國立雲林科技大學
96學年度博士班招生入學考試試題

所別：工程科技研究所
科目：工程數學 (甲)

1. Find the general solution for the following equations. (25%)

   (a). $\dfrac{dy}{dx} = -\dfrac{2xy^3+2}{3x^2y^2+8e^{4y}}$. (10%)

   (b) $(D^2+1)y(x) = 4x\cos(x) + 6\cos(2x)$; (15%) (note $Dy \equiv \dfrac{dy}{dx}$)

2. Compute A^{100}, where $A = \begin{bmatrix} 1 & 0 \\ 1 & -5 \end{bmatrix}$. (10%)

3. Find the solution for the following linear equation. (15%)

$$\begin{aligned} 3x_1 - 2x_2 - 6x_3 - x_4 &= -5 \\ 3x_2 + 3x_3 - 5x_4 &= 2 \\ -x_1 + 9x_2 + 13x_3 - 10x_4 &= -1 \\ 2x_1 + 4x_2 + 4x_3 - 6x_4 &= -8 \end{aligned}$$

4. f is a periodic function shown in Fig. 1, find the Lapalce transform of f(t).(17%)

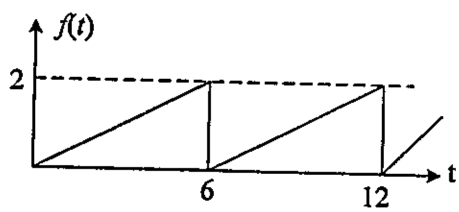

Fig. 1.

5. Let $L[f(t)]=F'(s)$, for s>b and suppose that F is differential. Then proof of $L[tf(t)]=-F'(s)$. (16%)

6. Let $f(t)=e^{-a|t|}$ for all real t, with a a positive constant. Please find out the Fourier transform of $f(t)$. (17%)

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1. 某發電廠有兩座發電機組 1 號與 2 號。由於例行保養與偶而發生故障，故任何一週 1 號與 2 號機不能發電的機率分別爲 0.01 與 0.02 (此兩事件分別以 E1 與 E2 表示)。在夏季每週因太熱(譬如，平均溫度> $29^{o}C$；此事件以 H 表示)，冷氣機大量使用結果導致需電量大增的機率爲 0.1。電量與供電能力的變化，有如下的三種可能情形。 (15%)

   (1) 充分供電 S：假設兩部機組均可供電，且氣溫又低於 $29^{o}C$。

   (2) 供電不充分 R：假設有一部機不能供電，且氣溫又高於 $29^{o}C$。

   (3) 勉強供電 M：上述兩者以外的情況。

   假設 H，E1 與 E2 互爲獨立事件。

   (a) 試以 H，E1 與 E2 來表示事件 S，R 與 M。

   (b) 問在任何一週裏，剛好一部機不能發電的機率爲若干?

   (c) 試問 P(S)，P(R)與 P(M)?

2. 試用動差法(method of moment) 導演指數分布 $P(\lambda)=\lambda e^{-\lambda x}$ 之參數? (20%)

3. x，y 之結合PDF爲 (15%)

$$f(x,y)=ae^{-2x-y} \quad ; \quad (x\geq 0, y\geq 0)$$
$$=0 \quad ; \quad 其它$$

   (a) 求 a 值?

   (b) 求 $p(x+y\geq 2)$?

   (c) 求 $p(x>y|x<2y)$?

4. (a) 一個二階變係數微分方程式 $a_0(x)y''+a_1(x)y'+a_2(x)y=r(x)$ 爲正合方程式（exact equation）的條件爲何？ (20%)

   (b) 試求下列ODE之解：$(1-x^2)y''-3xy'-y=1$

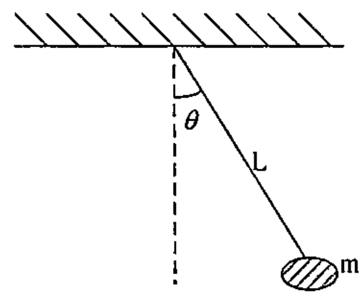
5. 試求下列ODE之解：$(x+2)^2y''-(x+2)y'+y=3x+4$ (15%)

6. 試求下列ODE之解：$y'=\dfrac{2x-5y+3}{2x+4y-6}$ (15%)

國立雲林科技大學
96學年度博士班招生入學考試試題

所別：工程科技研究所
科目：工程數學 (乙)

1. Find the solution of the following equation:
   a. (10%) $y' + 2y = e^x \sin 2x$
   b. (10%) $y' + \frac{1}{x} y = 2x^2 y^3$
   c. (10%) $4x^2 y'' + 4xy' - y = \frac{12}{x}$.
   d. (10%) $y'' + 4y' + 4y = \frac{e^{-2x}}{x^2}$, $y(1) = \frac{1}{e^2}$, $y'(1) = \frac{-2}{e^2}$
2. (15%)Determine the frequency of oscillation of the pendulum of length L in the figure. Neglect air resistance and the weight of the rod (Hint: $\sin\theta \fallingdotseq \theta$)



3. (15%)Find the divergence of the position vector to an arbitrary point in Cartesian , Cylindrical and spherical coordinates.
4. (10%)Find the surface integral

$$\iint_S F \bullet n \, dA \text{ , where } F = x^3 i + y^3 j + z^3 k \quad S: x^2 + y^2 + z^2 = 4$$

5. (10%)If $f(x) = \begin{cases} k, & -\frac{\pi}{2} < x < \frac{\pi}{2} \\ 0, & \frac{\pi}{2} < x < \frac{3\pi}{2} \end{cases}$, $f(x + 2\pi) = f(x)$

   (a) find the Fourier series (b) show that $1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots = \frac{\pi}{4}$
6. (10%)Find the Fourier transform of $e^{-a^2x^2}$

國立雲林科技大學
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所別：工程科技研究所
科目：營建文獻評論

請從後面兩個不同的附件中（附件 1 結構工程與材料領域：第 2 至 6 頁、附件 2 營建管理與建築領域：第 7 至 14 頁），選讀其中之一，然後針對所選讀的附件回答下列各問題。請清楚標明所選讀之附件編號。

選讀附件 1 者： (You can write your answers either in Chinese or English)

1. Explain the meaning of "seismic retrofit" in your own words. (10%)
2. According to this article, how many and what are the levels for the modifications of existing structures? (20%)
3. According to this article, make a **table** to classify different types of modification for existing structures. (20%)
4. According to this article, describe and compare different types of **dampers.** (20%)
5. According to this article, describe and compare different types of **reinforcement.** (30%)

選讀附件 2 者：

1. 本篇文獻之背景與研究目的(25%)。
2. 本篇文獻之研究方法(25%)。
3. 本篇文獻之具體貢獻(25%)。
4. 本篇文獻之缺點與限制(25%)。

附件 1

Seismic Retrofit

Seismic retrofitting is the modification of existing structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes. It is important to keep in mind that there is no such thing as an earthquake proof structure, although performance can be greatly enhanced through proper initial design or subsequent modifications.

Levels of modification

Seismic retrofit is primarily applied to achieve public safety, with various levels of structure and material survivability determined by economic considerations:

- Public safety only. The goal is to protect human life, ensuring that the structure will not collapse upon its occupants or passers by, and that the structure can be safely exited. Under severe seismic conditions the structure may be a total economic write-off, requiring tear-down and replacement.
- Structure survivability. The goal is that the structure, while remaining safe for exit, may require extensive repair (but not replacement) before it is generally useful or considered safe for occupation. This is typically the lowest level of retrofit applied to bridges.
- Primary structure undamaged and the structure is undiminished in utility for its primary application. A high level of retrofit, this ensures that any required repairs are only "cosmetic" - for example, minor cracks in plaster, drywall and stucco. This is the minimum acceptable level of retrofit for hospitals.
- Structure unaffected. This level of retrofit is preferred for historic structures of high cultural significance.

Types of modifications

Modifications fall into several categories:

Isolation

Generally required for large masonry buildings, excavations are made around the foundations of the building and the building (in piecemeal fashion) is separated from the foundations. Steel or reinforced concrete beams replace the connections to the foundations, while under these, layered rubber and metal *isolating pads* replace the material removed, these in turn are attached below to new or existing foundations. These allow the ground to move while the building, restrained by its inertial mass, remains relatively static. The pads absorb energy, transforming the relative motion between the ground and the structure into heat. While the pads tend to transmit some of the ground motion to the building they also keep the building positioned properly over the foundation. Careful attention to detail is required where the building interfaces with the ground, especially at entrances, stairways and ramps, to ensure sufficient free motion without damage to access means from compression or dismantling or falling from extension. Significant examples of the application of this method are the San Francisco and nearby Oakland City Halls in California.

Dampers

Dampers absorb the energy of motion and convert it to heat, thus "damping" resonant effects in structures that are rigidly attached to the ground. In these cases, the threat of damage does not come from the initial shock itself, but rather from the periodic resonant motion of the structure that repeated ground motion induces.

Slosh tanks

A large tank of water may be placed on an upper floor. During a seismic event, the water in this tank will slosh back and forth, but is directed by baffles - partitions that prevent the tank itself becoming resonant; through its mass the water may change or counter the resonant period of the building. Additional kinetic energy can be converted to heat by the baffles and is dissipated through the water - any temperature rise will be insignificant.

Shock absorbers

Shock absorbers, similar to those used in automotive suspensions, may be used to connect portions of a structure that are free to move relative to each other and that may collide during an earthquake. Where a rigid connection could break or impose excessive strain on the buildings, and a loose connection could be dismantled, the shock absorbers allow the relative motion to be restrained by transferring and dissipating energy. This can be especially effective if the two structures have differing fundamental frequencies of resonance, as each structure may then assist in inhibiting the motion of the other.

Tuned mass dampers

Tuned mass dampers employ movable weights with dampers. These are typically employed to reduce wind sway in very tall, light buildings. Similar designs may be employed to impart earthquake resistance in eight to ten story buildings that are prone to destructive earthquake induced resonances.

Active damping with fallback

Very tall buildings ("skyscrapers"), when built using modern lightweight materials, might sway uncomfortably (but not dangerously) in certain wind conditions. A solution to this problem is to include at some upper story a large mass, constrained, but free to move within a limited range, and moving on some sort of bearing system such as an air cushion or hydraulic film. Hydraulic pistons, powered by electric pumps and accumulators, are actively driven to counter the wind forces and natural resonances. These may also, if properly designed, be effective in controlling excessive motion - with or without applied power - in an earthquake. In general, though, modern steel frame high rise buildings are not as subject toO dangerous motion as are medium rise (eight to ten story) buildings, as the resonant period of a tall and massive building is longer than the approximately one second shocks applied by an earthquake.

Reinforcement

The most common form of seismic retrofit to lower buildings is adding strength to the existing structure to resist seismic forces. The strengthening may be limited to connections between existing building elements or it may involve adding primary resisting elements such as walls or frames, particularly in the lower stories.

Connections between buildings and their expansion additions

Frequently, building additions will not be strongly connected to the existing structure, but simply placed adjacent to it, with only minor continuity in flooring, siding, and roofing. As a result, the addition may have a different resonant period than the original structure, and they may easily detach from one another. The relative motion will then cause the two parts to collide, causing severe structural damage. Proper construction will tie the two building components rigidly together so that they behave as a single mass or employ dampers to expend the energy from relative motion, with appropriate allowance for this motion.

Shear failure in lowest story

In many buildings the ground level is designed for different uses than the upper levels. Low rise residential structures may be built over a parking garage which have large doors on one side. Hotels may have a tall ground floors to allow for a grand entrance or ballrooms. Office buildings may have stores in the ground floor which desire continuous windows for display.

Traditional seismic design assumes that the lower stories of a building are stronger than the upper stories and where this is not the case the structure will not respond to earthquakes in the expected fashion. Using modern design methods, it is possible to take a weak story into account.

Several failures of this type in one large apartment complex caused most of the fatalities in the 1994 Northridge earthquake.

Typically, where this type of problem is found, the weak story is reinforced to make it stronger than the floors above by adding shear walls or moment frames. Moment frames consisting of inverted **U** bents are useful in preserving lower story garage access, while a lower cost solution may be to use shear walls or trusses in several locations, which partially reduce the usefulness for automobile parking but still allow the space to be used for other storage.

Reinforced concrete column burst

Reinforced concrete columns typically contain large diameter vertical rebar arranged in a ring, surrounded by lighter-gauge hoops of rebar. Upon analysis of failures due to earthquakes, it has been realized that the weakness was not in the vertical bars, but rather in inadequate strength and quantity of hoops. Once the integrity of the hoops are breached, the vertical rebar can flex outward, stressing the central column of concrete. The concrete then simply crumbles into small pieces, now unconstrained by the surrounding rebar. In new construction a greater amount of hoop-like structures are used.

One simple retrofit is to surround the column with a jacket of steel plates formed and welded into a single cylinder. The space between the jacket and the column is then filled with concrete, a process called grouting. Where soil or structure conditions require such additional modification, additional pilings may be driven near the column base and concrete pads linking the pilings to the pylon are fabricated at or below ground level.

Brick wall resin and glass fiber reinforcement

Brick building structures have been reinforced with coatings of glass fiber and appropriate resin (epoxy or polyester). In lower floors these may be applied over entire exposed surfaces, while in upper floors this may be confined to narrow areas around window and door openings. This application provides tensile strength that stiffens the wall against bending away from the side with the application. The efficient protection of an entire building requires extensive analysis and engineering to determine the appropriate locations to be treated.

Reinforced concrete wall burst

Concrete walls are often used at the transition between elevated road fill and overpass structures. The wall is used both to retain the soil and so enable the use of a shorter span and also to transfer the weight of the span directly downward to footings in undisturbed soil. If these walls are inadequate they may crumble under the stress of an earthquake's induced ground motion.

One form of retrofit is to drill numerous holes into the surface of the wall, and secure short L-shaped sections of rebar to the surface of each hole with epoxy adhesive. Additional vertical and horizontal rebar is then secured to the new elements, a form is erected, and an additional layer of concrete is poured. This modification may be combined with additional footings in excavated trenches and additional support ledgers and tie-backs to retain the span on the bounding walls.

Reinforced concrete post to beam connections

Examination of failed structures often reveals failure at the corners, where vertical posts join horizontal beams. These corners can be reinforced with external steel plates, which must be secured by through bolts and which may also offer an anchor point for strong rods, as shown in the image at left. The horizontal rods pass across the beam to a similar structure on the opposite side, while the vertical rods are anchored after passing through a grouted anti-burst jacket.

Another method is to simply add a great amount of small attachment points, as in the wall reinforcement method described above, with additional rebar and concrete. In one retrofit every corner joint has been surrounded by a block-like jacket. These blocks serve to transfer bending forces to new added jackets on the vertical and horizontal elements. The goal is to achieve the type of strength afforded by the new construction shown at right (this is not a retrofit).

Soil

One of the most difficult retrofits is that required to prevent damage due to soil failure. Soil failure can occur on a slope, a slope failure or landslide, or in a flat area due to liquefaction of water-saturated sand and/or mud. Generally, deep pilings must be driven into stable soil (typically hard mud or sand) or to underlying bedrock or the slope must be stabilized. For buildings built atop previous landslides the practicality of retrofit may be limited by economic factors, as it is not practical to stabilize a large, deep landslide. The likelihood of landslide or soil failure may also depend upon seasonal factors, as the soil may be more stable at the beginning of a wet season than at the beginning of the dry season. Such a "two season" *Mediterranean climate* is seen throughout California.

In some cases, the best that can be done is to reduce the entrance of water runoff from higher, stable elevations by capturing and bypassing through channels or pipes, and to drain water infiltrated directly and from subsurface springs by inserting horizontal perforated tubes. There are numerous locations in California where extensive developments have been built atop archaic landslides, which have not moved in historic times but which (if both water-saturated and shaken by an earthquake) have a high probability of moving *en masse*, carrying entire sections of suburban development to new locations. While the most modern of house structures (well tied to monolithic concrete foundation slabs reinforced with post tensioning cables) may survive such movement largely intact, the building may be neither level nor properly located.

[adapted from Wikipedia, the free encyclopedia]

Key Performance Indicators for Strategic Healthcare Facilities Maintenance

Igal M. Shohet[1]

Abstract: The salient phases in a facility's service life that are most decisive for the effectiveness of its facilities management (FM) are the preliminary design, construction, and maintenance. The effectiveness of facilities is vastly affected by decisions pertaining to the strategy of the organization that owns or uses the facilities. The goal of this study was to develop key performance indicators (KPIs) for strategic FM that will provide a conclusive approach towards the facility's service life conditions. Parameters were developed by means of field surveys and statistical analyses, and were validated by means of case studies. The research resulted in a series of 11 KPIs for strategic healthcare FM, which can be classified into four categories: development, organization and management, performance, and maintenance efficiency parameters. The study proposes age and occupancy coefficients as essential parameters for the assessment of large healthcare facilities needs, as an effective measure for long term facility maintenance planning, and for measuring FM effectiveness. The paper stresses that strategic healthcare facilities management must integrate quantitative performance, manpower, and maintenance indicators.

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CE Database subject headings: Case reports; Healthcare facilities; Maintenance.

Introduction

During the past 3 decades, significant changes have taken place in the building sector that have led facilities management (FM) to evolve into a well-defined research and professional discipline. The factors contributing to this development were: (1) a rise in construction costs, particularly of office buildings and of public, commercial and industrial buildings; (2) greater recognition of the influence of space upon productivity (Brown et al. 2001); (3) a significant rise in performance requirements; (4) difficulties in initiating new projects due to new bureaucratic and statutory restrictions; and (5) an increase in the construction of high-rise buildings that results in the building's performance being highly dependent on its maintenance. All of the aforementioned trends are global and have similar implications on facilities management in all developed countries. These trends have resulted in a significant increase in investments in maintenance, restoration, renovation, and upgrading of existing facilities and infrastructures. In countries such as the United States, Great Britain, and Canada, the scope of investments in maintenance accounts for 40–50% of the activity in the construction sector (International Standardization Organization 2000; Mitropoulos and Howell 2002). In Israel, as well, a similar trend is developing, although the scope of investments in maintenance and renovation of facilities is smaller than in the aforementioned countries. As a result of these trends, a distinct need has emerged for the development of methods for the strategic management and maintenance of building portfolios. This trend is salient in the area of healthcare facilities, office buildings, infrastructures, and road structures. The healthcare industry, in particular, has witnessed a continuously growing demand for health services. With the limited amount of resources, the service patterns have evolved to minimize the number of days per inpatient admission and thus increase the capacity of hospitals in terms of annual inpatient admissions (American Hospital Association 2003; Federal Statistical Office Germany 2003). This pattern of health services has placed healthcare facilities under intensive service regimes that necessitate strategic and tactical planning of the facility maintenance and performance (Lennerts et al. 2003).

The objectives of the study were:

1. To develop a set of key performance indicators (KPIs) for monitoring the performance, maintenance, and cost effectiveness of hospital facilities;
2. To develop the KPIs for strategic planning; and
3. To implement the KPIs in case studies.

Literature Background

During the past decade, continuous research efforts have been undertaken to develop methods for strategic-level decision making in facilities management. Barrett (1995) emphasized that FM tends to have a technical, reactive rather than proactive orientation. The writer proposed a generic model based on the integration of various FM domains to obtain a network of interaction on the operational and strategic level of FM. Pitt et al. (2001) developed a concept for the optimization of passenger airport terminals based on strategic considerations. The researchers proposed an array of nine key parameters for the optimization of passenger

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Note. Discussion open until September 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on September 2, 2004; approved on September 21, 2005. This paper is part of the *Journal of Construction Engineering and Management*, Vol. 132, No. 4, April 1, 2006. ©ASCE, ISSN 0733-9364/2006/4-345–352/$25.00.

terminals. The suggested parameters included: level of passenger service, determination of performance standards, characterization of peak traffic hours, and the uncertainty of demand. These parameters emphasize various aspects of performance in the strategic planning of airports. The other five KPIs specify costs and specific performance characteristics of airports. The drawback of this study was that most of the quantifiable parameters were not expressed quantitatively, and therefore additional research and development are required in order to verify and validate the model.

Barrett (2000) proposed a model for the realization of the strategic and operational missions of FM using four key relationships: (1) identification of the organization's future needs by identifying external changes and their effect on the organization's activity; (2) identification of core domains in the organization that are affected by external changes; (3) verification of the organization's current needs by studying the organization's internal needs; and (4) internal benchmarking of the different FM divisions, as well as external benchmarking of the FM unit in relation to similar units in other organizations.

Shiem-Shin Then (1999) studied the need for strategic business planning to incorporate and integrate facilities parameters of business delivery. The researcher identified six strategic concerns in FM practice: (1) property portfolio management; (2) strategic facilities planning guidelines; (3) workplace strategies; (4) long-term asset management; (5) support services management; and (6) optimizing utilization of business resources. The research indicated the need for further development in order to meet the above needs.

A strategic facility plan (SFP) is a term often used to describe the consolidation of FM activities. A long-term SFP is expected to: (1) forecast facility implications on future business scenarios; (2) compare forecasts to existing resources; (3) annually update the plan and budget to forecast potential improvements; and (4) support functions of long-term facility planning through long-range strategic facilities plans (Langston and Lauge-Kristensen 2002). Klein (2004) defined five phases that characterize any SFP project: (1) launch; (2) data gathering; (3) analysis/synthesis; (4) recommendations; and (5) implementation. The analysis phase is aimed to critically assess the current situation and the long-range organizational and business directions the facilities are expected to support.

Smith and Jackson (2000) developed a system, based on artificial neural networks (ANNs), for the identification of the end user's needs during the project's preliminary design stage. After testing the system, the researchers emphasized that the effective implementation of such a process must involve an organizational atmosphere that supports a strategic culture.

Smith et al. (2003) went on to develop a methodology for strategic needs analysis. The methodology is based on an examination of six process characteristics, which were divided into 14 attributes. The researchers based their conclusions on six case studies, and reached the conclusion that the strategic analysis process must be integrated with factors from the organization's operational level.

Lunn and Stephenson (2000) examined the effect of tactical and strategic parameters on the automation of an FM decision-making process. The model proposed in this study also supports the integration of strategic and tactical parameters in senior-level decision making.

Critical success factors (CSFs) have been widely developed in a search to determine factors for successful projects. As the term CSF in context refers to factors predicting success on projects (Sanvido et al. 1992) CSFs tend to be process oriented rather than end product oriented, CSFs of construction projects may be classified according to five major groups (Chan et al. 2004): project related factors, project procedures, project management actions, human related factor, and external environment. The applicability of CSFs such as: "implementing effective quality assurance program," "technical solution advantage" for maintenance is yet implicit. Maintenance aspects may be introduced into these CSFs by implementing principles of maintainability and performance of the built facility into these CSFs.

The studies reviewed in this survey stipulate that FM must integrate tools of organizational performance, and cost effectiveness of facility management at the strategic planning level. The main drawback of the various studies carried out over the past decade on aspects of strategic management and maintenance of facilities is that they failed to develop quantitative indicators for strategic decision making. Furthermore, there exists a need to integrate between the engineering cost effectiveness and performance aspects of these indicators. Thus, this area remains dependent on the abilities and initiative of managers and lacks proven quantitative tools and well-based methodologies.

Despite all of the research and development, three paradoxes regarding FM exist even today: (1) Despite aspirations to turn FM into a strategic discipline, most of the tools developed and most of the decision makers active in the area operate on the organization's operational level. (2) Although from a professional point of view, FM aspires to constitute part of the professional core of the organization in which it operates, most of the FM services in the organization are provided by external consultants or by internal entities acting as consultants. (3) Facilities management, as a professional discipline, aspires to initiate and manage the changes in the organization, while in reality, FM serves as an agent that merely reacts to internal and external needs and constraints (Price 2002).

The proposed model integrates KPIs that enable prediction of future needs, by means of internal as well as external benchmarking, as was determined in previous studies. The paper presents 11 KPIs for the monitoring, management, and maintenance of healthcare facilities as a basis for strategic and tactical planning of acute care hospital facilities. The case study presents an analysis and a policy setting of an Israeli acute care hospital facility, in which this method has been implemented these past 3 years.

Key Performance Indicators

The source of the KPIs presented in this paper is an integrated maintenance management model that was developed and is being implemented in the maintenance and management of public acute care hospital facilities in Israel. The development is described in detail in Shohet et al. (2003). The basic model was further developed here for strategic decision making in healthcare FM.

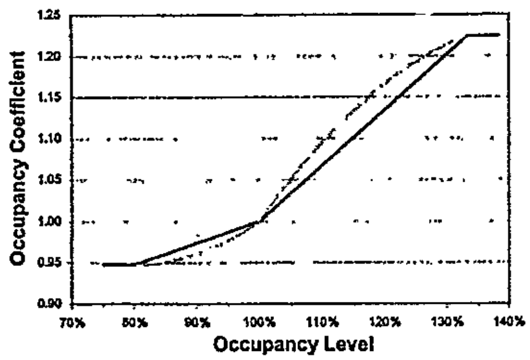
Key performance indicators are classified into four categories:

1. Asset development;
2. Organization and management;
3. Performance management; and
4. Maintenance efficiency.

Following is a concise description of the various parameters with reference to their implications on facility management and maintenance and to their interrelations.

Asset Development

1. Built area—The built area of a facility has two opposing effects: On the one hand, increasing the floor area creates a



LEGEND: linear Model Non-Linear Model

Fig. 1. Occupancy coefficient (for annual maintenance expenditure) for different occupancy levels

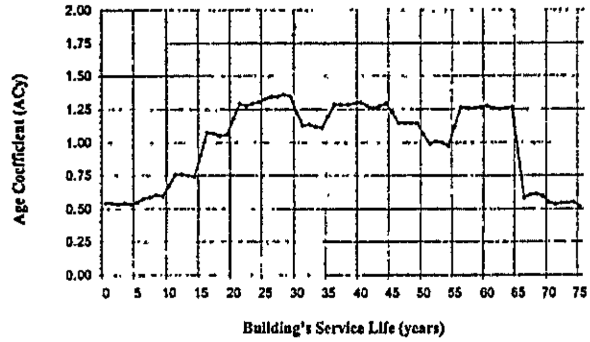


Fig. 2. Age coefficient (AC_y) versus building's service life

wide basis for the execution of maintenance and decreases the expense per square meter; on the other hand, large structures (high-rise buildings or a large portfolio of buildings spread out over a wide area) create functional and statutory requirements for infrastructures (water reservoirs for water supply and fire protection, security, internal traffic, etc.). which influence the reinstatement value of the facility per square meter and increase maintenance expenditures of the facility. In central buildings this has a significant effect in comparison with the savings incurred as a result of the facility's floor area.

2. Occupancy of the asset—This parameter reflects the facility's wear and tear rate. In densely occupied facilities (for instance, classrooms that are at times frequented by hundreds of students per day) the wear rate is relatively high. The occupancy of a hospital is defined as the number of patient beds per 1,000 m^2 built. Standard occupancy in Israeli hospitals is defined as ten patient beds per 1,000 m^2. Examinations performed in Israeli healthcare facilities have shown that increased occupancy (13.3 patient bed/m^2) requires 22% more resources in relation to standard conditions (ten patient beds). On the other hand, a low occupancy does not reduce maintenance costs to the same extent, but rather contributes a mere 5% savings in relation to standard conditions. This stems from the fact that part of the maintenance requirements (electricity, fire protection, elevators, and HVAC) are statutory requirements or carried out on a preventive basis that must be fulfilled under any occupancy conditions. Fig. 1 depicts the change in the occupancy coefficient (OC) in hospital buildings as a function of the relative occupancy of the hospital wards. The linear model is based on monitoring actual maintenance in hospital wards under different occupancy conditions. The nonlinear model, on the other hand, is being proposed and still requires further research. The case study in this paper used the linear model to quantify the effect of occupancy on facility maintenance.

3. Facility age—The age of the facility or of the building portfolio has many implications on its state and on the state of its systems. A database of life cycle of building components was developed from empirical and statistical research as well as from existing databases. The effect of the building's age was examined by analysis of the annual maintenance costs according to the life cycle of building components, as identified in surveys of energy and construction companies in Israel, and according to additional literary sources (Construction Audit Ltd. 1999; Building Performance Group 2001). Maintenance activities were deduced according to guidelines of *IS-1525-1* (Israel Standards Institution 2002). The life cycle of components is affected by the durability of components under the appropriate service conditions, for example stone claddings (designed life cycle of 44 years) versus synthetic rendering (designed life cycle of 21 years). The latter attribute is often associated with higher construction costs, nevertheless it contributes to better performance of the building and reduces maintenance along the building service life.

Fig. 2 presents the change in maintenance costs in relation to the perennial average for a hospital building with a planned service life of 75 years. The vertical axis represents the correction coefficient for the building's age (AC_y) according to the ratio between the annual expenditure (calculated according to a moving average over a 10 year period) and the average perennial expenditure.

It can be seen that in the first 16 years after the commissioning of the building, the annual maintenance expenditure is lower than the perennial average and that after that time there are three peak periods, around the 25th, 40th, and 60th years, which reflect the replacement of the building's electro-mechanical systems and the functional adjustments due to obsolescence or mission requirements such as remodeling of spaces. The graph illustrates well the wide fluctuations that occur throughout the building's service life, fluctuations that increase the more abundant the building is in electro-mechanical systems and interior finishing components. Thus, when planning the acquisition of an asset or the ongoing maintenance of an existing asset, the effect of such changes must be expressed economically. This coefficient influences the planning of the facility's maintenance via the allocation of resources required for such maintenance. The AC_y of a facility is calculated using a weighted average of the individual buildings' ages with respect to each of their floor area.

The three above-described parameters enable the identification of long- and short-term needs that are significant to the maintenance of the facility. Such needs will be expressed by the indicators that are to be developed in relation to facility management, investments, and the efficiency of resource utilization as follows.

Organization and Management

This category of parameters examines the human and external resources used in the execution of the building's maintenance. The indicators that will be proposed are interrelated; the extent of outsourcing affects the number of employees as well as the managerial span of control of the facility manager, and all of these parameters have an effect on the organizational structure of maintenance. Outsourcing is common today in many areas of the industry, as a means of executing activities that are not identified with the organization's core domains using outside contractors, who specialize in the said domain and can efficiently perform activities in their area of specialty (Langston and Lauge-Kristensen 2002). Such use of outsourcing contributes to savings in expenditures and to a reduction in the organization's internal managerial span of control.

4. Number of employees per 1,000 m^2 built area—This parameter reflects the scope of internal maintenance employees used. The number of employees per 1,000 m^2 built area in healthcare facilities in Israel (in which the average extent of outsourcing is 41.5%) is 0.64 (or one employee per 1,560 m^2 built area).
5. The scope of FM outsourcing—As mentioned, outsourcing constitutes an alternative to the implementation of maintenance activities by in-house employees, who require ongoing management. Outsourcing can serve as a source for the execution of seasonal preventive maintenance works, as well as rehabilitation, renovation, and replacement works. This parameter is characterized by a maintenance sources diagram (MSD), which presents the mix of internal and external maintenance resources, and expresses the extent of outsourcing (in percent) out of the total labor resources allocated for maintenance of the facility.
6. Managerial span of control (MSC)—This indicator is defined as the number of subordinates reporting to a given supervisor. It reflects the scope of managerial resources invested in the FM department. In a large FM organization, there will usually be at least two managerial levels: the head of the organization (maintenance engineer, who in fact serves as the facility manager), and the maintenance manager, who supervises ongoing maintenance activities and inspects in-house maintenance crews. The MSC expresses the number of employees who are directly subordinate to the manager. It was found in a previous study of MSC in the construction industry (Laufer and Shohet 1991) that the span of control affects the way managers divide their time and consequently the performance of the organization. The MSC, therefore, must be adapted to prevailing conditions. For a typical acute care facility (80,000 m^2) with 50 in-house maintenance personnel, the desired span of control at the head of organization level is no greater than six, while at the maintenance manager's level the desired span of control is eight subordinates.
7. Maintenance organizational structure—In the past decade, facilities management has in fact served as a principal means for the adaptation of the technological and cultural changes that organizations are undergoing in the postmodern society (Grimshaw 2003). In order to fulfill this role, FM is required to exhibit flexibility in resource allocation, and in adapting resources to the organization's dynamic needs: initiation and execution of restoration, renovation, upgrading and rebuilding projects, studying of technological alternatives and their implications for the organization's performance, as well as for the operation and maintenance of assets. A machine bureaucracy type structure, for instance, makes the adaptation of facilities to the organization's needs more difficult. The maintenance organization must therefore be flexible and of a learning nature (Honnecker et al. 1999). Garvin (1998) defined five main activities learning organization are skilled at: systematic problem solving, experimentation with new approaches, learning from their own experience, learning from experiences and best practices of others, and transferring knowledge efficiently through the organization. The assessment of the organizational structure uses the size of the organization, its principle structure, the level of absorption of learning attributes [information and communication technologies (ICT), structured maintenance policy setting, and life cycle costs approaches]. In addition to the latter, simultaneous analysis of KPIs 4–6 adds essential information as to the extent of labor, effective MSC at the top of the organization, and the use of outsourcing.

Performance Management

8. Building performance indicator (BPI)—This parameter enables the evaluation of the overall state of the building or of the building portfolio, according to the performance of its components and systems. The indicator is defined by a value, between 0 and 100, that expresses the building's state, including the performance of its various systems (P_n). P_n is graded according to performance scales between 0 and 100, where $P_n < 60$ indicates poor/dangerous performance condition, $60 < P_n \leq 70$ indicates deteriorating performance condition, $70 < P_n \leq 80$ indicates marginal (70) or satisfactory (80) condition, and $P_n > 80$ indicates good condition. The actual score for each system (P_n) is given on a scale of 0–100, and is expressed by the following equation. It is composed of three aspects of facility maintenance: (1) actual condition of the system (C_n); (2) failures affecting the service provided by the system (F_n); and (3) actual preventive activities carried out on the system to maintain acceptable service level (PM_n) (Israel Standards Institution 2002)

$$P_n = C_n^* W(C)_n + F_n^* W(F)_n + PM_n^* W(pm)_n \qquad (1)$$

where $W(C)_n$=weight of component condition of system n; $W(F)_n$=weight of failures in system n; and $W(pm)_n$=weight of preventive maintenance for system n. For every system n, the sum $W(C)_n + W(F)_n + W(pm)_n$ equals 1.

The score C_n is evaluated on the strength of a 100 point rating scale where 100 expresses complete performance score, 60 deteriorating, and 40 and 20 failure and poor performance, respectively. The preventive maintenance is evaluated on the basis of maintenance policy governing the component, and the frequency of proactive inspections carried out with respect to standards. Frequency of failures is evaluated on a scale between 100—no failure in 12 months, and 20—frequent occurrence (e.g., 12 times in the last 12 months in a roofing system). The combination of these three elements represents the performance score of the entire system (P_n). Weighting of each building system (W_n) in the BPI is accomplished by weighing the contributions of the system's components to the total cost of erection, maintenance, and replacement (life cycle costs). Table 1 presents weightings of hospital building systems. Once the systems' functional states have been diagnosed, the BPI is calculated. The BPI is obtained for each system by multiplying its weight by its score as follows:

$$BPI = \sum_{n=1}^{10} P_n W_n \qquad (2)$$

The desired BPI range is BPI > 80, though at such a performance score, any system or component at a performance score below 70 requires corrective maintenance measures. In a performance sur-

Table 1. Case Study Results of Building Systems Performance and BPI

Building system	(W_n)	P_n
Structure	12.4	84
Interior finishes	34.8	79.5
Exterior envelope	5.3	84.2
Fire protection	2.2	75.0
Water and sanitation	7.6	68.8
Elevators	4.1	57.1
Electrical systems	12.7	91.7
Communications	4.6	82
HVAC	13.7	85.0
Medical gases	2.6	100
BPI	100	81.4

Table 2. Expected Categories of KPIs

KPI	Category
Built floor area (m^2)	60,000–100,000
Occupancy (patient beds/1,000 m^2)	$13 \geq OC \geq 8$
AC_y	$1.36 \geq AC_y \geq 0.53$
Number of employees per 1,000 m^2	0.64
MSD	MSD ≥ 60%
MSC	6
Organizational structure	Learning
BPI	BPI ≥ 80
AME ($/$m^2$)	37.2
AME per patient bed ($/patient bed)	3,750
MEI ($/$m^2$)	$0.52 \geq MEI \geq 0.37$

vey carried out in public acute care hospitals in Israel in 2000, a mean BPI of 68.9 was observed, indicating a marginal–deteriorating condition (Shohet 2003a).

This KPI enables: (1) evaluation of the overall state of the building; (2) evaluation of the state of the building's systems; (3) benchmarking the asset's performance in relation to other buildings or facilities (interorganizational benchmarking); and (4) benchmarking the building's systems in order to compare the efficiency of the various maintenance crews (intraorganizational benchmarking). Thus, this indicator can be used both for the determination of the organization's strategy (in terms of performance requirements) and for decision making on a tactical level, as well as on the building's systems level.

Maintenance Efficiency

9. Annual maintenance expenditure (AME) per square meter—This parameter reflects the scope of expenditure per square meter built (excluding cleaning, energy, and security expenditures), but with no reference to the building characteristics and its use. From an organizational viewpoint, this parameter determines the annual expenditure on maintenance of the buildings, and it can also provide a measure of the overall expenditure on built assets in relation to the organization's turnover. From a managerial-professional viewpoint, however, the expenses must be analyzed in relation to the building's characteristics and with respect to the output (the building's performance). This examination is carried out in the framework of the maintenance efficiency indicator (MEI), as described below. Precise calculation of AME requires that all expenditures that are not directly related to maintenance be excluded from the total expenditure. This means that expenditures on remodeling, upgrading, and energy are not taken into account.
10. Annual maintenance expenditure per "output" unit (patient bed)—This parameter enables the identification of the scope of investment per output unit and is important in the assessment of the cost of the facilities and their maintenance per output unit. The parameter enables facility management and maintenance expenses to be added as an overhead cost, to the organization's core expenditures. In hospitals, this indicator will take the form of AME per patient bed, and in clinics—AME per 1,000 patients.
11. Maintenance efficiency indicator (MEI)—This indicator enables one to examine the investment in maintenance in relation to the facilities' performance (which is in fact the service provided to the organization by the FM department). The MEI is calculated by the following equation:

$$MEI = \frac{AME}{AC_y} * \frac{1}{BPI} * \frac{1}{OC} * i_c \qquad (3)$$

where AME=actual annual maintenance expenditure; AC_y=age coefficient for year y; BPI=monitored building performance indicator; OC=occupancy coefficient for the building or facility in question; and i_c=prices index. This indicator expresses the expenditure on maintenance per building performance unit, normalized using the age coefficient (AC_y) and occupancy coefficient (OC).

For a hospital maintained at the desired level, we assume a BPI of 100. The average annual maintenance expenditure (AME) per square meter was analyzed to be 2.22% of the reinstatement value of a hospitalization facility which was calculated to be $1,678/$m^2$ built. This AME was calculated to be $37.2 per annum. Assuming a facility with an age coefficient of 1.00, and an occupancy coefficient of 1.00 would yield a MEI value of 0.37. The upper and the central value of the desirable range were deduced from the standard deviation of the MEI for the hospital sample population. The MEI values are thus interpreted according to the following categories:

1. $MEI < 0.37$ indicates lack of resources and/or high efficiency with which the resources are utilized, or both;
2. $0.52 \geq MEI \geq 0.37$ reflects a reasonable range of maintenance, in which the lower limit indicates good efficiency while the upper limit indicates low efficiency and/or a high level of resources; and
3. $MEI > 0.52$ indicates high inputs relative to the actual performance. Such high indicator values may express high maintenance expenditures, low physical performance, or a combination of these two extreme situations.

Table 2 summarizes the standard values and the calculated KPIs as developed in the frame of the research. The following section presents a case study illustrating the implementation of the KPIs in the analysis of the maintenance of a large Israeli healthcare facility, as a basis for a strategic and tactical facilities management policy setting.

Case Study

In order to examine all aspects of the KPIs, an analysis of a university hospital's KPIs will be presented. The data were collected by a trained surveyor in 2004 with respect to year 2003. Typical data collection of a facility encompasses performance survey (including a sample of five major buildings constituting representative sample of 70% of the facility built floor area), a detailed collection of budgetary data, and organizational and manpower data. Data collection, processing, and validation require between 40 and 50 h. Typically a healthcare facility KPIs may change on an annual basis, however it may be better to conduct such analysis on a biannual basis to allow for organizational response time.

1. KPI 1: Built area of the healthcare facilities in the hospital—120,000 m^2.
2. KPI 2: Number of patient beds—700; number of patient beds per 1,000 m^2 built—six (expected range: between eight and 13). This finding means that the relative occupancy is 60%, and the occupancy coefficient derived from Fig. 1 for this facility is 0.95—expected range: 0.95–1.22.
3. KPI 3: The average age of the healthcare facilities is 25 years, age coefficient (average of buildings age coefficients) from Fig. 2—AC_y=1.15—expected range: 0.53–1.36.
4. KPI 4: Number of maintenance employees—120, consequently the built area per employee (including research laboratory areas)—1,200 m^2 (national average—1,560 m^2) and the number of patient beds per maintenance employee—5.5 (national average—12.9).
5. KPI 5: Outsourcing of maintenance out of the overall maintenance manpower mix (MSD)—30.5% (national average—41.5% and expected range: MSD > 60).
6. KPI 6: Span of control at the facilities manager level—9—expected value: 6.
7. KPI 7: The organizational scheme of the facility management division was drawn and analyzed. It was classified as machine bureaucracy—expected type: learning.
8. KPI 8: Hospital building performance indicator—BPI=81.4. Systems exhibiting unsatisfactory performance—elevators (P_n=57), water and sanitation (P_n=69) (Table 1)—expected range: BPI ≥ 80.
9. KPI 9: Annual maintenance expenditure per square meter built—$35/$m^2$ (national average—$37.2)—expected value 39 (assuming average MEI of 0.44).
10. KPI 10: Annual maintenance expenditure per patient bed is $8,100 compared to a national average of $4,500 and expected value of $3,750/patient bed. The latter parameter reflects the fact that the hospital is a university hospital with a relatively large support infrastructure.
11. KPI 11: MEI=0.40—expected range: 0.52 ≥ MEI ≥ 0.37.

Evaluation of Healthcare Facility Management According to Key Performance Indicators

1. In terms of the number of patient beds, the hospital is considered a medium sized facility. However, in terms of its built area, which totals 120,000 m^2 this hospital is a large one. Thus, the number of beds per 1,000 m^2 built (6), indicates that maintenance budgets should be examined primarily in relation to the built area.
2. The equivalent age of the healthcare facility was calculated as a weighted average of the buildings in the facility with respect to their floor area, and was found to be 25 years. The equivalent age coefficient was calculated using the following expression:

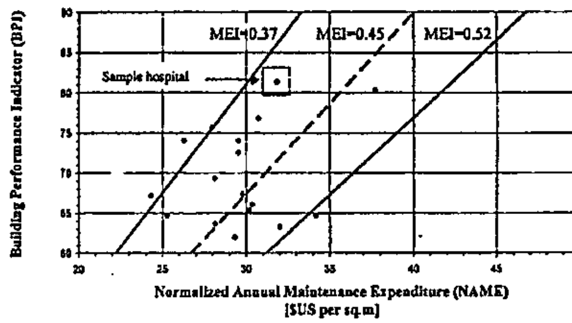


Fig. 3. Building performance indicator of hospital studied compared with population of public acute care hospital facilities in Israel

$$\overline{AC_y} = \frac{\sum_{i=1}^{m} AC_{yi} * a_i}{\sum_{i=1}^{m} a_i} \quad (4)$$

where $AC_{y,i}$=age coefficient of building i in year y; a_i=floor area of building i; and $\overline{AC_y}$=equivalent age coefficient of facility in year y.

The campus is composed of buildings older than 25 years together with buildings that are 5–15 years old. The equivalent age coefficient ($\overline{AC_y}$) of the hospital's buildings portfolio predicts a reduction of 5% in the required resources for maintenance in a planning horizon of 5 years (actual AC_y=1.15 and predicted AC_y=1.09 in 5 years). In light of this, there is no need to expand the allocated resources; this value shows that it will be possible to reduce the resources by up to 5% and still maintain the actual performance level.

3. The number of maintenance employees per 1,000 m^2 is 0.85 as compared with a national average of 0.64. It should be mentioned that the national average itself is high considering the fact that the maintenance model shows that healthcare facilities with a low occupancy level exhibit improved performance when the lion share of the preventive maintenance is contracted out (Shohet 2003b).
4. The MSD shows that the hospital's manpower mix relies on in-house labor—only 30.5% of the maintenance services are contracted out compared with an expected value of MSD > 60%. Such a labor profile reduces the maintenance department's flexibility in mobilizing resources and adapting execution to maintenance needs, which are not fixed, as indicated by the age coefficient (AC_y).
5. The span of control at the FM manager's (MSC) level is nine subordinates compared with the expected span of six in an average size facility. This span is evidently wide considering the size of the hospital's facilities.
6. The BPI is related to the hospital's physical-functional state and is determined according to a sample examination of buildings. The indicator (BPI=81.4 as detailed in Table 1) shows that the physical-functional state of the facility is good. Nevertheless, two of the facility's systems examined were found to be in poor or deteriorating condition: elevators (P_n=57) and water and sanitation (P_n=69.0). Corrective maintenance activities of these systems must take place in any priority setting plan in this facility.
7. Fig. 3 presents an examination of the hospital's BPI (dependent variable) compared with the annual maintenance expenditure per square meter after being "normalized" by

neutralizing the effect of age and occupancy (independent variables). The graph shows the hospital's performance compared with 18 public hospital facilities. The following findings are evident from the figure: (1) the hospital's physical-functional state is good, and is the highest among the population of public acute care hospital facilities in Israel, as measured in the past 3 years; and (2) the MEI value shows that the utilization of maintenance resources in the hospital is efficient but can, nevertheless, be improved by reducing the level of this indicator to 0.37.

8. Hospital maintenance efficiency can be improved by modifying the maintenance organization (reducing the span of control of the facility manager), improving organizational flexibility, increasing the outsourcing components, while gradually reducing the in-house labor sources (and consequently reduce the scope of the maintenance organization). The performance of the facility can be improved by executing corrective maintenance on the water and sanitation and elevators systems.

The deduction of conclusions is realized by the combination of the findings from different KPIs in each area. KPIs 4–7 indicate slack of in-house labor resources, the use of outsourcing is insufficient (KPI 5), the span of control is wide (KPI 6), and that the organizational culture needs shifting to a learning type. A combination of these conclusions outlines the guidelines for corrective activities in organizational and labor aspects.

The study elucidates that a combined analysis of facility KPIs can help create a transparent outline of FM activities with major strengths and deficiencies. In the case study, a facility manager can learn that in spite of the relative efficiency with which maintenance activities are carried out, and the standard level of expenditures, the combined analysis of organization and management indicators revealed that reshaping of organizational parameters (MSC) and the mixture of labor resources can improve the efficiency of the maintenance of the facility. The use of age and occupancy coefficients is essential for assessment of facility needs, and can be an effective measure for long-term facility maintenance and for measuring FM effectiveness.

Discussion

Resources required for the maintenance of existing healthcare facilities and infrastructures are expected to increase significantly within 1 decade. The allocation of resources for maintenance of building portfolios requires an analysis that is based on the buildings' designation, age, mode of use, performance, designed service life, as well as on an analysis of the buildings' life cycle costs. This paper presents a set of KPIs for the strategic and tactical maintenance management of healthcare facilities. These KPIs express the buildings' characteristics, human and organizational maintenance resources, the buildings' performance, and efficiency of resource utilization for maintenance. The parameters enable the reliable and fast identification of maintenance needs, the identification of systems that are in failure condition, as well as setting of priorities for the mobilization and allocation of resources. The parameters enable inter- and intraorganizational benchmarking of maintenance, and address the following principal issues in facilities management and maintenance:

1. Facility performance—overall quantitative measurement of building portfolio performance.
2. Performance of specific building systems—quantitative monitoring of the performance of specific building systems, as well as the identification of resources directed toward each such system (outsourcing versus in-house resources).
3. Prediction of maintenance needs within a 5–10 year planning horizon. Such forecasting can serve as a basis for the planning of building portfolios in the organization and for long-term planning of facility maintenance and management budgets.
4. Internal and external benchmarking, on several levels: On the intraorganizational level, the contribution of various crews and the efficiency of service supplier contractors can be quantified; on the interorganizational level, a profile can be obtained on the scope of resources allocated to maintenance and the efficiency of resource utilization. Short-term goals can be formulated (improved performance, reduction of expenditure and savings) alongside long-term objectives such as reduction of building portfolio size, development of outsourced service provision, and development of a facilities portfolio.
5. Quantification of the investment in maintenance in terms of $/output unit (patient bed). Thus, it is possible to treat maintenance costs as overhead on the products of the organization's core activities.
6. Quantification of the building's operation characteristics: building occupancy and age of buildings. These characteristics enable one to plan the building's maintenance as early as the design stage.

A facility manager can elucidate from the study that a combined diagnosis and analysis of KPIs related to facility parameters, organizational and labor aspects, as well as performance monitoring can provide a transparent outline for tactical and strategic FM. Occupancy and age of a building portfolio are evidently key parameters in setting maintenance short- and long-term plans. The efficiency of maintenance activities can be measured using the ratio between annual maintenance expenditures and the performance score of a facility. The annual maintenance expenditure should be normalized by age and occupancy coefficients.

The model presented in the paper can be improved by the introduction of additional parameters such as the quantification of the influence of the climatic environment of the building portfolio on the facility's performance and maintenance (particularly the exterior envelope). With proper calibration of its coefficients, the model can be implemented on various kinds of buildings: offices, road infrastructures and highways, public facilities, etc. Such calibration is required to the BPI weights and MEI expected categories, in order to adjust them to the structure, the systems, the reinstatement value, and the maintenance costs of the facility. Computerization of the model might afford facility managers with a facility overview that will enable real-time maintenance monitoring. Combined analysis of KPIs can provide guidelines for a strategic facility plan of healthcare facilities. The model can also serve as a design tool of building portfolios and for the planning of FM guidelines on maintenance resource allocation, performance, and supply services management. The system may be expanded to additional core topics of FM such as risk, operational management, and facility development.

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