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A return on investment analysis of applying health monitoring to LED lighting systems

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ABSTRACT

LED lighting systems have become desirable because of their environmental and energy-saving advantages. The lack of information regarding LED reliability is a barrier to the further expansion of LED use, especially in large-scale applications such as street lighting and traffic lights, and safety-related applications such as automotive headlights. Prognostics and health management (PHM) techniques can be utilized to provide LED reliability information to remove this barrier. However, the return on investment (ROI) for LED lighting systems has been of concern. To reduce life cycle cost, a PHM maintenance approach with system health monitoring (SHM) is considered as a means of providing early warning of failure, reducing unscheduled maintenance events, and extending the time interval of maintenance cycles. This paper presents the ROI from a PHM maintenance approach with SHM in LED lighting systems compared with the unscheduled maintenance approach based on different exponential and normal failure distributions. Three different exponential distributions with 10%, 20%, and 30% failure rates were used to investigate how ROI changes with different failure rates. For each failure rate, the mean times to failure (MTTFs) were 41,000 h, 20,500 h, and 13,667 h, respectively. Three normal failure distributions with the same MTTFs as those of the exponential distributions were utilized to compare the results with the exponential distributions. ROI results showed that the PHM maintenance approach with SHM is required for cost savings in the exponential failure distributions. In case of the normal distributions, the PHM maintenance approach with SHM shows ROI benefits when MTTFs are less than 30,000 h. The PHM maintenance approach with SHM needs to be considered in industrial applications based on the reliability of LED lighting systems to maximize the ROI benefit when the total life cycle cost of the system employing the unscheduled maintenance is greater than the total life cycle cost of the system employing the PHM maintenance approach with SHM.

1. Introduction

LEDs have been used in a wide variety of applications, including display backlighting and general illumination [1–3]. An LED consumes less electrical energy (LED power requirements are usually less than 4 W per LED) than an incandescent bulb or a fluorescent lamp because its luminous efficiency (i.e., the ratio between the total luminous flux emitted by a device and the total amount of electrical power) is higher than the luminous efficiencies of incandescent bulbs and fluorescent lamps. Typical value of luminous efficiency (lm/W) of LEDs is 100 lm/W for public lamp and maximum efficiency of LEDs is 180 to 200 lm/W in industrial applications. Incandescent lamp is 15 lm/W; fluorescent is around 100 lm/W; and Na lamp is up to 180 lm/W. Critical key values judging the quality of white light produced by phosphor converted LEDs are known as the color rendering index (CRI) and the correlated color temperature (CCT) [1,3]. CRI of LEDs can be more than 90 as close as CRI of the incandescent lamp. LEDs range from a narrow spectral band emitting light of a single color to a wider spectral band light of white with different distribution of luminous intensity and spectrums and shades depending on color mixing and package design.

LED lighting systems have differentiated themselves from traditional lighting systems (e.g., incandescent bulbs and fluorescent lamps) in terms of flexible lighting control and energy savings. Flexible lighting control means that an LED lighting system can give off light beneficial to human wellbeing by using artificial intelligence-based color and light output control [4]. An LED lighting

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system can provide comfortable white light close to the color of sunlight, which is considered beneficial to human biological rhythms and human psychology (by producing appealing colors that appear in nature) [4]. In addition to comfortable white light, LED lighting technology achieves digital convergence—the convergence of information technologies, telecommunication, consumer electronics, and entertainment into one conglomerate. LED usage is also compliant with environmental regulations for hazardous substances (e.g., the Kyoto Protocol, RoHS, and WEEE).

The LED industry, despite exciting innovations driven by technological advances and environmental/energy-saving potential, still faces challenges to widespread adoption. With the adoption of LED systems in Europe and the US, the LED industry is optimistic about the global LED street lamp market, but the reliability and, thus, the life cycle costs remain a concern. Tao [5] reported that failures of LED modules (i.e., an LED board with an electric driver) include case cracks, driver failures, and ESD failures [6]. Failures at the luminaire level (i.e., a complete lighting unit that includes a lamp or lamps, optics, ballasts or drivers, power supplies, and all other components necessary to have a functional lighting solution) include fractures due to vibrations, moisture-related crack failures, electrolytic capacitor failures, current imbalance failures in parallel LED strings, corrosion due to water ingression, and deposition of out-gassing material on the optics [5,7,8]. The electrolytic capacitor serves as an energy buffer between the pulsating input power and constant output power, without causing flickering while taking up the minimal volume. The electrolytic capacitor is a major failure component, as is cooling fan failure in power supplies [7]. Software failures, damage from strong winds, lens breakage, and electrical compatibility issues have been found at the lighting system level (i.e., a street light with a luminaire) [5,8].

To ensure the proper operation of LED lighting systems in applications that are safety–critical or involve operation in a harsh environment, it is necessary that optical degradation, current sharing, open and short circuit faults, and thermal tracking of LEDs be monitored, especially for high-power applications such as street lighting. Prognostics and health management (PHM) is an extension of condition-based maintenance of critical systems [9,10]. Prognostics is the ability to extrapolate the health condition of a product forward to predict its remaining useful life (RUL). Health management is based on system health monitoring (SHM). System health monitoring is defined as the ability to determine the instantaneous condition of a product through in-situ performance monitoring. The purpose of applying PHM is to assess the degree of deviation or degradation from an expected normal operating condition for a product, such as an LED lighting system [9,10]. The goals of using PHM include providing advance warning of failures, minimizing unscheduled maintenance, extending the time duration of the maintenance cycle, reducing the life cycle costs of equipment, and improving qualification and the design and logistical support of future products [10].

Freddi et al. [11] developed a fault diagnosis and prognosis methodology for LED lighting systems based on system health monitoring with a light sensor, motion sensor, temperature sensor, and current sensors that are controlled by a communications control system. They developed a fault diagnosis and prognosis supervision module integrated into a smart lighting system to detect and isolate faults. This module also provides an estimate of the remaining useful lifetimes of LED lighting systems for industrial and domestic applications. Sutharssan et al. [12] performed LED anomaly detection based on Euclidean distance (ED) and Mahalanobis distance (MD). They collected applied voltage, current, light, and temperature in real time for system health monitoring (SHM). The detection thresholds were identified at the point where the light output started to decrease. Furthermore, real-time system health monitoring was conducted based on data from a voltage sensor and a temperature sensor to monitor board temperature and forward current to predict the remaining useful life of LED lighting systems in the field using prognostics algorithms [13]. Fan et al. [14] monitored chromaticity coordinates u' and v' in real time to detect anomalies based on MD values. Two inputs (voltage and ambient temperature) and two outputs (current and body temperature of the light engine) were monitored to control LED current to a constant value with variation of the ambient temperature for ensuring stable optical output from LEDs [15].

Return on investment (ROI) is the monetary benefit derived from having spent money on developing, changing, or managing a product or system. ROI is a common economic measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. ROI is the ratio of gain to investment, often given by the equation

$$\mathrm{ROI} = \frac{return - investment}{investment} \tag{1}$$

An ROI of 0 represents a break-even situation, i.e., the monetary value gained is equal to the monetary value invested. If the ROI is <0 there is a loss, and if the ROI is >0 there is a gain, i.e., a cost benefit.

Studies have been conducted to evaluate the benefits of LED lighting systems as replacements for conventional lighting systems (such as high-pressure sodium (HPS) lighting systems [16–18], metal halide lighting systems [19], fluorescent lighting [20], mercury lamp lighting [21], and incandescent lamp lighting [22]). ROI research on LED lighting systems [16–22] has assumed that LED lighting systems are successfully maintained over long lifetimes (e.g., 100,000 operating hours [22]). These results have shown that LED lighting systems have financial benefits when compared to conventional lighting systems.

Recent ROI research on LED lighting systems has shown that ROI can be maximized with an interface with a wireless sensor network and by considering the optimal year for replacement of the conventional lighting systems [23,24]. Kathiresan et al. [23] implemented an interactive LED lighting interface using a wireless sensor network to adjust the illumination level of individual lamps to lower maintenance costs and provide higher energy savings for LED lighting systems. Potential energy savings using the smart lighting interface were reported as 3 SGD (Singapore dollars) per year per street light. Ochs et al. [24] developed a model to predict the optimal year for the most cost-effective replacement of HPS lighting systems with LED lighting systems. Delaying the purchase resulted in additional financial benefit because the cost of LEDs continues to decrease, and LED efficiency continues to increase. The proposed method recommended delaying adoption by an average by an average of 6.8 years, as compared to a traditional net present value (NPV) analysis. This delay resulted in an average life cycle savings of 5.37 percent over a 50-year life cycle when compared to the life cycle costs incurred by adopting LED streetlights in the first year that these streetlights were shown to have a positive NPV.

Even though previous ROI research on LED lighting systems assumed that LEDs are good replacements for conventional lighting systems, reliability issues with LED streetlights must be resolved to reduce life cycle costs caused by failures of LED modules, fractures due to vibrations, moisture-related crack failures, electrolytic capacitor failures, current imbalance failures, corrosion, and deposition of out-gassing material on the optics [5–8], as discussed earlier. A PHM approach using SHM can be used to improve the availability and achieve cost benefits when LED streetlights are installed. However, little research has been conducted on the determination of ROI to verify how PHM maintenance using SHM can be cost-effective and applicable to the LED lighting industry.

The ROI from implementing PHM in LED lighting systems was evaluated previously [25]. However, the ROI evaluation of applying health monitoring to LED lighting systems assuming different failure rates and MTTFs (i.e., different operating lives) has not been studied. This paper focuses on an approach to assess the ROI of LED systems using a PHM maintenance approach with SHM assuming exponential time to failure distributions with three different failure rates and normal time to failure distributions with three different MTTFs to investigate how ROI is impacted.

2. ROI methodology

The ROI of a system is driven by the costs associated with reliability and operational availability. Availability is the ability of a service or a system to be functional when it is requested for use or operation, and thus it is a function of both reliability (i.e., the frequency of failure) and maintainability (i.e., the ability to restore the service or system to operation after a failure), including repairs, replacements, and inventory management [26]. Maintenance can be unscheduled maintenance, fixed schedule maintenance, or condition-based maintenance (CBM). Unscheduled maintenance involves adopting a maintenance policy in which maintenance is only performed when the system fails. Fixed-schedule maintenance involves performing maintenance on a fixed schedule, whether it is actually required or not. CBM is based on using real-time data from a system to determine the state of a system via condition monitoring; thus, maintenance is only performed when necessary [27]. CBM provides the ability to minimize the unnecessary replacement of components as well as to avoid failures. Prognostics and health management (PHM) can enable the CBM of electronic systems [10,25].

Electronic systems have traditionally been managed via an unscheduled maintenance policy, i.e., systems are operated until failure and then repaired or replaced. The ROI of PHM in electronics is measured compared to unscheduled maintenance. Applying Eq. (1) to measure ROI relative to unscheduled maintenance gives [28]

$$\mathrm{ROI} = \frac{(C_u - I_u) - (C_{PHM} - I_{PHM})}{(I_{PHM} - I_u)} - 1 \tag{2}$$

where C_u is the total life cycle cost of the system when managed using an unscheduled maintenance policy; I_u is the total investment in the unscheduled maintenance policy; C_{PHM} is the total life cycle cost of the system employing a particular PHM approach; and I_{PHM} is the total investment in the PHM maintenance policy. With electronic systems, the total investment cost in the unscheduled maintenance policy is defined as $I_u = 0$, i.e., the investment cost in the unscheduled maintenance is indexed to zero by definition. This does not simply imply that the cost of performing unscheduled maintenance is zero, but reflects that a maintenance approach relying purely on unscheduled maintenance makes no investment in PHM [28]. Applying $I_u = 0$, Eq. (2) becomes

$$\mathrm{ROI} = \frac{C_u - (C_{PHM} - I_{PHM})}{I_{PHM}} - 1 \tag{3}$$

Eq. (3) simplifies to

$$\mathrm{ROI} = \frac{C_u - C_{PHM}}{I_{PHM}} \tag{4}$$

ROI in this paper is calculated by evaluating each C_u, C_{PHM}, and I_{PHM} in Eq. (4). The PHM investment cost (I_{PHM}) is the effective cost per socket of implementing PHM in a system, which includes the technologies and the support necessary to integrate and incorporate PHM into new or existing systems. A socket is defined as a unique instance of an installation location for a line replaceable unit (LRU) [25,28]. One instance of a socket occupied by an LED luminaire is its location on a particular LED light.

The PHM investment cost (I_{PHM}) is divided into recurring, non-recurring, and infrastructural costs based on frequency and role of the activities:

$$I_{PHM} = C_{NRE} + C_{REC} + C_{INF} \tag{5}$$

where C_{NRE} is the PHM non-recurring costs; C_{REC} is the PHM recurring costs; and C_{INF} is the annual PHM infrastructure costs (each term of I_{PHM} is evaluated in Section 3.3) [28]. C_{NRE} is the PHM total non-recurring costs (i.e., total for all fielded units divided by the number of fielded units). Non-recurring costs are one-time only activities that usually occur at the beginning of the timeline of a PHM program, although disposal or recycling non-recurring costs would occur at the end [28]. PHM NRE costs are the costs of designing hardware and software to perform PHM. This is the portion of the NRE cost charged to each unit. C_{NRE} includes the following terms:

$$C_{NRE} = C_{dev\_hard} + C_{dev\_soft} + C_{training} + C_{doc} + C_{int} + C_{qual} \tag{6}$$

where C_{dev_hard} is the cost of hardware development of SHM; C_{dev_soft} is the cost of software development of PHM; $C_{training}$ is the cost of training; C_{doc} is the cost of documentation; C_{int} is the cost of integration; and C_{qual} is the cost of testing and qualification of PHM.

PHM management recurring costs (C_{REC}) are related to activities that occur continuously or regularly during a PHM program. C_{REC} is calculated as

$$C_{REC} = C_{hard\_add} + C_{assembly} + C_{install} \tag{7}$$

where C_{hard_add} is the cost of PHM hardware added to each LED light; $C_{assembly}$ is the cost of assembly and installation of the hardware in each LED light (or socket), or the cost of assembly of PHM hardware for each socket or for each group of sockets; and $C_{install}$ is the cost of installation of PHM hardware for each socket or for each group of sockets, which includes the original installation and re-installation upon failure, repair, or diagnostic action.

PHM infrastructure costs (C_{INF}) are the costs of support features and structures necessary to sustain PHM over a given activity period [28,29]. C_{INF} associated with the application and support of PHM is evaluated as

$$C_{INF} = C_{prognostic\ maintenance} + C_{decision} + C_{retraining} + C_{data} \tag{8}$$

where $C_{prognostic\ maintenance}$ is the cost of maintenance of prognostic devices; $C_{decision}$ is the cost of decision support; $C_{retraining}$ is the cost of retraining to educate personnel in the use of PHM; and C_{data} is the cost of data management, including the costs of data archiving, data collection, data analysis, and data reporting [28,29].

In the case of PHM with SHM to LED lighting systems, the investment cost (I_{PHM}) includes all the costs necessary to develop, install, and support a PHM approach in a system, including the possible cost of purchasing additional LRUs due to pre-failure replacement of units; while the avoided cost is a quantification of the benefit realized through the use of a PHM approach. The simulation performed in this paper has unique characteristics for LED lighting systems, such as parameter selections and assumptions, as discussed in Section 3. The methodology used to assess ROI is performed using a stochastic discrete-event simulation that follows the life history of a population of LED lighting systems containing one or more LRUs and determines the effective life cycle costs and failures avoided for the sockets. In order to capture uncertainties in the characteristics of LRUs and in the performance of PHM approaches and structures, the simulation follows a population of sockets by sampling the probability distributions associated with time to failure and provides results in the form of the life-cycle cost distributions. For the simulation, the values of

Table 1
PHM investment costs (I_{SHM}) per LRU [28,29].

PHM non-recurring costs (C_{NRE})	$39
C_{dev_hard}	$10/LRU
C_{dev_soft}	$2/LRU
$C_{training}$	$15/LRU
C_{doc}	$1/ LRU
C_{int}	$2/LRU
C_{qual}	$9/LRU
PHM recurring costs (C_{REC})	$155
C_{hard_add}	$25/LRU
$C_{assembly}$	$65/LRU
$C_{install}$	$65/LRU
PHM infrastructure costs (C_{INF})	$20.3/year
$C_{prognostic\ maintenance}$	$2.7/LRU
$C_{decision}$	$5/LRU
$C_{retraining}$	$3/LRU
C_{data}	$9.6/LRU

PHM investment costs (see Table 1 in Section 3.3) were adopted to simulate the ROI of LED lighting systems from case studies in [28,29] with appropriate modification for LED systems.

3. ROI analysis of applying system health monitoring to LED lighting systems

Our ROI evaluation considers the acquisition of a precursor-to-failure PHM approach for LED lighting systems, in this case, 100,000 LED street lights. The representative LRU (i.e., line replaceable unit: a modular component within a system where all of the maintenance actions required to replace the component can be performed without having to return the system to a maintenance facility) in an LED street light is an LED luminaire (i.e., a complete lighting unit that includes a lamp or lamps, optics, ballasts or drivers, power supplies, and all other components necessary to have a functional lighting solution). The LED luminaire is then installed on top of a pole to create each street light. A socket is defined as a unique instance of an installation location for an LRU [25,28]. One socket occupied by an LED luminaire is located on top of the pole on each LED light so that the luminaire can be replaced and plugged into the electrical connection of the light. In this paper, one LRU is installed into one socket in each LED light (i.e., system).

Accordingly, the number of LRUs, sockets, and systems in the “fleet” is presumed to be 100,000. An LED luminaire is assembled on the top of a pole for LED street lighting. The rate of 4100 h/year for the annual operating schedule assumes 11 h of operation per night and applies to lamps that will be turned on and off once each night in accordance with a regular operating schedule selected by the customers [16]. Although LED streetlights are expected to have lifetimes that range from 50,000 to over 100,000 h (roughly 12 to 29 years at 4100 h per year), it is assumed that LED luminaires would still require some level of maintenance.

It is assumed that SHM is conducted in real time based on data collected by sensors for vibration, light, color, voltage, current, and temperatures integrated into LED lighting systems to detect and isolate faults and provide an RUL prediction using the PHM approach. A fault diagnosis and prognosis of LED lighting system based on SHM collects data using a light sensor, motion sensor, temperature sensor, voltage, and current sensors [11]. Anomaly detection is assumed to be conducted with MD and ED detection algorithms [12]. The detection thresholds are identified at the point where the light output and color start to decrease. Furthermore, real-time system health monitoring is conducted based on in-situ data to predict the remaining useful life of LED lighting systems in the field using prognostics algorithms [13,14].

The process flow for analyzing the ROI of a precursor-to-failure PHM approach using SHM relative to unscheduled maintenance is shown in Fig. 1 [28]. First, determine the prognostic distance that minimizes the life cycle cost for the precursor-to-failure PHM approach for a population of sockets. Second, track a socket through its entire life cycle using both an unscheduled maintenance approach and the PHM maintenance approach. Third, evaluate C_u, C_{PHM}, and I_{PHM}. Fourth, calculate the ROI of PHM relative to unscheduled maintenance for the socket using Eq. (2). Fifth, determine the ROIs for the population of sockets. Sixth, repeat this flow for each member of the population of sockets. An explanation of the details of this process flow can be found in Sections 3.1–3.4.

3.1. Failure rates and distributions for ROI simulation

Three-parameter Weibull distributions are applied to life distributions to calculate the life cycle cost of LED lighting systems, because a wide diversity of hazard rate curves can be modeled with the Weibull distribution. The distribution can be approximated to other distributions, such as the exponential distribution, Rayleigh distribution, lognormal distribution, and the normal distribution under special or limiting conditions. The Weibull distribution has been used for life distributions for industrial reliability test data or field test data of LEDs. The Weibull distribution can model a wide variety of data based on the selection of the shape parameter. If the shape parameter is equal to 1 (i.e., the failure rate is constant), then the Weibull distribution is identical to the exponential distribution. If the shape parameter is 3 to 4, then the Weibull distribution approximates a normal distribution.

The simulations in this paper are based on the concept of the “bathtub” curve for modeling the reliability of LED luminaires. The lifetime of a population of LED luminaires consists of an infant mortality period with a decreasing failure rate (i.e., the shape parameter is less than 1), followed by a long useful life period with a low, relatively constant failure rate of random failures (i.e., the shape parameter is approximately 1; an exponential distribution), and concluding with a wearout period that exhibits an increasing failure rate (i.e., the shape parameter is greater than 1; a normal distribution). This paper focuses on the useful life period and the wearout failure period. It is assumed that a mature product where design issues were resolved in the design process and are not relevant to the commercial LEDs.

The failure distributions of LED lighting systems are assumed to be exponential distributions or normal distributions with different

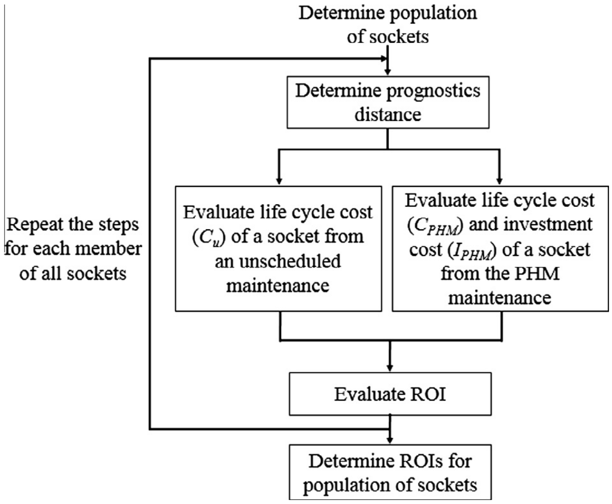

Fig. 1. Process flow for analyzing the ROI of a precursor-to-failure PHM approach using SHM relative to unscheduled maintenance [28].

constant failure rates (in the case of the exponential distribution) and different mean times to failure (MTTFs) to investigate how ROI changes if different LED lifetimes are selected in the population of LED lighting systems. In a realistic system, multiple failure mechanisms may need to be considered; the actual failure rates and MTTFs may be different from those in this study; and the distributions may be other than normal or exponential. However, the ROI methodology applied to LED lighting systems introduced here is applicable to any failure distribution and lifetime of an LED, because the ROI analysis methodology is independent of the reliability information.

For exponential failure distributions, three different failure rates are considered: 10%, 20%, and 30% annually. Each failure rate corresponds to an MTTF of 10 years (41,000 h), 5 years (20,500 h), and 3.3 years (13,667 h), respectively. These different cases using the exponential distributions are modeled with three-parameter Weibull distributions: TTF1 ($\beta = 1$, $\gamma = 0$ and $\eta = 41{,}000$), TTF2 ($\beta = 1$, $\gamma = 0$ and $\eta = 20{,}500$), and TTF3 ($\beta = 1$, $\gamma = 0$ and $\eta = 13{,}667$), respectively, as shown in Fig. 2.

Alternative normal distributions with the same characteristic lives (i.e., same η) as the exponential distributions are modeled with three-parameter Weibull distributions: TTF4 ($\beta = 3.5$, $\gamma = 0$, and $\eta = 41{,}000$), TTF5 ($\beta = 3.5$, $\gamma = 0$, and $\eta = 20{,}500$), and TTF6 ($\beta = 3.5$, $\gamma = 0$, and $\eta = 13{,}667$), as shown in Fig. 3. It is assumed that LED lights will most likely fail at 41,000 h, 20,500 h, and 13,667 h in both types of failure distributions. The LED lighting system is considered to have 4100 annual operational hours [30]. The maximum lifespan for LED streetlights is assumed to be 82,000 h (20 years of operation based on 4100 h/year) for ROI simulation. This assumption will likely overstate the lifetime of some LED lights due to reliability issues in LED lighting systems [31].

3.2. Determination of prognostics distance

Replacement or repair time (the time between failure and a completed repair) was considered under both an unscheduled maintenance approach and a precursor-to-failure PHM (data-driven PHM) maintenance approach using SHM. For unscheduled maintenance, the time varies from 1 day to 30 days depending on the size of the entire lighting system and the crew responsible for replacing the failed LED lights [32,33]. In Philadelphia, Pennsylvania, for example, streetlights are maintained by three service providers: Philadelphia Street Lighting Division, the street lighting maintenance contractor, and PECO Energy [34]. The street lighting maintenance contractor replaces streetlights that are out of service on a daily basis, while the city's Street Lighting Division maintains out-of-service streetlights on a 10-day basis, and PECO Energy replaces streetlights on a 20-day basis. The time to repair and replace for unscheduled maintenance was presumed to be 14 days after the LED lights failed. The time interval to repair and replace for the precursor-to-failure SHM maintenance approach was assumed to be 1.5 h based on PG&E's report on economic data and scenarios for LED repair cost analysis [34], because the PHM approach using SHM provides early warning of luminaire failures and enables the reduction of replacement/repair time considerably while LED lights are still functioning normally.

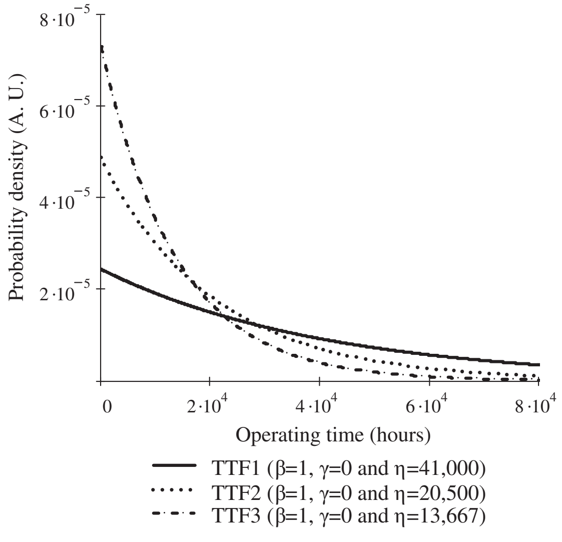

Fig. 2. Weibull distributions of TTF1, TTF2, and TTF3.

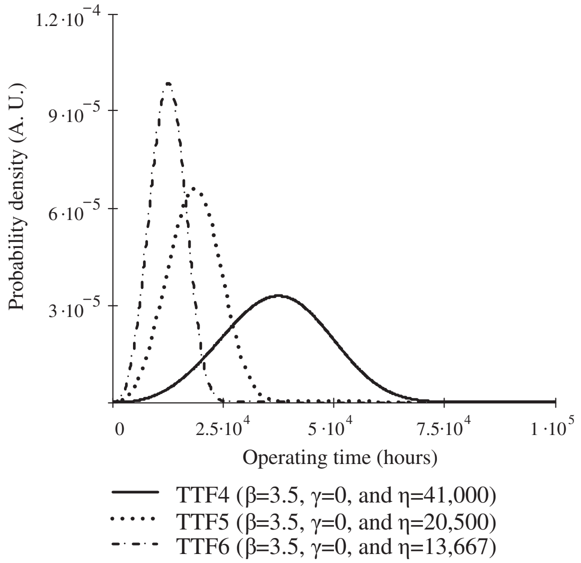

Fig. 3. Weibull distributions of TTF4, TTF5, and TTF6.

Prognostic distance is the time difference between the actual time to failure (TTF) of an LRU and the predicted TTF of the system health monitoring structures with the fuse or other monitored structures for lamps, optics, ballasts, drivers, power supplies, and all other necessary components based on the light sensors, motion sensors, temperature sensors, and current sensors that are manufactured with or within the LED luminaires before LED lighting system failure [11–15,28]. The prognostic structure is an LRU-dependent fuse that was designed to fail at some prognostic distance earlier than a system with light sensors, motion sensors, temperature sensors, and current sensors that are controlled by a communications control system. The LRU TTF probability density function (pdf) and the PHM TTF pdf (from the SHM sensors) could have different distribution shapes and parameters [25,26,28]. Having different shapes and parameters between the LRU TTF pdf and the PHM TTF pdf could increase the life cycle cost. The downtime cost is required to calculate the optimal prognostic distances.

Downtime cost is the value per hour out of service when an LED light (e.g., single LRU) is down and not operating due to repair, replacement, waiting for spares, or any other logistics delay time [25,26]. In this paper, downtime cost is evaluated through the change of crime rate before and after applying PHM with an SHM maintenance policy to LED lighting systems. Case studies of how an improved lighting system in the United States, Great Britain, and Sweden can reduce crime and fear at night and daytime were reported in [35–40]. Improved lighting deters potential burglars by increasing the risk that they will be seen or recognized when committing crimes [35–38]. Police become more visible, thus leading to a decision to desist from crime. Improved lighting can encourage more people to walk at night, which would increase informal surveillance [36–39]. If offenders commit crime in both light and darkness, nighttime arrests and subsequent imprisonment would reduce both daytime and nighttime crime [35]. However, the effects of improved street lighting are likely to vary in different conditions. They are likely to be greater if the existing lighting is poor and if the improvement in lighting is considerable. The effects may vary according to characteristics of the area or the residents, the design of the area, the design of the lighting, and the places that are illuminated [35].

In addition to studies in [35–40] showing that improved lighting systems have reduced crime rates in the United States, Great Britain, and Sweden, Painter and Farrington [41] studied the financial benefits of improved street lighting based on crime reduction. In Dudley, England, where a streetlight system was improved by installing 129 HPS white streetlights over 1500 m of roadway in 4 weeks, the incidence of crime (average crimes per 100 households) decreased by 41% after improved lighting, burglaries decreased by 38%, outside theft/vandalism decreased by 39%, vehicle crime decreased by 49%, and personal crime decreased by 41% [41]. Estimated cost savings from crime reductions in Dudley were broken down in terms of burglary, vandalism, vehicle crime, cycle theft, rob/snatch assault, and threat/pest. The total net savings for the area deducted from the cost savings of having unimproved lighting was £339,186 in 1993. Therefore, the financial benefit per unit lamp was £2629.35.

Adjusting this value for inflation and converting to US dollars, the 2013 benefit per unit lamp is $7739.33. This value was calculated for an entire year; thus, the value per hour is $1.89 per lighting unit. The results showed that the incidence of crime decreased by 43% in the experimental area by installing an improved lighting system [41]. This level of crime reduction can be maintained if the LED lighting system is enhanced by a precursor to failure PHM maintenance approach using SHM. Hence, the downtime cost (value per hour out of service per LRU in a single socket) of an LED with a precursor to failure PHM approach using SHM is $1.89, whereas the downtime cost of unscheduled maintenance of an LED lighting system without PHM is $4.38 based on the assumption that the probability of the crime rate is decreased by 43% due to the improved PHM approach using SHM. The downtime cost is the value per hour out of service when an LED light (i.e., a single LRU) is down and not operating due to repair, replacement, waiting for spares, or any other logistics delay time [26].

For the simulation, an operational profile is set using 11.2 operational hours per mission and the values per hour out of service (i.e., downtime cost) for both precursor-to-failure PHM maintenance using the SHM ($1.89) and unscheduled maintenance ($4.38). In this paper, exponential and normal distributions were chosen to model actual TTFs (i.e., TTF1 to TTF6) of LRUs, and a symmetric triangular distribution was chosen for the PHM TTF from the SHM sensors for illustration. The triangular distribution was assumed to have a width of 600 h. The optimal prognostic distances using precursor-to-failure PHM with SHM for three exponential distributions (i.e., TTF1 to TTF3) and three normal distributions (i.e., TTF4 to TTF6) are shown in Figs. 4 and 5, respectively. The support life (years/socket) is 20 years for both the exponential and normal distributions. Life cycle cost per socket ($) in each TTF distribution represents C_{PHM} in the years of the support life. The minimum prognostic distance using TTF1 = 300 h, TTF2 = 200 h, and TTF3 = 100 h resulted in minimum life cycle costs over the support lives. Similarly, the minimum prognostic distances using TTF4, TTF5, and TTF6 were 400 h, 300 h, and 300 h, respectively. Small prognostic distances cause PHM with SHM to miss failures. As a result, small prognostic distances increase the life cycle cost per socket, as shown in Figs. 4 and 5. Large prognostic distances also increase life cycle cost per socket, because it is conservative to replace LRUs before they fail, as shown in Figs. 4 and 5.

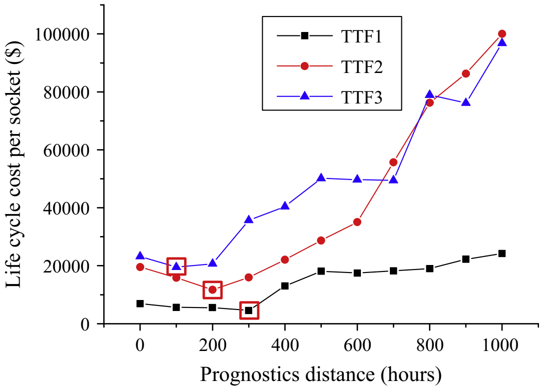

Fig. 4. Variation of life-cycle cost with precursor-to-failure PHM prognostic distance with the exponential distributions (i.e., TTF1 to TTF3).

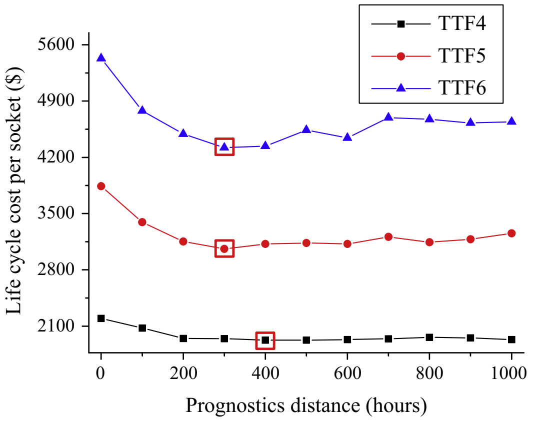

Fig. 5. Variation of life-cycle cost with precursor-to-failure PHM prognostic distance with the normal distributions (i.e., TTF4 to TTF6).

In the case of the exponential distributions for TTF1, TTF2 and TTF3, a large number of failures were observed from the beginning, as shown in Fig. 2. As the prognostic distance was increased to 1000 h, more failure predictions were missed in the early years of operation, because a significant amount of failures were not predicted by SHM devices due to the exponential failure distribution characteristic such that LED street lightings started to fail significantly at time 0. On the contrary, many failures were still captured by the SHM devices in the normal failure distributions, as the prognostic distance increased because it took time to reach the main failure time zone, as shown in Fig. 3. If failure predictions were unsuccessful, an unscheduled maintenance activity was performed, and a timeline for the socket was incremented by the actual TTF of the LRU instance. When the number of unsuccessful events increased, the total life cycle cost increased. These different characteristics of the exponential and normal distributions resulted in an order of magnitude difference in the life cycle cost per socket.

3.3. I_{PHM}, C_{PHM}, and C_U evaluation

The base cost of an LRU (without PHM) is considered to be $690, including a bulk luminaire cost of $675 and a delivery cost of $15. The bulk luminaire cost in the US market varies from $300 to $800; a cost of $690 was selected because it is in the cost range of the market [20]. Labor costs (per unit repaired) are $245 for unscheduled maintenance [16] and $170 for precursor-to-failure PHM maintenance (i.e., preventative maintenance) [34]. An additional labor cost of $50 was considered for an unscheduled maintenance event, because it requires a relatively quick service request to the service provider after an LED light has failed.

Table 1 shows a list of PHM investment costs for C_{NRE}, C_{REC}, and C_{INF}. The values were derived from case studies in [28,29] to obtain the costs of C_{NRE}, C_{REC}, and C_{INF}. C_{NRE} is the PHM development cost for an LED lighting unit; C_{REC} is the cost to realize PHM implementation in the LED lighting unit; and C_{INF} is the cost to maintain PHM implementation resources in an LED lighting unit annually. These values are conservative values, since the costs were determined for more complicated and much expensive commercial aircraft [28,29]. The amount of money for PHM implementation of LED lighting systems is thought to be less than the cost proposed in a previous study for commercial flights; real PHM investment costs may be much less (e.g., 10%) than these values.

LRU-level implementation costs are shown in Table 2. Recurring costs per LRU were calculated with the summation of base costs of an LRU without PHM and PHM recurring costs (shown in Table 1). The recurring costs per LRU totaled $845, and non-recurring costs per LRU totaled $39. For the system implementation costs, each item in Table 3 was considered to evaluate the recurring costs and infrastructure costs of the system. In this paper, it is assumed that one socket has one LRU in the LED lighting system. System implementation costs require installation cost and hardware cost to mount the LRU evaluated in Table 3.

Using the prognostic distances of 300 h for TTF1, 200 h for TTF2, 100 h for TTF3, 400 h for TTF4, 300 h for TTF5, and 300 h for TTF6, as shown in Figs. 4 and 5, a discrete event simulation was performed assuming no false alarm indications, no inventory costs, and a discount rate of 0.07, as shown in Figs. 6–8 for the exponential distributions, and Figs. 9–11 for the normal distributions. The simulation was performed with a stochastic discrete-event simulation that follows the life history of a population of LED lighting systems containing one or more LRUs and determines the effective life cycle costs and failures avoided for all of sockets. In order to capture uncertainties in the characteristics of LRUs and in the performance of PHM approaches and structures, the simulation follows a population of sockets and determines the probability distributions of the life cycle costs. In a support life of 20 years, entire failures were avoided using PHM for both the exponential failure distributions of TTF1 to TTF3 and the normal failure distributions of TTF4 to TTF6. In contrast, 0% of failures were avoided using the unscheduled maintenance approach for both the exponential failure distributions of TTF1 to TTF3 and the normal failure distributions of TTF4 to TTF6, as unscheduled maintenance replaced the LRUs when they failed.

Table 2
LRU-level Implementation Costs.

Recurring costs per LRU $845	
Base cost of an LRU without PHM	$690/LRU
PHM recurring costs (C_{REC})	$155/LRU
Non-recurring costs per LRU $39	
$C_{dev\_hard} + C_{dev\_soft} + C_{training} + C_{doc} + C_{int} + C_{qual}$	$39/LRU

Table 3
System implementation costs.

Recurring costs $90	
Installation per socket	$65/socket
Hardware per socket	$25/socket
Infrastructure costs $20.3	
$C_{prognostic\ maintenance}$	$2.7/year
$C_{decision}$	$5/year
$C_{retraining}$	$3/year
C_{data}	$9.6/year

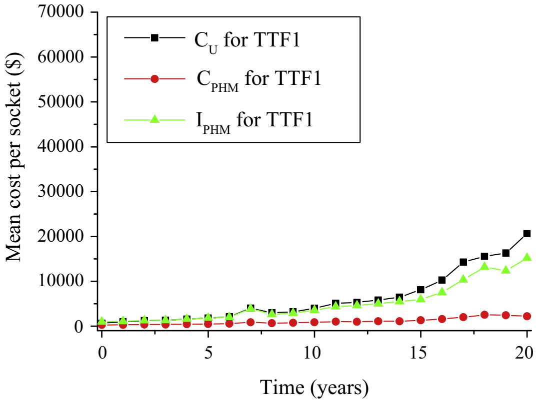

Fig. 6. Mean life cycle costs per socket using TTF1.

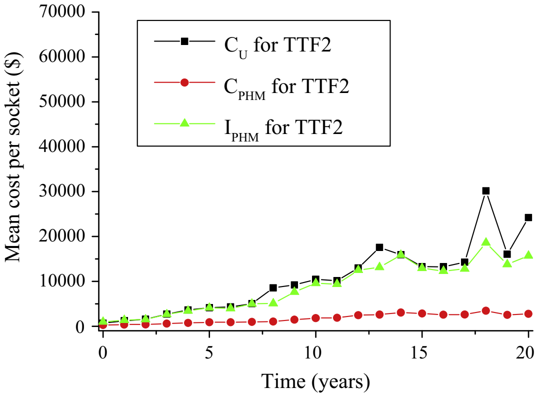

Fig. 7. Mean life cycle costs per socket using TTF2.

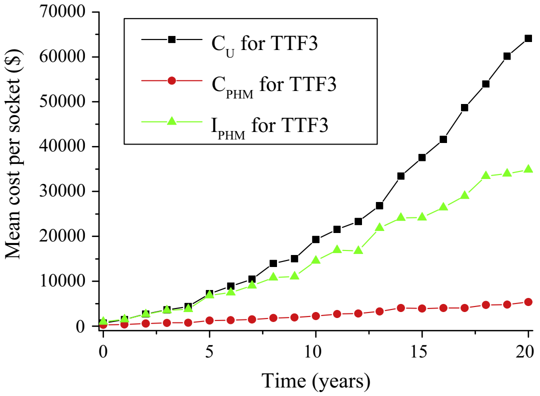

Fig. 8. Mean life cycle costs per socket using TTF3.

TTF1, TTF2, and TTF3 show that the values of CPHM and CU increase steadily due to a failure distribution dispersed from 0 h in Figs. 6–8. As the failure rates increase from 10% to 20% and 30%, the values of CU and CPHM increase. The mean life cycle costs per socket using TTF1 were CU = $20,648 and CPHM = $15,225, with IPHM = $2232 representing the cost of developing, supporting, and installing SHM for the PHM approach. The mean life cycle costs per socket using TTF2 were CU = $24,201 and

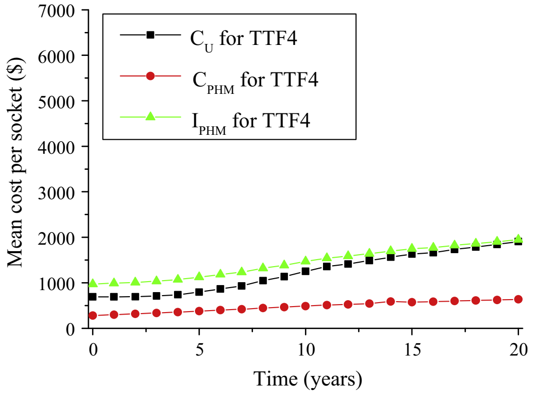

Fig. 9. Mean life cycle costs per socket using TTF4.

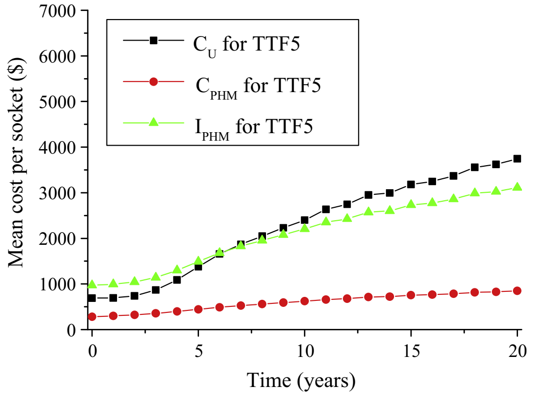

Fig. 10. Mean life cycle costs per socket using TTF5.

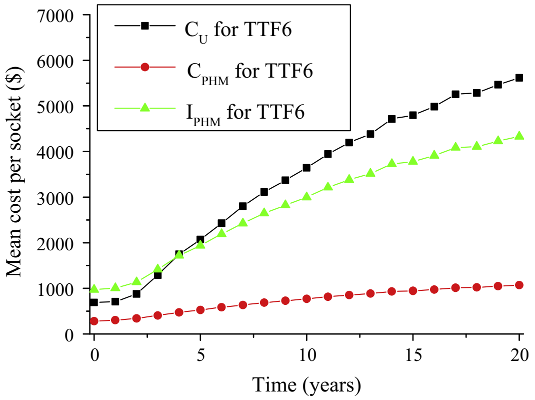

Fig. 11. Mean life cycle costs per socket using TTF6.

CPHM = \$15,703, with IPHM = \$2756. The mean life cycle costs per socket using TTF3 were CU = \$64,116 and CPHM = \$34,859, with IPHM = \$5355. Using Eq. (4), the ROIs of PHM were 2.43 for TTF1, 3.08 for TTF2, and 5.46 for TTF3. The total life cycle cost decreased (e.g., from year 7 to year 8 for CU and CPHM in Fig. 6), because the figures plotted the mean of a distribution of life cycle costs.

TTF4, TTF5, and TTF6 show that the values of C_{PHM} and C_U increase steadily due to a failure distribution dispersed from 0 h in Figs. 9–11. As the MTTF decreases from 10 years to 5 years to 3.3 years, the values of C_U and C_{PHM} increase. The mean life cycle costs per socket using TTF4 were $C_U = \$1907$ and $C_{PHM} = \$1950$, with $I_{PHM} = \$636$ representing the cost of developing, supporting, and installing SHM for the PHM approach. The mean life cycle costs per socket using TTF5 were $C_U = \$3745$ and $C_{PHM} = \$3112$, with $I_{PHM} = \$848$. The mean life cycle costs per socket using TTF6 were $C_U = \$5617$ and $C_{PHM} = \$4330$, with $I_{PHM} = \$1071$. Using Eq. (4), the ROIs of PHM were −0.07 for TTF4, 0.75 for TTF5, and 1.20 for TTF6. During the 20-year support time when all of the TTFs from TTF1 to TTF6 were assumed, the LED lighting system availability decreased using unscheduled maintenance events. The results explain the reason why the ROI of PHM increases as a function of time due to the increase in the life cycle cost of unscheduled maintenance (C_U). Figs. 6–11 show that PHM implementation improves LED lighting system availability for all distributions, because failure is avoided when PHM is applied by replacing the LRU in each socket before the lights fail.

The reliability of LED lighting systems was considered with different failure distributions using exponential and normal failure distributions in this paper. The time to repair and replace for both the unscheduled maintenance and PHM maintenance with SHM was assumed to be 14 days and 1.5 h after the LED lights failed, respectively, as discussed in Section 3.2. During the 20-year support time when TTF1, TTF2, and TTF3 were assumed, the LED lighting system availability decreased using unscheduled maintenance events, as shown in Fig. 12. The LED lighting system availability decreased using the unscheduled maintenance events during the 20-year support time when TTF4, TTF5, and TTF6 were assumed, as shown in Fig. 13.

The unscheduled maintenance using the exponential failure distributions with TTF1, TTF2, and TTF3 (up to 79.2%) shows a more

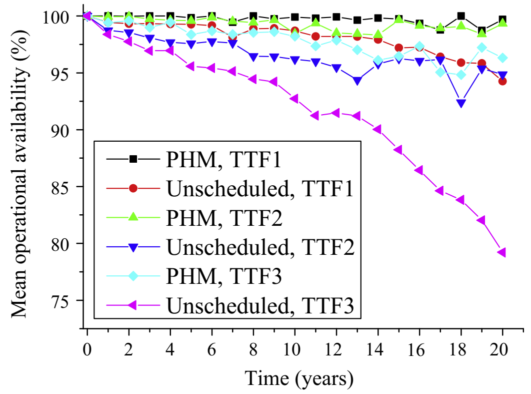

Fig. 12. System availability for the unscheduled and PHM with SHM maintenance approaches based on TTF1, TTF2, and TTF3 exponential failure distributions (100,000 LRUs sampled).

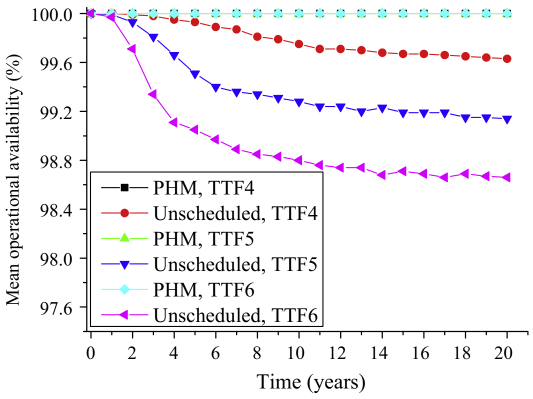

Fig. 13. System availability for the unscheduled and PHM with SHM maintenance approaches based on TTF4, TTF5, and TTF6 normal failure distributions (100,000 LRUs sampled).

significant decrease in the availability than the unscheduled maintenance using the normal failure distributions with TTF4, TTF5, and TTF6 (up to 98.7%). The PHM and solutions of TTF4, TTF5, and TTF6 reflected a lesser impact on availability than those of the exponential distributions, because very few sockets deplete the spares inventory [28]. The spare replenishment lead time was assumed to be 6 months. In TTF3, due to a fast failure rate of 30% with a spare replenishment lead time that was not enough to prepare the spares, the availability was decreased over time for the unscheduled case. The results explain the reason why the ROI of PHM is increased as a function of time due to the increase in the life cycle costs of unscheduled maintenance (C_U) and PHM (C_{PHM}). Figs. 12 and 13 show that PHM implementation improves LED lighting system availability for both exponential and normal failure distributions, because failure is avoided when PHM is applied by replacing the LRU in each socket before the lights fail.

3.4. ROI evaluation

The values for ROI as a function of time using the PHM maintenance approach with SHM applied to LED lighting systems relative to unscheduled maintenance for 100,000 units are shown in Figs. 14–16. The plotted ROIs are for an individual instance of the system (i.e., it is not a mean). Unscheduled maintenance, in this case, means that the LED lighting system will run until failure (i.e., until there is no remaining useful life). The discount rate is assumed to be 7%. The ROI starts at a value of -1 at time 0; this represents the initial investment to put the PHM technology into the LED lighting unit with no return ($C_u - C_{PHM} = -I_{PHM}$). After time 0, the ROI starts to increase. The investment costs represent the largest part of the PHM expenses. The ROI values are initially less than zero, but saving money on maintenance costs begins at the first maintenance event. As the number of maintenance events increases, the PHM system will break even because of the money saved from reduced downtime and maintenance costs.

In the exponential distributions of TTF1, TTF2, and TTF3, there are no failure-free times. LED lighting systems start to fail at year 1. The TTF1 case shows that the ROI is less than 0 until year 5. TTF2 reaches a break-even situation (ROI = 0) earlier than TTF1, because the PHM maintenance approach with SHM of TTF2 provides more benefits as failures rates are 20% when LED lights fail more, and more maintenance events are involved, as seen in Fig. 14. After year 5 (for TTF 1) and year 1 (for TTF 2), the savings in maintenance costs will become greater than the PHM investment costs (ROI > 0). The TTF3 with 30% of the failure rate in the exponential distribution shows an ROI benefit after year 1. The TTF3 has an ROI of -0.08 in year 1, while the TTF2 has an ROI of -0.38 in year 1.

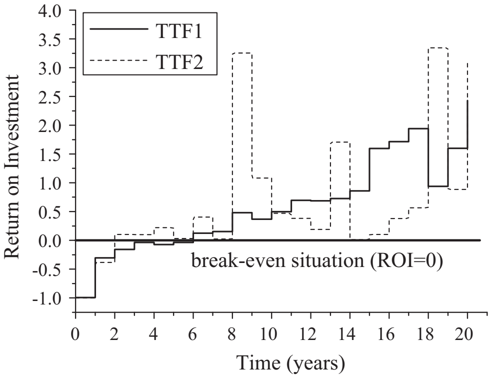

Fig. 14. ROI of LED lighting systems using exponential failure distributions of TTF1 and TTF2.

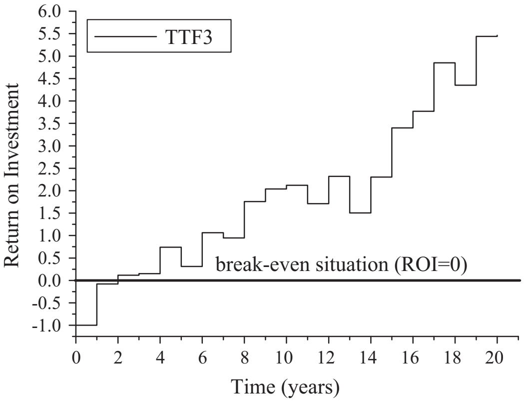

Fig. 15. ROI of LED lighting systems using an exponential failure distribution of TTF3.

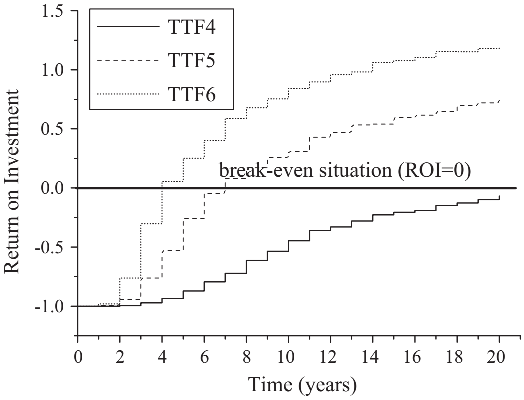

Fig. 16. ROI of LED lighting systems using normal failure distributions of TTF4, TTF5, and TTF6.

There are no failure-free times in the normal distributions of TTF4 (with MTTF 41,000 h), TTF5 (with MTTF 20,500 h), and TTF6 (with MTTF 13,667 h). The MTTF of TTF4 is longer than the MTTFs of TTF5 and TTF6. The ROI of TTF4 could not reach the break-even point until the end of the support life. The PHM approach with SHM does not bring cost savings if the LED lighting system has a long enough lifetime (in this paper, 41,000 h). When the MTTFs are 20,500 h in TTF5 or 13,667 h in TTF6, the PHM maintenance approach with SHM shows the ROI benefits from implementing PHM into an LED lighting system. The TTF5 case shows that the ROI is greater than 0 in year 7. TTF6 reaches a break-even situation (ROI = 0) in year 4, because the PHM maintenance approach with an SHM of TTF6 provides more benefits when LED lights fail more, and more maintenance events are involved.

After the break-even points, the annual total life cycle costs using the precursor to failure PHM approach with SHM decreases due to early warning replacement of failed LRUs (using about 300 h of prognostic distance), shorter time to repair or replacement (1.5 h vs. 157.3 h), lower replacement maintenance costs ($170 vs. $245), and lower downtime costs ($1.89 per hour out of service for single LRUs vs. $4.38), compared to the annual total life cycle costs using the unscheduled maintenance approach. Due to the longer time to replace or repair LRUs, there is a lower replacement maintenance cost with unscheduled maintenance. The time to repair (or replace) is the amount of downtime before and during maintenance service events. However, for the precursor to failure PHM approach with SHM, a maintenance event results in only 1.5 h of downtime, because the maintenance event is performed while the LED light is still working. The cost of implementing PHM will be more than offset by the savings from downtime and also the savings from crime prevention.

In a realistic system, multiple failure mechanisms may be different from the assumed exponential and normal failure distributions in this study. However, the ROI methodology is independent of the reliability information, and any failure distribution and lifetime of LEDs can be applied to the ROI methodology for LED lighting systems, as discussed in Section 3.1. ROI will be evaluated with different total annual life cycle costs of applied maintenance systems and investment costs.

4. Conclusions

Previous studies have demonstrated the return on investment (ROI) benefits of LED lighting systems compared to conventional lighting systems, such as incandescent bulbs or sodium vapor lighting systems. However, as LED lighting systems have been adopted, reliability problems have detracted from the life cycle value of LED lighting systems in fielded operations. In the authors' previous research, the ROI from implementing PHM in LED lighting systems was evaluated [25]. However, the ROI from applying health monitoring to LED lighting systems based on different failure distributions has not been studied. For this reason, this paper focused on an approach to assess the ROI of LED systems using a PHM maintenance approach with SHM in exponential distributions with three different failure rates and normal distributions with three different MTTFs to investigate how ROI changes if failure rates, MTTFs, and failure distributions are varied for the population of LED lighting systems.

LED industry needs to utilize the PHM maintenance approach with SHM based on the reliability of LED lighting systems to maximize the ROI benefit that is returned when the total life cycle cost of the system employing the unscheduled maintenance is greater than the total life cycle cost of the system employing a PHM maintenance approach with SHM. The ROI values were initially less than zero, but saving money on maintenance costs began at the first maintenance event. As the number of maintenance events increases, the PHM system breaks even because of the money saved from reduced downtime and maintenance costs. The PHM maintenance approach with an SHM provided more benefits when LED lights failed more, and more maintenance events were involved under exponential and normal failure distributions.

PHM with SHM implementation into LED lighting systems is currently an emerging technology in the LED lighting industry. In studying this new technology there are limitations in evaluating the ROI of applying health monitoring to LED lighting systems with actual PHM investment costs (I_{SHM}) of the LED street lighting industry data, including PHM non-recurring costs (C_{NRE}), PHM recurring costs (C_{REC}), and PHM infrastructure costs (C_{INF}). Further ROI research on LED street lighting would require real-time field data and knowledge of the main failure distributions from specific locations and environmental conditions. In a realistic system, multiple failure mechanisms may cause failure distributions that are different from the assumed exponential and normal failure distributions in this study. However, this paper will help to initiate the SHM implementation of LED lighting systems to maximize the cost benefits of LED street lightings with ROI methodology independent of the reliability information.

There are many international environmental and legal trends (e.g., China's 12th Five-Year Plan for 2011 to 2015) toward the increased adoption of LEDs for general lighting. However, the LED industry cannot meet this demand if their products do not meet the quality and reliability expectations of the customer. The methodology demonstrated in this paper will help the industry to evaluate LED technologies for their lifetime goals and enable them to make better informed product introduction decisions.

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References

[1] Krames MR, Shchekin OB, Mueller-Mach R, Mueller GO, Zhou L, Harbers G, et al. Status and future of high-power light-emitting diodes for solid-state lighting. J Display Technol 2007;3(2):160–75.
[2] Aoyama Y, Yachi T. An LED module array system designed for streetlight use. In: Energy 2030 conference, 2008. Energy 2008. IEEE; 2008. p. 1–5.
[3] Vittori R, Scaburri A. New solid state technologies and light emission diodes as a mean of control and lighting source applicable to explosion proof equipment, with the scope to reduce maintenance, to limit the risk of bad maintenance and to expand the plants' life, PCIC Europe, 2009. PCIC EUROPE'09. Conference record; 2009. p. 193–8.
[4] Baek J. LED light source technology trend and prospect, Korea photonics technology institute (KOPTI). In: 2010 IT industry prospect conference, Seoul, South Korea; Nov. 17, 2009. p. 1–38.
[5] Tao G. Trends and challenges in solid state lighting reliability, In: 2013 20th IEEE international symposium on the physical and failure analysis of integrated circuits (IPFA), Suzhou, China; July 15–19, 2013, p. 299–302.
[6] Shailesh KR, Kurian CP, Kini SG. Solid state lighting reliability from failure mechanisms perspective: a review of related literature. Int J Semicond Sci Technol 2012;3(1):43–50.
[7] Sinan L. Several reliability issues and solutions for LED lighting systems. Thesis for degree of doctor of philosophy at the university of Hong Kong; Oct. 2013, p. 1–296.
[8] Peck J, Ashburner G, Schratz M. Solid state LED lighting technology for hazardous environments; lowering total cost of ownership while improving safety, quality of light and reliability. In: 2011 Petroleum and chemical industry conference Europe conference proceedings (PCIC EUROPE), Rome, Italy; June 7–9, 2011. p. 1–8.
[9] Saxena A, Celaya J, Balaban E, Goebel K, Saha B, Saha S, Schwabacher M. Metrics for evaluating performance of prognostic techniques, In: 2008 International conference on prognostics and health management, Denver, CO; Oct. 6–9, 2008. p. 1–17.
[10] Pecht MG. Prognostics and health management of electronics. Hoboken, NJ: John Wiley & Sons, Inc.; 2008.
[11] Freddi A, Ippoliti G, Marcantonio M, Marchei D, Monteriu A, Pirro M. A fault diagnosis and prognosis LED lighting system for increasing reliability in energy efficiency buildings. In: IET Conference on control and automation 2013: uniting problems and solutions, Birmingham; June 4–5, 2013, p. 1–6.
[12] Sutharssan T, Stoyanov S, Bailey C, Rosunally Y. Prognostics and health monitoring of high power LED. Micromachines 2012;3:78–100.
[13] Sutharssan T, Bailey C, Stoyanov S. A comparison study of the prognostics approaches to light emitting diodes under accelerated aging. In: 2012 13th International conference on EuroSimE, Cascais; April 16–18, 2012. p. 1/8–8/8.
[14] Fan J, Yung KC, Pecht M. Anomaly detection for chromaticity shift of high power white LED with Mahalanobis distance approach. In: Proceeding of the 14th international conference on electronics materials and packaging (EMAP2012), Hong Kong; 2012. p. 13–26.
[15] Huang B-J, Hsu P-C, Wu M-S, Tang C-W. Study of system dynamics model and control of a high-power LED lighting luminaire. Energy 2007;32:2187–98.
[16] Pacific Gas and Electric Company. LED Street Lighting San Francisco, CA. Emerging technologies program, application assessment report #0727, final report prepared in support of the U.S. DOE solid-state lighting technology demonstration gateway program and PG&E emerging technologies program, city of San Francisco, California (Host Site); Dec. 2008. p. 1–142.
[17] Li Y, Pecht M, Zhang S, Kang R. Return on investment of a LED lighting system. 2011 Prognostics & system health management conference (PHM 2011 Shenzhen), Shenzhen, China; May 2011. p. 1–5.
[18] Shailesh KR, Tunuja S, Kamath MV. Analysis of energy savings from replacing HPSV lighting with LED lighting in road lighting application. In: 2012 International conference on emerging trends in electrical engineering and energy management (ICETEEEM), Chennai, India; Dec. 13–15, 2012. p. 473–477.
[19] Neary M, Quijano M. Solid state lighting for industrial locations. In: 2009 Petroleum and chemical industry conference (PCIC), Anaheim, CA; Sep. 14–16, 2009. p. 1–7.
[20] Strategies Unlimited and PennWell Corporation. The worldwide market for LEDs market review and forecast 2012; July 2012. p. 1–200.
[21] Hsiao H-C, Chang C-H. Economic benefit calculation and optimum design method about roadway lighting. In: 2012 international conference on future

electrical power and energy systems (ICFEPES), vol. 9, Sanya, China; Feb. 21–22, 2012. p. 477–82.

[22] Schratz M, Gupta C, Struhs TJ, Gray K. Reducing energy and maintenance costs while improving light quality and reliability with LED lighting technology. In: 2013 annual IEEE pulp and paper industry technical conference (PPIC), Charlotte, NC; June 23–27, 2013. p. 43–49.

[23] Kathiresan R, Kenneth YJ, Panda SK, Reindl T, Das P. An interactive LED lighting interface for high energy savings. In: 2014 IEEE innovative smart grid technologies – Asia (ISGT ASIA), Kuala Lumpur, Malaysia; May 20–23, 2014. p. 508–13.

[24] Ochs KS, Miller ME, Thal Jr AE, Ritschel JD. Proposed method for analyzing infrastructure investment decisions involving rapidly evolving technology: case study of LED streetlights. J Manage Eng 2014;30(1):41–9.

[25] Chang M-H, Pecht M, Yung KC. Return on investment associated with PHM applied to an LED lighting system. In: 2013 IEEE international conference on prognostics and health management, Gaithersburg, MD, USA; June 24–27, 2013. p. 1–8.

[26] Jazouli T, Sandborn P, Kashani-Pour A. A direct method for determining design and support parameters to meet an availability requirement. Int J Perform Eng March 2014;10(2):211–25.

[27] Williams JH, Davies A, Drake PR. Condition-based Maintenance and Machine Diagnostics. Springer; 1994. p. 1–200.

[28] Feldman K, Jazouli T, Sandborn PA. A methodology for determining the return on investment associated with prognostics and health management. IEEE Trans Reliab 2009;58(2):305–16.

[29] Sandborn PA, Wilkinson C. A maintenance planning and business case development model for the application of prognostics and health management (PHM) to electronics systems. Microelectron Reliab 2007;47:1889–901.

[30] Radetsky L. Specifier reports: streetlights for collector roads. National Light Prod Inform Prog 2010;13(1):1–48.

[31] U.S. Environmental Protection Agency. Energy Star® program requirements for solid state lighting luminaires. Eligibility Criteria – Version 1.3; Feb., 2009. p. 1–23.

[32] Doyle JM. The philadelphia story: every light…every night. Philadelphia's street lighting maintenance plan really is that simple – and that challenging, IMSA Journal; 2004. p. 26–9.

[33] EnergyAustralia. Public lighting management plan; June 2006. p. 1–10.

[34] Pacific Gas and Electric Company. LED Street Lighting Oakland, CA. Emerging technologies program, application assessment report #0714; Jan. 2008. p. 1–65.

[35] Clarke RV. Improving street lighting to reduce crime in residential areas. Problem-oriented guides for police response guides series no. 8, U.S. Department of Justice; Dec., 2008. p. 1–62.

[36] Painter K, Farrington DP. Street lighting and crime: diffusion of benefits in the stoke-on-trent project. Crime Prevent Stud 1999;10:77–122.

[37] Atkins S, Husain S, Storey A. The influence of street lighting on crime and fear of crime. Crime prevention unit paper no. 28. London: Home Office; 1991. p. 1–59.

[38] Pease K. A review of street lighting evaluations: crime reduction effects. Crime Prevent Stud 1999;10:47–76.

[39] Tien J, O'Donnell V, Barnett A, Mirchandani P. Street lighting projects: national evaluation program. Phase 1 report", National criminal justice reference service, US Department of Justice, Public Systems Evaluation Inc; 1979. p. 1–102.

[40] Welsh BC, Farrington DP. Improved street lighting and crime prevention: a systematic review. Swedish National Council for Crime Prevention, Edita Västerås; 2007. p. 1–36.

[41] Painter KA, Farrington DP. The financial benefits of improved street lighting, based on crime reduction. Light Res Technol 2001;33(1):3–12.