Building Infrastructure Functional Capacity Measurement Framework

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Abstract: Building infrastructure "performance" is a term which describes the in-service functioning of a building for a specified use. The concept refers to how effectively, safely, and efficiently a building supports its mission at any time during its life cycle. A building's performance state, which changes during time in service, is reflected by two different indicators: the physical condition state and the functionality state. The physical condition state relates to a facility's general "physical fitness," independent of its mission, as it deteriorates due to routine aging, excessive or abusive use, or poor maintenance. The functionality state relates to the facility's suitability to function as intended and required for the mission. The functionality state is distinct and independent from the physical condition state. Condition-based metrics are currently in use but a companion index of functionality was not developed at the same time. However, in order to fully describe a building's fitness for changing missions over its entire life cycle, a quantitative and objective functionality index (FI) is needed. This paper describes the methodology of this FI measurement.

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Introduction

Building assets represent a significant portion of the infrastructure capital held by federal, state, and local agencies, as well as private organizations. In the United States alone, the total value of this building infrastructure capital runs well into the trillions of dollars. For example, the U.S. Department of Defense manages nearly 577,000 structures valued at approximately $712 billion (Government Accountability Office 2008). In addition to the substantial investment these facilities represent, they also contribute a major role in support of the military's diverse set of missions.

Like all infrastructure domains, buildings provide services that enable a mission or processes to be performed. They also provide a space for people to live, work, and interact. When designing a building, the location, materials, and configuration are chosen to best support those purposes under the consideration of cost. As the building operates in service and ages, building materials, components, and systems deteriorate, leading to some less than optimal performance to support its mission. This performance loss is determined through a condition assessment process and may be measured by a condition metric. Building mission performance is also affected by obsolescence, which in itself is not a result of condition deterioration. Instead, obsolescence is a result of changes in building occupant or user requirements, improvements in building technologies, and amendments in codes and regulations. For example, as mission and building occupant requirements change, which is likely for permanent facilities, the building's capability to perform that new mission is also affected. This loss is determined through a functionality assessment and may be measured by a functionality metric. While building condition is improved through repair and/or restoration, an improvement in functionality is accomplished through facility modernization.

The decision about which buildings to invest restoration and modernization is of prime concern for large building portfolios, such as with the Department of Defense. Because of this, performance-based measures are needed to support a more logical and consistent decision-making process. Therefore, a functionality metric that is consistent, measurable, and meaningful helps facility managers make more informed building infrastructure investment decisions. This paper describes the development of a standard building functionality assessment framework that results in a functionality state metric.

Defining Building Performance

Building "performance" is defined as the behavior in service of a building for a specified use at a point in time (ASTM 1998). It incorporates issues of mission support, building safety, resource efficiency, and life safety, among others. The building performance state is a synthesis of two individual but sometimes coupled building attributes; the physical condition state and the functionality state. The condition index (CI) and functionality index (FI) measures together define a comprehensive performance index for the facility.

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Condition State

The physical condition state relates the general health of the building. Physical deterioration of the building due to normal aging, excessive or abusive use, or poor maintenance causes a reduction in the building's ability to perform its mission as required. For example, a deteriorated and leaking roof can reduce the building's ability to provide a comfortable moisture-free environment. Past research has focused on defining, quantifying, and measuring the condition state of a building in a consistent, objective, and repeatable fashion. One such methodology is the distress survey condition assessment process which results in a CI metric (Uzarski and Burley 1997). This CI relates the condition of building components, systems, and the building as a whole on a 0–100 scale due to the presence of distresses adversely affecting the condition of the asset.

Functionality State

The building's functionality state is related to the inherent suitability to provide services for the functions or mission it was designed for or is required to be used. Theoretically, it is independent of condition; that is, it is the capability of a building to perform as required in the absence of all physical condition deteriorations. Functionality loss due to an inefficient building layout, improper choice of materials or equipment, code violations, etc. can affect the building's ability to perform mission and meet occupant/user requirements. For example, a maintenance shop building that lacks the proper size and configuration to efficiently service the current vehicles and equipment would be less than fully suitable to perform its mission of supporting vehicle maintenance.

Loss of functionality can be qualitatively described by identifying issues that are inherent of the building and its design that lead to some less than optimal performance of mission when compared to a newly constructed building that incorporates all known current requirements to best provide service for mission. To classify the broad range of issues affecting the functionality state, building functionality loss is a result of one of three factors:

1. Occupant/user requirements—as tenant requirements change, or the underlying designated mission changes, the building's capability to provide service to its users is affected.
2. Regulatory/code compliance—as new building codes, regulations, or organizational policies take effect, the building must adapt to these changes.
3. Technical obsolescence—as new materials and technologies improve efficiency, maintainability, and overall building performance, existing building components become obsolete and have decreased capabilities to the new baseline.

Functionality Assessment Framework

The functionality metric proposed in this paper was developed to quantitatively describe the functionality state of a building or a logical subset of a building such as an area or component. Since functionality is the counterpart to condition in describing total building performance state, for consistency, the FI development methodology closely follows the processes previously established for the CI. The CI model is a sound and proven approach. It is an ASTM standard for pavement condition measurement (ASTM 2004) and the development procedure was replicated for building,

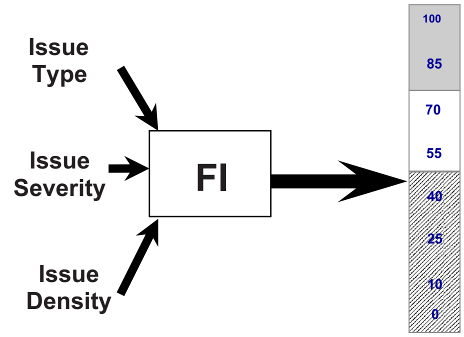

Fig. 1. FI model

roof, and railroad track structure condition state measurements. All index scales range from 0–100, with 100 being the perfect or ideal state.

The building functionality measure is a synthesis of three relevant factors: (1) the functional deficiency or functionality issues present; (2) the severity factor which represents how critical an issue affects the building's mission; and (3) a measure of the extent or percentage the building is affected by the functionality issue. This model is illustrated in Fig. 1.

To measure building functionality, a numerical scale was first defined that correlates the FI to varying degrees of qualitative functionality descriptors. This scale is shown in Table 1. The intervals on the scale are set such that the degree of functionality loss is proportional to a similar condition loss on the CI scale. This was a strict requirement to mesh with the previously mentioned CI metric. The FI scale provides a way of communicating the suitability of the building to provide necessary service in support of its specified mission. The description of the functionality loss in the scale takes into account the extent that the functionality loss impairs the ability to support mission for the building as a whole.

The FI methodology links the functional deficiencies identified during a building functional assessment process to the aforementioned functionality scale. These functional deficiencies are termed "issues." An issue is an observable building characteristic which adversely affects functionality. An extensive literature review was conducted to develop a comprehensive list of discrete and definable functionality issues related to a building's (1) occupant/user requirements; (2) technical obsolescence; or (3) compliance with codes, laws, and regulations. This list, which included more than 65 functionality issues, was reviewed and edited by a group of independent subject matter experts (SMEs) made up of architects, engineers, and facility property managers. After several rounds of revisions to the list based on SME feedback, the issues were grouped into 14 categories, as shown in Table 2.

The issue categories provide a general classification of building functional deficiencies. However, the issues within each category provide the depth and detail required to appropriately and objectively measure functionality loss. Each issue uniquely describes a building-related problem that can be addressed by an actionable corrective procedure. For example, the environmental/health category includes functionality issues identifying asbestos, indoor air quality (IAQ), radon, lead paint, etc. (see Table 2). Each of these issues individually affects the functionality of the building to support mission in a safe and efficient manner for its occupants.

Each issue has a specific definition and visual or technical

Table 1. Description of Functionality Index Intervals

FI	Rating definition	Modernization needs
100	• No functionality problems exist in building; • All occupant/user requirements are met, no component sections are obsolete, and • Building is in full compliance with all codes and regulations.	• None
86–99	• One or more, up to a very few, noncritical or critical component sections suffer from varying degrees of functionality loss; and/or • Up to a small number of component-section inventory items suffer from varying degrees of functionality loss; and/or • One or more building functional areas are experiencing slight functional impairment; and/or • Building, as a whole, is only slightly functionally impaired.	• Up to total modernization desired or required for up to a few component sections or few inventory items (i.e., items that collectively make up a component section) for given component sections; or • Minor modernization desired or required to certain building functional areas; or • Building relocation is an option under certain circumstances
71–85	• More than a very few, but not many, noncritical or critical component sections suffer from varying degrees of functionality loss; and/or • Combinations of a few noncritical and critical component sections suffer from varying degrees of functionality loss; and/or • Many component-section inventory items are experiencing varying degrees of functionality loss; and/or • One or more building functional areas are experiencing minor functional impairment; and/or • Building, as a whole, is functionally impaired but only to a minor degree.	
56–70	• Many, noncritical and critical component sections suffer from varying degrees of functionality loss; and/or • Large numbers of component-section inventory items are experiencing varying degrees of functionality loss; and/or • One or more critical building functional areas are experiencing moderate functional loss and other building functional areas may be experiencing functional loss to a moderate or a lesser degree; and/or • Building, as a whole, is functionally impaired to a moderate degree.	• Up to total modernization required to significant numbers of component sections or the inventory items for given component sections; or • Significant modernization required to one or more building functional areas; or • Major modernization required to small building portions; or • Building relocation desired but not required.
41–55	• One or more critical building functional areas are experiencing significant functional loss and other building functional areas may be experiencing functional loss to a significant or lesser degree; and/or • Building, as a whole, is functionally impaired to a significant degree.	
26–40	• One or more critical building functional areas are experiencing extensive functional loss and other building functional areas may be experiencing functional loss to an extensive or lesser degree; and/or • Building, as a whole, is functionally impaired to an extensive degree.	
11–25	• The majority of building functional areas is experiencing a functional loss to some degree with one or more being severe (total or nearly so); or • Building, as a whole, is barely able to serve its intended or proposed use.	• Major modernization required to large portions of or the entire building; or • Building relocation required.
0–10	• Building is totally unable to serve its intended or proposed use.	

criteria that must exist. This definition and criteria provide a building technician or a professional assessing the building functionality with a set of instructions for evaluating whether a particular issue is affecting the building. These functionality issues were a synthesis from a variety of sources, including codes, regulations, and design manuals. For example, the determination of Americans and Disabilities Act (ADA) compliance is based on the published code standards. The assessor goes through a simple checklist to identify ADA compliance issues for the building. The functionality evaluation procedure is a consistent and repeatable process by using the standardized list of building issues and the explicitly stated criteria for each issue.

Table 2. Functionality Issue Categories

Category	Description of issue and associated subissues
Location	Suitability of building location to mission performance
Building size/configuration	Suitability of building/area size and layout for the mission required
Structural adequacy	Capability of structure to support seismic, wind, snow, and mission-related loads
Access	Capability of building/area to support entry, navigation, and egress, as required
ADA	Level of compliance with the American with Disabilities Act
AT/FP	Compliance with antiterrorism/force protection requirements
Building services	Suitability of power, plumbing, telecom, security, fuel distribution, etc.
Comfort	Suitability of temperature, humidity, noise, lighting, etc. for facility occupants
Efficiency/obsolescence	Addresses energy efficiency, water conservation, and HVAC zoning issues
Environmental/life safety	Addresses issues such as asbestos abatement, lead paint, air quality, and fire protection
Missing/improper components	Availability and suitability of components necessary to support the mission
Aesthetics	Suitability of interior and exterior building appearances
Maintainability	Ease of maintenance for operational equipment
Cultural resources	Historic significance and integrity issues that impact utilization and modernization

In addition to identifying each functionality issue affecting the building's performance, the assessment also determines a level of "severity." The severity indicates the effect an identified issue has on operational, mission, and life-safety service capabilities. Three severity categories were defined using green, amber, and red conventions and each is discussed below:

1. Green—fully complies with the requirements of the subissue; it does not affect suitability to perform mission.
2. Amber—the issue is present, affecting suitability to perform mission but not to a significant degree, as described in red (below).
3. Red—the issue is present, greatly affecting suitability and capability to support performance of mission. Presence of issue puts life safety and/or mission accomplishment in jeopardy.

The definitions of the severity ratings are explicitly defined and fall back on the criteria provided in codes and regulations where applicable. This ensures that severity levels, an important input of the functionality measure, are applied in an objective way.

In addition to identifying and recording the functionality issues that are present, the amount or density of the issue negatively affecting building performance is also recorded. For example, an IAQ issue affecting approximately one quarter of the building based on total square footage would receive a density of 25%.

To quantitatively measure functionality, an evaluator will record the type of functionality issue present, the severity of that issue, and the measured density affecting the overall building performance. Therefore, functionality loss is a function of (1) functionality issue type; (2) issue severity; and (3) issue density. This is expressed mathematically through the weighted deduct-density model (Shahin et al. 1976)

$$\mathrm{FI} = 100 - \sum_{i=1}^{I} \sum_{j=1}^{J} a(T_i,S_j,D_{ij}) \times F(t,d)$$

where FI=FI measure; I=number of individual building functionality subissues present; J=number of individual severity levels present for ith issue; $a(\,)$=functionality deduct value for subissue Type I, severity S, and density D; and $F(\,)$=adjustment factor when multiple subissues are present based on total summed deduct t and number of subissues present d.

Development of Functionality Deduct Value Models

The FI is developed and designed to simulate the rating obtained by an evaluation from a panel of SMEs in building rehabilitation, including architects, engineers, and facility managers. This is accomplished by applying rating scale theory (Hutchison 1963). In effect, the rating scale provides a translation between the functionality loss issues defined and discussed above with meaningful numerical FIs. This is done by soliciting the expertise of a panel of experts in a rigidly controlled rating session setting. To develop the FI using this method, a number of assumptions were invoked:

- Functionality is a measurable attribute;
- Raters are capable of making quantitative judgments about functionality;
- The judgment of each rater can be expressed directly on an interval scale;
- Variability of judgment is a random error;
- Raters are interchangeable; and
- Average individual rating values can be used to estimate rating scale values.

During the rating session, each rater was individually presented with a number of different functionality loss scenarios for a hypothetical building. To separate the concept of condition from the functionality metric development, the raters were instructed not to consider condition as a reason for functionality degradation. Each functionality issue was presented, along with varying levels of severity and density. The panel members were instructed to each numerically rate the overall building functionality based on the individual issue, severity, and density presented in each scenario. Each rating was based on the 0–100 scale described in Table 1, which explicitly describes functionality loss for discrete intervals on the index. This scale provides the guidelines for judging the functionality scenario presented, determining which interval was the best fit, and selecting the actual score within that interval. Adherence to the guidelines ensured consistency and reduced error.

Analytical Approach

The functionality rating data obtained from the panel was compiled and analyzed to develop the models for translating the functionality issues into quantitative deduct values. Results were organized based on functionality issue type, severity, and density (see Table 3). Fig. 2 shows data plotted for the functionality subissue of inadequate IAQ, medium severity. This issue was rated

Table 3. Rating Data Analysis for IAQ Issue

Severity	Density (%)	Average FI rating	Deduct amount	Standard deviation	Number of ratings	Confidence interval
Poses health problem, high	100	53.7	46.3	7.8	10	4.8
Poses health problem, high	50	54.8	45.2	9.8	19	4.4
Poses health problem, high	25	60.4	39.6	8.8	16	4.3
Poses health problem, high	10	76.9	23.1	9.5	19	4.3
Poses health problem, high	1	84.5	15.6	9.5	20	4.2
Poses no health problem, medium	100	77.4	22.6	8.9	20	3.9
Poses no health problem, medium	50	78.9	21.1	8.3	19	3.7
Poses no health problem, medium	25	86.0	14.0	6.3	20	2.8
Poses no health problem, medium	10	87.7	12.3	6.5	19	2.9
Poses no health problem, medium	1	93.7	6.3	3.7	20	1.6

by the panel at density levels of 1, 10, 25, 50, and 100% of the building affected and the associated deduct in functionality is plotted for each rater. After outlier data are removed, the mean deduct value is computed and is represented on Fig. 2 by the filled data points. Consequently, the middle trend line represents the density-deduct curve for the issue of medium severity, inadequate IAQ.

The dotted envelope curves on Fig. 2 represent the 95% confidence interval based on the rating data. The study required a sufficiently large pool of raters to limit the confidence interval to plus or minus 5 points of the mean density-deduct curve. This constraint allows a consistent and meaningful index to represent the subject matter expert panel with statistical rigor.

This data analysis was performed for each of the 65 unique functionality issues defined previously in the process. Where the collected data indicated a large standard deviation for a subissue, reratings were performed to correct rater mistakes and narrow the confidence intervals. As a result of this analysis, a mean density-deduct curve was developed for each functionality issue severity.

Adjusting for Impact of Multiple Functionality Issues

When multiple functionality subissues exist, the effect on functionality loss is not purely cumulative. If so, it is conceivable that several functionality subissues could result in an overall building FI less than 0, which exceeds the bounds of the index metric. In addition, the phenomenon of "psychophysics" results in a reduction in the influence of any given issue when additional issues are present (Weaver and Clark 1977). Therefore, a deduct correction factor is applied to the sum of the individual deducts to reflect the nonlinear effect of additional functionality loss issues.

The adjusted deduct factor was derived by providing the subject matter expert panel with several scenarios containing multiple functionality loss issues. Depending on the nature of the issue and number of issues present, this overall rating score will result in a functionality deduct value somewhat less than the sum of the individual issue deduct values, as obtained above. By plotting the sum of the individual deduct values on the x axis of a graph and the direct rating of the combined multiple issues on the y axis, a correction factor for multiple issues was derived. This correction factor is represented by the slope of each line for the number of issues present, shown in Fig. 3.

Calculating a Functionality Index

The data models for the functionality density-deduct curves and the multiple issue adjustment factors have been incorporated into a computerized building assessment and management system called BUILDER (Construction Engineering Research Lab 2008). This allows for automatic calculation of the FI.

Each of the issues is essentially posed as a question that the evaluator answers to determine the severity and density that the

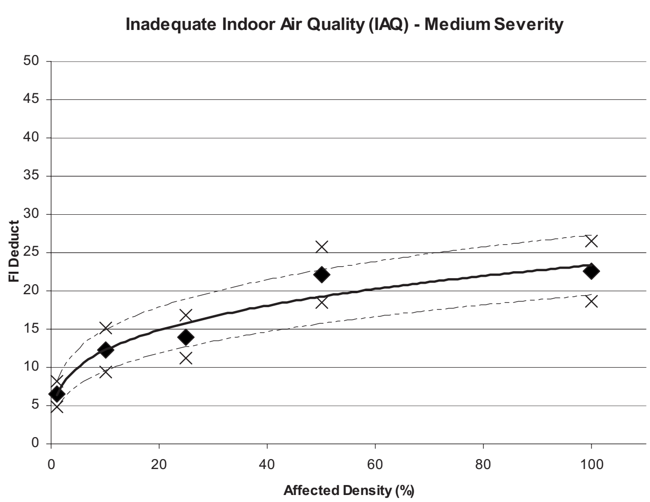

Fig. 2. Example deduct rating data

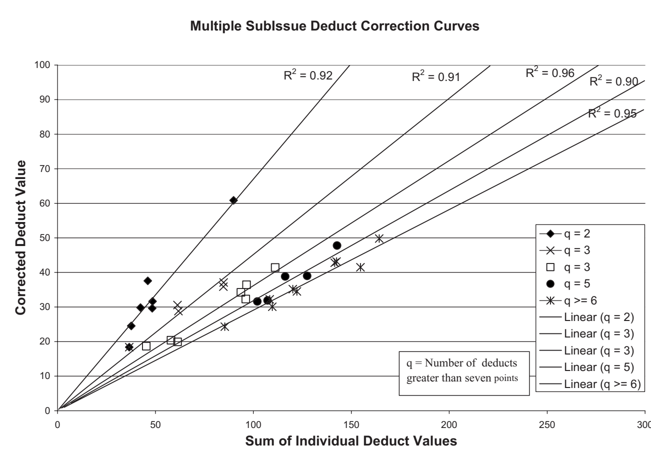

Fig. 3. Adjusted deduct factor for multiple issues

functionality issue affects the buildings suitability to support its mission. The results of these issue questions determine the rating for the functionality issue category and are used to calculate the FI metric for the building as a whole. These results are based on the specific functional building deficiencies identified by the evaluator, with input from building users and maintenance personnel. The completion of the evaluation allows for a consistent, repeatable, and objective metric of functionality that can easily be used to communicate the suitability of the building to its designated use and mission.

An example calculation for the FI is given below. In this example, the building is identified to have two functionality issues present that are affecting the overall performance:

1. Medium severity, IAQ—it is determined that an inadequate IAQ issue exists in the building, however, it is not deemed a life-safety issue, hence severity is medium. This IAQ affects 50% of the total building area. Referring to the density-deduct curve in Fig. 2 for this subissue, the functionality deduction is 19 points.
2. High severity, inadequate electrical distribution—it is determined that the facility has inadequate electrical distribution due to insufficient number of outlets, which significantly impacts mission accomplishment, hence the severity is high. This inadequate electrical distribution issue affects 10% of the overall facility, resulting in a deduction of 31 points.

The total sum of all deductions from the subissues identified is $19+31=50$. However, since there are multiple issues, the aggregate index value is reduced by the multiple issue correction factor, which is 0.67 for two issues. Thus, the overall building deduction is 34 points and the building FI is measured to be $100-34=66$, which is moderately degraded.

Functionality Metric for SRM Decision Making

The FI is important to building sustainment, restoration, and modernization (SRM) decisions because it is an objective indicator metric. It indicates how suitable the building's inherent characteristics (size, location, configuration, etc.) are in supporting its designated purpose, including the safety and overall well being of the building occupants. As planners evaluate different scenarios, the FI resulting from the functionality assessment procedure is a practical tool for measuring the capabilities and performance of the existing infrastructure portfolio.

The FI also serves as an execution metric. When the functionality measure for a building falls below some minimum threshold standard defined by policy (as illustrated in Fig. 4), modernization requirements can be generated. Because the FI is a metric generated by a standardized evaluation process, it provides a more objective way of justifying modernization needs.

In addition to determining functionality requirements for a building's current purpose, the approach described here can be used to perform functionality assessments to determine future requirements for a proposed purpose. For example, military base closures would require missions (along with the supporting people, material, and equipment) being transferred to other bases. The functional characteristics of existing buildings on these bases could be assessed to measure their ability to support a new proposed mission. This may be the case if a new type of aircraft was scheduled to be stationed at the base and hangar modernization was required to support this new mission. Multiple "what-if" scenarios for different building uses and configurations can be assessed and the results can be used in the analysis of modernization requirements.

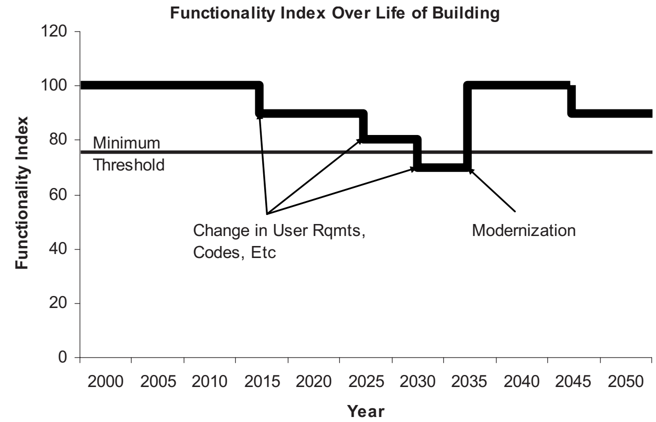

Fig. 4. FI over time

The functionality metric can also be used to assess newly constructed buildings or even the proposed building designs. While it is generally assumed that the functionality will be 100% functional at the start of its life cycle, this is sometimes not the case due to poor design, poor construction, or budget constraints. In addition, the design/construction stages can take up to several years to complete and a fully functional building at initial design may be less than fully functional by the beneficial occupancy date. The functionality framework presented above could identify such issues early in the life cycle for potential correction.

The building FI, coupled with the CI, provides a means of justifying building rehabilitation, which includes restoration and modernization, versus demolition and new construction. This supports short- and long-range work plans developed on sound investment strategies, prioritization criteria, and budget constraints.

Conclusions

The functionality assessment process discussed above fills a necessary gap to completely measure and describe building performance. It provides a logical scientific approach to quantifying the effects of changes in user requirements, codes, efficiency, and obsolescence. The resulting FI provides an objective, meaningful, and auditable measure of the infrastructure's capability to provide services to meet mission requirements. Together, the assessment process and index coupled with previously developed condition-based metrics enhance building SRM decision support by providing transparency to better realize and execute mission-focused facility objectives.

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References

American Society of Testing and Materials (ASTM). (1998). “Standard terminology of facility management (building-related).” *ASTM E 1480-92(1998)e1*, West Conshohocken, Pa.

American Society of Testing and Materials (ASTM). (2004). “Standard test method for airport pavement condition index surveys.” *ASTM D 5340-04*, West Conshohocken, Pa.

Construction Engineering Research Lab. (2008). “BUILDER engineered management system.” ⟨http://www.cecer.army.mil/td/tips/product/details.cfm?ID=64&TOP=1⟩ (Oct. 09, 2008).

Government Accountability Office. (2008). “Defense infrastructure—Continued management attention is needed to support installation facilities and operations.” *Rep. No. GAO-08-502*, Washington, D.C., ⟨http://www.gao.gov/docsearch/locate?searched=1&o=0&order_by=rel&search_type=publications&keyword=08-502⟩ (April 24, 2008).

Hutchison, B. G. (1963). “Principles of subjective rating scale construction.” *Transportation Research Record. 46*, Transportation Research Board, Washington, D.C., 60–70.

Shahin, M. Y., Darter, M. I., and Kohn, S. D. (1976). “Development of a pavement maintenance management system.” *Rep. No. AFCEC-TR-76-27*, Air Force Civil Engineering Center, Tyndall Air Force Base, Fla.

Uzarski, D. R., and Burley, L. A. (1997). “Assessing building condition by the use of condition indexes.” *Proc., Infrastructure Condition Assessment: Art, Science, Practice*, ASCE, Reston, Va., 365–374.

Weaver, R. J., and Clark, R. O. (1977). “Psychophysical scaling of pavement serviceability.” *Rep. No. 7.41-6-SEM-9*, New York State Dept. of Transportation Soil Mechanics Bureau, Albany, N.Y.