Formulation of Construction Equipment Replacement and Retrofitting Strategies for Emission Reduction

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Abstract

It is widely considered that the problem of extensive emissions from construction equipment is one of the main threats to human health. Thus, owners of construction equipment must formulate proper replacing and retrofitting strategies to reduce emissions with resource constraints. Therefore, this study proposes an optimization model to help owners of construction equipment to formulate proper replacing and retrofitting strategies, by employing the theory of integer linear programming (ILP). This optimization model incorporates environmental considerations into their decisions making, which can minimize the sum of the economic and environmental costs associated with purchasing new construction equipment, salvaging and retrofitting old in-use construction equipment, operating construction equipment over the period of analysis. The replacing and retrofitting strategies formulated by using the optimization model can also ensure the achievement of the emission reduction target of making the overall emission level of construction equipment fleets at or under a certain level. This study also demonstrates the applicability of the proposed model through a case study, which suggests that the proposed model can make informed strategies of replacing and retrofitting for the case excavator fleet. It is observed that the requirements of various environmental regulations and incentive initiatives do impact the making of replacing and retrofitting strategies and pose a financial burden on owners of construction equipment. Moreover, this study suggests that governments can also adjust subsidy grant levels to allocate the responsibility of reducing emissions from construction between governments and owners of construction equipment.

Keywords

Construction equipment emissions; Replacing and retrofitting; Optimization model; Emissions reduction; Cost-effectiveness

1 Introduction

Air pollutants, one of the greatest threats to the sustainable development of human beings, can cause health problems such as respiratory, eye irritation and lung diseases (Jacobs et al., 2010; Tian, Yao, & Chen, 2019). As reported by World Health Organization (2014), air pollutants can lead to approximate 3.7 million people died annually around the world. Construction equipment has been widely considered one of the significant air pollutant sources (Fu et al., 2012; Frey et al., 2010; Szamocki et al., 2019). In Hong Kong, non-road mobile machines mainly comprised of construction equipment produced about 8% emissions, as shown in the 2018 Hong Kong Emission Inventory Report issued by the Environmental Protection Department of Hong Kong (2020). According to the United States Environmental Protection Agency (US EPA, 2006), construction equipment emitted approximate 32% of all land-based non-road NOx emissions and more than 37% of land-based non-road Particulate Matter (PM10) in 2005. According to London Atmospheric Emissions Inventory (LAEI) 2016 (London Datastore, 2019), construction equipment was responsible for 7% of NOx emission, 34% of PM10 emission, and 15% of PM2.5 emissions in London. Thus, it is critical that owners of construction equipment shoulder the emission reduction responsibility through sustainably managing their equipment. Namely, they should incorporate environmental considerations into their formulation of replacing and retrofitting strategies, which traditionally is undertaken only with economic considerations.

On the other hand, to control the increasing emissions from construction equipment, a host of initiatives have been implemented in many countries, in particular forms of grant incentives, tax incentives, modified contracting procedures and so on. Typical grant incentives include California's Carl Moyer Memorial Air Quality Standards Attainment Program and The Texas Emissions Reduction Plan administered by the Texas Commission on Environmental Quality, which funds equipment for replacement, repowering or retrofitting (US EPA, 2005). Two typical tax incentives are Oregon's Pollution Control Tax Credit Program and Georgia diesel particulate emission reduction technology equipment tax credit program (US EPA, 2005). Moreover, some projects like the Massachusetts Central Artery/Tunnel project adopted a contract requirement to promote the retrofitting of contractor-owned diesel equipment (US EPA, 2005). Thus, owners of construction equipment are being constrained to act strictly in accordance with these initiatives. The revenues or costs incurred by participating in these initiatives change the cash flow of construction equipment and finally have an impact on equipment management (Huang et al., 2021a). However, traditional equipment replacement models fail to consider this environmental impact, which are used to determine when to purchase new equipment and when to salvage which equipment in fleets merely under the economic constraints. With the constraints of environmental regulations and incentives, affected owners of construction equipment are faced with more challenging management of their equipment. They also need to make informed decisions about when to retrofit which equipment and which emission reduction technologies should be adopted. Traditional equipment replacement models are unable to help owners of construction equipment to deal with this challenge. With the problem of extensive emissions from construction being widely concerned, it is predictable that more and more initiatives will be implemented. The need of proposing a model to formulate proper replacing and retrofitting strategies is becoming urgent, which can minimize costs or maximum revenues under not only economic but also environmental considerations.

Previous studies have employed the integer programming theory to make replacement decisions of construction equipment. however, there are no studies, which considered the impact of economic incentives on the replacing and retrofitting strategies and proposed a model for addressing this issue. For example, Gunawardena (1990) uses the technique of Integer Linear Programming to find the optimum replacement strategy for equipment with the objective of either cost minimization.

Therefore, this study aims to propose an optimization model with economic and environmental considerations to help owners of construction equipment make proper replacing and retrofitting strategies for emission reduction. The proposed model can be used to optimizes the number of purchased, in-service, salvaged, replaced and retrofitted construction equipment in each period, so that the total cost is minimized and the emission reduction targets of various initiatives that the owners of construction equipment participate in can be achieved.

2 Methodology

In this section, this study proposes an optimization model with economic and environmental considerations for construction equipment management by employing the theory of integer linear programming.

To take into the economic factors, this study includes the costs of purchasing new construction equipment due to normal depreciation of aging, salvaging old equipment, maintaining and operating in-service equipment during the planning periods.

Owners of construction equipment must limit the emission levels of their equipment according to the requirements of environmental regulations and initiatives that they are constrained to. Thus, to take into the environmental factors, this study formulates an emission cap, which is an important constraint in the optimization model as shown in Equation (4). The proposed optimization model also incorporates the costs and revenues incurred by using retrofitting technologies to control emission levels under the emission gap.

The outputs of the model include the optimal decision on the mix of construction equipment that should be purchased, salvaged, retrofitting and in-service in each period. This model optimizes decisions over a planning horizon with T periods. Each construction equipment is specified by type k=*1*,…, *N*, and age *i*=0,…, *I*, where *N* and I present the number of types of construction equipment and the maximum age respectively. Purchase, salvage and retrofitting action are taken at the beginning of each period. Decision variables and parameters of the optimization model are as follows:

Decision variables:

$Y_{kij,A-B}$ number of k -type and i -period-old construction equipment retrofitted from US Tier *A* emission standards to Tier B at the beginning of period j, with (*A-B*) ∈{*1-2, 1-3, 1-4i, 1-4f, 2-3, 2-4i, 2-4f, 3-4i, 3-4f, 4i-4f*};

X_{kij} number of k-type and i-period-old construction equipment used in period j;

$X_{kij,A}$ number of k -type and i -period-old construction equipment meeting US Tier A emission standards, used in period j, with A ∈{*1, 2, 3, 4i, 4f*};

$X_{kj,A}$ number of k -type construction equipment meeting US Tier A emission standards, purchased in period j;

$S_{kij,A}$ number of k-type and i-period-old construction equipment meeting US Tier *A* emission standards, salvaged at the beginning of period j;

Economic parameters:

C_j budget available for purchasing new construction equipment in period j;

P_{kj} purchase cost of a new k-type construction equipment at the beginning of period j;

OC_{ki} cost of operating a piece of k-type and i-period-old construction equipment;

r_{ki} revenue from salvaging a k-type and i-period-old construction equipment;

EP subsidy or penalty level for reducing emissions by replacing or retrofitting construction equipment;

hp_k engine power of k-type construction equipment;

D_{kj} number of k-type construction equipment demanded in period j;

OT_{kij} operating time of a piece of k-type and i-period-old construction equipment in period j;

$X0_{ki1,A}$ number of k-type and i-period-old construction equipment meeting US Tier A emission standards at the beginning of period 1;

Environmental parameters:

a_m the equivalent coefficient of emission m;

$e_{km,A}$ emission level of a piece of k-type construction equipment meeting US Tier 1 emission standards in regard of emission m;

e^0_{km} emission level of a piece of k-type construction equipment meeting the emission requirement of governments in regard of emission m;

$R_{k,A-B}$ cost of retrofitting a piece of k-type construction equipment from US Tier A emission standards to Tier B;

The objective function is the minimization of the sum of the economic and environmental costs associated with purchasing new construction equipment, salvaging and retrofitting old in-use construction equipment, operating construction equipment over the period of analysis, i.e. from year one to the end of year T:

Minimize:

$$\sum_{k=1}^{N}\sum_{j=1}^{T}\sum_{A=1}^{4f} X_{kj,A}P_{kj} - \sum_{k=1}^{N}\sum_{i=0}^{I}\sum_{j=1}^{T}\sum_{A=1}^{4f} S_{kij,A}r_{ki} + \sum_{k=1}^{N}\sum_{i=0}^{I}\sum_{j=1}^{T}\sum_{(A-B)=(1-2)}^{4i-4f} R_{k,A-B}Y_{kij,A-B} + \sum_{k=1}^{N}\sum_{i=0}^{I}\sum_{j=1}^{T} X_{kij}OC_{ki} - EP\left\{\sum_{k=1}^{N}\sum_{i=0}^{I}\sum_{j=1}^{T}\sum_{m=1}^{M}\left[a_m \times hp_k \times OT_{kij} \times (T+1-j) \times \left(\sum_{A=1}^{4f} e_{km,A}S_{kij,A} + \sum_{(A-B)=(1-2)}^{4i-4f}\left(e_{km,A}-e_{km,B}\right)Y_{kij,A-B}\right)\right]\right\} \quad (1)$$

This objective function is subject to the following constraints:

$$\sum_{i=0}^{I} X_{kij} \geq D_{kj}, \forall\, k=1,\ldots,N;\ \forall\, j=1,\ldots,T \quad (2)$$

$$\sum_{k=1}^{N}\sum_{A=1}^{4f} X_{kj,A}P_{kj} \leq C_j, \forall\, j=1,\ldots,T \quad (3)$$

$$\frac{\sum_{k=1}^{N}\sum_{i=0}^{I}\sum_{m=1}^{M} e^0_{km}a_m hp_k X_{kij}}{\sum_{k=1}^{N}\sum_{i=0}^{I} hp_k X_{kij}} \geq \frac{\sum_{k=1}^{N}\sum_{i=0}^{I}\sum_{m=1}^{M} a_m hp_k\left(\sum_{A=1}^{4f} e_{km,A}X_{kij,A}\right)}{\sum_{k=1}^{N}\sum_{i=0}^{I} hp_k X_{kij}}, \forall\, j=1,\ldots,T; \quad (4)$$

$$\sum_{(A-B)=(1-2)}^{1-4f} Y_{kij,A-B} + S_{kij,1} \leq X_{k(i-1)(j-1),1}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (5)$$

$$\sum_{(A-B)=(2-3)}^{2-4f} Y_{kij,A-B} + S_{kij,2} \leq X_{k(i-1)(j-1),2}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (6)$$

$$\sum_{(A-B)=(3-4i)}^{3-4f} Y_{kij,A-B} + S_{kij,3} \leq X_{k(i-1)(j-1),3}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (7)$$

$$Y_{kij,4i-4f} + S_{kij,4i} \leq X_{k(i-1)(j-1),4i}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (8)$$

$$S_{kij,4f} \leq X_{k(i-1)(j-1),4f}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (9)$$

$$\sum_{(A-B)=(1-2)}^{1-4f} Y_{ki1,A-B} + S_{ki1,1} \leq X0_{ki1,1}, \forall\, k=1,\ldots,N;\ i=0,\ldots I \quad (10)$$

$$\sum_{(A-B)=(2-3)}^{2-4f} Y_{ki1,A-B} + S_{ki1,2} \leq X0_{ki1,2}, \forall\, k=1,\ldots,N;\ i=0,\ldots I \quad (11)$$

$$\sum_{(A-B)=(3-4i)}^{3-4f} Y_{ki1,A-B} + S_{ki1,3} \leq X0_{ki1,3}, \forall\, k=1,\ldots,N;\ i=0,\ldots I \quad (12)$$

$$Y_{ki1,4i-4f} + S_{ki1,4i} \leq X0_{ki1,4i}, \forall\, k=1,\ldots,N;\ i=0,\ldots I \quad (13)$$

$$S_{ki1,4f} \leq X0_{ki1,4f}, \forall\, k=1,\ldots,N;\ i=0,\ldots I \quad (14)$$

$$\sum_{(A-B)=(1-2)}^{1-4f} Y_{k0j,A-B} + S_{k0j,1} = 0, \forall\, k=1,\ldots,N; \forall\, j=2,\ldots,T \quad (15)$$

$$\sum_{(A-B)=(2-3)}^{2-4f} Y_{k0j,A-B} + S_{k0j,2} = 0, \forall\, k=1,\ldots,N; \forall\, j=2,\ldots,T \quad (16)$$

$$\sum_{(A-B)=(3-4i)}^{3-4f} Y_{k0j,A-B} + S_{k0j,3} = 0, \forall\, k=1,\ldots,N; \forall\, j=2,\ldots,T \quad (17)$$

$$Y_{k0j,4i-4f} + S_{k0j,4i} = 0, \forall\, k=1,\ldots,N; \forall\, j=2,\ldots,T \quad (18)$$

$$S_{k0j,4f} = 0, \forall\, k=1,\ldots,N; \forall\, j=2,\ldots,T \quad (19)$$

$$X_{kij,1} = X_{k(i-1)(j-1),1} - S_{kij,1} - \sum_{(A-B)=(1-2)}^{1-4f} Y_{kij,A-B}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (20)$$

$$X_{kij,2} = X_{k(i-1)(j-1),2} - S_{kij,2} + Y_{kij,1-2} - \sum_{(A-B)=(2-3)}^{2-4f} Y_{kij,A-B}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (21)$$

$$X_{kij,3} = X_{k(i-1)(j-1),3} - S_{kij,3} + \sum_{A=1}^{2} Y_{kij,A-3} - \sum_{(A-B)=(3-4i)}^{3-4f} Y_{kij,A-B}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (22)$$

$$X_{kij,4i} = X_{k(i-1)(j-1),4i} - S_{kij,4i} + \sum_{A=1}^{3} Y_{kij,A-4i} - Y_{kij,4i-4f}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (23)$$

$$X_{kij,4f} = X_{k(i-1)(j-1),4f} - S_{kij,4f} + \sum_{A=1}^{4i} Y_{kij,A-4f}, \forall\, k=1,\ldots,N;\ \forall\, j=2,\ldots,T;\ i=1,\ldots I \quad (24)$$

$$X_{ki1,1} = X0_{ki1,1} - S_{ki1,1} - \sum_{(A-B)=(1-2)}^{1-4f} Y_{ki1,A-B}, \forall\, k=1,\ldots,N;\ \forall\, i=1,\ldots I \quad (25)$$

$X_{ki1,2} = X0_{ki1,2} - S_{ki1,2} + Y_{ki1,1-2} - \sum_{(A-B)=(2-3)}^{2-4f} Y_{ki1,A-B}\ , \ \forall\, k = 1, \ldots, N;\ \forall\, i = 1, \ldots I$ (26)

$X_{ki1,3} = X0_{ki1,3} - S_{ki1,3} + \sum_{A=1}^{2} Y_{ki1,A-3} - \sum_{(A-B)=(3-4i)}^{3-4f} Y_{ki1,A-B}\ , \ \forall\, k = 1, \ldots, N;\ \forall\, i = 1, \ldots I$ (27)

$X_{ki1,4i} = X0_{ki1,4i} - S_{ki1,4i} + \sum_{A=1}^{3} Y_{ki1,A-4i} - Y_{ki1,4i-4f},\ \forall\, k = 1, \ldots, N;\ \forall\, i = 1, \ldots I$ (28)

$X_{ki1,4f} = X0_{ki1,4f} - S_{ki1,4f} + \sum_{A=1}^{4i} Y_{ki1,A-4f}\ , \ \forall\, k = 1, \ldots, N;\ \forall\, i = 1, \ldots I$ (29)

$X_{k01,1} = X0_{k01,1} - S_{k01,1} + X_{k1,1} - \sum_{(A-B)=(1-2)}^{1-4f} Y_{k01,A-B}\ , \ \forall\, k = 1, \ldots, N$ (30)

$X_{k01,2} = X0_{k01,2} - S_{k01,2} + X_{k1,2} + Y_{k01,1-2} - \sum_{(A-B)=(2-3)}^{2-4f} Y_{k01,A-B}\ , \ \forall\, k = 1, \ldots, N$ (31)

$X_{k01,3} = X0_{k01,3} - S_{k01,3} + X_{k1,3} + \sum_{A=1}^{2} Y_{k01,A-3} - \sum_{(A-B)=(3-4i)}^{3-4f} Y_{k01,A-B}\ , \ \forall\, k = 1, \ldots, N$ (32)

$X_{k01,4i} = X0_{k01,4i} - S_{k01,4i} + X_{k1,4i} + \sum_{A=1}^{3} Y_{k01,A-4i} - Y_{k01,4i-4f},\ \forall\, k = 1, \ldots, N$ (33)

$X_{k01,4f} = X0_{k01,4f} - S_{k01,4f} + X_{k1,4f} + \sum_{A=1}^{4i} Y_{k01,A-4f}\ , \ \forall\, k = 1, \ldots, N$ (34)

$X_{kj,A} = X_{k0j,A}, \forall\, j = 2, \ldots, T;\ \forall\, A \in \{1, 2, 3, 4i, 4f\};$ (35)

$X_{kij} = \sum_{A=1}^{4f} X_{kij,A}\ , \ \forall\, k = 1, \ldots, N; \forall\, j = 1, \ldots, T;\ i = 0, \ldots I$ (36)

$X_{kIj,A} = 0, k = 1, \ldots, N; \forall\, j = 1, \ldots, T;\ \ \forall\, A \in \{1, 2, 3, 4i, 4f\};$ (37)

The number of in-service construction equipment of each type should be equal to or greater than the required number in every period (Eq.(2)). Cost of purchasing new equipment cannot exceed the annual budget available for buying new equipment (Eq.(3)). The annual emission level of the construction equipment fleet should not exceed the specific environmental cap (Eq.(4)). Retrofitting and salvaging equipment occurs at the beginning of each period. Therefore, at the beginning of each period except period 1, the number of retrofitted and salvaged equipment should not exceed the number of in-service equipment within the last period (Eqs. (5)-(9)). At the beginning of period 1, the number of retrofitted and salvaged equipment should not exceed the number of initial construction equipment at the beginning of the planning horizon (Eqs. (10)-(14)). Eqs. (15)-(19) can ensure that newly purchased age-0 construction equipment can not be retrofitted or salvaged immediately. The number of in-service equipment within any period except period 1 equals the number of in-service equipment in the last period subtracting the number of equipment retrofitted and salvaged at the beginning of this period (Eqs. (20)-24)). The number of in-service equipment within period 1 equals the number of initial equipment at the beginning of the planning horizon subtracting the number of equipment retrofitted and salvaged at the beginning of period 1 (Eqs. (25)-(29)). The in-service construction equipment of age 0 within period 1 is the initial age-0 equipment adding the newly purchased age-0 equipment and subtracting the retrofitted and salvaged equipment at the beginning of period 1 (Eqs. (30)-(34)). In each period except period 1, the number of in-service age-0 equipment equals to that of new purchased age-0 equipment (Eq.(35)). The number of in-service equipment in each period is the sum of equipment meeting emission standards of US Tier 1 to US Tier 4f (Eq.(36)). It is assumed that any equipment reaches its maximum age I will be salvaged (Eq.(37)).

3 Case study

In this section, this study uses an excavator fleet belonging to a construction company in Hong Kong as a case to demonstrate the application of the proposed optimization model. The planning horizon is 10 years (T=10). The maximum age of the excavators is 20 (I=20). This fleet consists of 6 excavators. Table 1 shows the number of excavators with some important information.

Table 1 Some important information about the case excavator fleet

Equipment type	Excavator of type 1 (*k*=1)	Excavator of type 2 (*k*=2)	Excavator of type 3 (*k*=3)
Number	2	2	2
Age	8,9	7,11	10,10
Tier	2	2	2
Horsepower	91*KW*	69*KW*	80*KW*
Bucket capacity	0.46 m^3	0.28 m^3	0.39 m^3

Using the historical records of the company, the economic parameters were estimated for the coming year. The input economic parameters are presented in Table 2. In this case, this study assumes that the subsidy or penalty level for reducing emissions by replacing or retrofitting construction equipment is $6800 per ton.

Table 2 Estimated economic parameters

Parameter	Function	Unit
C_j	16,000,000	$
P_{kj}	50000+10,000(j-1), for *K*=1; 40000+10,000(j-1), for *K*=2; 30000+10,000(j-1), for *K*=3.	$
OC_{ki}	231500+3000t, for *k*=1; 135750+1500t, for *k*=2; 40500+1000t, for *k*=3.	$
r_{ki}	500000*0.85^i, for *k*=1; 400000*0.85^i, for *k*=2;	$

	300000*0.85^i, for k=3.	
EP	6800	\$/ton
D_{kj}	2	piece
OT_{kij}	8*250	hours

In this case, this study only considers NOx reduction from the case excavator fleet through making proper replacement and retrofitting strategies, given that only NOx are the main types of emissions in Hong Kong among all of emissions generated by construction equipment (Legislative Council of HK, 2018). In Hong Kong, new imported construction equipment is required to meet US Tier 3 emission standards. In line with this regulation, in this case, the average emission level of the case excavator fleet is limit to US Tire 3.

The retrofitting costs are driven from a report issued by ICCT (2018), as shown in Table 3.

Table 3 The costs of retrofitting construction equipment to meet more stringent emission standards

Equipment type	K=1	K=2	K=3
From Tier 2 to Tier 3	\$1366	\$850	\$1366
From Tier 2 to Tier 4i	\$2227	\$1569	\$2227
From Tier 2 to Tier 4f	\$2808	\$2544	\$2808
From Tier 3 to Tier 4i	\$861	\$719	\$861
From Tier 3 to Tier 4f	\$1442	\$1694	\$1442
From Tier 4i to Tier 4f	\$581	\$975	\$581

By applying data shown in Table 1-3 to the established model in Section 2, the objective value \$9,437,829 is obtained, which represents the sum of economic and environmental costs. The number of newly purchased, salvaged, retrofitted and in-service excavators in each period is provided in Table 4. As shown in Table 4, to minimize the economic and environmental cost and meet the emission reduction requirements, at the beginning of the first year, the owner of the case excavator fleet needs to replace two pieces of type-3 excavators aged 10 years with a new excavator meeting US Tier 4f emission standards, retrofit two type-1 excavators aged 8 and 9 years respectively to meet US Tier 4f emission standards, and retrofit one type-2 excavator aged 10 years to meet the US Tier 4i emission standards.

Table 4 Values of decision variables in the excavator fleet case

<u>Period 1-New purchased excavators</u>
$X_{31,4f}$=2

<u>Period 1-Retrofitted excavators</u>
$Y_{181,2-4f}$=1, $Y_{191,2-4f}$=1, $Y_{2(10)1,2-4i}$=1

<u>Period 1- Salvaged excavators</u>
$S_{3(10)1,2}$=2

<u>Period 1- In-service excavators</u>
$X_{191,4f}=1$, $X_{181,4f}=1$, $X_{271,4i}=1$, $X_{2(11)1,2}=1$, $X_{301,4f}=2$

<u>Period 2- In-service excavators</u>
$X_{1(10)2,4f}=1$, $X_{192,4f}=1$, $X_{282,4i}=1$, $X_{2(11)1,2}=1$, $X_{312,4f}=2$

<u>Period 3- In-service excavators</u>
$X_{1(11)3,4f}=1$, $X_{1(10)3,4f}=1$, $X_{293,4i}=1$, $X_{2(11)1,2}=1$, $X_{323,4f}=2$

<u>Period 4- In-service excavators</u>
$X_{1(12)4,4f}=1$, $X_{1(11)4,4f}=1$, $X_{2(10)4,4i}=1$, $X_{2(11)1,2}=1$, $X_{334,4f}=2$

<u>Period 5- In-service excavators</u>
$X_{1(13)5,4f}=1$, $X_{1(12)5,4f}=1$, $X_{2(11)5,4i}=1$, $X_{2(11)1,2}=1$, $X_{345,4f}=2$

<u>Period 6- In-service excavators</u>
$X_{1(14)6,4f}=1$, $X_{1(13)6,4f}=1$, $X_{2(12)6,4i}=1$, $X_{2(11)1,2}=1$, $X_{356,4f}=2$

<u>Period 7- In-service excavators</u>
$X_{1(15)7,4f}=1$, $X_{1(14)7,4f}=1$, $X_{2(13)7,4i}=1$, $X_{2(11)1,2}=1$, $X_{367,4f}=2$

<u>Period 8- In-service excavators</u>
$X_{1(16)8,4f}=1$, $X_{1(15)8,4f}=1$, $X_{2(14)8,4i}=1$, $X_{2(11)1,2}=1$, $X_{378,4f}=2$

<u>Period 9- In-service excavators</u>
$X_{1(17)9,4f}=1$, $X_{1(16)9,4f}=1$, $X_{2(15)9,4i}=1$, $X_{2(11)1,2}=1$, $X_{389,4f}=2$

<u>Period 10- In-service excavators</u>
$X_{1(18)(10),4f}=1$, $X_{1(17)10,4f}=1$, $X_{2(16)(10),4i}=1$, $X_{2(11)1,2}=1$, $X_{39(10),4f}=2$

4 Discussion

To reveal how the requirements of various environmental regulations and incentive initiatives impact replacing and retrofitting strategy-making of the case fleet, this study runs the model established in

Section 2 with mere economic parameters. The results are that only the type-2 aged 8 excavators are replaced at the beginning of the first period and the corresponding minimum cost is $9,086,236. This study also runs the model with economic parameters and the emission reduction requirement constraint and without subsidy grants from the Hong Kong government. The corresponding optimum cost is $9,623,765. The two type-3 aged 10 years excavators are replaced at the beginning of the first year. Comparing the optimum costs between the replacing and retrofitting strategies with mere economic parameters and with both economic and environmental parameters, it can be concluded that environmental regulations and incentive initiatives with a subsidy level of $6800 per ton of NOx reduced will pose a financial burden on the owner of the excavator fleet. However, this financial burden may not be heavy, because only around 3.73% of the optimum cost ($9,437,829) is the cost of replacing and retrofitting the case excavator fleet for emission reduction after being offset against by the subsidy grants from the government. Comparing the two optimum cost of $9,086,236 and $9,623,765, a financial burden of $5,37,529 over the 10 years are posed on the owner of the excavator fleet if there is no available subsidy grant, which is about 5.92% of the optimum cost of $9,086,236. The subsidy level of $6,800 per ton of NOx reduced can reduce the financial burden generated by the requirements of environmental regulations and incentives to some extent.

From the above discussion, it can be concluded that the strategies of replacing and retrofitting the excavator fleet are informed. In this case, the emission reduction target of Hong Kong limiting the construction equipment fleet emission level at or under US Tire 3 can be achieved through replacing or retrofitting excavators in some periods. Moreover, the costs incurred by replacing and retrofitting excavators also do not put heavy financial burdens on the owner of the case excavator fleet.

The cost-effectiveness of reducing NOx emission can be examined from the perspectives of the Hong Kong government and the owner of the excavator. The cost-effectiveness of reducing NOx emission of Hong Kong government equals its subsidy grant level of $6,800 per ton. Over the planning horizon of 10 years, through replacing and retrofitting excavators, 53.84 tons NOx has been reduced and the cost of reducing NOx emission is $553,726. Thus, the cost-effectiveness of reducing NOx from the perspective of the owner of the excavator fleet is $10,284,66. The cost-effectiveness of reducing NOx emission from an overall societal perspective is about $17,084 per ton of reduced NOx emission. This suggests that the government can adjust the subsidy grant level to allocate the responsibility of reducing emissions from construction equipment between governments and owners of construction equipment.

5 Conclusions

The problem of extensive emissions from construction equipment has been widely recognized around the world. As the producer of emissions, owners of construction equipment should shoulder the emission reduction responsibility through formulating proper replacing and retrofitting strategies. Therefore, this study proposes an optimization model to help owners of construction equipment to formulate proper replacing and retrofitting strategies. This optimization model incorporates environmental considerations into their formulation of replacing and retrofitting strategies, which can minimize the sum of the economic and environmental costs associated with purchasing new construction equipment, salvaging and retrofitting old in-use construction equipment, operating construction equipment over the period of analysis. The replacing and retrofitting strategies formulated by using the optimization model can also ensure the achievement of the emission reduction target of making the overall emission level of construction equipment fleet at or under US Tier 3 emission standards.

This study also formulates replacing and retrofitting strategies for a fleet of excavators located in Hong Kong. From this case study, it can be concluded that the requirements of various environmental regulations and incentive initiatives do impact the formulation of replacing and retrofitting strategies and pose a financial burden on owners of construction equipment. Moreover, this study suggests that governments can also adjust the subsidy grant level to allocate the responsibility of reducing emissions from construction between governments and owners of construction equipment. The proposed optimization model is scalable across a range of off-road equipment for its sustainable management, including not only construction equipment but also agricultural and mining equipment.

In contribution, an optimization model is proposed in this study to help owners of construction equipment make informed replacing and retrofitting strategies. governments can also employ this optimization model to determine the subsidy grants levels to motivate owners of construction equipment to participant in various incentive programs initiated by governments.

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