Key performance indicators for facility performance assessment: simulation of core indicators

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Received 5 November 2013; accepted 22 September 2014

Assessing a facility’s performance is important for measuring its contribution towards organizational goals. Among many approaches to performance assessment is the holistic key performance indicator (KPI) approach. However, there are numerous KPIs available, and the chosen KPI needs to be relevant to facility goals and must be calculated, analysed and evaluated to allow for the future state of the facility to be acceptable at the lowest cost. The value of several key descriptive analytics in facility performance assessment may be enhanced through the use of simulation. Simulation transforms the descriptive analytics into predictive and prescriptive analytics by allowing for the robust assessment of plans and future outcomes through the creation of multiple scenarios, in this case, for an education facility. The simulation approach quantifies the interrelationship and interdependence of KPIs, and is potentially effective in analysing how maintenance expenditures can be optimized to maintain a desired level of Condition Index as demonstrated by several simulation scenarios.

Keywords: Educational facilities, facility management, key performance indicators, maintenance, simulation.

Introduction

The context of this study

Evaluating a facility’s performance is critical for tracking its contribution towards accomplishing organizational goals and for making future decisions regarding facilities management (Douglas, 1996; Amaratunga et al., 2000; Barrett and Baldry, 2003; Cable and Davis, 2004). A facility supports core business activities by providing a conducive and productive work environment (Douglas, 1996). A range of measurement approaches have been proposed in the literature, such as benchmarking, balanced scorecard, critical success factor, and key performance indicator (KPI) method (Lavy et al., 2010), with a preference for the KPI method being emphasized (Lavy et al., 2010). However, an extensive list of KPIs exists that includes indicators that are either not quantifiable, not measurable, or provide redundant measurements (Neely et al., 1997; Shohet, 2006). A need to weed out unnecessary and repetitive indicators and to derive a concise list of core, quantifiable, and measurable indicators has been highlighted by numerous scholars (Slater et al., 1997; Hinks and McNay, 1999; Augenbroe and Park, 2005; Gumbus, 2005; Shohet, 2006).

Facility managers face increasing pressure to prioritize the direction of limited resources to address maintenance and capital renewal needs. The consequences of failing to prioritize the direction of sustainment and capital appropriately may include unscheduled facility maintenance, or system availability, and additional expense to repair or replace failed components or systems due to short/emergency notice procurements. Equipped with KPI simulation (modelling) tools, facility managers can better prioritize maintenance and capital renewal actions by developing scenarios to examine the interrelationships between funding levels, funding timing, business rules and critical KPIs. This enables them to make more informed decisions, and offers another way to communicate funding priority requirements to other stakeholders in order to build enterprise awareness and support for requirements.
An organizational plan is divided into three levels. The highest level contains organizational goals, which focus the attention of different stakeholders and constituents toward achieving a set of goals that are believed to advance the organization. In the case of education facilities, organizational goals may include raising student scores, decreasing student absenteeism, reducing teacher turnover, eliminating lost time in class, and reducing student accidents to the lowest possible level, among others. The second level, which supports these organizational goals, is the facility performance assessment. This level involves setting targets for aspects that affect the facility’s operation, such as personnel (e.g. recruiting, training, retaining), maintenance issues (e.g. frequency, quality), environmental issues (e.g. noise, air quality, aesthetics), space (e.g. amount of space, quality of space, privacy), among other factors. If an organization is unsuccessful in assessing its progress towards reaching these targets at the facility performance assessment level, how does it know that it is still on track to achieve its organizational goals? These targets can, of course, be refined and modified with time, as per changes that may occur in the business environment as well as changes that may occur in the overall organizational goals (level one). Level three is where key performance indicators may be found. At this level, the organization develops metrics (performance indicators) to help it measure (past), analyse trends (present), and predict (future) how successful it is and what action is to be taken in order to successfully achieve the targets set at the second level: facility performance assessment. In other words, the KPIs (in level three) support reaching the targets set in facility performance assessment (level two), which in turn, support reaching the organizational goals (level one). This is the typical hierarchy of an organizational plan.

The scope of this paper is limited to the third level of the organizational plan hierarchy, i.e., the level of development of key performance indicators in order to set facility performance assessment targets. This study focuses on educational facilities due to the fact that, according to various studies, such as the American Federation of Teachers (2006), Young et al. (2003), Cash and Twiford (2009), and Collins and Parson (2010), there is strong evidence that the condition of space, privacy), among other factors. If an organization is unsuccessful in assessing its progress towards reaching these targets at the facility performance assessment level, how does it know that it is still on track to achieve its organizational goals? These targets can, of course, be refined and modified with time, as per changes that may occur in the business environment as well as changes that may occur in the overall organizational goals (level one). Level three is where key performance indicators may be found. At this level, the organization develops metrics (performance indicators) to help it measure (past), analyse trends (present), and predict (future) how successful it is and what action is to be taken in order to successfully achieve the targets set at the second level: facility performance assessment. In other words, the KPIs (in level three) support reaching the targets set in facility performance assessment (level two), which in turn, support reaching the organizational goals (level one). This is the typical hierarchy of an organizational plan.

The literature review

Facility performance assessment

Measuring a facility’s performance includes reviewing past and current conditions to compare its performance within similar and across different organizations. The process of performance assessment evaluates the contribution of a facility to achieving organizational goals, and therefore is vital to establishing future facility management strategies (Kincaid, 1994; Lebas, 1995; Amaratunga and Baldry, 2000; Barrett and Baldry, 2003; Cable and Davis, 2004). Decisions relating to a facility’s extension, acquisition, and strategic changes depend on reviewing the facility’s performance (Douglas, 1996; Amaratunga and Baldry, 2000). Syakima et al. (2011) explained that the term ‘facilities’ includes the services required to support core business activities of an organization, whereas the term ‘performance’ relates to efficiency and effectiveness. Hence, facility performance means assessing a facility’s efficiency and effectiveness in providing services for organizational business activities. The performance measurement helps in understanding the impacts of management decisions on success and
failure of the facility portfolio and in suggesting possible improvements (Cable and Davis, 2004). According to Atkin and Brooks (2000), in a performance assessment, it is important to identify issues crucial to organizational success. Such issues can be tied to organizational goals and objectives and eventually to performance measures.

Among the most common approaches for performance evaluation are benchmarking, balanced scorecard, post-occupancy evaluation (POE), key performance indicators (KPIs) and critical success factors (CSFs). According to Ho et al. (2000), the performance metrics that include KPIs can be used for making comparisons within and across organizations. Hitchcock (2002) and O’Sullivan et al. (2004) stated that performance metrics can define performance objectives clearly and quantifiably. Assessing a facility’s performance using a set of KPIs provides the user with an opportunity to select the indicators of choice (Lavy et al., 2010).

Performance assessment of school facilities

According to Syakima et al. (2011), the assessment of performance must focus on physical condition (poor, good or excellent), functional appropriateness (ability of facilities to support required functions) and issues relating to user satisfaction and productivity. In the case of school facilities, the quality of the built environment affects the performance of students and teachers significantly. Research has shown that the condition of school facilities is strongly and positively correlated with student achievement (American Federation of Teachers, 2006; Cash and Twiford, 2009; Collins and Parson, 2010). If socioeconomic factors are controlled, a significant difference (5–17 percentile points) between academic performance of students from poor and standard school conditions is suggested by studies such as American Federation of Teachers (2006), Young et al. (2003) and Earle and Earleman (2002). The condition of school facilities also has an impact on teacher empowerment, which is strongly related to student academic achievements (Collins and Parson, 2010).

The factors responsible for poor school conditions can be categorized as physical, spatial and environmental (Young et al., 2003; Lippman, 2010). The physical condition of a school includes factors such as interior and exterior conditions, for example age of the building and its components, structural damage, leakage, cracks, and expired building components. Spatial factors include aspects that affect the adequacy of space to fulfil the required function. Despite having sufficient floor area, a school facility could have inadequate space due to the lack of proper space management. Three types of spaces exist in a school environment: instructional (e.g. classrooms), supplemental (e.g. laboratories) and support spaces (e.g. gymnasium and auditorium), with space standards for each. The National Clearinghouse for Educational Facilities provides space standards for school settings at various levels such as elementary, middle and high school. The space standards are provided in gross square foot area per student for different annual enrolment categories. Space standards for various instructional, supplemental and support school spaces are also provided by state agencies such as Rhode Island Department of Education or RIDGE (2007) and counties such as Clark County School District in Nevada (Fife, 2006). The assessment of space management can be performed by comparing existing floor areas with those specified by the standards. The quality of school spaces is governed by issues such as cleanliness, indoor air quality, lighting, thermal comfort and noise. Young et al. (2003) covered these issues under the environmental category.

Although numerous sets of KPIs have been derived in the literature to cover most aspects of a facility’s performance, the sets are extensive and, in some cases, include KPIs that are not relevant, measurable, or quantifiable (Shohet, 2006; Lavy et al., 2010). For instance, Hinks and McNay (1999) derived a list of 172 KPIs categorized under eight categories: business benefits, equipment, space, environment, change, maintenance/services, consultancy, and general.

According to literature (Slater et al., 1997; Ho et al., 2000), a succinct list of core KPIs that are quantifiable on the basis of readily available information is still lacking. The existing extensive lists must be filtered through a set of criteria to develop a concise list of those indicators that express one or more aspects of performance assessment effectively (Slater et al., 1997; Ho et al., 2000). Hinks and McNay (1999) and Slater et al. (1997) suggested establishing concise lists of no more than 4–6 and 7–12 KPIs, respectively. Literature also recommends identifying the core KPIs that not only cover financial aspects but also focus on aspects such as business, organization goals, and other non-financial qualitative aspects (user satisfaction and productivity). The core KPIs must also be measurable and quantifiable on the basis of readily available information in the industry in order to make genuine comparisons (Tsang, 1998; Tsang et al., 1999; Ho et al., 2000; Chan et al., 2001; Shohet, 2003; Cable and Davis, 2004; Augenbroe and Park, 2005; Gumbus, 2005).

Performance measurement approaches using KPIs

According to Ahluwalia (2008), a building houses a range of components (up to 170 different types of
components) that have differing maintenance requirements, making the building's maintenance a complex exercise. Moreover, each component has a different service life, making replacement and its schedule complicated. One conventional focus of facility maintenance is on reducing maintenance expenditures while providing a healthy, comfortable and safe workplace for occupants (De Groot, 1995; Horner et al., 1997; Tsang et al., 1999; Office of the Legislative Auditor, 2000; Kutucuoglu et al., 2001; Shohet and Lavy, 2004). It is also vital to determine how often a facility is replacing its components that are expired or nearing the end of their service life (Association of Higher Education Facilities Officers et al., 2003; Kinnaman, 2007). The Facility Condition Index (FCI) is an indicator often used for the condition assessment of a facility, demonstrating the impact of deferred maintenance as a ratio of deferred maintenance to total current replacement value (Vanier, 2000; Briselden and Cain, 2001; Teicholz and Edgar, 2001). The condition assessment at each building system level and at overall building level is more accurate, as it demonstrates specific defects and their severity (Ahluwalia, 2008). Ahluwalia (2008) defined Condition Index (CI) as a value between 0 and 100, derived mathematical expressions and conducted a case study.

In order to evaluate the maintenance performance of a facility, a Maintenance Efficiency Indicator (MEI) was proposed by Lavy and Shohet (2004). An MEI is defined as the ratio of maintenance expenditure to a facility's CI. The amount spent on deferred maintenance was calculated as a ratio of actual to targeted deferred maintenance by Lavy et al. (2014b), who also defined a Replacement Efficiency Indicator (REI) to be the ratio of the sum of capital renewals to the total cost of expired systems in a given year. The purpose of MEI and REI is to provide metrics to assess the maintenance and replacement of a facility.

Apart from the facility's maintenance, replacement, and condition, it is important to evaluate the suitability of a facility to house a particular function. The functional suitability depends on the provision of sufficient space in the facility and effective space management (Douglas, 1993/94; Schroeder et al., 1995; Douglas, 1996). Other indicators, such as indoor air quality, are responsible for health, comfort and safety of building occupants and hence could affect a facility's overall performance (Fowler et al., 2005; Prakash, 2005; Mozaffarian, 2008).

A facility's performance over its life cycle can also be assessed using various computer and web-based tools currently available. Tools such as BLAST, ECOTECT, TRNSYS, HOT 2000, Energy Plus, DOE 2.1 (US DOE), RIUSKA, MOIST 3.0, CONDENSE, Airpak and hygIRRC can be used to simulate the economic and environmental performance of a built facility (Crawley et al., 2005). Although a facility's performance can be simulated using computer programs, it still needs validation (Hammad et al., 2005). Moreover, often complex inputs are required for running the simulation collection, which can be either time-consuming or expensive (Bazjanac, 2001; Hamza and Horne, 2007).

Among studies focused on KPIs are Shohet (2003), who developed and validated four KPIs for healthcare facilities by performing six case studies; Ahluwalia (2008) derived an approach to assess the condition of building components on the basis of maintenance data and validated the approach using a case study approach; and Enoma and Allen (2007) developed a set of KPIs for assessing the performance of airport facilities using a case study method to validate the KPIs.

**Data analytics for facility management**

KPIs have become a part of a growing area of study called analytics, a field that is more prescriptive than descriptive in nature (Cooper, 2012; Neiger et al., 2012). By prescriptive, we mean that decisions regarding how to improve the performance of a facility are made based on data analysis. These decisions are actionable rather than a mere description or reporting. In the context of post-compulsory education, Cooper (2012) defined the field of analytics as 'the process of developing actionable insights through problem definition and the application of statistical models and analysis against existing and/or simulated future data'. In simpler terms, analytics is the process of generating and obtaining an optimal, realistic decision based on existing or simulated data.

Elias (2011) discussed a five-step process of academic analytics that involves data capturing, reporting, predicting, acting, and refining. The gathered and refined data is then analysed from three perspectives (Evans, 2012). The first perspective is descriptive, which answers the questions of what has happened in the past and what is currently happening (Fitz-enz, 2009; Evans, 2012). According to Fitz-enz (2009), descriptive analytics help identify and analyse the relationships and differences of various groups of a dataset. The second perspective is predictive, which predicts what will happen next based on the analysis of past data (Evans, 2012). Prescriptive is the third level, also the most advanced one, which utilizes the process of optimization to identify the best solution. In other words, it prescribes how to achieve the best outcome considering the effects and variability (Fitz-enz, 2009; Evans, 2012). This is the recommendation phase where decision and support tools are coupled with expert opinions to create tactical and strategic guidance for the organization. The process of data analysis may be performed...
using actual data or simulated data that is based on reasonable assumptions (Cooper, 2012). In summary, the process of analytics can be effectively used with simulated data to analyse the relationships and impacts of KPIs.

Simulations in facility management

Simulation as a descriptive or prescriptive tool has been used in maintenance and operations management (Montazer et al., 2003). In a study of steel rolling mills, Bala Krishnan (1992) divided an entire multistage machine into sub-systems and simulated maintenance policy options. According to his findings, opportunistic maintenance is far better than other maintenance policies. Chen et al. (2003) developed and used a Markov Regenerative Process (MRGP) model to simulate condition-based maintenance with generally distributed inspection intervals as opposed to the exponential distribution adopted by previous studies. In an effort to integrate a maintenance evaluation tool into a building’s design and construction phase, Dessouky and Bayer (2002) developed a simulation model using maintenance type, maintenance quality attributes, and task hours to estimate excess labour hours. By optimizing labour hours, they were able to allocate a maintenance cost to a building’s construction and design phase. Montazer et al. (2003) noted how simulation has become not only a descriptive but also a predictive tool for making decisions about future strategies in operations management.

Another area in which simulation has been extensively used as a descriptive, predictive, and prescriptive tool is the assessment of a facility’s energy performance. Zhu (2006) conducted an energy simulation study of a complex facility in the southeast region of the United States to help facility managers optimize the facility’s energy performance. In this study, eQuest was used to simulate the energy performance in order to devise strategies to save energy use in the facility’s operations (prescriptive role). According to Augenbroe (2002), simulation modelling that was once used mainly during the design and construction phase is now being applied extensively to post-construction phases such as commissioning and facility management. In fact, simulation has become an integral part of the whole building design, engineering, and operations process (Augenbroe, 2002).

Research methods

A simulation approach was applied in this study to analyse the impacts of key input variables on facility KPI estimates and robustness, as well as relationships between and among input variables and KPIs. The KPIs calculated from simulating outputs from the input variables include CI, MEI, and REI. The main variable considered for optimization is the Net Present Value of Dollars Spent. A complete list of the variables and abbreviations used in this paper may be found in the Appendix. The simulation process is presented in a high level flowchart in Figure 1 (life cycle simulation of a single system). The flowchart illustrates the process of converting input variables in KPIs and the Net Present Value of Dollars Spent throughout the process.

The following sections describe the simulation scenarios and the main assumptions made to perform them.

Simulation scenarios

This study contains two parts. In Part 1, we simulate and examine input and output variable relationships for a single system within a facility (note that the single system may be the facility itself). In Part 2, we simulate and examine input and output variable relationships for multiple systems within a facility. The difference between Part 1 and Part 2 is an added level of complexity. One could imagine adding sub-systems within systems which would add yet another level of complexity. Downsides to adding levels of complexity include the need to gather additional data, adding more time-consuming and complex simulations, and the introduction of bias. Bias is introduced because the finer the details introduced, the higher the likelihood that other, more subtle but just as important, fine details would be missed. On the positive side, adding levels may reduce the variability in outputs, as well as better map out the impact and relationships between and among major KPIs, such as Condition Index (CI), Maintenance Efficiency Index (MEI), and Replacement Efficiency Index (REI). Ultimately, recognizing the mutual impacts of these KPIs may lead to a better understanding of organizational goals, such as students’ test scores and absenteeism rates. The following paragraphs describe Part 1 and Part 2 in more detail.

Part 1: This included an analysis of the relationships between CI and its variables, such as Plant Replacement Value (PRV) and/or System Replacement Value (SRV), Deferred Maintenance (DFM), and Dollars Spent on Maintenance (DSM) at a facility level. In this part, four scenarios were analysed. The service life of the educational facility was assumed as 50 years. The main goal at this stage was to identify maintenance budget and equipment replacement strategies to maintain a desirable CI while optimizing the total spending on maintenance.
Part 2: In this part, the KPIs were calculated and analysed for their relationships and dependence at individual system levels. The main goal at this stage was to study the impacts of KPIs at individual system levels for the overall condition of the facility. In this scenario, five building systems were considered in the calculation of the Facility Condition Index: Roof, HVAC, Plumbing, Electrical, and Other (the remaining major systems in a typical building, combined into one system).

Values for the input data used in the simulations for Parts 1 and 2 are listed in Tables 1 and 2, respectively; four scenarios were developed for each part. While numerous input variables are possible, the maintenance budget and the years until replacement are the only variables changed over the four scenarios. The other difference to note between the two parts is that built-in variability is shown in the plots of KPIs in Part 2, but not in Part 1. All costs in the simulation scenarios are given in thousands of dollars ($k). Also, the plant represented in Table 1 is a different plant than the one in Table 2, therefore, only trends can be compared between the two, but not costs.

To better explain the simulations, let us take, for example, scenario 1 of Part 1 (line item #13 in Table 1) and analyse its input variables: one building system represents all building systems and components. The estimated life cycle of this system is 45 years (line item #1), and it originally cost $10 000 to install (line item #4). The annual average increase in the System Replacement Value is 3%, distributed as 2% for inflation (line item #11) plus an additional 1% increase due to environmental/safety laws/other concerns (line item #12). This rate, however, is an estimated average, and is subject to variability according to the beta distribution; therefore, it is possible that in any single year, the combined rate could be 2% or 4%, or anything in

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**Figure 1** Life cycle simulation of a single system
between. This specific scenario assumes that the system is kept for 45 years (variable X, line items #6 and 13), which means that it would be replaced at the end of its service life (similar to line item #1). It also assumes that the maintenance rate in the first year is 2% of the System Replacement Value (line item #2), increasing to 100% of the System Replacement Value in its last year of service life (45) (line item #3). However, only 70% of its maintenance needs are funded each year throughout its entire service life (variable Y, line items #8 and 13). The unfunded maintenance goes into a deferred maintenance backlog, which increases at a rate of 2% per year (line item #10). The annual discount rate, or the rate for opportunity cost of capital, is considered to average 2% (line item #9), and is also subject to variability according to the beta distribution. The value shown for the Current System (Plant) Replacement Value (end of Year 1) (line item #5) is the value in line item #4 plus the average rate of inflation (line items #11 and 12). The Renewal Rate Factor of PRV

### Table 1 Input data for Part 1

<table>
<thead>
<tr>
<th>Item #</th>
<th>Variables/Parameters</th>
<th>Value field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Estimated Life Cycle (Years)</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>Initial Maintenance Rate or Maintenance Rate in the First Year (%) of PRV</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Maintenance Rate in the Final Year (%) of PRV</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>System (Plant) Replacement Value when New/Replaced</td>
<td>$10 000</td>
</tr>
<tr>
<td>5</td>
<td>Current System (Plant) Replacement Value (end of Year 1)</td>
<td>$10 300</td>
</tr>
<tr>
<td>6</td>
<td>Years Until Planned Replacement</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>Renewal Rate Factor of PRV for Replacement</td>
<td>1.05</td>
</tr>
<tr>
<td>8</td>
<td>*Current Budget for Maintenance as a Percent of Yearly Maintenance</td>
<td>Y</td>
</tr>
<tr>
<td>9</td>
<td>*The Discount Rate; Rate for Opportunity Cost of Capital (%)</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>*Rate of Inflation for Deferred Component Maintenance (%)</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>*Rate of Inflation for System (%)</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>*PRV Rate of Increase Due to Environmental/Safety Laws/Concerns (%)</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Scenario 1: X = 45, Y = 70%</td>
<td>X = 45, Y = 70%</td>
</tr>
<tr>
<td>14</td>
<td>Scenario 2: X = 50, Y = 50%</td>
<td>X = 50, Y = 50%</td>
</tr>
<tr>
<td>15</td>
<td>Scenario 3: X = 23, Y = 50%</td>
<td>X = 23, Y = 50%</td>
</tr>
<tr>
<td>16</td>
<td>Scenario 4: X = 45, Y = 99.9%</td>
<td>X = 45, Y = 99.9%</td>
</tr>
</tbody>
</table>

*Note: *These variables are subject to variability according to the beta distribution in the simulation.

### Table 2 Input data for Part 2

<table>
<thead>
<tr>
<th>Variables/Parameters</th>
<th>Value fields for each system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Life Cycle (Years)</td>
<td>Roof</td>
</tr>
<tr>
<td>Initial Maintenance Rate (%)</td>
<td>20</td>
</tr>
<tr>
<td>Final Maintenance Rate (%)</td>
<td>100</td>
</tr>
<tr>
<td>PRV when New/Replaced</td>
<td>$110</td>
</tr>
<tr>
<td>Current PRV (end of Year 1)</td>
<td>$113</td>
</tr>
<tr>
<td>Years Until Planned Replacement</td>
<td>X</td>
</tr>
<tr>
<td>Renewal Rate Factor</td>
<td>1.2</td>
</tr>
<tr>
<td>*Budget for Maintenance</td>
<td>Y</td>
</tr>
<tr>
<td>*The Discount Rate (%)</td>
<td>2</td>
</tr>
<tr>
<td>*Rate of Inflation for DFM (%)</td>
<td>2</td>
</tr>
<tr>
<td>*Rate of Inflation for System (%)</td>
<td>2</td>
</tr>
<tr>
<td>*Environmental, etc. Rate (%)</td>
<td>1</td>
</tr>
</tbody>
</table>

*Note: *These variables are subject to variability according to the beta distribution in the simulation.
for Replacement (in line item #7) represents the additional cost factor to replace one system with another (the cost to remove, haul, and dispose of the old system), if a replacement is pursued (for example, in scenario 3, where the value of variable X is less than the building’s life cycle). Similarly, scenarios 2 through 4 in Part 1 (line items #14 through 16, respectively), as well as scenarios 1 through 4 in Part 2 (as shown in Table 2) can be analysed in terms of their input variables.

The simulation program was constructed using Microsoft Excel 2010. Based on user inputs, a period of 50 years for the facility was simulated up to 100 times. The KPIs were calculated and graphed based upon the simulated results.

Assumptions

While the simulation scenarios represent an oversimplified example of an educational building, extensive collaboration and debate should be employed for analysing actual cases. The following assumptions were made in this study for the development of the simulation scenarios:

1. The Facility Condition Index is an aggregate of the CI of each individual system weighted only by costs. Therefore, if the HVAC system is more expensive than the Roof serving classrooms, by default, the HVAC system would have a larger influence on the CI. Nevertheless, the authors recognize that there may be other methods to weight the individual systems rather than cost (such as importance to the overall mission of the organization) in calculating the CI.

2. The life of a building system is based upon an exponential rate of deterioration model where the costs of maintenance increase exponentially as the system ages (New Zealand National Asset Management Steering Group, 2011). The maintenance model adopted in this study is shown in Figure 2. The maintenance costs in the first and the final year of a system’s service life are assumed as a percentage of its System Replacement Value (SRV). According to the maintenance model:

   (a) Maintenance Cost Index = 1000 \times \{\text{Maintenance Cost} / \text{SRV}\}

   (b) Figure 2 shows three examples of components with 10, 20, and 30 years of service life. Each one presents two scenarios: (1) initial maintenance cost is 0.1% of SRV and final maintenance cost is 100% of SRV; and (2) initial maintenance cost is 10% of SRV and final maintenance cost is 100% of SRV. The exponential equations and trend lines in Figure 2 are set simply by commanding Microsoft Excel to fit an exponential curve between the initial and final maintenance costs. Nevertheless, the authors recognize that the values used in this assumption for both initial and final maintenance costs, as well as the pattern of deterioration, may differ on a case-by-case basis.

3. The total cost of maintenance is the sum of preventive and corrective maintenance. The fraction of preventive and corrective maintenance in the total maintenance cost was assumed based on the inferences of the survey conducted by Whitestone Research Corporation (1999). According to the survey results, each building system has a unique value ranging from 21% to 63% of the total maintenance cost that occurs due to corrective maintenance.

4. The cost and probability of corrective maintenance are not functions of the accumulated deferred maintenance to date. One might hypothesize that both the cost and probability of corrective maintenance would increase with the accumulation of deferred maintenance. One reason that we assume an exponential rate of deterioration model for the life of building systems is that we do not currently have a quantifiable estimate of the relationship between the cost and probability of corrective maintenance and the accumulation of deferred maintenance.

5. A user of the simulation program could specify the years until replacement of a system even if the length of time exceeds the estimated service life of the system. At this point in time, the maintenance cost in a given year could not exceed the SRV for that year.

6. The SRV is assumed to increase in time as a function of the rate of inflation and the rate of cost increase due to environmental factors, safety regulations, etc.

7. The budget for maintenance is set as a percentage of expected yearly maintenance, and distributed as a random variable that follows the beta probability distribution. In addition, the rates of inflation are distributed as random variables following the beta probability distribution. The beta distribution is a family of continuous probability distributions. It is defined on an interval greater than 0 and less than 1, with the shape of the distribution...
defined by two positive shape parameters, denoted by $\alpha$ and $\beta$. The advantage of the beta distribution is that it is flexible in characterizing percentages and rates. Also, the interest rate converges in law to a beta distribution (Delbaen and Shirakawa, 2002).

(8) While the simulation could start at any life cycle stage for each system, in this study, all systems are assumed to start as new systems.

(9) Traditional life cycle cost analysis (LCCA) is a technique used to determine the total cost of facility ownership, including the first cost of acquisition and/or construction (Langston, 2005). For existing facilities, the total cost of ownership incorporates the sunk costs of acquiring the facility, the ongoing costs of operations and maintenance, and the future costs of disposing of a facility. To minimize
the variability associated with land acquisition and initial construction costs, as well as future disposal or resale costs, this paper focuses solely on operation and maintenance costs for a performance period of 50 years.

(10) There are three independent appraisal methodologies commonly used to evaluate real estate in the United States (Ling and Archer, 2012):

(a) Cost approach: sums the value of real estate (land) and the depreciated value of the improvements to the land (facilities, equipment, infrastructure, etc.) to determine a total replacement cost for a property. The cost approach is commonly used when appraising specialty properties (e.g. factories, public works, laboratories, etc.).

(b) Sales comparison: assumes that a property’s market value is closely correlated to the current value of a substitutable comparable property. The sales comparison approach depends on an assessment of
similar marketplace transactions to establish value, and is commonly used in residential markets.

(c) Income capitalization approach: develops a financial pro forma based on the anticipated market return of a property, and establishes cost based on the discounted cash value of that property over a given performance period. The income approach is commonly used to evaluate commercial or investment properties. To minimize the variability associated with real estate market cycles and regional land values, this paper utilizes the cost approach to establish the Plant Replacement Value (PRV). For the purpose of this analysis,
PRV is based on the depreciated value of the improvements to the land (facilities, equipment, infrastructure, etc.) and excludes the acquisition cost of the land itself, in order to focus the discussion on operation and maintenance costs.

Results

Part 1

In Part 1, we simulated various input variables in order to calculate the Condition Index (CI), Plant Replacement Value (PRV), Deferred Maintenance (DFM), and Dollars Spent on Maintenance in four different scenarios over a facility’s service life of 50 years. Figures 3 through 6 show the results of the simulations for the four scenarios of Part 1. The left side axis represents all the KPIs with monetary values (PRV, DFM, and $ Spent on Maintenance), while the right side axis represents the Condition Index, with values ranging from a minimum of 0 (not functioning at all) to a maximum of 1 (condition is as good as new). It must be emphasized that the minimum acceptable threshold for the Condition Index is up to the facility manager in each specific organization to determine, based on the organization’s mission, goals, policies, and standards. As seen in Figures 3 through 5, as DFM increased, the value of CI decreased. At the point that DFM equalled PRV, the CI reached its minimum value, but funds were still increasingly being spent on maintenance. This is demonstrated in Figures 3 and 4. After the point where DFM equals PRV, the spending continues but the CI cannot be improved until system replacement. The situation is akin to making minimum payments on credit card debt: while payments may be the smallest they can be without going into default, the debt can never be paid and the amount spent over the life of the loan adds up to many times the cost of the original loan. The key to understanding and using these graphs is knowing that, while taking on some deferred maintenance (akin to taking on debt) is advantageous due to the time value of money, too much deferred maintenance (akin to too much debt) leads to poor conditions that are increasingly expensive to maintain.

One might expect that the best overall CI over the 50 years would have occurred under scenario 4 (highest budget of 99.9%), and the worst under scenario 2 (lowest budget and postponed replacement). This assumption was shown to be correct, as seen in Figures 3 through 6. The least amount of money spent on maintenance occurred in scenario 3 ($47k), followed by scenario 1 ($121k). Maintenance budgeting and replacement strategies in these scenarios prevented an excessive build-up of DFM. In this part, it was interesting to note that the strategy in scenario 3 led to much less maintenance expenditure than in scenario 1: this was due to an early replacement strategy that included the least years until planned replacement. Note that this strategy did not work in all scenarios: it only worked because of the assumption of the exponential
Part 1.

The original cost to install the building (all five building systems, under scenarios 1 through 3 is shown in Figures 7 through 9, respectively. The variability in the CI calculations can also be seen in these Figures. It can be noticed that the variability in the estimated CI increased as the age of the system moved further away from the point when it was new or replaced; that happened because there is more uncertainty as we move further into forecasting the future.

Due to an early replacement on a system-by-system basis, the CI under scenario 3 did not fall below 80% (see Figure 9). Overall, it appeared to be the best strategy that resulted in a balanced maintenance cost and CI. However, care must be taken in assessing scenario 3; as mentioned previously, this strategy worked well due to the assumption of the exponential rate of deterioration. This strategy also worked because the facility's CI was calculated as an aggregate of the CIs of all individual systems weighted only by their costs. This means that the facility's CI could be over 80% even if some individual system's or multiple systems' CIs were still below 80%. This strategy could be misleading from the standpoint of organizational goals: for instance, if the facility's CI was above 80% but the CI of the HVAC system dropped below 60%, it might adversely affect factors such as students' performance and/or absenteeism more than for any other system.

Two other KPIs that could help find a robust strategy that maintained an appropriate CI while spending the least amount of money on maintenance were the Maintenance Efficiency Indicator (MEI) and the Replacement Efficiency Indicator (REI). It was no coincidence that the best overall MEI and REI, given that we were targeting 100% for these KPIs, belonged to scenario 3, as seen in Figures 10 through 12 (note that the MEI for scenario 4 is not shown because it is extremely high and distorts the graph). The target CI for the MEI graphs was 80%. Therefore, in this scenario, MEI of 100% meant that the exact amount necessary to maintain the target CI was being spent in the given year on DFM. MEI below or above 100% demonstrated a lack, or a surplus, of maintenance expenditure, respectively. Conventionally, a facility's CI greater than the targeted CI resulted in an MEI higher than 100%, and vice versa. However, note that even if the facility's CI was greater than the target CI, the MEI could drop below 100%, if the necessary preventive maintenance actions were ignored.

Part 2

In Part 2, we looked at the relationships between CI, PRV, DFM and Dollars Spent on Maintenance, but the calculations were rolled up over five different building systems (Roof, HVAC, Plumbing, Electrical, and Other). Random variability was incorporated into the calculations and the results of the simulations were plotted in order to highlight the variability. Once again, four different maintenance budget and replacement strategy scenarios were considered, similar to those in Part 1. Studying a facility at both facility and individual system levels generated similar results in terms of CI and Dollars Spent on Maintenance. Using a rollup approach required more upfront work because each system, and even sub-system, was characterized and assessed individually. The incorporation of variability into the simulation also improved the relationship to actual practice, and allowed for more 'real-world' robust and sensitivity analysis. In this part, the original cost to install the building (all five systems combined) was $5610; and therefore, the values below cannot be compared to those calculated in Part 1.

The least amount of money spent on maintenance occurred in scenarios 3 (NPV over 50 years of $35k) and 1 ($51k), with scenario 3 being the lowest. The best scenario for Condition Index was, again, scenario 4 (~$69k) where CI was always close to 100%. However, it was almost twice as expensive as scenario 3 (the least expensive). The CI, rolled up over all systems, under scenarios 1 through 3 is shown in Figures 7 through 9, respectively. The variability in the CI calculations can also be seen in these Figures. It can be noticed that the variability in the estimated CI increased as the age of the system moved further away from the point when it was new or replaced; that happened because there is more uncertainty as we move further into forecasting the future.

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rate of deterioration, which may or may not be true. Scenarios 2 and 4 were the most expensive because they did not have the correct balance of taking on some deferred maintenance (scenario 2) and too much deferred maintenance (scenario 4), as mentioned above.

Even though the overall maintenance costs over the entire building's service life were lowest under scenario 3, the CI was under 80% for 20 of the 50 years of service life. Scenario 1 had its CI below 80% for 28 of the 50 years of service life, and in scenario 2, the CI was below 80% in 37 of the 50 years of service life. It is evident that the best scenario in terms of CI was scenario 4, in which the CI was always close to 100%. However, this was also the most expensive scenario ($166k, which is 253% more expensive than scenario 3), and, if such a high CI was not necessary, a significant amount of maintenance dollars could have not been spent. The key is always to find the strategy that maintains a desired CI while spending the least amount on maintenance. This strategy should also be more robust to changes in assumptions than other strategies. In other words, a strategy that is slightly more expensive, but more insensitive to slight changes to the budget, the interest rate, or the discount rate might be better than a strategy that is optimal under assumed conditions, but changes drastically in response to any changes in the assumptions.
**Maintenance rate sensitivity analysis**

As seen from the results of Parts 1 and 2, a simulation approach based on hypothetical data can be utilized for understanding the interrelationships and interdependence of KPIs and key variables affecting them. This approach can also show the combined effects of KPIs over the higher level organizational goals such as students’ scores and absenteeism. However, these results were based on some assumptions such as the initial maintenance rate, the final maintenance rate, the renewal rate, inflation rate, and life of systems after replacement. Through sensitivity analyses, the best solution over a range of assumptions can be calculated. For example, Figure 13 shows the Net Present Value (NPV) as a function of the number of years until replacement (x axis), the initial maintenance rate (set at 2% in all but one scenario) and the maintenance rate.

**Figure 9** Simulated CI under scenario 3 based on user inputs and assumptions

**Figure 10** MEI and REI under scenario 1 based on user inputs and assumptions
in the final year, over a period of 50 years. In all scenarios, the annual maintenance budget was assumed at 99.9% (maximum possible rate to keep the CI at 1 at all times), and the initial cost of the system (PRV) was considered at $10 000. The maintenance rate in the final year ranged from 100% to 80%, 60%, 40%, 20%, 10%, 4%, and 2% (the last value yields a maintenance rate constant over the entire service life).

The following is observed from Figure 13:

(1) The NPV was found to behave in a saw-tooth pattern because it is a function of how many replacements occur over 50 years of service life, in addition to years until replacement, initial maintenance rate, and final maintenance rate. So any jumps that occur are due to a different
number of replacements within the 50-year period. If the NPV were calculated over a period of infinite years, there would be no saw-tooth pattern. However, calculating over a period of infinite years is not necessarily the best method because optimizing over infinity is not realistic. Therefore, it is very important that the NPV be optimized over the true period of study, whether that is 25, 50 or 100 years.

(2) The optimum NPV for a maintenance rate of 100% and 80% in the final year was achieved when replacement was performed at 18 years, i.e., two replacements over a period of 50 years. The near-optimum NPV for these scenarios was 26 years.

(3) The optimum NPV for all other maintenance rates in the final year was achieved when replacement was performed at 26 years, i.e.,

Figure 13  Net Present Value over a period of 50 years under various maintenance rate assumptions

Figure 14  Net Present Value over a period of 25 years under various maintenance rate assumptions
one replacement over a period of 50 years. The reader should keep in mind that this may not be optimal for any rates over a period of 52 years because of the added cost of the system being replaced twice instead of once.

(4) NPV was flat, or close to flat, from the replacement periods of 26 to 50 years for all final year maintenance rates below 10%.

This, basically, leads to the following two major conclusions:

(1) For a service life of 50 years, the optimum, or near-optimum, NPV was achieved with a replacement at 26 years in all scenarios.

(2) If there is a high degree of confidence that the initial maintenance rate was 2%, and the final maintenance rate was no more than 4% of the System Replacement Value, there was found to be no financial justification to replace a system expected to last 50 years. In these scenarios, if we only consider economic reasoning, the recommendation would be to keep maintaining the system; however, this might severely impact on the condition of that system, which might result in other negative effects to the building and/or the building users.

As mentioned earlier, there is a saw-tooth pattern in the NPV, which means that it is very important to optimize the NPV over the true period of service life of the building. While optimizing it over a five-year period is too short term because it only serves ‘selfish’ short-term benefits, a period of 1000 years, on the other hand, is unrealistic. Simulations may be performed over a range of periods to identify the optimum solution to this question.

In Figures 14 and 15, the NPV is calculated over a period of 25 years and 150 years, respectively. Even though the life expectancy of the system is the same in Figures 13 through 15, it can be seen that the number of years until replacement to optimize NPV depends on the number of years over which the NPV is to be optimized (25, 50 or 150).

**Conclusions**

Under the specific set of assumptions utilized in this study, Part 1 shows that scenario 4 (full maintenance) maintained the highest Condition Index for the building throughout its service life; however, scenario 3 (early replacement) was the least expensive to implement while still maintaining a better overall CI than scenarios 1 or 2. Scenario 3 was also found to be the least expensive in Part 2 of the simulation, where one building was substituted by five separate building systems that together rolled up to the building level. The conclusions themselves may not be important because they may differ somewhat from real-world settings and assumptions. However, it is important to note that the analysis and conclusions are not all obvious and could not have been drawn without the use of simulation. Is early replacement of a system always the best strategy? Of course it is not. The best strategy depends
on all of the circumstances, inputs, influences, and variabilities considered and analysed simultaneously. Simulation is the tool that enables this pursuit.

As facility managers are faced with increasing pressure to prioritize the direction of limited resources, this paper develops a tool that may assist them in their decision-making regarding maintenance and replacement of building systems. Better prioritization of maintenance and capital renewal actions could be achieved by using a simulation (modelling) tool to examine the interrelationships between the variables that are to be considered for making more informed decisions. The significance of using the KPI approach for assessing a facility’s performance has been highlighted in the literature. This paper builds upon the proposed set of five KPIs, as identified in Lavy et al. (2014a, 2014b). The analysis performed in this paper shows that the interdependence and the relationships of KPIs can be investigated using the simulation approach. Moreover, it can also be used to understand the combined impact of KPIs over organizational goals. However, to truly understand the state of a facility and how the facility’s maintenance expenditure is optimized while keeping the CI at a desired level, a simulation based upon actual data is needed. The process begins with understanding goals, objectives, functions and inputs, as well as capturing and analysing relevant data. Key performance indicators (KPIs) are an important part of the data to be captured, but much more information needs to be collected and stored in order to understand the cause and effects among various KPIs.

This study had four main objectives. The first objective was to simulate the identified core KPI outputs for facility performance assessment using hypothetical input data. This is clearly demonstrated in both Parts 1 and 2, where computer simulations were conducted to analyse the effect of core KPIs on facility performance assessment. The second objective of this study was to demonstrate how simulation allows for the study of correlations and relationships between and among KPIs. This was conducted in both Parts 1 and 2, and is evident in Figures 3 through 12, where correlations between KPIs are presented and analysed. The third objective of this paper was to highlight the sensitivity of outputs and outcomes to input variable sensitivity. Evidence of this may be found in Figures 13 through 15, where the sensitivity of an output variable (Net Present Value over a 50-year period) was tested against changes in one input variable (final year’s maintenance rate).

The fourth objective of this study was to demonstrate that due to variability and future uncertainty, simulation is a valuable tool for generating future possible scenarios and making decisions based upon forecasts and logic. The accomplishing of this objective is evident throughout the paper, as simulation is a powerful tool in understanding and projecting relationships among KPIs, their inputs, and their outputs. Simulations may be used to play out complex relationships and interactions, test sensitivity to changes in inputs and assumptions, predict the effect of various scenarios, and optimize objectives. However, as with any predictive tool, the results are only as good as the assumptions and inputs. Extremely important questions to answer include whether or not we have identified all the potential variables that influence KPIs and whether the assumptions regarding variable relationships and behaviours are reasonable. In this paper, the authors demonstrate the power and potential of understanding and using KPIs through computer simulations. Additionally, output variability increases as the prediction refers to a point which is further away from the present time. This happens due to the fact that there is more uncertainty as one moves further into forecasting the future.

There is no ‘right or wrong’ answer to the question of how to better prioritize available resources. Is a five-year solution preferred over a 10-year, 20-year, or 50-year solution, or vice versa? We argue that individual users should determine the best solution for their specific circumstances. As long as decision-makers understand the hierarchy of how key performance indicators may affect facility performance assessment decisions, which in turn, may affect the achievement of organizational goals, simulation tools can be used to examine various scenarios. In our simulation, we estimated a building’s life cycle of 50 years, which is considered as the economic service life of a building, but the tool is flexible enough to work with different assumptions as well.

One additional area of concern involves short- and long-term objectives, goals, and decision-making. It is not illogical for a president, chief executive officer, chief financial officer, facility manager, or a person holding any other function/position in an organization to plan their actions based on the amount of time (‘term’) they will serve in their position. However, this type of planning strategy may result in deferring decisions or actions, such as for maintenance and/or replacement of building systems and components, to a later date. This planning may be akin to scenario 2 in our examples, and could lead to the situation of taking on too much deferred maintenance wherein the amount of maintenance expenditure is poor; a point at which the Condition Index cannot be improved will be reached, and this might be a very expensive strategy.

Composite KPIs can more directly link KPIs such as those addressed in this paper to ultimate performance goals/metrics. For example, while there are assumed correlations between some of these KPIs...
to facility performance assessment and ultimately, to organizational goals, e.g., student academic performance, there needs to be a balance of critical systems’ KPIs (such as HVAC), and functional KPIs (such as space, technology, access, air quality) to better link to organizational performance metrics (in the case of education facilities: test scores, promotion rates, etc.).

For future research, the authors propose:

1. Validating the identified core KPIs and the simulation results using actual data. Data to be used for such a study could be obtained from different organizations spread over various industries.

2. Selecting actual facilities with available historical data supporting these KPIs, and comparing assumptions yielding optimum simulated results (using the simulation methods described in this paper) with simulation results using actual data. This will be the first step to characterize the relationship between the simulation models and actual operations to better define facility asset management decision support.

3. Identifying composite KPIs to better link KPIs defined in this paper to organizational performance.

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Rhode Island Department of Education (2007) RIDF School Construction Regulations, Rhode Island Department of Education, RI.
Appendix

List of the variables and abbreviations used in this paper

Estimated Life Cycle (Years)

This is the estimated life of the system of interest. Changing the life cycle affects the rate of deterioration of the system and the rate of maintenance costs. The simulation may start at any point of the life cycle for the system, but for the purposes of this paper, all systems start as new.

Initial Maintenance Rate (%)

This is the expected rate of maintenance in the first year of the system. The amount of maintenance ($) expected for the system in the first year is calculated by multiplying the rate by the System Replacement Value at the end of the first year.

System Replacement Value (SRV)/Plant Replacement Value (PRV)

This is the cost to replace the system/plant without accounting for the Renewal Rate. It is assumed to increase due to the Rate of Inflation for System and Environmental Rate.

Final Maintenance Rate (%)

This is the expected rate of maintenance in the final year of the system. The amount of maintenance ($) expected for the system in the final year is calculated by multiplying the rate by the projected System Replacement Value at the end of the final year.

Years Until Planned Replacement

This is when we plan to replace the system, which does not have to be at the end of the life of the system. The simulation allows us to study how KPIs are affected by altering this value.

Renewal Rate Factor

This rate is multiplied by the SRV/PRV to estimate the cost of replacement accounting for the use of existing infrastructure or the cost of tear down and haul away.

Budget for Maintenance

Treated as a random variable in the simulation (we have an expected target, but it fluctuates from year to year due to variability). This is the rate of the SRV to determine how much is spent during the year on maintenance. The difference between the amount spent on maintenance and the amount needed to be spent on maintenance is the Deferred Maintenance. If the budget is 100%, the amount spent on maintenance is simply the current SRV, and there is no Deferred Maintenance for that particular year.

Deferred Maintenance (DFM)

The difference between the amount ($) spent on maintenance and the amount ($) needed to be spent on maintenance.

Targeted Deferred Maintenance

The amount of DFM ($) tolerated to maintain a target CI.

The Discount Rate (%)

Treated as a random variable in the simulation (we have an expected target, but it fluctuates from year to year due to variability). This is the rate for opportunity cost of capital, which is used in the calculation of the Net Present Value.
Net Present Value of Dollars Spent

The equivalent present value of all future cash outflows that enable to conduct maintenance and replacement (capital renewal) activities, given a specific discount rate.

Rate of Inflation for DFM (%)

Treated as a random variable in the simulation (we have an expected target, but it fluctuates from year to year due to variability). The cost of repair, for maintenance that is not performed, is estimated to increase by this rate of inflation each year.

Rate of Inflation for System (%)

Treated as a random variable in the simulation (we have an expected target, but it fluctuates from year to year due to variability). The cost of repair, for maintenance that is not performed, is estimated to increase by this rate of inflation each year.

Environmental Rate (%)

Treated as a random variable in the simulation (we have an expected target, but it fluctuates from year to year due to variability). The cost of replacement for a system is estimated to increase by this rate each year due to environmental laws and regulations, updated building codes, etc.

Condition Index (CI)

CI is a metric to assess the readiness of a system, plant, and/or facility. If the CI equals 1, the system is ‘as good as new’; if the CI equals 0, the system life is expired.

\[
CI = \left(1 - \frac{Total \ Text{Current Deferred Maintenance}}{Total \ Current \ SRV}\right)
\]

Maintenance Efficiency Indicator (MEI)

MEI is a metric to assess the efficiency of maintenance expenditure. MEI of 100% means that the exact amount necessary to maintain the target CI was spent in the given year on deferred maintenance. MEI below 100% means that not enough was spent, and MEI above 100% means that more was spent than needed. If MEI equals 60%, for example, that means we underspent on what was needed to be spent on deferred maintenance to either maintain the target CI or take care of preventative maintenance costs by 40%. If MEI equals 110%, then we spent 10% more than necessary to maintain the target CI.

\[
MEI = 100 \times \left(1 - \frac{\$\text{Amount Spent on Maintenance (Excluding Replacement)}}{DFM - Targeted DFM}\right)
\]

Replacement Efficiency Indicator (REI)

REI is a metric to assess the efficiency of system replacement expenditure. Given that systems typically do not expire each year, REI is not a smooth continuous function. REI below 100% means that not enough was spent on replacement and REI above 100% means that more was spent than needed. In this paper, the REI is capped at a maximum of 200%.

\[
REI = 100 \times \left(1 - \frac{\$\text{Amount Spent on System Replacement} + 0.001}{Total \$\text{Cost of Expiring Systems} + 0.001}\right)
\]