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Research paper

# Reward and Penalty Model for the Lighting of Public Thoroughfares Contracts: An Empirical Study in a Distribution Company

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## Abstract

Lighting continuity is one of the preferences of the citizens. The quality of lamps and defect correction time are paramount in lighting continuity. Selecting skilled workers and high-quality lamps has a significant impact on risk reduction during the maintenance contract. Sharing the benefits between the contract parties in the public-lighting system assures a win-win condition support stakeholders' satisfaction. In this research work, we proposed a model to improve the strategies for public-lighting asset management. In this regard, the guarantee period and maximum correction time are used for the reward and penalty mechanism. The results obtained show that the commitment to a lifetime guarantee has encouraged the contractor to purchase quality lamps, and ultimately, receive a reward in 2018 and 2019. Similarly, incentives on the correction time have caused the employees to reduce the detection and correction time to less than two days from 2016 to 2019.

## 1. Introduction

Due to the natural monopoly on the public lighting system, the government must set some policies to cover safety, security, and public expectation. These policies improve the quality of services and people’s satisfaction, and impose considerable maintenance costs. Accordingly, an asset management model for having a sustainable public lighting system is necessary.

### 1.1. Literature Review

Decision-making in asset management becomes problematic, if the asset's failure data are limited and malformed. By gathering some examples from the other industries, a general method has been introduced in [1]. Hundreds of models have been designed for the maintenance of systems. The models are classified into several maintenance group strategies such as run to fail, age replacement, bulk replacement, and contingency maintenance strategy. The approaches has been compared and organized for single and multi-unit systems [2]. A model has been analyzed to maintain multi-unit systems in detail [3]. In this study, the run to fail strategy and the single-unit system has been used.

There is a need to develop mathematical models in order to make the maintenance contracts more productive and the forecast future costs built into the contract price. A conceptual model has been developed for estimating the cost of outsourcing maintenance of complex and essential assets taking into account both the corrective and preventive maintenance as servicing strategies and risks and penalty costs associated with such contracts [4]. In the previous study, the maintenance, inspection, and accident risk costs have been well-estimated, but no specific mechanism has been provided for penalties. A model has been proposed to measure the costs for rescheduling the maintenance interventions, thus considering them defining a service contracts and when running it [5].The spare parts management significantly impacts the equipment availability in maintenance outsourcing, and hence on business success. A decision-making framework to efficiently integrate the contractual conditions with essential spare stock-holding has been provided in [6]. The performance-based contract is able to produce a good service performance compared with the implementation of the in-house system or the contract-based input projects [7]. The suitability of combining project and asset management as integrated approaches has been proposed in public infrastructure sector contracts [8]. The most important variables that affect the operational stage of contracts are the minimum level of performance, mean frequency of inspection, and penalty fee. A sensitivity analysis on the main variables show the importance of flexibility in decisions between the parties in order to improve maintenance decisions [9].

The continuity of supply and the cost of preventing public lighting outages are very important for a distribution company. An assessment of the life cycle of the public lighting technologies for diode lights and sodium vapor lamps has been done in [10]. An economic study on the replacement of the traditional ballasts with electronic ones has been done in public lighting [11] and also a comparative study has been performed between the operation of sodium-vapor bulbs with electronic and traditional ballasts [12]. The lifecycle analysis models for inflammatory bulbs have been investigated, and a modified model has been proposed in order to analyze the lifetime of bulbs [13]. In the previous study, the average lifetime has been considered, while the deviation from the average lifetime that is included in the lamp specifications has a significant effect on the failure rate of a set of lamps.

Fault detection is one of the most critical concerns in the street lighting networks. For high impedance fault detection in the distribution electricity network a method including a combination of the wavelet transform and fuzzy function approximation has been proposed in [14]. Fault detection method using genetic algorithm in clustered wireless sensor networks indicated that the proposed method performs better in fault detection accuracy and a false alarm rate [15]. A new method to estimate the lamp failure rate and the impact of technological improvements on the failure rate of public lighting systems has been proposed, and also a process to select the best bulb in the market has been suggested [16]. However, there is no executive guarantee to ensure the purchase of quality lamps. The contractor has no incentive to procure a higher quality lamp, and does not necessarily follow the recommendations in supplying the lamp. In estimating the labor costs, more attention has been paid to wages according to the law, and no incentive has been considered to reduce the duration of inspections and replace light bulbs. The public-lighting management structure is composed of the three main participants. The regulatory unit, lighting managers, and private contractors are the three main participants in the public lighting management structure. Optimal assignment of price, duration of contracts, and human resource management alleviate the challenges of public lighting maintenance contracts [17]. In calculating the optimal contract duration, it is assumed that the number of lights is constant over a period of 30 years. However, in practice, due to the continuous development of cities, the number of lights will vary, and these changes will challenge the optimal contract period, and must be considered.

## 1.2. Motivation and Contribution

Sharing the benefits between the regulator, public, and private parties in the public lighting system so as assures a win-win-win condition supports the asset management process.

This work is distinguished from the previous researcher works in the following cases:

a) A motivational mechanism is proposed for the reward and penalty schema.
b) Lamp survival factor (LSF) is introduced as a reasonable basis for the natural lifetime guarantee (NLG). It is used as a critical indicator in order to assure the lamp's quality, and the lamp's quality is used for the reward and penalty mechanisms as an acceptable factor to the stakeholders.
c) Failure Detection and correction time (DCT) is a crucial indicator of the executive operators' agility and skill**.** The agility and skill of the executive operators are used for the reward and penalty mechanisms as an inevitable criterion for the stakeholders' satisfaction.
d) The natural and long-time data and irregular annual installation changes are the undeniable and unique features of the case study, and demonstrate the model's ability to predict the conditions in the future contracts.
e) The effect of the mean and standard deviation changes on lamp failure and data loss on failure rate estimation is shown in this work.

In this work, the maintenance costs of public lighting are simulated for a period of thirty years. The variables are classified according to the labor and trade laws. The model provides a reward and penalty mechanism with understandable, simple mathematical functions in order to choose the best policy for the public- lighting contracts.

This work is organized as what follows. In Section 2, the method and formulation for calculating the failure rate is described. The proposed methodology is introduced as an appropriate approach to the reward and penalty mechanism in Section 3. The numerical study and discussion based on an empirical data is presented in Section 4. In Section 5, the conclusion and in Section 6 recommendation is presented. Finally, the case study data and information from the North Kerman Power Distribution Company (NK-PDC) are presented in the appendix.

## 2. Method and Formulations

Damaged lamps in the public lighting systems are replaced with the new ones. As shown in Figure 1 at the beginning, N luminaires are installed to supply lighting. After one year, some lamps have been damaged and replaced with the new ones by the lighting operators, and the others have passed one year of their useful lifetime. At the end of the second year, some previous one-year old lamps have been damaged, and some of them are still working well and have passed two years of their useful lifetime. This procedure also takes place for the new lamps installed at the beginning of the second year. At the end of the second year, the damaged lamps are replaced with the new ones again. Briefly, at the end of each year, some previous sound lamps are damaged, and some of them have passed one more year of their useful lifetime. This cycle continues similarly for the subsequent years [16]. Most of the variable and value guides are demonstrated in Table Some of them are implicitly time-dependent. In other words, $T$ represents the discrete time. $D_j[T]$ is the number of defective lights with $j$ years old at the end of the $T^{th}$ year, and $D[T]$ is the number of defective lights at the end of the $T^{th}$ year. Defected lights at the end of the $T^{th}$ year are equal to the sum of the defected lights with different ages at the end of the $T^{th}$ year.

Based on this model for calculating defective lights at the end of each year, Equation (1) is established.

$$\lambda_i = D[T] = \sum_{j=1}^{Y} D_j[T] \tag{1}$$

The number of intact lights at the first of each year is calculated based on Equation (2), where $j = 1, 2, ..., Y$ .

$$S[\mathrm{T}] = S_0[T] + \sum_{j=1}^{Y} S_j[T] \tag{2}$$

In this equation, $S_0[T]$ is the number of zero age lights at the start of each year. In other words, $S_0[T]$ is equal to $D[T]$, the number of defective lights at the end of the previous year, and $S_0[0]$ is equal to $N$ , the number of installed lights at the beginning of the first year. The number of intact lamps with different ages and defective lights is estimated based on Equation (3)

$$\begin{cases} D_j[T] = S_{j-1}[T-1] \cdot P_j \\ S_j[T] = S_{j-1}[T-1] \cdot (1-P_j) \end{cases} \tag{3}$$

In this equation, $P_j$ is the probability of damaging lights at the age of $j$ years. $S_{j-1}[T]$ is the number of intact lights by the age of $(j-1)$ at the end of the $T^{th}$ year. As mentioned in [16], a normal distribution function is suitable for modeling the light lifetime. As shown in Equation (4) the probability of light failure in the $j^{th}$ year is equal to the integration of the normal distribution function in the interval $(-\infty, x_j]$ [18].

$$P_j = \int_{-\infty}^{x_j} \frac{1}{\sqrt{2\pi}} e^{-\left(\frac{(x_j-\mu)^2}{2\sigma^2}\right)} dx_j \tag{4}$$

In this equation, $x_j$ is equal to $(h \times j)$ and is a non-standard normal distribution function, and $\mu$ and $\sigma$ are the average lifetime and standard deviation, respectively. $h$ is the average number of hours that each light is on in a year. The number of full-time workers in the $T^{th}$ year is obtained as follows:

$$N_{wr}^{T} = \frac{D[T]}{\eta_{wr}} \tag{5}$$

In this equation, $D[T]$ is the number of defective lamps in the $T^{th}$ year, $\eta_{wr}$ is the Human Resource (HR) efficiency index, and signifies the average number of damaged lamps that each worker should replace in a year, and $N_{wr}^{T}$ is the number of required workers in the $T^{th}$ year. The number of full-time workers in the $T^{th}$ year resulting from Equation (6) as follows:

$$N_{we}^{T} = \begin{cases} [N_{wr}^{T}] & ; \; if \;\; \dfrac{N_{wr}^{T} - [N_{wr}^{T}]}{[N_{wr}^{T}]} \le \dfrac{h_m}{h_c} \\ [N_{wr}^{T}] + 1 ; & if \;\; \dfrac{N_{wr}^{T} - [N_{wr}^{T}]}{[N_{wr}^{T}]} > \dfrac{h_m}{h_c} \end{cases} \tag{6}$$

In this equation, $N_{we}^{T}$ is the number of full-time required workers in the $T^{th}$ year, $[N_{wr}^{T}]$ is the bracket function of $N_{wr}^{T}$ (integer value of $N_{wr}^{T}$ ), $h_m$ is the maximum extra work duration (for example 2 h a day), and $h_c$ is the number of regular working hours (for example, 8 h a day).

The number of full time workers in the $T^{th}$ year resulting from Equation (6) is as follows:

$$N_{we} = \min\left\{N_{we}^{T}\right\}, \forall T \in \left\{1, 2, 3, ..., Y\right\} \tag{7}$$

In this equation, the number of full-time required workers is $N_{we}$

A trade-off must be made between the extra work duration for full-time workers and the newly required employed workers so that the efficiency of the workers is enhanced, and the workers' wages are decreased simultaneously.

If extra work of the fulltime workers is required, then the extra hours for a worker per day in the $T^{th}$ year can be calculated as:

$$h_a^T = \begin{cases} (\frac{N_{wr}^T}{N_{we}} - 1) \times h_c ;if & \frac{N_{wr} - [N_{wr}]}{[N_{wr}]} \le \frac{h_m}{h_c} \\ 0 \qquad ;if & \frac{N_{wr} - [N_{wr}]}{[N_{wr}]} > \frac{h_m}{h_c} \end{cases} \tag{8}$$

In this equation, $h_a^T$ is the extra work duration, and $h_c$ is the number of regular working hours (for example 8 h a day). The number of new workers to be employed in the $T^{th}$ year is calculated as follows:

$$N_{wn}^T = N_{wr}^T - N_{we} \tag{9}$$

In this equation, $N_{wn}^T$ is the number of new workers to be employed in the $T^{th}$ year. The total cumulative human resource cost in the lifespan of lighting system (Y years) is obtained as:

$$HRC = \sum_{T=1}^{Y} \left\{ \begin{matrix} (N_{we} + N_{wn}^T) \times (W_b + W_a) \\ +(N_{we} \times \frac{h_a^T \times 365}{\eta_{wr}}) \times (W_b(1+a)) \end{matrix} \right\} \cdot (1+i_{fn})^T \tag{10}$$

In this equation, $HRC$ is the human resource cost, $W_b, W_a$ are the basic wage of workers in the first year and augmented workers cost, $\alpha$ is the presence of extra work costs (for example 40%), and $i_{fn}$ is the inflation rate.

$$LP = \sum_{T=1}^{Y} LP^0 \times (1+i_{fn})^T \tag{11}$$

In this equation, $LP^0$ is the basic lamp price in the first year. The total cumulative cost in the lifespan of lighting system (Y years) can be obtained as:

$$TCC = HRC + LP \tag{12}$$

In Equation (13) $\beta$ is the interest rate, Since the inflation rate has been taken into account, a certain percentage of all charges (for example 10%) has been considered as the contractor's interest, regardless of whether the contract is for one year or several years. The other parameter is the yearly side cost of the lighting system. The total cumulative price for lifespan of the lighting system can be obtained as:

$$TCP = (TCC + CSC)(1+\beta) \tag{13}$$

$$CSC = \sum_{T=1}^{Y} SC^0 \times (1+i_{fn})^T$$

The total cumulative price (TCP) is a function of the total cumulative cost (TCC), cumulative side cost (CSC), and benefit rate.

## 3. Proposed Methodology

Public lighting management from the viewpoint of city residents improves the social welfare, and lighting continuity is one of the citizens' preferences. The quality of the lamps and lighting defect detection and correction are essential in lighting continuity. The reward and penalty mechanism plays a vital role in this regard. Selecting the labor and lamps has a significant impact on risk reduction during the contract period. Guarantee and maximum permissible lighting defect detection and correction time are used for the reward and penalty mechanism in this research work.

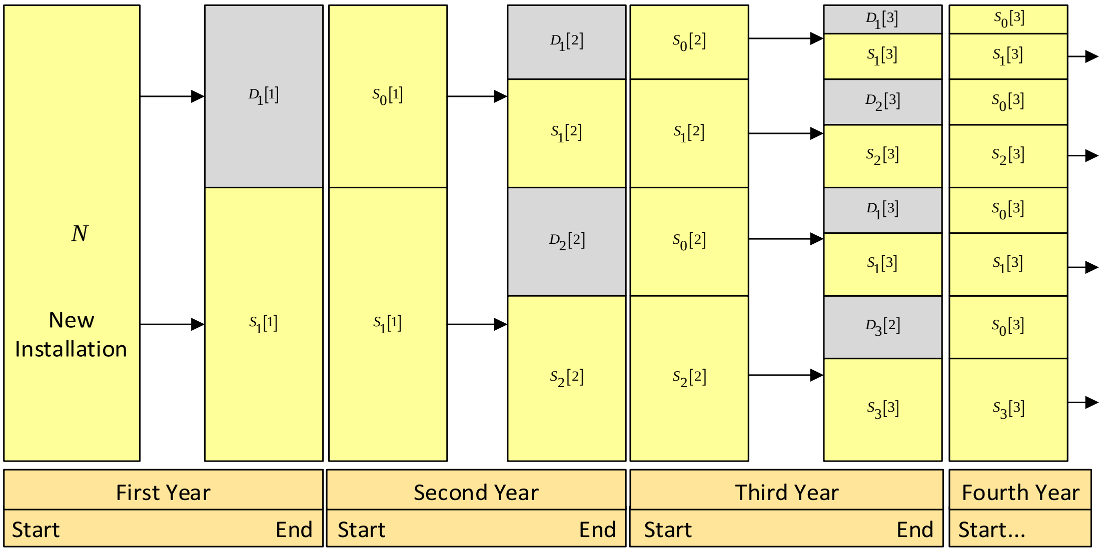

**Figure 1. Lamps replacement process over time.**

### 3.1. Guarantee Natural Lifetime

The manufacturers generally guarantee the product unconditionally for a period in order to ensure quality, and durability, and have the ability to produce a wide range of lamps with different lifespans. Naturally, a longer life requires a higher price. LSF is a characteristic of lamp that the manufacturers publish in manuals. LSF is the ratio of the electrically intact lamps to the total number of lamps in a specific quantity of lamps at a defined number of hours of operation in percentage.

The lamp failure rate can be estimated from the LSF data. In other words, the failure rate based on LSF will be a good basis for the natural lifetime guarantee. In order to avoid complexity, it is assumed that the external factors cause an increasing failure rate to $(1+\delta)\lambda_i$ . Thus, the reward and penalty mechanism for NLG

Can be proposed as follows:

$$\begin{cases} RC = +\left|(CP_{\lambda_a} - CP_{(1+\delta)\lambda_i})\right| \ , \lambda_a \le (1+\delta)\cdot\lambda_i \\ PC = -\left|(CP_{\lambda_a} - CP_{(1+\delta)\lambda_i})\right| \ , \lambda_a > (1+\delta)\cdot\lambda_i \end{cases} \tag{14}$$

In this equation, RC is the reward cost, PC is the penalty cost, $\lambda_a$ is the actual failure rate, and $\delta$ is a positive number less than one that shows the extra failure rate due to the external factors.

### 3.2. Detection and Correction Failure

In the public lighting systems, the defects are reported through night visits or citizens, and are fixed during the day. An improper planning will lead to delays in fixing the defect. The public lighting energy consumption for a number of lights during the year can be calculated from the following equation:

$$\begin{cases} ENS_a = E_N - E_{ai} \\ E_N = N \times W_{watt} \times h \times 365 \\ ENS_a = \lambda_a \times W_{watt} \times h \times t_{xi} \\ ENS_p = \lambda_a \times W_{watt} \times h \times t_p \end{cases} \tag{15}$$

In this equation, $E_N$ is the energy consumption for N luminaires in each year, $ENS_{\lambda i}$ is the unused energy due to lamp defect in the $i^{th}$ year, $E_{ai}$ is the actual energy consumption in the $i^{th}$ year, $W_{watt}$ is the power consumption of each luminaire, h is the daily switch on hour of lamp, and $t_{xi}$ is the actual average time that luminaire is off due to defect lamp. For calculating the actual average off time, rewrite the Equation (16) as follows:

$$t_{xi} = \frac{N \times 365}{\lambda_a} - \frac{E_{ai}}{\lambda_a \times h \times W_{watt}} \tag{16}$$

For citizen satisfaction, it is necessary to decrease $t_{xi}$ as much as possible. For this purpose, the reward and penalty mechanism for DCT can be proposed as follows:

$$\begin{cases} 1)\, RC = +\gamma \times HRC \ , \ \ 0 < t_x \le t_p \\ 2)\, PC = -\gamma \times HRC \ , \ \ t_p < t_x \le 2t_p \\ 3)\, PC = -2\gamma \times HRC \ , \ \ 2t_p < t_x \le 3t_p \\ 4)\, PC = -3\gamma \times HRC \ , \ \ 3t_p < t_x \end{cases} \tag{17}$$

In this equation, $0 < \gamma < 1$ is the reward and penalty factor (for example 0.1), and $t_p$ is the maximum permissible time that a luminaire can be off (for example 2, day per each defect). Thus, if the actual time is larger than the maximum permissible time, the penalty cost calculated based on the function 2, 3, and 4, and if it is smaller than $t_p$ , the reward cost is calculated based on function 1.

### 3.3. Improving Influential Categories

The model of contract pricing and influential categories is shown in Figure 2. All parties to the contract are subject to the labor and trade laws, so in the model, the labor parameters are separated from the economical parameters. The contractor is committed to perform the activities on time and with quality. Human resource plays an important role in this case, so the main mission of a contractor is to choose the right workforce. In the model, the contractor performance index is shown by the human resource efficiency index ( $\eta_{wr}$ ). The manufacturer is committed to guarantee LSF. A reasonable price plays an important role in this case, so the most important mission of a manufacturer is to provide a qualitative product at a reasonable price. In the model, the manufacturer's performance index is shown at a lamp price with a guaranteed LSF. The employer is undertaken to provide work explanation, workload, expected technical specifications like average lifespan, and standard deviation. Based on the employer desires, the failure rates ( $\lambda_i$ ) are calculated. All parties to the contract are subject to the labor laws, so the number of workers required and extra work hours ( $N_{wr}, h_a$ ) are calculated based on the labor working hour laws' constraints. The estimated cost for the beginning of the first year is calculated based on the workers wage and lamp price. The inflation rate is included in the total cost (TC) estimation. Ancillary costs including transportation and temporary warehouse are added in the contract price (CP) and the contractor's profit applied to it. Eventually, TCP is calculated based on the reward and penalty mechanism.

**Table 1.Variable and value guide.**

| Variable | Description | Value/Unit | Variable | Description | Value/Unit |
|---|---|---|---|---|---|
| $\eta_{wr}$ | HR Efficiency Index | 8 Replacement per day | $N_{wr}$ | Required Workers | - |
| $h_c$ | Regular Working hours daily | D:8 hour/Y:2920 hour | $N_{we}$ | Full time Workers | - |
| $h_m$ | Max. Extra Working hours | D:2 hour/Y:720 hour | $N_{wn}$ | New Workers | - |
| $h_a$ | Extra Working hours | - | $\lambda_i$ | Failure Rate | - |
| $h$ | Switch on hours | D:10.8/Y:3942 hour | $\mu$ | Average | 20000 hour |
| $i_{fn}$ | Inflation Rate (%3) | 3% | $\sigma$ | Std. | 4000 hour |
| $W_{by}, W_{bh}$ | Wage of Worker | Y:2400$/h:0.8219$ | $p$ | Probability of Failure | - |
| $W_a$ | Insurance/ Facilities of Worker | Y:800$ | $TC$ | Total Cost | $ |
| $\alpha$ | Percent of Extra Pay | 40% | $SC$ | Side Cost | $ |
| $\beta$ | Interest Rate | 10% | $CP$ | Contract Price | $ |
| $\delta$ | External Factors Effect | $0<\delta<1$ | $\gamma$ | Reward and Penalty Factor | $0<\gamma<1$ |

### 3.4. Contract Pricing Flowchart

Figure 3 shows a flowchart of the improved method for contract pricing. In the first step, after getting the required data (first box), the failure rates at the end of each year are estimated by calculating the probability of lamp failure based on the normal distribution function. On average, each lamp is on for about 11 hours a day. In other words, a lamp works in the first, second, and third years at about 4000, 8000, and 12000 hours, respectively. The probability of lamp failure is obtained from Equation (4). Based on this possibility, some lamps are defective every year. For example, in such cases, the number of sound bulbs is calculated with a lifespan of one year, two years, and three years in the fourth year using Equation (3). Also the number of defective lamps at the end of each year is calculated using Equation (1), and based on that, the number of workers required to replace them is calculated from Equation (5). The number of workers required and extra working hours are calculated subject to the human resource efficiency and labor laws. The number of workers required is calculated annually, and the lowest number in the entire life cycle of the lighting network is considered permanent workers. The amount of extra work is calculated using Equation (8). Suppose that the extra work is less than the allowable overtime ceiling. In that case, it is preferable to refer the extra works to the existing workers; otherwise, the number of new workers required for a fixed-term contract is calculated from Equation (9).

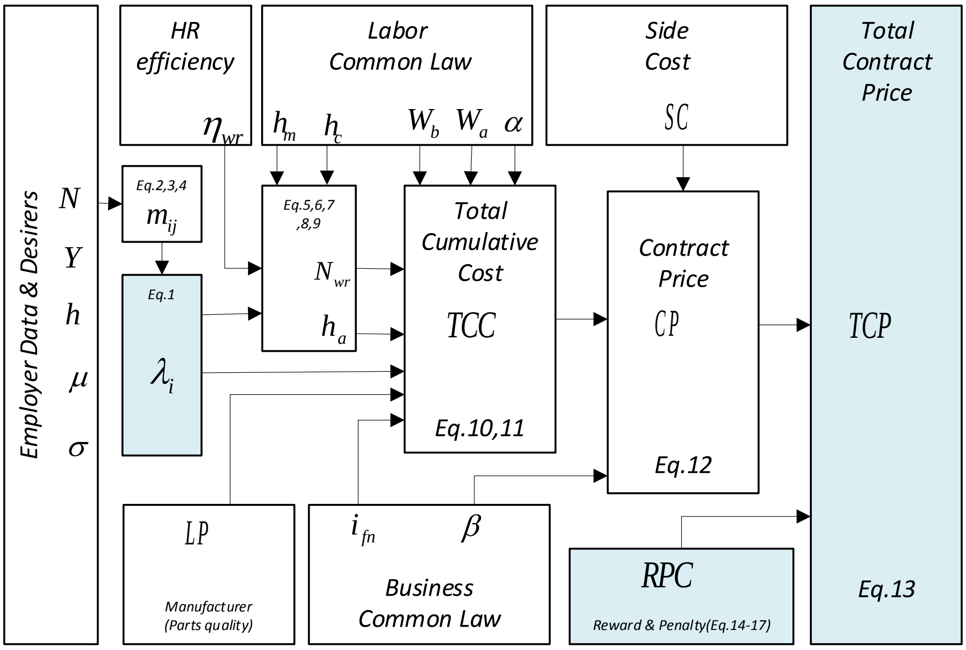

**Figure 2. The procedure of contract pricing and influential categories.**

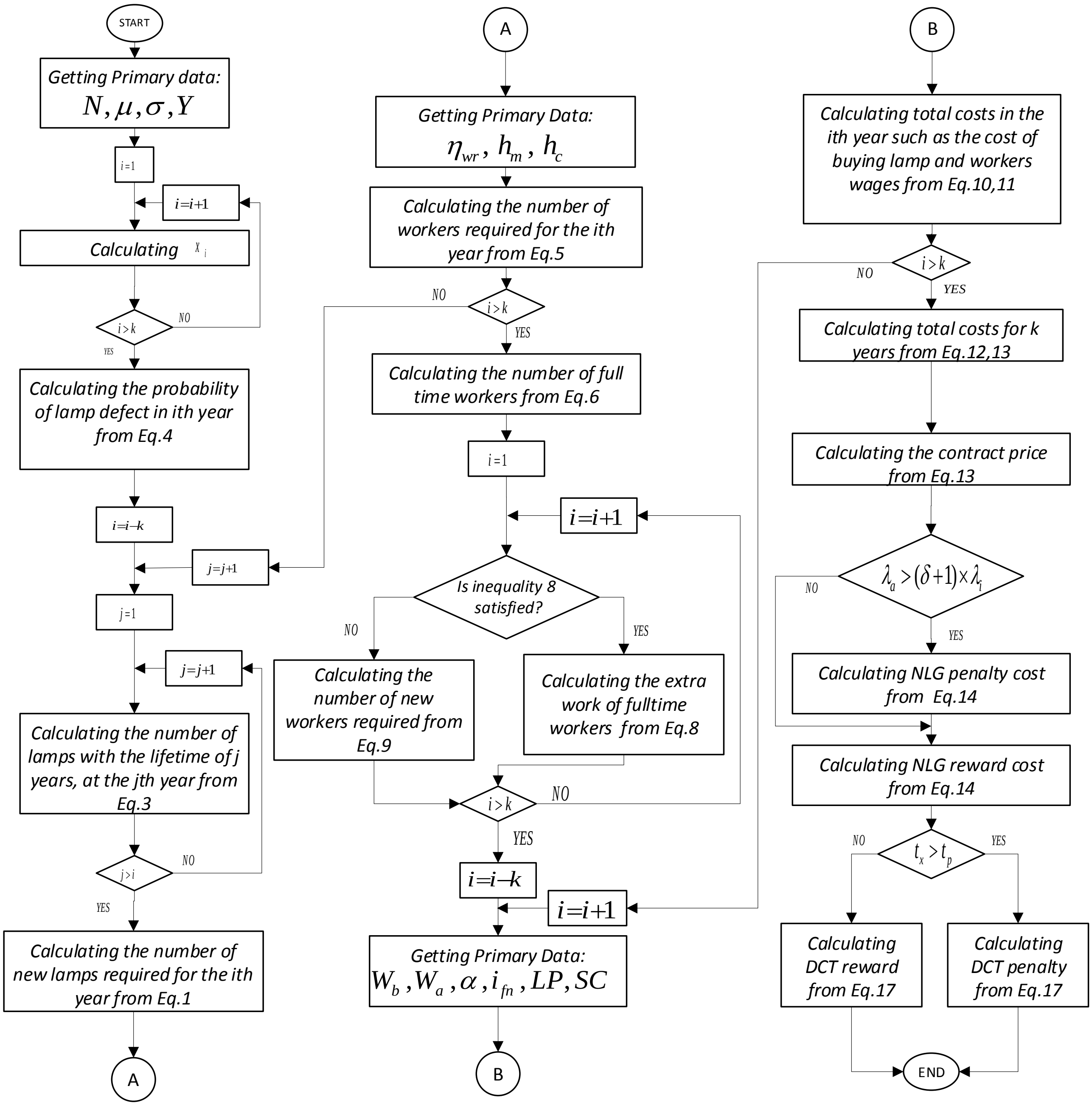

**Figure 3. The flowchart of the improved method for contract pricing.**

After getting the required data, including the labor cost (subject to minimum permissible workers wage in law), wages and overtime of fixed workers over the lifespan of the lighting system, and the wages of new workers in some years are calculated using Equation (10).The cost of purchasing lamps and ancillary costs over the lifespan of public lighting system is estimated using Equations (11) and (13). It should be noted that the inflation rate is applied in the wages, lamps, and side costs in the following years. The total cumulative cost, and total contract price is calculated by Equations (13). In order to motivate the contractor to buy higher quality lamps, a life guarantee mechanism has been considered in Equation (14). On the other hand, in order to increase the speed of identifying and replacing defective lamps, an incentive mechanism has been predicted in Equation (17). Finally, the reward and penalty cost based on the LSF guarantee and permissible detection and correction time is calculated.

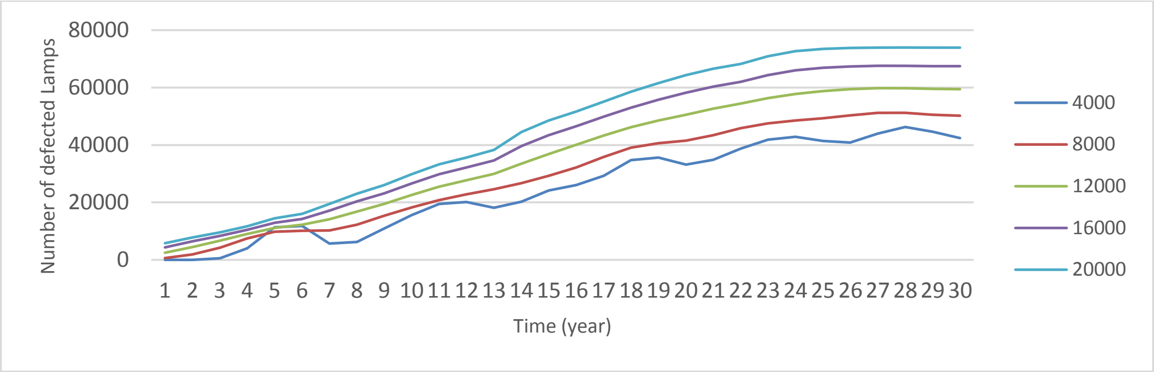

**Figure 4.** Impact of STD on lamp failure rate over 30 years ( $\mu = 20000$ ).

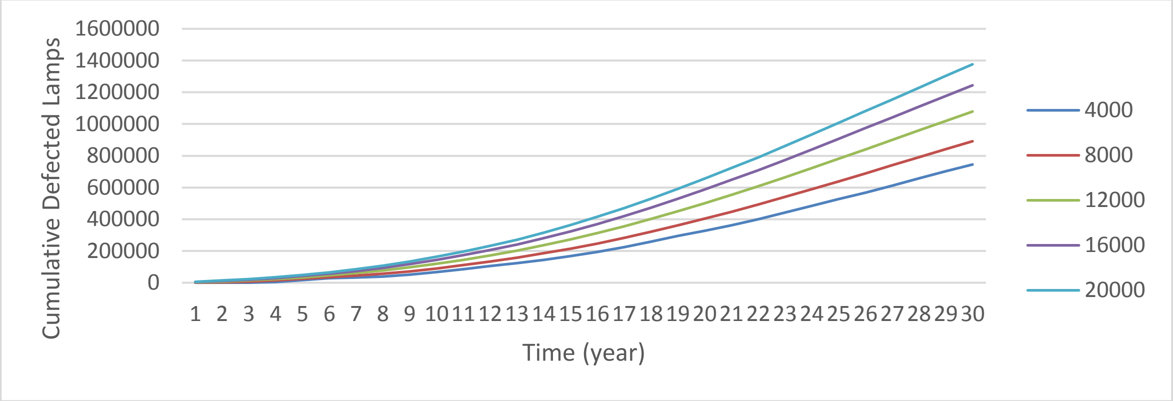

**Figure 5.** Cumulative failure rate of lamp over the lifespan.

## 4. Numerical Study and Discussions

A public lighting system is usually designed for a lifespan of 25 to 30 years. This system is consists of medium voltage network, power transformer, low voltage network, and luminaire. Lamp has a direct impact on lighting continuity of luminaire so the failure rate should be taken into account. The public-lighting system in the North Kerman Power Distribution Company (NK-PDC) in Iran is used as a case study in this research work.

There are a few resources to declare the lifespan of the luminaire components, and the life definitions are varied in this regard. It is hard to find out about the nominal lifespan of luminaire parts as a characteristic in standards. By considering the lifespans based on the reports and catalogs of the manufacturers [19] , [20] , [21] the replacement of parts will be inevitable during the lifespan of the public-lighting system. In this work, the average lifespan and standard deviation of lamps are assumed 20000 and 4000 hours, respectively.

### 4.1. Impact of Standard Deviation

The failure rate follows the normal distribution function. Increasing the standard deviation significantly increases the failure rate over a lifespan. The lamp failure rate over a thirty-year period with a standard deviation of 4000 to 20000 hours is shown in Figure 4. As shown in the figure, the failure rate of a lamp with an average lifespan of 20000 hours and standard deviation of 4000 hours will fluctuate, the choice of contract period strongly depends on the agreed standard deviation, and there is a risk in choosing the term of the contract.

The large standard deviation indicates the low quality of the lamp, so increasing the standard deviation increases the failure rate. The cumulative failure rate over the lifespan is shown in Figure 5. As shown in this figure, by increasing the standard deviation from 4000 hours to 20000 hours, the cumulative failure rate will increase by 80%. It is recommended that in addition to obtaining a guarantee for the average life, it is necessary to get a suitable guarantee on standard deviation. In order to evaluate the accuracy of the lamp failure rate based on the normal distribution function, the probability of a lamp is compared with the LSF in the data sheet of lamp manufacturer [21]. The comparison between the results of the probability distribution function and manufacturer laboratory test shows that the use of the normal distribution function with acceptable accuracy is possible.

**Table 1. Impact of data loss on failure rate estimation.**

| Historical Data From 1996 To 2014 | $N_{ai}$ | Actual and Estimated Failure Rate | | | | | Estimation Error (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2015 | 2016 | 2017 | 2018 | 2019 | | | | | |
| | | $\lambda_a$ | | | | | | | | | |
| | | 39529 | 42872 | 52365 | 45692 | 51282 | | | | | |
| | | $(1+\delta)\lambda_i$ | | | | | 2015 | 2016 | 2017 | 2018 | 2019 |
| 1996 | 27466 | - | - | - | - | - | - | - | - | - | - |
| 1997 | 30834 | 44590 | 41496 | 43553 | 48391 | 52344 | 13 | -3 | -17 | 6 | 2 |
| 1998 | 33607 | 45503 | 40171 | 41866 | 48191 | 53600 | 15 | -6 | -20 | 5 | 5 |
| 1999 | 39473 | 48261 | 41195 | 40379 | 46300 | 53376 | 22 | -4 | -23 | 1 | 4 |
| 2000 | 49917 | 49435 | 44203 | 41495 | 44678 | 51314 | 25 | 3 | -21 | -2 | 0 |
| 2001 | 53276 | 46601 | 45581 | 45028 | 45989 | 49410 | 18 | 6 | -14 | 1 | -4 |
| 2002 | 67111 | 41284 | 41996 | 46771 | 50456 | 51068 | 4 | -2 | -11 | 10 | 0 |
| 2003 | 79464 | 40190 | 36321 | 42945 | 52318 | 55836 | 2 | -15 | -18 | 15 | 9 |
| 2004 | 87488 | 49030 | 34944 | 35796 | 47498 | 58180 | 24 | -18 | -32 | 4 | 13 |
| 2005 | 100534 | 59521 | 45411 | 34165 | 39034 | 52474 | 51 | 6 | -35 | -15 | 2 |
| 2006 | 110887 | 54233 | 56963 | 45690 | 37238 | 43154 | 37 | 33 | -13 | -19 | -16 |
| 2007 | 116153 | 37300 | 50885 | 58963 | 50480 | 41090 | -6 | 19 | 13 | 10 | -20 |
| 2008 | 124939 | 25184 | 32209 | 52259 | 65120 | 55696 | -36 | -25 | 0 | 43 | 9 |
| 2009 | 150012 | 31708 | 19516 | 32696 | 58099 | 71031 | -20 | -54 | -38 | 27 | 39 |
| 2010 | 161492 | 75259 | 26535 | 19044 | 37056 | 63479 | 90 | -38 | -64 | -19 | 24 |
| 2011 | 168261 | 81039 | 78825 | 27470 | 20664 | 38214 | 105 | 84 | -48 | -55 | -25 |
| 2012 | 178814 | 30128 | 85048 | 83763 | 29735 | 20566 | -24 | 98 | 60 | -35 | -60 |
| 2013 | 189568 | 4594 | 32003 | 90246 | 88386 | 30019 | -88 | -25 | 72 | 93 | -41 |
| 2014 | 199010 | 291 | 4866 | 33874 | 95278 | 92349 | -99 | -89 | -35 | 109 | 80 |

### 4.2. Impact of Data Loss

Historical data plays an important role in estimating the failure rates. In this work, yearly installation data ( $Ni$ ) from 1996 to 2019 has been used. Unfortunately, access to yearly installation data was not possible before 1996. In order to investigate the effect of yearly data loss, the cumulative installation data ( $Nai$ ) is calculated and listed in Table 1. In other words, the number of 27466 lights registered for 1996 is the total number of lights installed until the end of 1996.

In this case, the failure rate from 2015 to 2019 is calculated based on the historical data from 1996 to 2014, and shown in the second row of the table. If the data for 1996 was not available, the failure rate based on the data from 1997 to 2014 would be in accordance with the third row of the table. The calculation process is continued assuming the unavailability of the historical data in the later years, and the results obtained are given in Table 1. It can be seen; the estimation error increases with increasing years with inaccessible data.

Figure 6 shows the trend of changes in the estimation error due to the unavailability of the historical data. As it can be seen, if the data is available from 1996, the estimation error of 2018, 2019 will be reduced to less than 5%.

As the lack of data increases, the estimation error increases as well.

This error increases to 20% if the external factors are not considered ($\delta = 0$).

The dominant maintenance strategy of public lighting is run to failure maintenance in NK-PDC. In this strategy, the assets are deliberately allowed to operate until they break down. In Table 2, the number of new lights installed and defective lamps from 1996 to 2019 in NK-PDC is shown. HR, lamp, and side costs based on actual failure rate are given annually in the table.

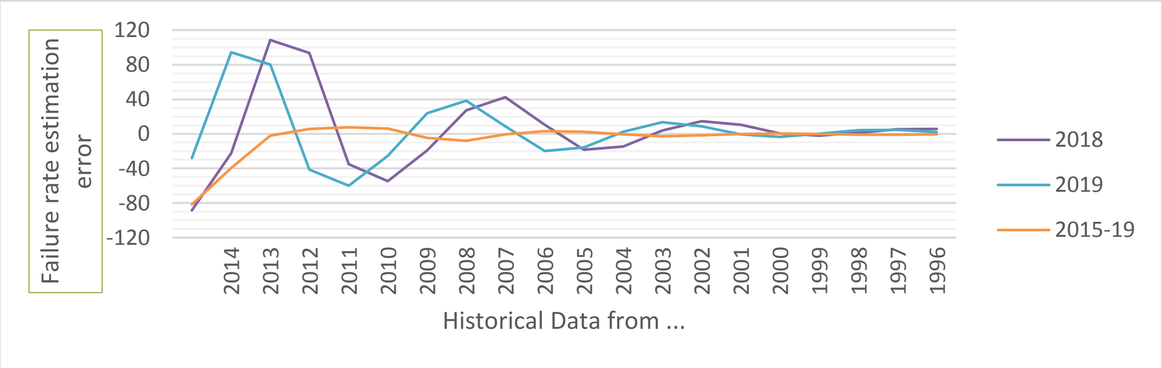

**Figure 6. Failure rate estimation error based on data loss.**

**Table 2. Results for reward and penalty for natural life guarantee (NLG).**

| | **Failure rate** | | | **Human resource, Lamp & Side cost based on $\lambda_a$ (*1000$)** | | | **Contract price(*1000$) Based on:** | | | **Reward (+) & penalty (-) (NLG)** |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\mu = 20000$ | | | | | | | | | |
| | $\sigma = 4000$ | | | | | | | | | |
| **Year** | $N_i$ | $\lambda_i$ | $\lambda_a$ | **Lamp** | **HR** | **Side** | $\lambda_i$ | $(1+\delta)\lambda_i$ | $\lambda_a$ | $\times 1000$ $ |
| 1996 | 27466 | - | - | - | - | - | - | - | - | - |
| 1997 | 3368 | 1 | 12533 | 163.0 | 15.61 | 0.718 | 4.4 | 4.4 | 179.4 | -175 |
| 1998 | 2773 | 34 | 7255 | 97.2 | 9.37 | 0.740 | 4.9 | 5 | 107.3 | -102.3 |
| 1999 | 5866 | 567 | 13120 | 181.1 | 17.38 | 0.762 | 12.4 | 14.4 | 199.2 | -184.8 |
| 2000 | 10444 | 3969 | 15464 | 219.9 | 21.04 | 0.785 | 65.1 | 79.3 | 241.7 | -162.4 |
| 2001 | 3359 | 11366 | 16215 | 237.5 | 22.77 | 0.809 | 183.6 | 228.9 | 261 | -32.1 |
| 2002 | 13835 | 11831 | 16975 | 256.0 | 24.61 | 0.833 | 196.3 | 245.2 | 281.5 | -36.3 |
| 2003 | 12353 | 5685 | 20624 | 320.4 | 30.81 | 0.858 | 97.8 | 121.9 | 352.1 | -230.2 |
| 2004 | 8024 | 6255 | 29622 | 474.0 | 45.49 | 0.883 | 110.6 | 139.4 | 520.4 | -381 |
| 2005 | 13046 | 10874 | 33296 | 548.8 | 52.69 | 0.910 | 197.4 | 246.4 | 602.4 | -356 |
| 2006 | 10353 | 15561 | 35853 | 608.6 | 58.62 | 0.937 | 290.4 | 362.8 | 668.2 | -305.4 |
| 2007 | 5266 | 19465 | 39841 | 696.6 | 67.12 | 0.965 | 373.9 | 467.3 | 764.7 | -297.4 |
| 2008 | 8786 | 20134 | 35394 | 637.5 | 61.37 | 0.994 | 398.4 | 497.9 | 699.8 | -201.9 |
| 2009 | 25073 | 18145 | 34212 | 634.6 | 61.01 | 1.024 | 370 | 462.1 | 696.6 | -234.5 |
| 2010 | 11480 | 20279 | 38236 | 730.5 | 70.28 | 1.055 | 425.7 | 532 | 801.9 | -269.9 |
| 2011 | 6769 | 24185 | 43012 | 846.5 | 81.53 | 1.087 | 522.8 | 653.2 | 929.1 | -275.9 |
| 2012 | 10553 | 26055 | 46899 | 950.6 | 91.59 | 1.119 | 579.9 | 724.9 | 1043.3 | -318.4 |
| 2013 | 10754 | 29246 | 43762 | 913.7 | 88.07 | 1.153 | 670.3 | 837.7 | 1002.9 | -165.2 |
| 2014 | 9442 | 34676 | 51626 | 1110.1 | 106.76 | 1.187 | 818.6 | 1023.1 | 1218.1 | -195 |
| 2015 | 8237 | 35672 | 39529 | 875.5 | 84.34 | 1.223 | 867.4 | 1083.8 | 961.1 | 122.7 |
| 2016 | 5967 | 33197 | 42872 | 978.0 | 94.19 | 1.260 | 831.3 | 1039 | 1073.5 | -34.5 |
| 2017 | 3968 | 34842 | 52365 | 1230.5 | 118.39 | 1.297 | 898.8 | 1123.3 | 1350.2 | -226.9 |
| 2018 | 9818 | 38713 | 45692 | 1105.8 | 106.44 | 1.336 | 1028.5 | 1285.2 | 1213.6 | 71.6 |
| 2019 | 5306 | 41875 | 51282 | 1278.4 | 122.89 | 1.376 | 1145.7 | 1431.8 | 1402.7 | 29.1 |

The contract price based on the actual and estimated failure rate is calculated. The effect of external factors on the failure rate with $\delta = 0.25$ coefficient is considered and added to the estimated failure rate of the guaranteed life of the lamp. The reward and penalty for NLG are calculated and given in the Table 2. The number of workers required, daily extra working time, and new workers are calculated for the actual and estimated failure rate. The actual and estimated ENS due to the lights being off is given, and based on that, the average time interval between fault to diagnosis and troubleshooting is calculated. The results obtained are shown based on the actual failure rate. The reward for the quick reaction and penalty for delay identifying and repairing defective lights are calculated and given in Table 3.

## 5. Conclusion

Due to the natural monopoly on public lighting system in Iran, the TAVANIR must set some policies in order to cover safety, security, and public expectation. These policies improve the quality of services and people's satisfaction, and imposes considerable maintenance costs. Accordingly, an asset management model for having a sustainable public lighting system is necessary. Lighting continuity is one of the preferences of the citizens**.** Public lighting management from the viewpoint of city residents improves social welfare. The reward and penalty mechanism plays an important role in this regard. Selecting labor and parts has a significant impact on the risk reduction during the contract period.

Guarantee period of lamps and maximum permissible lighting defect detection and correction time are used for the reward and penalty mechanism. In this work, the maintenance costs of public lighting in NK-PDC were simulated over a period of thirty years. The results obtained shows that the natural life guarantee and permissible correction time have a considerable effect on the maintenance cost. This work provided a model for regulating the annual budget allocation. Consequently, a new budgeting system based on the annual variation of maintenance cost was required. This work is also capable of comparing nominal (manufacturer's information) and actual lifespan of lamps in public lighting systems.

## 6. Recommendation

An open topic for a further research work could be the investigation of the effects of some other abnormal conditions on public lighting asset management and the development of the model.

**Table 3. Results for reward and penalty for detection and correction time (DCT).**

| Year | Failure rate | | Workers required, extra work(min), and Human resource cost based on $\lambda_a$ (*1000$) | | | | | | | Nominal & actual energy consummation, energy not supply & days the lamp was off | | | | | Reward (+) & penalty (-) (DCT) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\mu = 20000$ | | | | | | | | | | | | | | |
| | $\sigma = 4000$ | | Base on $\lambda_i$ | | | Base on $\lambda_a$ | | | | | | | | | |
| | $N$ | $\lambda_a$ | $N_{wr}$ | $H_a$ | $N_{wn}$ | $N_{wr}$ | $H_a$ | $N_{wn}$ | HRC | $E_N$ | $E_a$ | $ENS_a$ | $ENS_P$ | $t_{xi}$ | $\times 1000$ $ |
| 1996 | 27466 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 1997 | 3368 | 12533 | 1 | 0 | 0 | 4 | 213 | 2 | 15.61 | 12,155 | 12,060 | 95 | 27 | 7 | -4.683 |
| 1998 | 2773 | 7255 | 1 | 0 | 0 | 2 | 707 | 0 | 9.37 | 13,248 | 13,201 | 47 | 16 | 6 | -1.874 |
| 1999 | 5866 | 13120 | 1 | 0 | 0 | 4 | 359 | 2 | 17.38 | 15,560 | 15,447 | 113 | 28 | 8 | -5.214 |
| 2000 | 10444 | 15464 | 2 | 0 | 1 | 5 | 172 | 3 | 21.04 | 19,677 | 19,560 | 117 | 33 | 7 | -6.312 |
| 2001 | 3359 | 16215 | 4 | 0 | 3 | 5 | 323 | 3 | 22.77 | 21,001 | 20,896 | 105 | 35 | 6 | -4.554 |
| 2002 | 13835 | 16975 | 4 | 38 | 3 | 5 | 475 | 3 | 24.61 | 26,455 | 26,345 | 110 | 37 | 6 | -4.922 |
| 2003 | 12353 | 20624 | 2 | 0 | 1 | 6 | 517 | 4 | 30.81 | 31,325 | 31,147 | 178 | 45 | 8 | -9.243 |
| 2004 | 8024 | 29622 | 2 | 208 | 1 | 9 | 371 | 7 | 45.49 | 34,488 | 34,264 | 224 | 64 | 7 | -13.647 |
| 2005 | 13046 | 33296 | 3 | 705 | 2 | 10 | 409 | 8 | 52.69 | 39,631 | 39,451 | 180 | 72 | 5 | -10.538 |
| 2006 | 10353 | 35853 | 5 | 192 | 4 | 10 | 665 | 8 | 58.62 | 43,712 | 43,479 | 232 | 77 | 6 | -11.724 |
| 2007 | 5266 | 39841 | 6 | 324 | 5 | 11 | 701 | 9 | 67.12 | 45,788 | 45,572 | 215 | 86 | 5 | -13.424 |
| 2008 | 8786 | 35394 | 6 | 436 | 5 | 10 | 619 | 8 | 61.37 | 49,251 | 49,098 | 153 | 76 | 4 | -6.137 |
| 2009 | 25073 | 34212 | 5 | 709 | 4 | 10 | 501 | 8 | 61.01 | 59,135 | 58,950 | 185 | 74 | 5 | -12.202 |
| 2010 | 11480 | 38236 | 6 | 460 | 5 | 11 | 556 | 9 | 70.28 | 63,660 | 63,412 | 248 | 83 | 6 | -14.056 |
| 2011 | 6769 | 43012 | 7 | 535 | 6 | 12 | 664 | 10 | 81.53 | 66,328 | 66,143 | 186 | 93 | 4 | -8.153 |
| 2012 | 10553 | 46899 | 8 | 337 | 7 | 13 | 687 | 11 | 91.59 | 70,488 | 70,235 | 253 | 101 | 5 | -18.318 |
| 2013 | 10754 | 43762 | 9 | 330 | 8 | 12 | 726 | 10 | 88.07 | 74,728 | 74,444 | 284 | 95 | 6 | -17.614 |
| 2014 | 9442 | 51626 | 10 | 548 | 9 | 15 | 521 | 13 | 106.76 | 78,450 | 78,227 | 223 | 112 | 4 | -10.676 |
| 2015 | 8237 | 39529 | 10 | 647 | 9 | 11 | 673 | 9 | 84.34 | 81,697 | 81,569 | 128 | 85 | 3 | -8.434 |
| 2016 | 5967 | 42872 | 10 | 400 | 9 | 12 | 652 | 10 | 94.19 | 84,049 | 84,003 | 46 | 93 | 1 | 9.419 |
| 2017 | 3968 | 52365 | 10 | 564 | 9 | 15 | 570 | 13 | 118.39 | 85,613 | 85,500 | 113 | 113 | 2 | 11.839 |
| 2018 | 9818 | 45692 | 11 | 599 | 10 | 13 | 594 | 11 | 106.44 | 89,483 | 89,434 | 49 | 99 | 1 | 10.644 |
| 2019 | 5306 | 51282 | 12 | 570 | 11 | 15 | 498 | 13 | 122.89 | 91,575 | 91,520 | 55 | 111 | 1 | 12.289 |

**A f**uture research work could refine the relationship between the parties as a local contract. **A f**uture research work could consider the role of adaptive performance evaluation approaches to the regulation of public lighting.

## Appendix

NK-PDC started its operation to distribute and deliver reliable electricity to the consumers including residential, general, industrial, and agricultural. This company has announced its independence from the Kerman Regional Electricity Company in November 2006 using the independency laws of distribution companies in Iran. It operates as a subset of TAVANIR under the supervision of the Ministry of Energy. The operation domain of this company includes managing seven cities: Kerman, Rafsanjan, Zarand, Ravar, Shahrbabak, Kohbanan, and Anar. The statistics of high-pressure sodium lamps, defective lamps, energy consumption, and energy not supplied between 1996 till 2019 are presented.

**Table 4. Case Study Data and information from North Kerman Power Distribution Company.**

| Year | sym. | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| New Installation | $N$ | 27466 | 3368 | 2773 | 5866 | 10444 | 3359 | 13835 | 12353 | 8024 | 13046 | 10353 | 5266 |
| Defective Lamp | $\lambda_a$ | - | 12533 | 7255 | 13120 | 15464 | 16215 | 16975 | 20624 | 29622 | 33296 | 35853 | 39841 |
| Energy Consumption | $E_a$ | - | 12,060 | 13,201 | 15,447 | 19,560 | 20,896 | 26,345 | 31,147 | 34,264 | 39,631 | 43,479 | 45,572 |
| Energy Not Supply | $ENS_a$ | - | 95 | 47 | 113 | 117 | 105 | 110 | 178 | 224 | 180 | 232 | 215 |
| **Year** | sym. | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** |
| New Installation | $N$ | 8786 | 25073 | 11480 | 6769 | 10553 | 10754 | 9442 | 8237 | 5967 | 3968 | 9818 | 5306 |
| Defective Lamp | $\lambda_a$ | 35394 | 34212 | 38236 | 43012 | 46899 | 43762 | 51626 | 39529 | 42872 | 52365 | 45692 | 51282 |
| Energy Consumption | $E_a$ | 49,098 | 58,950 | 63,412 | 66,143 | 70,235 | 74,444 | 78,227 | 81,569 | 84,003 | 85,500 | 89,434 | 91,520 |
| Energy Not Supply | $ENS_a$ | 153 | 185 | 248 | 186 | 253 | 284 | 223 | 128 | 46 | 113 | 49 | 55 |

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