished. The Illuminating Engineering Society (IES) has announced that in the future, visual performance will replace illuminance recommendations as the basis of lighting design standards. Three visual quality metrics commonly discussed in detail in current lighting design literature include Equivalent Sphere Illuminance (ESI), Relative Visual Performance (RVP), and Visual Comfort Probability (VCP). Despite the present ability of computer programs to calculate these metrics, their application to lighting system design still requires practitioner experience and expert judgment. Continuing research into the development of rigorous quantitative metrics for the evaluation of visual performance is periodically reported in the *Journal of the Illuminating Engineering Society* and *Lighting Research & Technology.*

Equivalent Sphere Illuminance (ESI) is a derived measure related to visual performance that addresses task visibility. A lighting system that produces high background luminance, but low task contrast (*i.e.,* low perceived difference between black letters and the white paper on which they are printed) can have the same visual performance effect due to task visibility as a system that produces low background luminance, but high task contrast. ESI measures the ability of a lighting system to illuminate a task and produce a visual effect equivalent to that produced under reference diffuse hemisphere illumination (IESNA, 1993a). ESI therefore allows a task visibility comparison between two alternative lighting system designs or between a given design and a recommended ESI level. Formally, ESI is defined as the task surface illuminance created by a uniformly bright enclosing hemisphere that produces the same task visibility as a given lighting system design (DOE, 1993). While most interior point lighting computer programs are capable of calculating ESI for a simulated lighting system, field measurement of existing systems requires specialized equipment and complex calculations. For this reason ESI is more valuable as a design tool than a real-world measuring method. In the past, attempts have been made to use ESI as the basis for design recommendations instead of illuminance levels. However, more recently the IES has been exploring the possibilities of using another measure of visual performance, referred to as RVP, for these purposes

Relative Visual Performance (RVP) is a measure of visual performance that measures the percentage likelihood of seeing a visual target accurately (DOE, 1993). RVP is an alternative to ESI that precisely evaluates a lighting system design in terms of relative occupant performance instead of equivalent illuminance. For example, a lighting system that has a 99% RVP can be said to provide statistically significant improved visibility over a system that has a 98% RVP, for a given visual task and a given occupant. For critical visual tasks RVP should range between 95% and 100%. RVP requires specialized equipment that combines a video camera, illuminance meter, and RVP calculation software to evaluate an existing system. Most interior point lighting computer programs are capable of calculating RVP for a simulated lighting system.

Visual Comfort Probability (VCP) is a quantitative measure of visual comfort that evaluates a lighting system in terms of the fraction of occupant population that will accept the visual environment as being comfortable (IESNA, 1993a). The primary criterion of comfort used in the VCP calculation is that of occupant perception of discomfort glare. Discomfort glare is caused by either high levels of brightness or extreme variations between the darkest and brightest surfaces within a field of view. Extreme variations in surface brightness is also referred to as high luminance contrast. Most assessments of discomfort glare are based on the location, size and luminance of light sources, and the background luminance within the field of view. It should be noted that discomfort glare does not necessarily interfere with visual performance unless it is accompanied by veiling luminance (the reflection of a light source from the visual task such as a computer monitor) which can cause disability glare. VCP can either be calculated for a specific occupant location and field of view or based on the average worst case location within a specified space. The primary limitations of VCP come from the fact that it is a system based on empirical relations derived from experiments using only uniform layouts of lensed fluorescent luminaries. The application of VCP to different lighting systems (*i.e.,* different luminaries or daylighting) is not recommended.

While each of the lighting and visual comfort metrics described above may appear to objectively quantify various characteristics of a lighting system design, it must be kept in mind that most recommended values for these metrics are still set by expert committee consensus methods. Thus, application of these metrics to the evaluation of lighting system performance remains fundamentally subjective in nature. The addition of psychological considerations of light such as color temperature (*i.e.,* warm or cold light), color rendering (*i.e.,* perceived similarity to natural light), spatial distribution (*i.e.,* spot or uniform lighting), and temporal variation (*i.e.,* fluctuating daylight levels) make exact quantification of lighting metrics a long term research goal.

Thermal Comfort

Thermal comfort is a metric which has been explored in significant detail. Since individuals differ in their metabolic heat production, activity, and clothing, there is no one thermal environment that will satisfy everyone. ASHRAEs Thermal Environmental Conditions for Human Occupancy (ASHRAE, 1992) proposes a standard to specify a range of thermal conditions which will satisfy most occupants. According to ASHRAE the most important factors affecting thermal comfort are: clothing, metabolic activity level, air temperature, mean radiant temperature, humidity, and air speed.

The first two factors, clothing and metabolic activity level, relate to the individual person. In general, clothing and activity level are determined by the prevailing standards of fashion and the season, and the nature of the occupants duties. Clothing usually changes with the seasons, with light-weight clothing being more typical during the summer months, while thicker, heavier clothes are favored during the winter. Individual control over clothing, *i.e.,* putting on a sweater, gives individuals a way of adjusting their thermal environment. Activity level is primarily determined by the nature of the occupants duties. While activity level must be accounted for, it is unreasonable to think that this factor can be altered to achieve thermal comfort. (We would consider such a building to be performing very poorly.) Instead, we must focus on the remaining factors, adjusting them as necessary in order to support the occupants in their activities.

The remaining four factors, air temperature, mean radiant temperature, humidity, and air speed, are environmental factors. Unlike the individual factors, the building operators may [depending on a variety of factors relating to equipment, zoning and controls for this to happen] be able to change these, especially air temperature, in order to create an acceptable environment. We will define our thermal comfort metric to be the percent of the occupants who are dissatisfied with their environment. Building Operators will then work to minimize this number.

Thermal Comfort Metric = Predicted Percent Dissatisfied (PPD). Ideally, operators will aim to keep PPD at 0.20 or less. ASHRAEs Handbook of Fundamentals, 1993 gives the following relationships (variables defined below):

(1)

$$PPD = 100 - 95exp[-(0.03353PMV^4 + 0.2179PMV^2)]$$

(2)

$$PMV = [0.303exp(0.036M) + 0.028]L$$

(3)

$$L = (M - W) - 1.196*10^{-9}f[(t + 460)^4 - (R + 460)^4] - fh(t - T)$$
$$0.97[5.73 - 0.022(M - W) - 6.9P] - 0.42[(M - W) - 18.43]$$
$$0.0173M(5.87 - 6.9P) - 0.00077M(93.2 - T)$$

(4)

$$t = 96.3 - 0.156(M-W) - 0.88I[(M - W) - 0.97[5.73 - 0.022(M - W) - 6.9P]$$
$$- 0.42[(M - W) - 18.43] - 0.0173M(5.87 - 6.9P)$$
$$- 0.00077M(93.2 - T)]$$

(5)

$$h = 0.361(t - T)^{0.25} \quad \text{if } 0.361(t - T)^{0.25} > 0.151(V^{0.5}), \text{ or}$$
$$h = 0.151V^{0.5} \quad \text{if } 0.361(t - T)^{0.25} < 0.151(V^{0.5})$$

(6)

$$f = 1.0 + 0.2C \quad \text{if } C < 0.5 \text{ clo, or}$$
$$f = 1.05 + 0.1C \quad \text{if } C > 0.5 \text{ clo}$$

	TABLE OF VARIABLES	Defaults
C	Thermal Resistance of clothing [clo]	0.5 clo summer; 1.0 clo winter
f	Clothing area factor, dimensionless	
h	Sensible Surface Heat Transfer [Btu/(h*ft^2*°F)]	
L	Thermal load on the body [Btu/(h*ft^2)]	
M	Metabolic Heat Production [Btu/(h*ft^2)]	22 Btu/(h*ft^2) for typical office
P	Water vapor pressure in ambient air [psi]	
PMV	Predicted Mean Vote, dimensionless	
PPD	Predicted Percent Dissatisfied, dimensionless	
R	Mean Radiant Temperature [°F]	
t	Temperature at clothing surface [°F]	
T	Temperature of air [°F]	
W	External Work accomplished [Btu/(h*ft^2)]	= 0 for typical office activity

While all the variables can be assigned values appropriate to the situation, it is helpful to have some default values in the case where one is unable or unwilling to assess the clothing or metabolic rate of building occupants.

The ASHRAE Standard 55-1992 summarizes this information in a graph which gives a range of values of operative temperature and humidity for people in typical summer and winter clothing during light, primarily sedentary activity, based on a 10% dissatisfaction criteria. Building operators who wish to bypass all the equations above and just select a standard temperature may be interested in knowing the optimum and acceptable ranges of operative temperature for 50% relative humidity, assuming the air speed is close to zero (as it usually is in office situations). In the winter, the optimum operative temperature is 22°C (71°F), with an acceptable range of 20-23.5°C (68-75°F). In the summer, optimum operative temperature is 24.5°C (76°F), with an acceptable range of 23-26°C (73-79°F). There are slight corrections to these temperatures as the humidity changes, with a higher humidity calling for slightly lower temperatures. The humidity level itself should be kept between a maximum of 60% and a minimum of 30% during winter months. The minimum can go even lower in the summer. As activity level increases, operative temperature can be decreased. Non-directional air speed has no minimum for comfort within the acceptable temperature ranges mentioned above. Rather, it is important to avoid drafts, especially for sedentary persons. Persons with a higher activity level can comfortably experience higher air speeds, though the relationship has not been precisely determined.

Operative temperature can then be estimated from air temperature, mean radiant temperature, and air speed by the relation (ASHRAE 55-1992)

$$O = a(T) + (1-a)(R) \tag{7}$$

where O = operative temperature, T = air temperature, R = mean radiant temperature, and (a) is a weighting factor that depends upon the air speed as follows:

air speed (m/s)	0-0.2	0.2-0.6	0.6-1.0
air speed (fpm)	0-40	40-120	120-200
a	0.5	0.6	0.7

Besides the four main environmental factors, there are other factors which affect the thermal comfort level, though their effect is usually substantially less than the four main factors detailed above. For time-varying temperatures, if operative temperature fluctuates in a cycle (for time periods less than 15 minutes) with peak cyclic variation exceeding 1.1°C (2°F), then the rate of temperature change must not exceed 2.2°C/h (4°F/h). Non-cyclic operative temperature changes, or temperature drifts, that begin at 21- 23.3°C (70-74°F) should occur at a maximum rate of 0.5°C/h (1°F/h), should not extend beyond the upper temperature limits of the comfort zone guidelines by more than 0.5°C (1°F), and should not remain elevated beyond this temperature zone for longer than one hour. As for spatial variations of temperature in the occupied space, vertical temperature difference, measured at 0.1-m (4-in.) and 1.7-m (67-in.) should not except 3°C (5°F). Radiant temperature asymmetry in the vertical direction should be less than 5°C (9°F) and in the horizontal direction less than 10°C (18°F). The surface temperature of the floor should be between 18-29°C (65-84°F) for people wearing typical indoor footwear.

Measurement

To measure the air temperature, one must try and minimize the effect of thermal radiation on the sensor. Examples of sensors that may be used to measure air temperature are liquid-in-glass thermometer, resistance thermometer, thermocouple, and bimetallic thermometer. Mean radiant temperature can be measured using a globe thermometer or a two-sphere radiometer. Air motion can be measured with the following instruments: hot-wire anemometer, heated sphere anemometer, heated resistance anemometer, vane anemometer, and cup anemometer.

Humidity can be measured in several ways. Acceptable measuring instruments include psychrometer, dew-point hygrometer, and electrical conductivity or capacity hygrometer. Radiant temperature asymmetry can be measured with a net radiometer or a directional radiometer. Surface temperature can be measured with a contact thermometer or an infrared sensor.

These measurements should ideally be made where the occupants spend most of their time, during the time in which they occupy the building. ASHRAE also recommends that measurements be taken in locations where the most extreme values of the parameters are likely to occur. Humidity need only be measured at one location in each occupied room or HVAC-controlled zone.

PRODUCTIVITY

While health, safety, an indoor environmental concerns are usually quite important to the occupants of the building, the employer of those occupants may often be more concerned about their productivity. Productivity depends not only on occupant acceptability of the space but also on its functionality for the particular tasks. In one sense productivity is dependent on the other building service metrics, but because it is of separate economic importance to the employer, it merits is own metric.

Although productivity is probably the most important building service to the employer of the building occupants, it usually cannot be measured. Productivity is only easy to quantify for certain repetitive tasks, *i.e.*, jobs such as sorting and assembly-line work. Because productivity is so important and so difficult to quantify, it is necessary to consider a variety of measures which might be used as indicators of an effect on productivity. This was the subject of an ASHRAE Workshop in Baltimore in September, 1992, at which the following measures were recommended (Wyon, 1993):

1. Absence from work or workstation; unavailability on telephone
2. Health costs, including sick leave, accidents, injuries
3. Observed downtime, interruptions
4. Controlled independent judgments of work quality, mood, etc.
5. Self-assessment of productivity
6. Component skills, task measures, as speed, slips, accuracy
7. Output from pre-existing work-groups
8. Total unit cost per product or service
9. Output change in response to graded reward
10. Voluntary overtime or extra work
11. Cycle time from initiation to completion of discrete process
12. Multiple measures at all organizational levels
13. Individual measures of performance, health, well-being at work
14. Time course of measures and rates of change

Although it is difficult to measure productivity for most workers on the job, it is clear that missed work days are a definite loss in productivity, reducing worker efficiency by 100%. Studies of many Dutch office workers have indicated that sick leave due to Sick Building Syndrome (SBS) symptoms is reduced by 34% when workers can control their own thermal environment compared to workers occupying offices where they must accept conditions that are optimum for the group rather than for the individual (Preller, 1990). Similar studies investigating office workers in the UK found that self-estimates of efficiency are significantly higher when individuals can control their own thermal climate, ventilation, or lighting levels compared to office workers who have no individual control (Raw, 1990). In light of these findings, the idea of Environmentally Responsive Workstations (ERWs) has become a popular choice for the designer. These systems allow the individual to control the climate of their surroundings to a substantial degree.

Thus productivity is linked to many of the other building services metrics, especially the ones pertaining to comfort. For example, workers may be working inefficiently if the lighting in their work area is insufficient or inappropriate for the nature of their work. Likewise, viruses spread by the HVAC system in the building are a Health, Safety, and Security issue, but they also affect worker productivity. Productivity is an indirect service in that it is the result of the interaction between the occupants of the building and their perceived environment. Although the connection between worker satisfaction and productivity seems intuitive, a recent study exploring the connection (Das and Mital, 1994), has found no substantial or consistent correlation between the two. In fact, some work (Pepler, 1968) has shown that while workers feel most comfortable at 27°C, they also exerted the least effort and performed the least work. They performed the most work at 20°C, although most of the subjects felt uncomfortably cold at this temperature.

However, as mentioned in the visual comfort section, Romm and Browning, (1994), claim several cases in which efficient lighting, heating, and cooling have significantly improved worker productivity, measured as increased production rate or quality of product, or decreased absenteeism. They also calculate that office workers salaries cost approximately 72 times as much as the energy supplied to the office. Thus a 1% increase in productivity will mean a savings of the entire energy budget. This gives a perspective on the economic value of productivity versus energy use, and explains why productivity is the largest driver in delivering building services.

LABELING AND CODE REQUIREMENTS

Code and labeling requirements may cross-cut many of the other metrics. In general code requirements represent pass/fail criteria on a number of related issues deemed important by the authorities having jurisdiction. It is true, unfortunately, that full consideration of many of the metrics is abrogated in the minds of the designers and/or owners and replaced by merely meeting code requirements.

In some ways these metrics may more properly belong in the section because they are generally put in place to address societal concerns such as health, safety, energy consumption, etc. The reasons for the codes may be addressed there; but to the building owner demonstrating compliance with regulation is very much a building service, since he cannot get any benefit from his building without it.

As mentioned above in Health, Safety, and Security, it is important to meet the safety codes to minimize the risk of accident or illness. The code requirements that the building must meet are specific to its location. Though they may differ in specifics, almost all buildings will have to meet basic building codes in areas such as structural and fire safety. This metric will quantify the level of code compliance and will apply individually to each applicable code (*i.e.,* health, safety, energy, etc.). Thus a target for this metric will be full compliance.

Related issues such as labeling are more quantitative than the pass/fail requirements of many regulations. For example, home energy rating systems, electrical and fire rating, appliance labels, and equipment rating all have a spectrum of values that can be used in different ways. Many of these metrics are self-defined by specific user groups.

FIRST COSTS

First costs generally receive the most attention and are usually given the highest priority by building project planners. There are numerous cost centers associated with first costs as indicated in the example hierarchical organization shown in Figure 2. As shown here, the first costs metric is considered to include costs for design, initial construction and commissioning. An additional first cost category included here is that of building renovation which, although it may take place in the future, will incur similar categorical costs to that of initial design, construction and commissioning.

First Cost ($ Total, $/m2)

- *Design ($Total, $/m2)*
  - Planning ($Total, $/m2)
  - Schematic design ($Total, $/m2)
  - Design development ($Total, $/m2)
  - Detailed design ($Total, $/m2)
- *Construction ($Total, $/m2)*
  - Management ($Total, $/m2)
  - Labor ($Total, $/m2)
  - Materials ($Total, $/m2)
  - Equipment ($Total, $/m2)
- *Commissioning ($Total, $/m2)*
  - Planning and Analysis ($Total, $/m2)
  - Labor ($Total, $/m2)
  - Equipment ($Total, $/m2)
- *Renovation ($Total, $/m2)*

Figure 2. Hierarchical breakdown of First Costs.

These are one-time costs associated with capital creation and improvements. All major capital improvements go under this first cost heading, Costs for normal building equipment optimization, repair and replacement are handled as maintenance costs and not as first costs.

It is important even before the design stage begins to establish cost and performance goals for any capital project. In current practice these goals may be too narrowly defined (and thereby inhibit performance optimization).

DESIGN

Design is the beginning stage of an overall building project. As indicated in figure 2, there is an initial planning phase that generally starts with a feasibility study that takes place prior to actual building design activities. Following a go-ahead approval, architectural programming is undertaken to identify client requirements and constraints. Schematic design, followed by design development and detailed design then result in a final design that is submitted to potential construction managers or contractors for purposes of bidding on construction costs.

This stage of a building project involves architects and design engineers, and is likely to be high in labor and low in materials. The final dollar amount paid for these services is most often determined as a percentage of the initial first costs of the building, the vast bulk of which are spent on construction.

CONSTRUCTION

The construction phase of the building is accomplished by construction managers, the contractors and their subcontractors, and is substantially higher in material costs than design, renovation, or commissioning activities, as well as being by far the most expensive of all first costs.

Construction costs can be estimated prior to actual construction using a wide variety of methods based on the current design stage, as well as the desired levels of accuracy and estimating effort. Some of these methods and their relationship to design phase, precision, and estimating time or cost are shown in Figure 3. One example of an order of magnitude method used during the feasibility study stage of a project is based on cost indexes regularly published by such sources as the Engineering News Record (ENR) magazine. Using this method, a cost estimate is calculated from the known cost of a previous similar project and the building cost indexes (BCI) for the current and previous project time and location (Ibbs, 1992). As more detailed design progresses, estimation is accomplished more formally using construction component take-offs and unit-price methods.

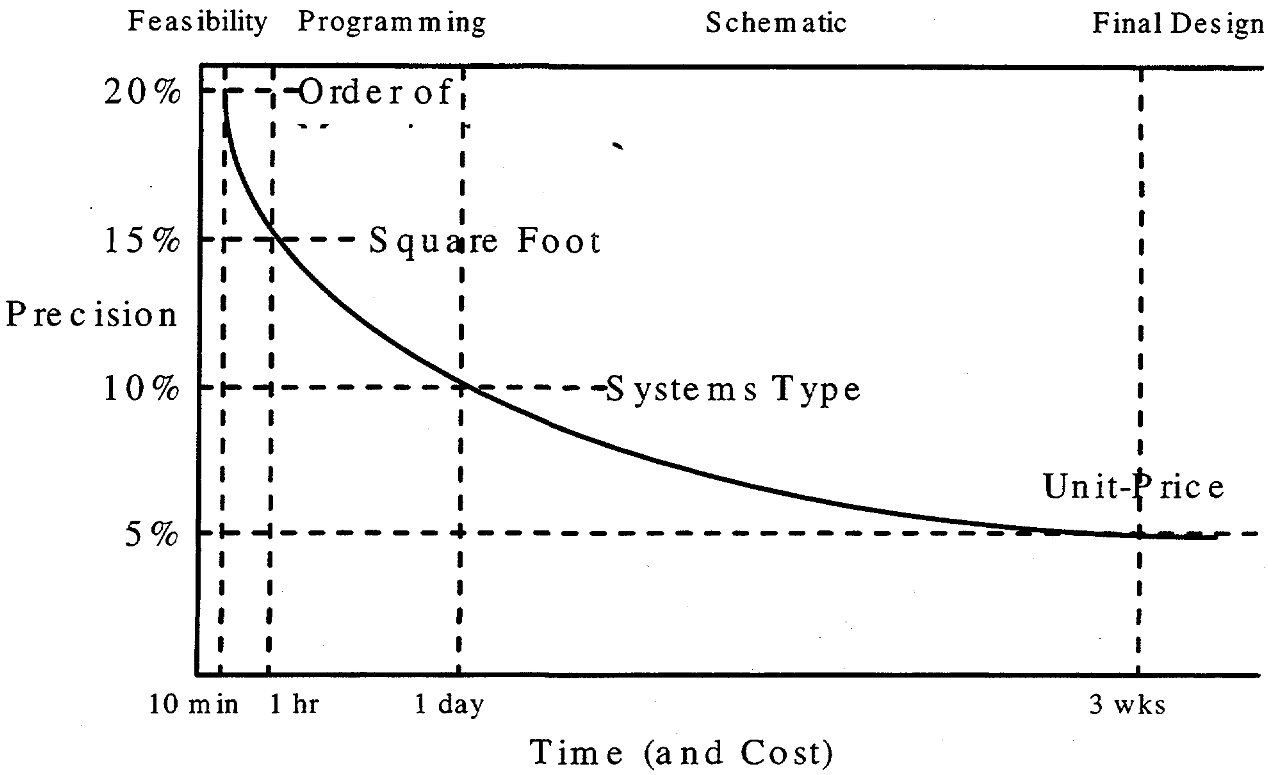


Figure 3. Precision and cost of design stage appropriate estimating methods. (Ibbs, 1992)

The most detailed construction cost estimation methods are based on project Work Breakdown Structures (WBS) that hierarchically decompose construction tasks and associate individual costs for labor, materials, equipment and management with each task. The WBS cost estimate can also be linked to a construction schedule, such as a Critical Path Method (CPM) plan, and used as a sophisticated method of project cost control during construction.

COMMISSIONING

Commissioning is the last of the main phases described in this section. It is the process by which a building is inspected and tested in order to ensure that it is capable of operating as intended. Commissioning often necessitates hiring a commissioning agent. Thus, like the design metric, it will probably be high in labor costs and low in materials. Although it can be highly cost-effective commissioning is rarely done. Many of the institutional barriers to commissioning can be addressed with a better lifecycle understanding of the building.

RENOVATION

Renovation, including rehabilitation, is another material-intensive phase. It differs from construction in that it is usually done later, after the building has been occupied for some time. Renovation involves redesigning a specific system or area of the building, and thus is not the same as a simple replacement of equipment. This will be covered in Operation Costs and Maintenance Costs.

OPERATING COSTS

The costs of operating a building are considered in this section[1]. In this report we have separated operation and maintenance costs into two different sections. Operating costs are the costs of delivering the building services. The units for all the Operating Costs metrics are dollars/year. For certain metrics, (*i.e.,* Utilities), it may also be helpful to divide this expression by the floor area, weather or other equivalent extensive quantity of the building, thus facilitating comparison between different buildings.

Flexibility during the operations phase is a very important quality in most buildings. The costs of designing for flexibility usually show up as increased operating costs. Many systems may be oversized or excessively complicated to allow for different demands than those that actually occur. For example, most chiller system in commercial buildings are significantly oversized in part to accommodate future load expansion and, therefore, tend to run at less than optimal cooling efficiency most of the time. While some of this cost can be mitigated by recommissioning systems for the actual demands, some cannot.

UTILITIES

This metric will account for the cost of providing energy to the utilities in the operation of the building. While services such as water or waste collection are included as utilities, the major costs are normally the energy-related utilities. This utility bill gives total energy consumed and dollars spent. Annual costs are probably the most common time period over which these costs are calculated, though they can be calculated for any time period desired. Operators may find it helpful to calculate energy per square foot by dividing the energy consumed by

---

[1] Operating costs should not be confused with the *Operation Phase* of the building, which is the phase in which the building is capable of being occupied. While the operating costs occur only in this phase, other costs also appear in the Operation Phase of the buildings lifecycle

the floor area of the relevant space. This will allow comparison of utilities between different buildings. See energy use intensity, below, for more discussion on calculating area. In many circumstances, however, demand or time-of-use charges can be more important than energy intensity.

STAFF COSTS

Operations staff includes building operators, security staff, etc. This metric would be easily calculated if the staff for Operations is kept separate from the Maintenance staff. If not, then either the metrics can be combined into O & M staff costs, or the O & M staffs hours must be split between Operations and Maintenance. This metric will be measured in dollars per year

SUPPLIES

As with Staff Costs, this metric is easily calculated when the Operations supplies are recorded separately from the Maintenance supplies. Example of supplies might include oil for machinery, archival media for documentation, or other consumables. This metric will be measured in dollars per year.

MAINTENANCE COSTS

Maintenance costs are the costs of keeping the building capable of delivering building services. As with Operating Costs, the ultimate metric for Maintenance Costs will be in units of dollars/year, though normalizing this quantity by the floor area of the building will give dollars/sqft-yr, and this may be helpful in comparing Maintenance costs of different buildings. Deferred maintenance is thus apparently a cost savings, but usually shows up in other metrics by degrading performance or incurring higher costs. By deferring normal maintenance, performance degradation is enhanced; the section on performance degradation covers this issue more fully.

STAFF COSTS

Maintenance staff includes janitorial staff, building engineering staff, etc. This metric measures the maintenance staff costs. As mentioned above in Operations Costs, this is easily quantified when the Operations staff is different from the Maintenance staff. This is often the case, since it is increasingly common to see the maintenance work contracted out. If not, the options are either to combine the O & M staff costs into one metric, or to somehow allocate a fraction of the costs to Operations and the rest to Maintenance. This metric will be measured in dollars per year.

EQUIPMENT REPLACEMENT

Equipment replacement is distinguished from the Renovation metric in the First Costs section in that equipment replacement is simply replacing equipment which can no longer operate as it did originally or as it was designed to operate. This metric will be measured in dollars per year.

SUPPLIES

The cost of Maintenance supplies is usually small compared with staff costs, and is easily calculated from Maintenance records. Material necessary for minor repairs or refurbishing may also be included in this category. This metric will be measured in dollars per year.

ENERGY AND ENVIRONMENTAL FACTORS

Energy and environmental issues are metrics that may be more important to society than to the owner occupants directly. The metrics described in this section can be used to evaluate building performance for a variety of criteria, which may be exogenous to the building owner and its occupants.

There are two approaches to consider when measuring energy efficiency. The first is the load, the buildings need for energy. This level can be a focus for reducing energy costs. The second focus for reducing energy costs is to deliver the needed energy in the most efficient manner. We will consider energy efficiency in terms of the various systems of the building. The Energy Use Intensity metric is a measure of the energy load itself.

ENERGY USE INTENSITY

The building demands energy to run and operate as intended. The HVAC and lighting systems mentioned above need energy input, as do the elevators, computers, and the myriad of other energy-consuming systems of the building. The annual energy use intensity metric, or EUI, will measure the total energy required by all the major end-uses in the building, including heating, cooling, lighting ventilation, and other miscellaneous uses, and will be normalized by the building floor area. The EUI metric will thus be in units of kBTU/ft2-year. This metric is purely a measure of how much energy is used per space in the building. It does not tell how well that energy is being used. The higher this quantity, the more energy is being used.

The EUI can be used to evaluate a given buildings energy use. This energy use can then be compared to the EUI of comparable buildings. CBECS-West surveyed over 7000 commercial buildings nationally, and gives 104 kBTU/sqft-yr as the average EUI for west coast office buildings. Surveys from California utility companies (PG&E and SCE) and also the Building Owners and Managers Association (BOMA) show an average of about 104 kBTU/sqft-yr, ranging from 66 to 120 kBTU/sqft-yr in southern California.

Of course, comparing EUIs is complicated since the buildings energy use needs may differ considerably. But in general, a good EUI (for office buildings) is one that is less than 80 kBTU/sqft-yr, while best-practice is any EUI less than the BECA-CN average of 69 kBTU/sqft-yr, as given by Piette (1986). Ideally, there would be a large data base containing energy use information pertaining to a wide variety of buildings, and thus the building in question could be compared to one which is similar in energy-using services provided, as well as being located in a similar climate.

An important measurement in calculating EUI is an accurate accounting of the buildings floor area. The relevant floor areas are net-rentable area (the smallest area, which excludes stairways and common lobby areas), conditioned area (which does include lobbies), gross area, and gross area including parking. When comparing a buildings EUI to a target value, the floor areas must be calculated in the same way to make the comparison meaningful.

The descriptions below are brief summaries of some of the major energy-related systems and their efficiency metrics. Each sub-entry has a larger literature associated with than can be referenced here. One global reference is the *Handbook of Conservation and Renewable Energy* (1996).

Lighting System

The lighting system metric indicates how well the energy supplied to the lights is being used to deliver the desired lighting. Different lighting fixtures and arrangements will produce different values for this metric. The units will be lumens/W. The higher this quantity, the more efficient the lighting system is at using the power supplied to it.

Lamp efficiency, fixture efficiency, and lighting distribution (*i.e.,* room) efficiency all contribute to the overall lighting system efficiency. Control systems may also affect efficiency (as well as use), especially if daylighting can be used. It is often more appropriate to consider this issue individually

HVAC System

This system is divided into three main subsystems: heating, cooling, and ventilation. In large buildings cooling is typically further divided into three main components: the chiller, cooling tower, and pumps. These systems (along with the lighting and internal gains) can be highly interactive, so it is not always appropriate to separate them. Novel systems including heat recovery or thermal storage may not be easily separated; high efficiency cooling (*i.e.,* evaporative) may require more complex descriptions. In most large office buildings, however, they can be so separated and we can describe them as follows:

Heating

Heating is accomplished by a furnace or boiler. Both are pressure vessels which generate heat (by combustion or by an electric resistance-type heating element) and then transfer this heat to a fluid. In boilers, this fluid is usually water in the form of liquid or steam. In furnaces, this fluid is air. The efficiency metric used to evaluate performance of a fuel-burning boiler is defined as input minus stack or chimney losses, divided by input. This value commonly ranges from 75 to 86%.

Cooling System

The cooling system includes the chiller, chiller and condenser water pumps, and the cooling tower. Cooling is typically needed in all large buildings and in perimeter zones when outside temperatures reach about 55°F. The cooling load, like the heating load, is determined by the building envelope and orientation, internal gains (produced by the lights, computers, and people), and the weather. Many buildings use economizers that allow an increase in outdoor air for cooling when temperatures outside are less than the desired temperature inside, thus reducing the need for compressor cooling.

Total cooling plant performance is expressed in kW/ton. This is the ratio of the energy consumed by the cooling system (in kW) to the cooling load imposed on the chiller (in tons). Thus it is the inverse of what is normally considered efficiency, and so optimizing this figure means minimizing it. The total cooling system performance in kW/ton is the sum of the kW/ton performances of each individual component. The kW/ton is lower (*i.e.,* the cooling system is more efficient) when the cooling plant is more fully loaded.

Cooling: Chiller

The chiller cools the building to the desired temperature by absorbing unwanted heat throughout the building. It performs this task by sending chilled water through a system of pipes. As the water warms and comes to equilibrium with its surroundings, it lowers the temperature of the building environment. So power is supplied by the chiller as water is sent through the system. The efficiency metric will be measured in units of kW/ton, in agreement with traditional chiller efficiency ratings. The kWatts in the numerator refers to the power consumed by the chiller, and the tons in the denominator to the cooling load to be removed from the occupied space. Chiller performance is usually rated (in kW/ton) by the American Institute of Refrigeration (ARI) at standard reference conditions. These conditions are that chilled water is supplied by the chiller at 44°F, and condenser water is supplied to the chiller from the cooling tower at 85°F. In actual practice, these precise conditions are often not met. If this is the case, then the actual kW/ton will vary from this figure.

Cooling: Cooling Tower

The cooling tower is a complex system, made up of several different pieces of equipment. The cooling tower cools water by using a combination of heat and mass transfer. The water to be cooled is usually sprayed to expose a large surface area of water to atmospheric air. Some of the water absorbs heat to change from a liquid to a vapor at constant pressure. The heat of vaporization is supplied by the water remaining in the liquid state. Overall efficiency for the cooling tower will also be measured in kW/ton. Cooling towers typically use much less energy than chillers do.

Cooling: Pumps

The pumps in the cooling system each have their own individual efficiencies. These efficiencies will also be measured in kW/ton, or motor efficiency.

Ventilation

The efficiency of the ventilation system will be expressed in units of kW/cfm. That is, how much energy does it take to ensure that the ventilation system delivers the necessary flow rate. As with the other metrics in the section, this is the inverse of what is normally considered efficiency, and thus optimization of this metric will be achieved by minimizing this value.

Building Envelope

While the building envelope does not itself consume any energy, it responsible for managing the energy exchange between inside and outside the building: solar radiation, thermal conduction and air flow. The energy requirements of perimeter zones of buildings are usually dominated by envelope performance. Thus it is quite appropriate to define energy efficiency metrics for envelope properties.

Insulation

The most basic energy property of building envelopes are their ability to retard the flow of heat by conduction. In envelope dominated structures (*i.e.*, smaller buildings) the level if insulation is the single biggest determinant of space conditioning energy. The envelope conductance can be used as the appropriate metric for thermal insulation.

Windows

Window systems control the amount of daylighting and attendant solar gain from the exterior, as well as conduction through the window itself. Each of these three window properties has their own set of metrics

Air Leakage

All envelopes contain leaks which allow air to be exchanged between indoors and out. The metric which characterize this leakage is the Normalized

Leakage of ASHRAE Standard 119-89. The infiltration allowed by this air leakage is characterized in air changes per hour.

Thermal Mass and Storage

The affect of thermal mass in a building is a strong function of the control systems used. Capacity is a relatively simple metric, but availability is even more important and harder to quantify

Thermal Distribution Systems

Thermal Energy Distributions (TED) systems require energy themselves in order to distribute energy (*i.e.,* fans and air handlers), but this consumption is not usually their biggest energy impact. Poorly designed or controlled TED systems can cause significant inefficiencies by delivering improper amounts of heating or cooling to zones or by losing their energy efficiency in much the same way as envelopes do (*i.e.,* conduction and leakage). Metrics for quantifying the TED efficiency are currently being developed.

Other Systems

Besides the main lighting and HVAC systems, there are other systems, specific to the building, which will have energy efficiency targets. Examples of such other systems include elevators and office equipment

WASTE AND TOXIC MATERIAL PRODUCTION

Almost every building that is occupied generates some kind of waste. Some buildings also house activities that generate toxic material. This metric could potentially be measured in dollars, assuming that all the waste is properly disposed of. Then the resulting cost of disposing of the garbage, sewage, and hazardous waste is one useful measure of the amount generated. The metric could also be measured in the number of violations of environmental laws. Environmental laws include wetlands permit provisions of the Clean Water Act, hazardous waste regulations, recycling regulations, and storage tank regulations. If treated as a code requirement the metric would be number of violations, but other metrics involving specific quantities and toxicity's could be considered as well.

Embodied Energy

One measure of ecological impact of capital projects is that of embodied energy. The production of materials consumes energy either directly or indirectly; such energy is one measure of the waste stream. Amortizing this waste over the life-cycle of the building estimates its impact. To the extent that such externalities are reflected in the economics of the situation, the price of the materials will reflect their embodied energy. Where pricing is highly skewed other mechanisms may be necessary.

Material Recycling

In order for the building industry to become Green it will be necessary to design and build in the capability to re-use and recycle building components to minimize waste. Because buildings have a long design life normal economic considerations do not put much weight on decommissioning costs and hence there is little incentive to consider recycling. While small efforts in such places as central Europe are beginning, this issue is generally not yet considered. The are, however, more active recycling efforts in particular materials that help provide building services such as paper or refrigerants.

Material Flow

The issue of material flow (*i.e.,* water, paper, sewage, etc.) is rarely considered in the context of buildings outside of the industrial sector. While reduction of these flows could be considered a building service, it is not normally reflected in design.

SOCIAL IMPACT

A building exists in an environment that is usually shared by other neighbors. Different residential, commercial, and agricultural activities may take place in the surrounding area. There are then many individuals and communities that will be affected, at least tangentially, by the building. The physical envelope of the building will have an effect, but so will the activities taking place within the building. The location of the building will indicate what kind of human or wildlife communities will be affected. The building activities considered will range from the services or products supplied by the occupants to the community outreach programs. For commercial buildings, hiring, retirement and health care policies and on-site childcare could also have a big impact on the community. This metric is difficult to quantify. A start would be to do an environmental impact study, and also an approval rating survey around the community.

LIFE-CYCLE COSTS

In each of the individual cost categories outlined above, the target operation variables are budgeted money spent on the building in each category. To compare the advantages and disadvantages of spending money in one area vs. another, we can calculate the net present value (NPV) of money spent on the building, including all life-cycle costs and accounting for the time value of money. In this way we can evaluate variations in allocations of money spent under the different headings from a true life-cycle perspective. An overall life-cycle cost outline aggregating the cost centers discussed above is shown in Figure 4.

Life-Cycle Cost ($Total, $/m2)
- *First Cost ($Total, $/m2)*
  - Design ($Total, $/m2)
    - *Planning ($Total, $/m2)*
    - *Schematic design ($Total, $/m2)*
    - *Design development ($Total, $/m2)*
    - *Detailed design ($Total, $/m2)*
  - Construction ($Total, $/m2)
    - *Management ($Total, $/m2)*
    - *Labor ($Total, $/m2)*
    - *Materials ($Total, $/m2)*
    - *Equipment ($Total, $/m2)*
  - *Commissioning ($Total, $/m2)*
    - Planning ($Total, $/m2)
    - Labor ($Total, $/m2)
    - Equipment ($Total, $/m2)
  - *Renovation ($Total, $/m2)*
- *Operation Cost ($Total/yr, $/m2/yr)*
  - Utilities ($Total/yr, $/m2/yr)
    - *Heating ($Total/yr, $/m2/yr)*
    - *Cooling ($Total/yr, $/m2/yr)*
    - *Lighting ($Total/yr, $/m2/yr)*
    - *Ventilation ($Total/yr, $/m2/yr)*
    - *Equipment ($Total/yr, $/m2/yr)*
  - Staff ($Total/yr, $/m2/yr)
  - Supplies ($Total/yr, $/m2/yr)
- *Maintenance Cost ($Total/yr, $/m2/yr)*
  - Staff ($Total/yr, $/m2/yr)
  - Equipment Replacement ($Total/yr, $/m2/yr)
  - Supplies ($Total/yr, $/m2/yr)

Figure 4. Hierarchical aggregation of life-cycle costs.

Decisions made in the design, construction, commissioning, and renovation phases affect operation and maintenance costs as well as first costs. For example, an owner or operator may be deciding whether to renovate the HVAC system. This renovation is an investment that will require substantial initial capital outlay but potentially reduce energy consumption costs down the line. If one looks only at the First Costs Metrics, then the decision to invest money in a new system might look like a bad investment since first costs go up. But by considering O & M Costs as well, all in net present value, a more accurate picture of the long-term potential costs and benefits can be reviewed.

PERFORMANCE DEGRADATION

Building performance is not a static quantity. While the metrics that make up building performance may be static targets during the design phase, actual building performance is an ever changing thing as are the component metrics that make it up.

The operations phase of the building lifecycle is the one that takes up the vast majority of the buildings life. All of the metrics we have defined are relevant and changing. For the majority of time these metrics are changing in such as way as to cause degradation of the buildings performance.

Performance degradation is a normal effect; there are two different kinds of reasons for it. The major reason is that the components of the building age. That is either they malfunction or they no longer meet operational requirements and either loose capacity, efficiency, or ability to deliver service. Secondarily, performance may degrade, because the currently desired services have evolved beyond the original design intent.

There are essentially three symptoms of degradation. First, and usually least noticeable, is loss of flexibility and capacity. As building systems age, the O&M staff will normally attempt to optimize the system to meet current operational demands. This often reduces their ability to respond to significant changes. Second, as components age their efficiency often gets lower requiring increased operational costs and they begin to need more minor repair etc. thus increasing maintenance costs. Finally, and most noticeably, at some point their capacity to provide building services will drop below the acceptability threshold.

All is not lost, of course; there are a set of restoratives that are used to combat performance degradation. The most ordinary one, but not the one most universally used, is that of preventive maintenance. When systems and component are cleaned and checked at regular intervals, minor repairs and replacements can be done to keep short-term reductions in performance from happening. These activities are normally done by the regular O&M staff.

As seasons, occupancies and efficiencies change, it can become effective to re-tune the systems and controls to achieve better performance. This kind of system optimization during normal operation is sometimes called *recommissioning.* Like commissioning it is a low capital cost activity that can be done by a trained professional. These costs ought to be considered as maintenance costs.

If a components performance has degraded sufficiently or has reached the end of its useful life, component replacement or *minor retrofit* is needed to improve performance, usually above the capability of the original design. Such retrofit is usually limited to a sub-system (*i.e.,* a chiller and its controls) that can provide the same parts of the building service as the original design. As discussed earlier, we include such equipment replacement under maintenance costs.

If the demands on the building have changed significantly enough, or if enough of the building systems are obsolete enough, it becomes time to consider a major retrofit or *renovation.* Such a project takes on many of the same properties of the original design phase, except that there is an existing building to work with. One would hope that such major projects would not be necessary before the design service life of the major building components had elapsed. Proper design should allow sufficient flexibility to respond to changes in use with minimal cost impacts. In any case, these renovation costs are normally considered to be first (construction) costs.

While performance can not usually be measured directly in dollars it can usually be quantified and acceptability relative to design intent determined. Figure 5 generically depicts how performance typically degrades over time for a building service and how various interventions can mitigate the degradation. This metric shown is one in which there is a definable threshold of performance rather than a continuous spectrum. This threshold may be set either by code or specification.

PERFORMANCE DEGRADATION

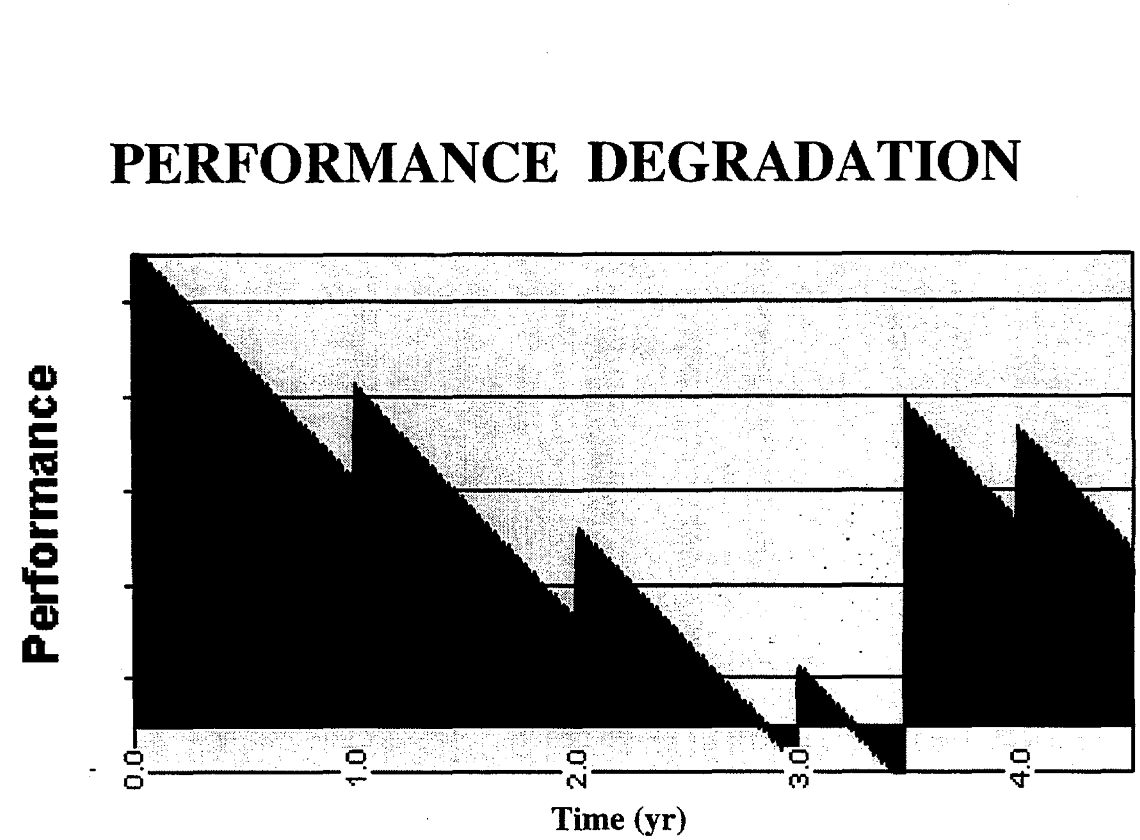


Figure 5: Performance Degradation a generic building service

Figure 6 shows one of the important performance metrics (*i.e.,* thermal comfort) from the end of the start of the operation phase. The zero of performance is the minimum acceptable level. The area under the curve (shaded) is a measure of performance quality, maintainability or system flexibility. If appropriately weighted for economic considerations it becomes the life-cycle benefit. This figure depicts (and the paragraphs below describe) one particular set of maintenance decisions including both major and minor interventions. (For metrics in which there is a continuous spectrum of acceptable performance different decision making procedures are needed.)

Construction provides for some potential performance by defining physically achievable ranges of performance. During the commissioning phase (not shown in the figure) the potential performance became actual performance and is well above the acceptability threshold for that metric. As time continues the performance degrades because of changes to the components and in the occupancy. A closer examination of the that decay would show that the downward trend has punctuated upward steps as regular maintenance is performed. Without regular maintenance the curve would drop much faster and performance quality would degrade, but even with regular maintenance there will be a need for interventions such a recommissioning, repair, or renovation.

Without intervention the performance soon degrades sufficiently that a decision is made to repair, tune, or recommission the system. This effort improves the performance principally by changing the control to better match the current demands to the current system capabilities. Eventually, the normal maintenance and minor repair and re-tuning cannot keep the systems operating acceptably. At this time (about 3.5 years in the example), a major repair or replacement is needed. This intervention brings the performance back almost to original level of performance. The cycle continues until whole systems have reached their useful life and/or renovations are necessary.

Associated with these performance benefits are costs to provide O&M including the interventions. Figure 6 depicts this cost stream

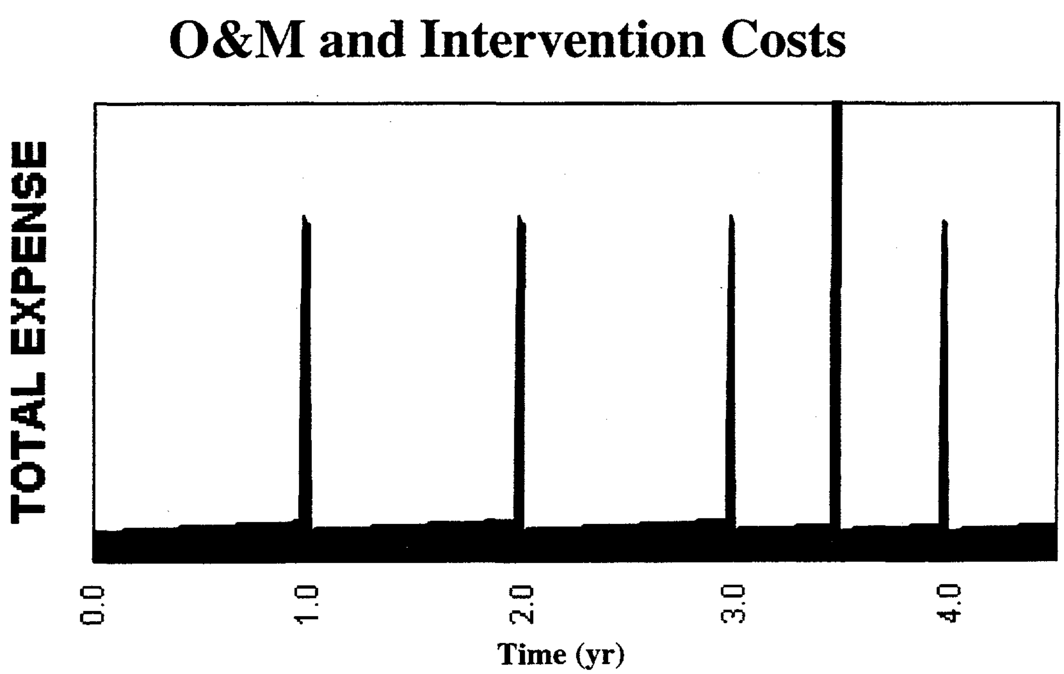


Figure 6: Costs required to provide the building services

Figure 6 tracks the same activities but from the costs side rather than the building service side. There is a baseline cost stream required for the normal operations and maintenance; the interventions required to bring up the performance appear as spikes. One can note that the costs between spikes are slowly rising to indicate the usual trend of operations costs slowly increasing as systems get out of tune.

Using the lifecycle cost principles from above, this cost stream cost be combined with the first cost to get a total life-cycle cost. The major repair at 3.5 years, like the original first cost (not shown) is off-scale. If the performance benefits could be converted to dollars it would be possible to do a full benefit-cost analysis rather than just a life-cycle cost minimization.

In such a case different alternatives scenarios could be considered. For example, a larger regular maintenance outlay may extend the time between repairs. Conversely, more regular recommissioning may reduce the need for other forms of maintenance. Each of these scenarios would have a different looking performance and cost plot, which could then be used to help make appropriate economic decisions.

DISCUSSION

We have briefly reviewed the metrics by which people and institutions commonly evaluate buildings. This review is intended to be extensive and obviously does not cover any of the issues in significant depth. The relevance of this work stems not from any new performance issue raised, but from the way in which these issues are viewed. The metrics can be summarized in the following table

METRIC	Sub-Metric	Comments
Health, Safety, Security		Occupants and Regulators watch this one
Space Requirements and Functionality		Lessors and Employers use for decisions
Appearance and Aesthetics		Owners, Occupants, Visitors care about curb appeal
Indoor Environment	Indoor Air Quality	IAQ problems = potential litigation
	Acoustic Comfort	Can cause complaints and productivity loss
	Visual Comfort	Task dependent; big electricity users
	Thermal Comfort	Occupant complaints and/or big utility bill
Productivity		Employers want to know
Code Requirements		Often are defacto metrics
Design Costs		Usually a fixed percentage of construction
Construction Costs		Biggest single expense
Commissioning Costs		Not realized in typical buildings.
Renovation Costs		Equivalent sequence to original construction
Utility Costs		Dominated by Energy
Operating Staff Costs		Often insufficient to keep building running optimally
Operating Supply Costs		Low budget item normally
Maintenance Staff Costs		Deferred maintenance increases lifecycle costs
Equipment Replacement		Often not properly budgeted for
Maintenance Supply Costs		Minor repair, cleaning, etc.
Energy Use	Lighting	Lamp, ballast, & room efficiencies
	HVAC	Cooling most important in big buildings
	Other	Office equipment, Elevators or other process use
Waste Production	Embodied Energy	Usually reflected in purchase price
	Recycling	Almost never considered
	Material Flow	Mot yet integrated into building services
Social Impact		Land use, siting, etc.

Historically, the U.S. building industry has been balkanized by the drive to minimize costs at each individual phase of the buildings lifecycle. This sub-optimization has created a situation in which the building services desired or designed into the building are not provided adequately or cost effectively. Because key pieces of information are lost along the way or never gathered, the design intent of the building cannot be assured during operation and building performance suffers.

Performance metrics offers an approach to quantifying and documenting the original design intend and its subsequent changes in a way that could allow for rational choices to be made. Currently the decision makers are limited to making decisions at one stage in the buildings lifecycle at a time with some vague hope that the are doing the right thing.

METRICS IN BPA

In current phases of the Building Performance Assurance project we are only using a few of these metrics to demonstrate our vision. We have been focusing on chiller performance. We are currently developing a commissioning and performance tracking tool focused on chillers for commercial buildings.

In the course of developing and using this chiller tool, we have touched on several of the metrics presented in this report: thermal comfort, commissioning costs, utility costs, and chiller efficiency. We have been focusing on using measured commissioning and operations data to evaluate chiller performance. We anticipate that a case study and prototype tools using these metrics will be produced in the next phase of the project.

FUTURE DIRECTIONS

This report has contained a review and compilation of metrics for assuring building performance. Few of the metrics can actually be quantified for the extant buildings. Either the metrics themselves are not yet quantifiable or the data necessary to quantify them is not normally collected.

In the future it will be necessary to work on both of these issues. It will be necessary to develop some of the metrics much further and to the point that they can be incorporated into economic analyses. For some metrics, such as productivity, this is quite a long term task.

While sufficient data could be taken in many of today's buildings to track others of these metrics, it is not deemed cost-effective to do so. While many sensors available today have too high a life-cycle cost to use, much of the reluctance to use sensors is due to lack of perceived benefit.

The issue of production of lower cost sensors is one that can be addressed by continued research and product development. In the future phases we intend to demonstrate that capturing such information and using it to evaluate performance will have sufficient economic benefit to justify the investment.

REFERENCES

ASHRAE 1989. ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality.* Atlanta, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.

ASHRAE 1992. ANSI/ASHRAE 55-1992, *Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE 1993. Physiological Principles and Thermal Comfort, chapter 8, pp. 8.1 - 8.18, *ASHRAE Handbook - 1993 Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

CRC, Handbook of Conservation and Renewable Energy, Chemical Rubber Company *(In Press), 1996)*

Das, B., and Mital, A. 1994, Production feedback and standards as moderators of the worker satisfaction-productivity relationship, *Ergonomics*, Vol. 37, no. 7, 1185-1194.

DOE Building Operation Workshop, Dallas: November 29, 1994.

DOE 1993. Advanced Lighting Guidelines: 1993. U.S. Department of Energy Report. Available to the public from the National Technical Information Service, U.S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

Egan, M. D., 1988. *Architectural Acoustics*. McGraw-Hill, p. 27-32.

Environmental Protection Agency (EPA). August 1989. Report to Congress on Indoor Air Quality. Volume II: Assessment and Control of Indoor Air Pollution. 5-1 - 5-21.

Ibbs, C.W. 1992. *Advanced Construction Cost Estimating and Analysis,* Course Reader for CE 268A, Department of Civil Engineering, University of California at Berkeley, Berkeley, CA.

IESNA 1993a. Lighting Handbook: Reference and Application. 8th Edition. Illuminating Engineering Society of North America, New York, NY.

IESNA 1993b. *Field Measurements.* Lighting Handbook: Reference and Application. 8th Edition. pp. 59-64. Illuminating Engineering Society of North America, New York, NY.

LBL 1994. *SUPERLITE 2.0 User Manual.* Building Technologies Program, Lawrence Berkeley Laboratory, Berkeley, CA.

Lovins, A., Energy-efficient Buildings: Institutional Barriers and Opportunities, *Strategic Issues Papers,* E-Source, 1992

Pepler RD, Warner RE. Temperature and learning: an experimental study. ASHRAE Transactions, 1968, 74:211-219.

Piette, MA, *et al*, Technical Report on Performance of Failure Mode Analysis and Evaluation of Diagnostic Techniques for Detecting and Diagnosing the Modes of Failure, LBL Report 1996.

Piette, M.A, L.W. Wall, B.L. Gardiner, Measured Energy Performance of Energy-Efficient New Commercial Buildings: Results from the BECA-CN Data Compilation, ASHRAE Journal, Vol 28, No. 1, Jan. 1986, LBL Report No 19413.

Preller L, Zweers T, Brunekreef B, Bolej JSM. Sick leave due to work-related health complaints among office workers in the Netherlands. Indoor Air 90, Ottawa: Canadian Mortgage & Housing Corporation. 1990;1:227-230.

Raw GJ, Roys MS, Leaman A. Further findings from the office environment survey: productivity. Indoor Air 90, Ottawa: Canadian Mortgage & Housing Corporation. 1990;1:231-236.

Romm, J.J., and Browning, W. D., 1994, Greening the Building and the Bottom Line: Increasing Productivity Through Energy-Efficient Design, ACEEE Summer Study on Energy Efficiency in Buildings, Vol 9, 9.259-9.268.

Stein, B., and Reynolds, J. S., 1992. *Mechanical and Electrical Equipment for Buildings.* John Wiley & Sons, Inc.

Ventre, F. T., Establishing Appropriate Measurements for the Performance of Buildings and the Serviceability of Facilities, Performance of Buildings and Serviceability of Facilities, ASTM STP 1029, Gerald Davis and Francis T. Ventre, eds, American Society for Testing and Materials, 1990.

Ward, G. 1993. *The RADIANCE 2.3 Synthetic Imaging System,* Building Technologies Program, Lawrence Berkeley Laboratory, Berkeley, CA.

Wyon, D. P. Healthy Buildings and Their Impact on Productivity, Proceedings of the 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland, July, 1993.