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Optimal lighting project maintenance planning by a control system approach [*]

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Abstract:
The energy savings achieved by implementing energy efficiency (EE) lighting projects are not sustainable and vanish rapidly given that project population decays without proper maintenance. In this study, it is proposed that an optimal maintenance plan (OMP) can be designed to decide the number of failed lighting EE devices to be replaced. This problem is formulated in a control system framework. Based on the existing study of the project population decay modelling, the project population dynamics are taken as the plant of the control system. The number of replaced lighting EE devices is taken as the input of the control system. As different lighting technologies have different population decay dynamics and different rebate tariffs, the control inputs can be optimally decided based on the project budget plan. The optimal maintenance planning problem is then translated into an optimal control problem and solved by a model predictive control (MPC) approach. By solving the problem, the project sponsors receive extra energy savings over a 10-year's project crediting period. In addition, the project developers also obtain extra benefits with a small amount of reinvestment for the lighting project maintenance. The design of an optimal maintenance plan for a lighting retrofit project is taken as a case study to illustrate the effectiveness of the control system approach.

Keywords: Energy Efficiency, Optimal Control, Lighting, Maintenance Planning, MPC

1. INTRODUCTION

Lighting is the first service offered by electric utilities and continues to be one of the largest electrical end-uses. For 2005 it is estimated that grid-based electric lighting consumed 2 651 TWh of electricity, which is 19% of all global electricity consumption (Internatinoal Energy Agency (2006)). Past research has shown that a great potential of energy savings can be generated with the energy efficiency (EE) solutions of lighting retrofit or lighting control (Mills (2002), Internatinoal Energy Agency (2006) and Roisin et al. (2008)). The lighting energy savings can be achieved either by reducing the input wattage or the operation hours (Mahlia et al. (2005)). The lighting retrofit approach is to replace inefficient lamps with efficient ones. This solution mainly contributes to the reduction of input wattage. In the literature, compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) are widely used in the lighting retrofit projects (Pode (2010), Lee (2000) and Mahlia et al. (2005)). The lighting control approach basically refers to the control and tuning of the lighting operation conditions. For example, automatic on/off control, dim control and daylight harvesting systems are applied in the following studies (Wen (2008), Galasiu et al. (2004) and Atif and Galasiu (2003)) to reduce lighting energy consumption by either reducing the lamp input wattage or the operating hours.

Due to the great savings potential of lighting energy usage, a large number of lighting retrofit and lighting control projects have been implemented either under the international policy and regulations or under national EE and demand side management (DSM) programmes. These EE lighting projects generally share a similar life cycle of project design, implementation, performance evaluation and project rebate issuance (Mundaca and Neij (2007) and UNFCCC (2007)). However, the maintenance of the EE lighting population is generally neglected for the existing lighting projects. The scope of the maintenance refers to the replacement of the failed lighting equipment as project population decays due to the occurrences of non-repairable lamp burnouts and the lighting control device failures. Practically, the following barriers hold the project developers (PDs) back from performing the maintenance activities. Firstly, the maintenance activities can only be carried out when the project device failures are observed. However, continuously monitoring and sampling the EE devices failures is very costly when large decentralised population is involved in an EE lighting project. Secondly, the maintenance activities also require reinvestments for the procurement and installation of new EE devices. The reinvestments sometimes contribute to a tighter project budget plan.

Without proper maintenance of the existing EE lighting projects, the achieved energy savings for the lighting projects are not sustainable as the functioning project population decays. Therefore, a long-term optimal maintenance plan for the entire EE lighting projects' crediting

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period is designed under the framework of the control system in order to maintain sustainable performance of the EE lighting projects, where the sustainable project performance requires to maintain the project performance above 50% of the initially achieved energy savings over its crediting period. The control system framework is applicable as the population dynamics of the EE lighting projects are identified as the first order Markov process (Fleming and Soner (2006)). Specifically, the project population decay dynamics are characterised and modelled as state space equations. The dynamics of the project population are taken as the plant of the control system. For simplicity, the lighting project population is classified into several homogeneous groups. For each group, the following classification criteria are satisfied. Firstly, devices in the same group are of the same type, same rated power, same life span, same operating schedules and working conditions. Secondly, each device only belongs to one group where the maximum homogeneity to the other devices in the same group can be observed. Basically, devices from the same group are deemed to have the same energy and economic performance, same population decay dynamics. In this case, the state variables can be chosen as the survived lighting project population in each homogeneous group. In order to achieve sustainable energy savings and maximise the project profits, it is recommended to control/replace the failed lighting devices. The number of replaced lighting devices is taken as the control variable of the control system. As different lighting technologies have different population decay dynamics and different rebate tariffs, the control inputs can be optimally decided based on the project developers' (PDs') budget plan. Bringing the lighting project maintenance plan design into the control system framework exhibits the following advantages. Firstly, the problem can be formulated as an optimal control problem. By solving this problem, the project sponsors receive extra energy savings that is sustainable over a 10-year's project crediting period. In addition, the PDs' profit is maximised with a small amount of reinvestments for the project maintenance. Secondly, standard control theories and methodologies can be applied to further improve the designed maintenance strategy. For instance, model predictive control approaches (MPC) can be incorporated to improve the control system performance when uncertainties and disturbances are present in modelling and measurement. All these advantages are illustrated by a sustainable EE lighting project. The proposed optimal control model will be widely applicable for other lighting EE projects.

2. PROBLEM FORMULATION

The lighting project maintenance aims to maintain the installed EE devices in good conditions by necessary replacements of the failed EE devices, whereas the project sponsors will receive sustainable energy savings from the project and the PDs will consequently obtain additional benefits. In this study, an optimal maintenance plan (OMP) is designed for predetermined maintenance intervals during the lighting projects' crediting period. The maintenance activities can be performed once every month, every year or every the other year. In this study, the main issue of designing the OMP is to optimally decide the quantities of the replacements for each scheduled maintenance instead of simply replace all the failed EE devices to their original full population. Note that this maintenance policy is not applicable to some critical public lighting services such as traffic lighting or security lighting, which require immediate replacements when failures occur. The OMP problem for the EE lighting projects is a cost optimisation problem, of which the objective is to maximise the PDs' benefits within the PDs' budget constraints. For the maintenance of EE lighting projects, the replacement quantity need to be properly decided by taking into account the procurement price, energy saving performance, population decay dynamics, rebate values of the EE devices. As discussed previously, this problem can be formulated under the control system framework and solved by control system approaches.

2.1 OMP problem from a control system perspective

In this section, the OMP problem is formulated under the control system framework. Given an EE lighting project with both the lighting control and lighting retrofit solutions. Assume that I kinds of EE devices are involved and each kind of EE devices is classified into the same group. Let i be the counter of the lighting groups, t_0 and t_f denote the beginning and end of the project crediting period, respectively. Once the project crediting period and the maintenance schedules are determined, $t_k = t_0 + kT$, $k = 0, 1, \ldots, K-1$ is used to denote the time schedule for the maintenance, where T is a fixed maintenance interval. When time sequence $\{t_k\}$ and T are both determined, t_k can be simply denoted by k and the time period $[t_k, t_{k+1})$ is simplified as $[k,\ k+1)$. $x_i(0)$ denotes the quantity of the initial installation of the EE lighting devices in the ith group. Generally, this OMP problem is to find an optimal control sequence $\mathbf{u}(k)=[u_1(k), u_2(k), \ldots, u_I(k)]^T$ within the time period $[0, K)$. Here $u_i(k)$ is the control system input, which is the replacement quantity for the interval $[k,\ k+1)$ in the ith group. Then the OMP problem under the control system framework is formulated in the following general form:

$$\begin{cases}\mathbf{x}(k+1) = \mathbf{f}(\mathbf{x}(k)) + \mathbf{u}(k) + \mathbf{w}(k),\\ \mathbf{y}(k) = \mathbf{x}(k) + \mathbf{v}(k),\end{cases} \tag{1}$$

where $\mathbf{x}(k)=[x_1(k), x_2(k), \ldots, x_I(k)]^T$, denotes the state variable that corresponds to the number of survival EE devices for the time interval $[k,\ k+1)$ in the ith group. The system output $\mathbf{y}(k)$ is the measurements of $\mathbf{x}(k)$, more precisely, $y_i(k)$ is the sampling result of $x_i(k)$ at time k in the ith group. $\mathbf{f}(\mathbf{x}(k))$ denotes the function to model the project population decay dynamics. In addition, $\mathbf{w}(k)=[w_1(k),\ w_2(k),\ \ldots,\ w_I(k)]^T$ and $\mathbf{v}(k)=[v_1(k),\ v_2(k),\ \ldots,\ v_I(k)]^T$ denote the disturbances on the state variables and the system output, respectively.

2.2 Population decay dynamics modelling

In order to solve the OMP problem, the lighting population decay dynamic model $\mathbf{f}(\mathbf{x}(k))$ needs to be identified. In the literature, a linear lamp population decay model is proposed in the AMS-II.J (UNFCCC (2010)). Although this model is widely used for CDM lighting project design, this model is not good enough to charaterise the lamp population decay dynamics as it assumes a constant hazard rate of the lighting EE devices (Carstens et al. (2013)). The recent study (Carstens et al. (2013)) offers an informative review on the existing lamp population decay dynamic models as can be found in (Navigant Consulting (1999) and (Botha-Moorlach and Mckuur (2009))). In addition, (Carstens et al. (2013)) also proposed a general form of the population decay dynamic model by re-calibrating existing models established from biological population dynamics study or from reliability engineering experiments. The general form of the model is provided in Eq. (2).

$$s(t) = \frac{1}{c + ae^{bt}}, \tag{2}$$

where $s(t)$ is the percentage of survived devices at time t for a lighting project, t is counted from the beginning of lamp installation. $a = e^{-L}$ and L is the rated average life span of a certain model of the EE devices. Follow the CDM guideline (UNFCCC (2010)), the rated average life span is declared by the manufacturer or responsible vendor as being the expected time at which 50% of any large number of EE devices reach the end of their individual lives. b is the slope of decay and c is initial percentage lamp survival at $t = 0$. Thus, with a given L, b and c can be obtained by solving the following equations:

$$\begin{cases} s(0) = 1, \\ s(L) = 0.5. \end{cases} \tag{3}$$

The discrete and dynamical form of model (2) is also given in (Carstens et al. (2013)) as follows

$$s(k+1) = bcs(k)^2 - bs(k) + s(k), \tag{4}$$

where $s(k)$ is the survived percentage of the lighting project population at the kth sampling interval. Note that for different lighting EE devices, the parameters b and c are different and they can be obtained by the system identification approach proposed in (Carstens et al. (2013)).

Given that $s(k)$ in model (4) is a percentage against the total population, this model can be easily converted into

$$f_i(x_i(k)) = b_i c_i x_i(k)^2 / x_i(t_0) - bx_i(k) + x_i(k). \tag{5}$$

Note that the Eq. (5) is only applicable when the following assumptions hold.

1. The EE devices in the ith category are homogeneous and follow the same decay dynamics.
2. The time delay for the individual EE device installation and commissioning can be ignored.
3. The replacements of the failed EE devices will not change the lamp population decay dynamics.

2.3 Control objective and constraints

For the lighting project mentioned in Subsection 2.1, PDs will receive different rebate values for EE devices in different lighting groups, denoted by R_i (R[1]/kWh) on annual basis over a 10 years crediting period after the project implementation. However, PDs have to pay for the project transaction cost including the project design, implementation, performance evaluation and maintenance at their own budget. The initial investment of the project is estimated by

$$\Theta_1 = \sum_{i=1}^{I} \alpha_i x_i(0) + \beta, \tag{6}$$

where α_i denote the cost related to individual lighting EE device, including the procurement price, delivery, removal of an old device and installation of a new device in the ith lighting group; Θ_1 denotes the initial investment of the project; β denotes the project transaction cost, usually β occupies 10% of Θ_1.

The performance of a project is usually quantified by a measurement and verification (M&V) approach, where the energy savings of the project are stated as the difference between the adjusted baseline and the real energy consumption in the project crediting period (Efficiency Valuation Organization (EVO), Xia and Zhang (2013)). As a simplified M&V approach, the lighting projects performance is calculated by the product of the functioning project population of light bulbs or EE devices and the average savings of an individual EE device.

As time goes by, the total project rebate will become smaller and smaller given that the EE device population decays if the failed devices are not replaced. In case no maintenance is carried out, the PDs' benefit is calculated by

$$\Pi_1 = \sum_{i=1}^{I} \sum_{k=0}^{K-1} r_i \bar{x}_i(k) - \Theta_1, \tag{7}$$

where r_i is the rebate per EE device in the ith group, $r_i = R_i Es_i$. Es_i is the energy saving (in kWh) per EE device that is determined by the M&V process. r_i is constant if Es_i in each sampling interval $[k,\ k+1)$ is constant. $\bar{x}_i(k)$ represents the number of functioning EE devices in the ith group during the time period $[k, k+1)$. $\bar{x}_i(k+1)$ is calculated by Eq. (5) where

$$\bar{x}_i(k+1) = f_i(\bar{x}_i(k)).$$

As discussed previously, proper replacements of failed project equipment contribute to a sustainable project performance, which will consequently increase the PDs' benefit. From PDs' point of view, although the project maintenance brings additional benefits, it requires some reinvestments. If a number of $u_i(k)$ failed EE devices will be replaced in the sampling interval $[k, k+1)$, then the PDs' benefit is calculated by

$$\Pi_2 = \sum_{i=1}^{I} \sum_{k=0}^{K-1} [r_i x_i(k) - \alpha_i u_i(k)] - \Theta_1, \tag{8}$$

where $x_i(k)$ represents the number of functioning EE devices in the ith group during the time period $[k,\ k+1)$ and $x_i(k)$ is calculated by Eq. (1). Note that cost β is usually a once-off payment in the project budget plan. When replacing the failed EE devices, the additional investment only needs to cover the basic expenses denoted by α_i.

With additional reinvestments for a proper project maintenance, the PDs' benefit Π_2 might be greater than Π_1. However, a greater Π_2 does not imply that the project with maintenance is more beneficial than the project without maintenance since this is not a fair-comparison. To ensure a fair-comparison, the total project benefit needs to be

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[1] R is short for the South Africa Currency: Rand. The annual average USD to Rand exchange rate in 2012 is 1 USD = R 8.209.

normalised against the project total investment. This normalised value is an input-output ratio between the total project profit and the total project investment. The input-output ratio J_1 for the project without maintenance is calculated by Π_1/Θ_1. The input-output ratio J_2 for the project with maintenance is calculated by Π_2/Θ_2 where

$$\Theta_2 = \Theta_1 + \sum_{i=1}^{I}\sum_{k=0}^{K-1}[\alpha_i u_i(k)].$$

Therefore, to maximise PDs' benefits, the following objective function is adopted

$$J_2 = -\frac{\Pi_2}{\Theta_2}. \tag{9}$$

The constraints of the OMP problem is given as

$$\begin{cases} x_i(k) \le x_i(0), \\ x_i(k) \ge 0.5x_i(0), \\ \sum_{i=1}^{I}\sum_{j=0}^{k-1}[\alpha_i u_i(j) - r_i x_i(j)] \le 0, \end{cases} \tag{10}$$

where the first two constraints indicate that the project population shall be within the boundary of $[0.5x_i(0), x_i(0)]$. The lower bound is ensure the sustainable performance of the project and the upper bound is required since $x_i(0)$ is decided by the project scope boundary. The third constraint is another hard constraint given that this is the limit of the available budget for the lamp replacement. In other words, the expense for the maintenance at time k must not exceed the cumulative rebates of the project during the the time period $[0, k)$.

The OMP problem in the control system framework is then defined as follows:

Given the control system dynamics (1), the objective function (9) and the constraints (10), the control is to find an optimal sequence $u_i(k)$ that minimises J_2 subject to the constraints (1) and (10).

3. MPC FOR THE OPTIMAL MAINTENANCE PLAN PROBLEM

The OMP problem in Section 2 is defined over the time interval [0, K) to optimise the control variables $[u_i(0), u_i(1), \ldots, u_i(K-1)]$. It is obvious that when the same OMP problem is considered over the time interval $[m,\ m+N)$, $m \in [0, K-N)$, then the control variables are changed into $[u_i|_m(m), u_i|_m(m+1), \ldots, u_i|_m(m+N-1)]$. In an MPC approach, a finite-horizon optimal control problem is repeatedly solved and the first input is applied to the system. Consider a horizon with length N. The OMP problem over the time interval $[m, m+N)$ can be defined as the following optimisation problem:

$$\min\ \tilde{J}_2 = -\tilde{\Pi}_2/\tilde{\Theta}_2, \tag{11}$$

subject to

$$\begin{cases} x_i|_m(m+h) \le x_i(0), \\ x_i|_m(m+h) \ge 0.5x_i(0), \\ \pi(m) + \sum_{i=1}^{I}\sum_{q=m}^{m+h-1}[\alpha_i u_i|_m(q) - r_i x_i|_m(q)] \le 0, \\ x_i|_m(m+h) = f_i(x_i|_m(m+h-1)) + u_i|_m(m+h-1), \end{cases} \tag{12}$$

where $h \in [1, 2, \ldots, N-1)$ and the notation $|_m$ means that the value is obtained based on the information available at time m.

$$\pi(m) = \sum_{i=1}^{I}\sum_{q=0}^{m-1}[\alpha_i \bar{u}_i(q) - r_i x_i(q)], \tag{13}$$

where $\bar{u}_i(q)$ are the control inputs obtained at time q.

$$\tilde{\Pi}_2 = \sum_{i=1}^{I}\sum_{h=m}^{m+N-1}[r_i x_i|_m(h) - \alpha_i u_i|_m(h)] - \Theta_1, \tag{14}$$

$$\tilde{\Theta}_2 = \Theta_1 + \sum_{i=1}^{I}\sum_{h=m}^{m+N-1}[\alpha_i u_i|_m(h)]. \tag{15}$$

Both the objective functions (11) and (12) are nonlinear as the population decay model in Eq. (5) is nonlinear. Then the interior-point algorithm is chosen to solve the problem (Rao (2009)). The MPC formulation of the OMP problem in Eq. (11)-(15) can be solved over the interval $[m, m+N)$ given the initial condition $x_i(m)$. Let the obtained optimal control inputs denote by $\{\mathbf{u}_i|_m, i = 1, 2, \ldots, I\}$, then only the optimal solution in the first sampling period $[m, m+1)$ is applied, denoted by $\bar{\mathbf{u}}_i|_m = \mathbf{u}_i|_m(1)$. According to Eq. (1), the obtained optimal $\bar{\mathbf{u}}_i|_m$ is applied to calculate $\mathbf{x}(m+1)$ and $\mathbf{y}(m+1)$. $\mathbf{y}(m+1)$ then becomes the initial condition of the MPC formulation over the time horizon $[m+1, m+N+1)$. When $N > K-m$, the control horizon is reduced to be $N = K-m+1$. This process will be repeated until all the optimal control inputs $\bar{\mathbf{u}}$ are obtained over the period $[0, K)$. For an undisturbed control system model, where the modelling uncertainties $\mathbf{w}(k)$ and measurement disturbances $\mathbf{v}(k)$ are not considered, the system output $\mathbf{y}(k)$ equals the predicted state variable $\mathbf{x}(k)$, $\mathbf{y}(k)$ is taken as the initial state for the open loop optimal control problem over the next finite horizon, thus a closed-loop feedback is obtained. The above ideas can be formulated into the following MPC algorithm.

Algorithm 1 MPC algorithm to the OMP problem

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Initialisation: Given $K$, $N$ and input $\mathbf{x}_i(0)$ and let $m$=0.
(1) Compute the open loop optimal solution $\{\mathbf{u}_i|_m\}$ of the problem formulation in the Eqs. (11)-(15).
(2) Apply the MPC controller $\bar{\mathbf{u}}_i|_m$ to the OMP problem. The rest of the solutions $\{\mathbf{u}_i|_m(h)\}$ are discarded. $x_i(m+1)$ is calculated by
        $x_i(m+1) = f_i(x_i(m)) + \bar{\mathbf{u}}_i|_m$.
(3) Let $m := m+1$ and go back to Step (1).
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The above MPC algorithm is executed over the entire control period $[0, K)$ to solve the OMP problem.

In practice, the modelling uncertainties and measurement disturbances are unavoidable. Thus the predicted state of the system will not be the same as the actual one. Taking the advantage of the measured feedback, the MPC algorithm is modified accordingly. In Step (2), the actual state is obtained by

$$x_i(m+1) = f_i(x_i(m)) + \bar{\mathbf{u}}_i|_m + w_i(m), \tag{16}$$

and the measurement of the system output

$$y_i(m) = x_i(m) + v_i(m) \tag{17}$$

is taken as the true plant state by the MPC controller in the next optimisation horizon to improve the plant performance. The terms $w_i(m)$ and $v_i(m)$ are simulated by random noises in this study.

4. CASE STUDY

In this section, an optimal maintenance planning for an EE lighting project is taken as a case study to illustrate the effectiveness of proposed optimal control model.

A lighting retrofit project that aims to reduce the lighting load in the residential households is going to be implemented. A large number of energy efficient CFLs and LEDs will be installed to replace existing inefficient incandescent lamps (ICLs) and halogen downlighters (HDLs), respectively. The removed HDLs and ICLs will be counted, stored and destroyed by a contracted disposal company. The CFLs have a rated life of 3 years while the LEDs have a rated life of 6 years. Both lamps have the equivalent lumen to the replaced old lamps. Since LEDs are more expensive than the CFLs, the PDs will receive a higher rebate rate from the installation of LEDs. More project details that provided by the PDs are listed in Table 1.

Table 1. Information of the lighting project

Parameters	**CFLs**	**LEDs**
Initial population	$x_1(0)$=404876	$x_2(0)$=207693
Unit price	a_1=R 32	a_2=R 260
Daily burning hours	O_1=5 h	O_2=10 h
Power of old lamps	P_1=60 W	P_2=35 W
Power of EE lamps	$\hat{P}_1$=14 W	$\hat{P}_2$=4 W
Rebate per kWh	R 0.42	R 0.55
Coefficient 1	$b_1c_1 = 0.7478$	$b_2c_2 = 0.8936$
Coefficient 2	$c_1 = 0.8553$	$c_2 = 0.9201$

In addition, PDs need to comply with the following general project regulation policies in order to receive their maximum economic benefits from this EE lighting project.

(1) PDs will implement the project at their own cost.
(2) The crediting period of this project is 10 years during which PDs can receive their rebate on annual basis. All newly installed EE devices must be properly maintained. If more than 50% of one kinds of lamps is malfunctioned, the rebate will be ceased.
(3) The performance of the project will be reported once a year by a third-party M&V inspection company. The M&V company verifies the number of survived lamps by sampling and surveys. Once device failures are observed, PDs' are allowed to replace some (or all) of the failed EE devices at the end of each crediting year.

In order to design an OMP for this project, the coefficients in the population decay models (5) are identified by the system identification approach proposed in (Carstens et al. (2013)) and provided in Table 1. This OMP problem is then solved by the MPC algorithms that are introduced in Section 3. In addition, the parameters appear in (11)-(15) and the initial conditions of the control system can also be found in Table 1. In this case study, all computations are carried out by the Matlab program. In particular, the optimal control inputs are computed by the "fmincon" code of the Matlab Optimisation Toolbox. The computation results are presented in Figs. 1-2 and Table 2.

In the Figs. 1-2, the horizontal axis indicates the sampling instants and the vertical axis shows the quantity of the EE devices. The solid lines (in blue) denote the system states of the functioning EE devices at each year over the crediting period. The dash-dotted line (in black) denotes the survived EE device population over the crediting periods without control/maintenance. The stem lines with a circle (in red) denote the number of EE devices to be replaced over the 10-years' crediting period. As shown by the solid lines (in blue), EE device failures are observed at the end of each year, then a number of these failed devices will be replaced as denoted by the stem lines. The optimal control strategy in the CFL group tends to maintain the lamp population at the full population. However, no failed LEDs are going to be replaced in the 7th-10th year given that the initial invest for LEDs are very high comparing to the CFLs.

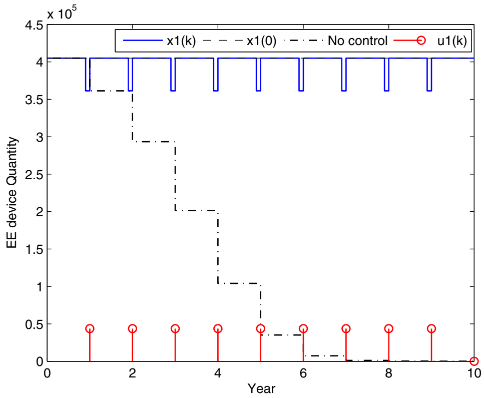

Fig. 1. Optimal control strategy for the CFL group.

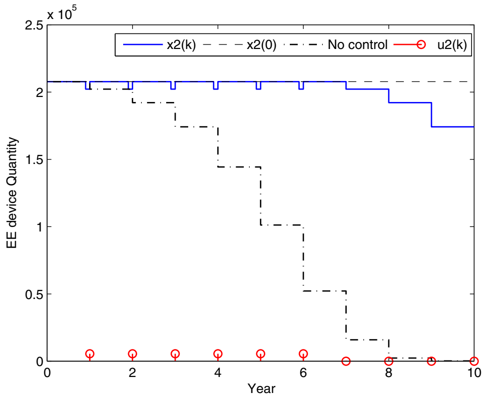

Fig. 2. Optimal control strategy for the LED group.

Table 2. Project KPI analysis.

KPI	NMP	OMP	Increase	OMP$_d$	OMP$'_d$
TotalInv	74.396	95.507	28%	95.868	95.504
TotalPro	53.180	201.650	279%	201.280	198.030
ioRatio	0.7148	2.1113	195%	2.0995	2.0735
EngSav	265500	636690	140%	636580	629970

The key performance indicators (KPI), such as the total investments (TotalInv in million Rand (MR)) , total profits

(TotalPro in MR), the input-output ratio (ioRatio), and the total energy savings (EngSav in MWh) for the EE lighting project under the scenarios with no maintenance plan (NMP), optimal maintenance plan (OMP), OMP with disturbance (OMP_d) are summarised and compared in Table 2. The comparison of the performance between NMP and OMP indicates that the energy savings are increased by 140% with an OMP. In addition, PDs receive 279% more profits with an extra 28% reinvestment for the project maintenance. The MPC approaches are applied to the control system with disturbances. In the case study, the uniformly distributed random noises are used to represent the disturbances $\mathbf{w}(k)$ and $\mathbf{v}(k)$, and the error bands the noises are ±1%. The noises are added on the system output and a system output feedback is employed in the MPC approach. In the Column OMP'_d, the project KPI are calculated by applying the OMP solutions without disturbances to the scenario with the presence of the system disturbances. Comparing the performance of OMP_d and OMP'_d, the optimal solution for the OMP_d contributes to better economic benefits and energy savings. It illustrates that the MPC approach with the system output feedback is advantageous in handling the system disturbances.

5. CONCLUSION AND FUTURE WORK

In this study, an optimal maintenance planning problem for the entire crediting period of the EE lighting project is formulated under the framework of the control system. Based on the existing study of the lighting project population decay modelling, it is recommended to optimally control/replace the failed lighting EE devices in order to achieve sustainable energy savings and maximum project profit. The optimal maintenance planning problem is translated into an optimal control problem. The number of lighting devices to be replaced is taken as the input of the control system. As different lighting technologies have different population decay dynamics and different rebate tariffs, the control inputs can be optimally decided based on the project budget plan. By solving this problem, the project sponsors receives additional energy savings over a 10-years' crediting period. In addition, the PDs' profit is maximised with a small amount of reinvestment for the lighting project maintenance. A case study of designing the optimal maintenance plan for a sustainable EE lighting project is presented for illustration purpose.

Future work for the optimal lighting project maintenance planning problem will be focus on the following aspects **1)** optimal maintenance planning over infinite time period other than 10 year; **2)** designing of optimally scheduled maintenance plan.

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