Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 736 - 751, 2005

SCHEDULING PURCHASE AND RENEWAL OF INTERNATIONAL AIRPORT DEPARTURE FACILITIES

Chaug-Ing HSU
Professor
Department of Transportation Technology and Management
National Chiao Tung University
1001 Ta Hsueh Road, Hsinchu, Taiwan 30050 R.O.C
Fax: 886-3-5720844
E-mail: cihsu@nctu.edu.tw

Ching-Cheng CHAO
Ph.D. Candidate
Department of Transportation Technology and Management
National Chiao Tung University
1001 Ta Hsueh Road, Hsinchu, Taiwan 30050 R.O.C
Fax: 886-3-5720844
E-mail: jawcc@cksairport.gov.tw

Abstract: This study formulates a dynamic programming model to determine the optimal facility purchase and replacement scheduling by considering facility renewal costs, aviation safety, passenger service level, and airport finance. The study constructs various cost functions on facility depreciation, operation, maintenance and delay for different facilities at different time stages according to passenger volume, facility reliability and utilization so as to reflect dynamic variations in those costs. Moreover, this study uses CKS international airport as an example to demonstrate the application of the model. The results indicate when the malfunction rate is higher than a certain level, such that the total maintenance and delay costs are higher than the total capital, depreciation and abandon costs to renew the facility, then the replacement must be done. This study provides the airport authority optimal strategic decisions on the purchase and replacement of various facilities in terms of quantities and timing.

Key Words: international airport, delay cost, equipment replacement

1. INTRODUCTION

The efficiency of airport management and operation has become an important issue at major international airports around the world. Airport authority not only explores new sources of income but also strives to reduce costs of operation. The expenditures of airports include facility depreciation, maintenance and operating costs, personnel expense, subcontracting charges, and noise pollution prevention and control expenses. Among those costs, facility depreciation, operating and maintenance costs account for a relatively large proportion. The capacity of an airport not only depends on the optimal investment but also the efficient management of various facilities. Furthermore, maintaining a stable and efficient operation can ensure the quality of airport service and aviation safety. In recent years, the consumer rights of passengers have been much emphasized and protected. In addition, airline business has been trapped in a quagmire in the aftermath of the September 11 tragedy. All these have attracted great attention on the maintenance of airport facilities to ensure airport safety and flight delay caused by inadequate handling capacity due to security inspection. Purchase and replacement made too early will result in a waste of investment, while that implemented too late will cause inadequate handling capacity, leading to increased congestion for passengers and more frequent breakdown of facilities. Not only will such deteriorate service quality and increase maintenance costs, but also cause flight delay and undermine aviation safety. Therefore, issues regarding the timely purchase and replacement of various facilities are of significant importance. The optimal purchase and replacement scheduling of international airport terminal facilities has seldom been investigated and will become an important issue.

Among various approaches in literature, Bellman (1995) first adopted dynamic programming on scheduling facility purchase and replacement. The unique feature of dynamic programming is that it can reflect the changes of various decision costs with time. Hartman (2001) developed an economic replacement model with probabilistic asset utilization, which also changes with time. In his approach, decision variables such as service age and accumulated usage are taken into consideration to derive an optimal purchase and replacement schedule. However, related applications of dynamic programming in industrial engineering literature are mostly limited to the optimal purchase and replacement scheduling of production facilities in factories. Furthermore, most of those considered single equipment and emphasized mainly on analyzing production cost and defective rate.

Facility maintenance has been widely studied in industrial and mechanical engineerings. In general, facility maintenance can be divided into two categories, i.e. preventive maintenance and corrective maintenance. Preventive maintenance corresponds to actions taken to maintain the operation of the system at a certain specific state, while corrective maintenance refers to actions taken to restore the operation of the system at a certain specific state when an individual component or part of the system fails. Canfield (1986) stated that system operation produces stress which results in degradation. The more the system degenerates, the higher the instantaneous hazard rate becomes. Chan and Shaw (1993) also found that preventive maintenance can reduce failure rates; the intensity of which is affected by the service age of the facilities and the frequency of maintenance performed. Sherif and Smith (1981) presented a state-of-the-art review of the literature related to the optimal maintenance models of systems subject to failure. They listed eight optimization techniques employed for obtaining optimal maintenance policies which include linear programming, nonlinear programming, dynamic programming, Pontryagin maximum principle, mixed-integer programming, decision theory, search techniques and heuristic approaches.

In addition to various cost components considered in previous studies above, delay cost due to inadequacy or failure of airport facilities is further considered in our studies for exploring the optimal scheduling of facility purchase and replacement. In recent years, consumer rights of travelers have been much emphasized with legislation enacted for protecting these rights. Hence, it is foreseeable that the airport authority will be liable to compensate the travelers for flight delay due to the failure of facilities and inefficient management. As stipulated in Article 19 of the Warsaw Convention, the transporter is liable to compensate for the damage due to delay in transporting the passengers, baggage or goods. However, the transporter is not held responsible for such damage in some cases. Hence, airline companies are responsible for compensating the passengers in case of flight delay including the loss in terms of vacation and travel inconvenience caused. Despite the rules and regulations governing the liability of transporters, airline companies, compared with the operators of other transportation modes confront with more uncertainty and difficulty arisen from weather, aviation control, airport facility malfunction, changes in flight schedule and mechanical maintenance requirements. Nevertheless, delay caused by weather, aviation control and airport facility problems are beyond the control of the airline operators who should not be responsible for such; hence there exist practical problems when laying down a standard compensation scheme for delays in different modes of transportation.

This study aims to determine the optimal scheduling of airport facility purchase and replacement by considering facility renewal costs, aviation safety, passenger service level, and airport finance. The study constructs a dynamic programming model to determine the optimal facility purchase and replacement scheduling by minimizing the total related costs while ensuring service quality. Various costs are formulated, including facility depreciation, operating, maintenance, delay and abandonment costs. Moreover, this study uses CKS international airport in Taiwan as an example to demonstrate the application of the model.

The remainder of this paper is organized as follows. Section 2 describes the departure-related terminal facilities and operations at an international airport. Section 3 formulates related cost functions and constructs a mathematical programming model for scheduling the purchase and replacement of various facilities. Subsequently, section 4 presents a case study demonstrating the application and results of the models. Concluding remarks are finally made in section 5.

2.DEPARTURE-RELATED FACILITIES AND OPERATIONS

Passenger terminals of international airports involve very complicated operations. International passenger terminals are equipped not only with standard facilities such as ticketing, check-in and boarding; but also operations such as immigration, security check and quarantine. Figure 1 displays the flowchart of procedures undertaken by departure passengers and the related facilities. Departure passengers arriving at the passenger terminal are required to complete all necessary departure procedures and go to the gate on time. Inefficient handling or inadequate capacity due to the failure of related facilities will lengthen the waiting time for passengers; and moreover lead to flight delay. Therefore, this study focuses on departure facilities. However, delay cost incurred by such inefficiency or failure varies with different facilities involved. Table 1 summarizes the impacts due to failures of various departure-related facilities. For example, problems related to check-in, immigration and security facilities will usually increase the waiting time of passengers and only in some cases cause flight delay. However, this may indirectly affect the concession revenue of airport because passengers, who spend too much time on departure process due to facility problems, may not have enough time for commercial activities such as shopping or dining. In the case when boarding facilities fail, flight delay will be inevitable or even affect passengers' subsequent itinerary. For those failures related to baggage transport, as long as the loading of all baggage can be completed before takeoff, passengers will not be affected in any way. In addition, facilities involved in immigration, security and baggage sorting are usually shared by passengers of all flights; hence any failure in one of those facilities will cause problems to all flights at that particular time slot; while failure in any one of facilities related to check-in, boarding and baggage transport will only affect the particular flight involved. In this study, only the hardware facilities related to departure terminals are examined.

3.FACILITY PURCHASE AND REPLACEMENT SCHEDULING MODEL

The construction cost of an international airport is generally very high. So it is important to set up a master plan in accordance with predicted economic growth and traffic volume at different stages, thereby making use of facilities and lowering constructing and operating costs. This study explores the optimal facility purchase and replacement scheduling during study period between two building extension stages. The failure rate of a facility is dependent on its service accumulation and expected life and maintenance frequency. The effect of facility failure on processing time for passengers depends on its utilization. For a newly opened airport or recently installed facilities, occasional failures have little impact on the normal operation of the airport because the passenger volume has not yet reached the maximum handling capacity. However, when passenger volume approaches facility capacity, failures of facilities will cause inadequate capacities and incur serious problems. The study applies mathematical programming methods and attempts to minimize facility total costs including facility depreciation, operating, maintenance, delay and replacement loss while considering aviation safety, service quality, and financial status of the airport management. The passenger volume of an international airport varies with the global economic environment and other factors such as terrorism. This study constructs various cost functions on facility depreciation, operating, maintenance and delay for different facilities at different time stages according to passenger volume, reliability and utilizing rate so as to reflect the variation in those costs. Based on these cost functions, the study further investigates variations in various costs for different facilities with changing service age and passenger volume and analyzes the optimal purchase and replacement decision.

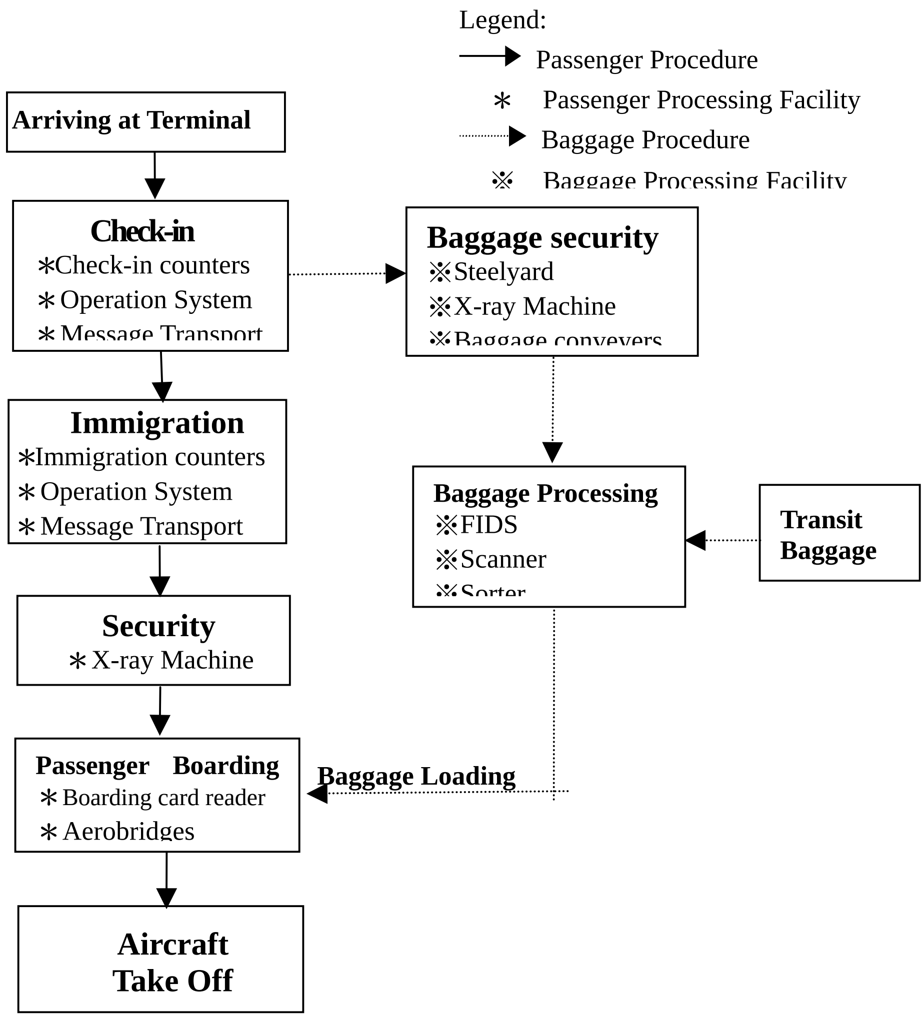


Figure 1. Departure Procedure and Facilities at International Airport

3.1 Various Costs of Facilities

Costs related to terminal operation facilities include those incurred by facility depreciation, operating, maintenance, delay and replacement loss. Generally, the reliability of facilities deteriorates with the increase in service age, which further leads to higher operating,

maintenance and delay costs. On the other hand, the depreciation cost of facilities decreases with service age. If the residual value of the facility after replacement is less than the purchase cost minus the depreciation cost, such purchase and replacement would result in a loss. In this study, the cost functions of different facilities are constructed by considering the ages of different facilities and the change in passenger volumes over different decision time periods.

Table 1. Impacts due to Failures of Various Departure-related Facilities

Facilities	Check-in	Immigration	Security	Boarding	Baggage Processing
Flights affected	∇	∞	∞	∇	∞
Consequences	#	#	#	◊	◊

Notation: ∇ : Single flight

∞ : All flights

: Passenger waiting and flight delay

◊ : Flight delay or no influence

Costs related to terminal operation facilities include those incurred by facility depreciation, operating, maintenance, delay and replacement loss. Generally, the reliability of facilities deteriorates with the increase in service age, which further leads to higher operating, maintenance and delay costs. On the other hand, the depreciation cost of facilities decreases with service age. If the residual value of the facility after replacement is less than the purchase cost minus the depreciation cost, such purchase and replacement would result in a loss. In this study, the cost functions of different facilities are constructed by considering the ages of different facilities and the change in passenger volumes over different decision time periods.

Facility has a limited lifetime and its value decreases with the increase in service age. Its depreciation cost is usually listed on annual basis to comply with the accounting principle and cost-apportionment. Let C^s_{fit} represent the depreciation cost of facility f with service age t at time period i, then C^s_{fit} can be formulated as:

$$C^s_{fit} = Z_{fit} \cdot X^{ge}_t \tag{1}$$

where Z_{fti} represents the original investment cost of facility f with service age t at period i, X^{ge}_t denotes the depreciation rate of facility with service age t when the interest is g and the expected life is e.

Technology advance and new development in airport operating software have innovated highly automated terminal facilities, which results in lower operating and maintenance costs than before. Thus existing facilities though not yet reach their service life limits may still be replaced due to out-of-date technology; thus result in the premature loss of costly equipment. Examining the total costs of facilities; thus comparing the depreciation, operating, maintenance and delay costs between the existing facilities and new facilities may shed light on whether and when should purchase and replacement be made. Let C^r_{fit} represent the replacement loss of facility f with service age t at period i, then C^r_{fit} can be formulated as:

$$C^r_{fit} = I_{fit} \cdot [Z_{fi}(1 - \sum_{t=1} X^{ge}_t) - A_{fit}] \tag{2}$$

$$I_{fit} = \begin{cases} 1, \text{ if facility } f \text{ with service age } t \text{ at period } i \text{ has been replaced;} \\ 0, \quad \text{otherwise.} \end{cases}$$

where A_{fit} is the salvage value of facility f with service age t at period i.

Operating costs include expenses paid on power consumption, labor and raw material, which all vary with passenger volume and degree of automation. Technological advances bring out automated facilities which require less labor. On the other hand, power and material needed for operation increase with the service age. In this study, operating cost is divided into two parts, namely, fixed cost and variable cost, which changes with passenger volume. Let C^o_{fit} represent the operating cost of facility f with service age t at period i, then C^o_{fit} can be formulated as:

$$C^o_{fit} = K_{fit} + \alpha_{fit} \cdot N_i \cdot N_{fit} / N_{fi} \tag{3}$$

where K_{fit} and α_{fit} denote the fixed operating and the unit variable cost of facility f with service age t at period i, respectively. N_i is the departure passenger volume at period i and N_{fit} is the capacity of facility f with service age t at period i. Assuming that different facilities with different lifetime have the same utilization rate, we can then express the actual volume of passengers at period i handled by facility f with service age t as $N_i \cdot N_{fti} / N_{fi}$, where $N_{fi} = \sum_t N_{fti}$.

Previous studies (MIL-STD-2173, 1986; Lam, 1997) suggest various actions be chosen when facility failure occurs. These actions include maintenance, repair and replacement. Maintenance aims to improve the operating conditions of facilities by eliminating factors that deteriorate their performances. Repair is to fix the damage of facilities aging over time, slow down degradation, and restore the reliability of aged components, thereby reducing the failure rate. Replacement is the renewal of damaged or degraded facilities, which are beyond repair. Preventive maintenance can be periodic and non-periodic. Adopted mostly by industries, periodic preventive maintenance is routinely performed to relieve stress temporarily and slows the rate of degradation. Failure occurring within the maintenance interval may necessitate repair actions (Park et al., 2000; Tsai et al., 2001). Non-periodic maintenance includes “Failure limit policy” (Lie and Chun, 1986; Jayabalan and Chaudhuri, 1992), “Sequential PM policy” (Pham and Wang, 1996; Dedopoulos and Smeers, 1998), and “Repair limit policy” (Pham and Wang, 1996).

Based on abovementioned studies, the costs considered in the study include those for preventive maintenance, preventive replacement, corrective maintenance and minimal repair. Moreover, the models constructed herein take the maintenance interval and the number of repairs being optimized to derive the optimal maintenance and replacement policy, which aims to minimize the expected total cost. In this study, maintenance costs consist of expenditures on preventive maintenance and repair. Preventive maintenance cost is related to the facility age and utilization, while repair cost, which depends on the frequency and severity of malfunction, reflects the reliability of the facility. Let C^m_{fit} represent the maintenance cost of facility f with service age t at period i under optimal maintenance policy, then C^m_{fit} can be formulated as:

$$C_{fit}^{m} = [(\beta_f + \delta_f \cdot t) \cdot N_i / N_{fi} + (1 - R_f(t)) \cdot \phi_f] \cdot F_{fit} \tag{4}$$

where β_f is the routine preventive maintenance cost of facility f with normal utilization in the first year. The value of β_f is influenced by the original investment cost, the characteristics and operating environment of facility f. And δ_f denotes the increasing routine preventive maintenance cost of facility f with a increasing utilization rate per year. Assuming that different facilities with different lifetime have the same utilization, and N_i / N_{fi} is the average utilization of facility f at period i. Let ϕ_f represent the annual repair cost of facility f, which varies with its reliability. Therefore, F_{fit}, $(\beta_f + \delta_f \cdot t) \cdot N_i / N_{fi} \cdot F_{fit}$ and $(1 - R_f(t)) \cdot \phi_f \cdot F_{fit}$ are the number, preventive maintenance cost and repair cost of facility f with service age t at period i, respectively.

The reliability function of facility f, $R_f(t)$, depends on both the inherent characteristics of its components and the outside conditions. Weibull distribution is widely adopted to describe mechanism failure as well as the estimation of lifetime in various fields including mechanical, chemical, medical and electronic engineerings. This study employs Weibull distribution to describe facility reliability and failure functions (Smith and Bain, 1975; Dhillon, 1981), which are

$$R(t) = \exp\{-[\ln(\lambda t + 1)]^{b+1}\}$$

$$h(t) = \frac{(b+1)[\ln(\lambda t + 1)]^{b}}{(\lambda t + 1)}, \text{ for } b \geq 0, \lambda > 0, t \geq 0$$

where b, λ and t denote shape, scale parameter and time, respectively.

Inadequate facilities may increase waiting time for passengers going through check-in, immigration and security. Commercial concessions are very important for international airports. Nowadays, most concessions are charged based on a certain proportion of store revenue. Hence, passengers arriving late will not have enough time for other activities such as shopping or dining, thus decreasing the business income of an airport. Reasons causing flight delay are many, which include poor weather conditions, mechanical failure and delayed ground operations. The airport authority should provide the needs of passengers free of charge when flights delay due to failed or insufficient facilities. Thus, delay cost incurred by not timely and appropriately purchasing and replacing facilities will result in inefficient handling or increased incidence. Delay cost may also include the reduction in concession revenue and compensation due to flight delay.

Let D_{fit}^{u} represent the reduction in concession revenue due to the failure of facility f with service age t at period i, then D_{fit}^{u} can be formulated as:

$$D_{fit}^{u} = N_i \cdot \theta_{fit} \cdot W_{fit}^{'} \cdot U \tag{5}$$

$$W_{fit}^{'} = \begin{cases} [N_i / (N_{fi} - \theta_{fit} \cdot N_{fit}) - 1] \cdot P_{fi} & \text{if } N_i > (N_{fi} - \theta_{fit} \cdot N_{fit}) \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$\theta_{fit} = a_f \cdot (1 - R_{fit}) \tag{7}$$

where N_i is total departure passengers at period i. And θ_{fit}, $N_i \cdot \theta_{fit}$ and $W_{fit}^{'}$ represent the ratio of breakdown time to total operating time, the total number of waiting passengers, and the average additional waiting time of each passenger due to the breakdown of facility f

with service age t at period i, respectively. U is the average reduced concession revenue per passenger per minute due to increased wait time for passenger to complete the procedure. P_{fi} denotes the average time required for a passenger to complete the procedure using facility f at period i and a_i is the ratio of the repair time to the operating time of facility f.

In case of long delay due to severe failure, passengers should be provided with free meals and accommodation and be compensated for itinerary delay. Let D^v_{fit} represent the compensation for flight delay due to the failure of facility f with service age t at period i, then D^v_{fit} can be formulated as:

$$D^v_{fit} = \begin{cases} 0 & \text{if } W'_{fit} < t' \\ N_i \cdot r^m_i \cdot s^m \cdot V' \cdot \theta_{fit} & \text{if } t' \le W'_{fit} < t'' \\ N_i \cdot (r^m_i \cdot s^m \cdot V' + r^n_i \cdot s^n \cdot V'') \cdot \theta_{fit} & \text{if } t'' \le W'_{fit} \end{cases} \tag{8}$$

where r^m_i and r^n_i represent the ratios of departure passengers during mealtime and midnight to total departure passengers at period i, respectively. s^m and s^n are the ratios of mealtime and midnight to the operating time of the airport, respectively. V' and V'' denote the compensations for meals and itinerary delay because of flight delay due to the failure of facility, respectively. t' and t'' are the thresholds of flight delay time, beyond which airport authority ought to compensate passengers for meals and itinerary delay, respectively.

As mentioned above, delay cost also includes the reduction in the concession revenue of airport and the increase in the compensation due to flight delay. Since passenger volumes are changing at different time periods, the delay costs of various facilities vary with their service ages. Let C^d_{fit} represents the delay cost due to the failure of facility f with service age t at period i, then C^d_{fit} is $D^u_{fit} + D^v_{fit}$.

The increase in facility demand due to increasing passenger volume is not always met by expanding existing facilities or installing new facilities. As a result, inadequacy in passenger handling may occur during peak season, which increase the waiting time of passengers. Although the delay will not be long, it still causes a reduction in concession revenue of airport. Let $C^{d'}_{fi}$ represent the delay cost due to the inadequacy of facility f at period i, then $C^{d'}_{fi}$ can be formulated as:

$$C^{d'}_{fi} = N_i \cdot r^p_i \cdot W''_{fi} \cdot U \tag{9}$$

$$W''_{fi} = \begin{cases} (N_i \cdot r^p_i / N_{fi} - 1) \cdot P_{fi} & \text{if } N_i \cdot r^p_i > N_{fi} \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

where r^p_i represents the ratio of departure passengers during the peak hour to total departure passengers at period i.

3.2 Aviation Safety, Passenger Service Level, and Airport Finance

International airports currently are in a highly competitive environment and moreover are increasingly financially self-reliant. Airport authorities not only should focus on reducing operation costs but also on aviation safety. Whether an airport can become a hub of air transport depends not only on its location, but also on the quality of service provided. Hence, while aiming to minimize total costs, the model developed in this study takes into consideration aviation safety, quality of service and financial status, which will be discussed in details in the following.

Passenger and baggage security checks are very important in preventing suspected passengers from check-in or bringing on-board dangerous items. Due to terrorist or bio-chemical attack, more advanced monitoring and screening techniques and facilities are employed to ensure maximum safety. This study analyzes security-related facilities and suggests that replacement be made when the reliability of those drops below a certain level, such as:

$$R_{f^*it} \geq r_{f^*}^{\min} \tag{11}$$

where R_{f^*it} denotes the reliability of security-related facility f^* with service age t at period i, and $r_{f^*}^{\min}$ is the lower bound of the reliability of security-related facility f^*.

The failure and/or inadequate handling capacity of a facility will increase the waiting time of passengers and moreover delays flights. This study specifies the maximum acceptable delay imposed on the passengers, above which the delay related facilities should be replaced or new ones should be added. The formulation is:

$$\sum_{f^p} W_{f^p i} \leq t^w \tag{12}$$

$$\max\{T_i^p, T_i^b\} \leq t^d \tag{13}$$

where t^w and t^d are the maximum acceptable delay time for passenger processing and for a flight due to the failure and/or inadequacy of facility, respectively. Because a flight without completing its passenger-boarding and baggage-loading procedures will not be allowed to take off, therefore the delay time of a flight is the maximum of passenger-boarding delay and baggage-loading delay. T_i^p and T_i^b denote the delay times of passenger processing and baggage processing at period i, respectively, and can be formulated as:

$$T_i^p = \sum_{f^p} P_{f^p i} + \sum_{f^p} W_{f^p i} - t_0 \tag{14}$$

$$T_i^b = \sum_{f^b} P_{f^b i} + \sum_{f^b} W_{f^b i} - t_0 \tag{15}$$

where f^p and f^b are the facilities related to passenger processing and baggage processing, respectively. And t_0 denotes the time from the end time of check-in to boarding time.

Constructing the infrastructure of an airport involves huge investment with revenue coming in only upon completion. Hence, a sound finance budgeting is important to ensure good financial management and sustainable operation. As passenger volume increases up to the service capacity of certain facilities, the purchase and replacement of the facilities ought to be done. Part of the revenue should be allocated for implementing the purchase and replacement plans. This study specifies that excluding aviation safety related expenses, the total annual expense on the purchase and replacement of facilities should not exceed the sum of the budget for such purchase and replacement and the remaining balance from the previous year’s account. However, expenses on facilities related to aviation safety are not subject to such restriction so as to ensure safety and to prevent the airport authority from financial woe. The formulation is :

$$\sum_{f^{**}=1}^{k-k^*} Z_{f^{**}i0} \leq M_i + \sum_{i=0}^{i-1} (M_i - \sum_{f=1}^{k} Z_{fi0}) - \sum_{f^*=1}^{k^*} Z_{f^*i0} \tag{16}$$

where M_i denotes the maximum budget for the purchase and replacement of all facilities at period i. f, f^* and f^{**} represent all facilities, facilities related to aviation safety and facilities not related to aviation safety, respectively. k and k^* are the numbers of all facilities and facilities related to aviation safety, respectively. Moreover, $\sum_{i=0}^{i-1}(M_i - \sum_{f=1}^{k} Z_{fi0})$ denote the remaining balance from the previous year's account and $\sum_{f^*=1}^{k^*} Z_{f^*i0}$ is the total set-up cost of facilities related to aviation safety at period i.

3.3 Decision Model

This study applies a dynamic programming model to determine the optimal facility purchase and replacement scheduling by considering facility renewal costs, aviation safety, passenger service level, and airport finance. The model is formulated as:

$$\min \sum_{i=0}^{T} \sum_{f=1}^{k} \min\left\{C_{fi}(S_{fi}, d_{fi}^{\theta})\right\}$$

$$= \min \sum_{i=0}^{T} \sum_{f=1}^{k} \min\left\{C_{fi}(S_{fi}, d_{fi}^{0}), C_{fi}(S_{fi}, d_{fi}^{1}), C_{fi}(S_{fi}, d_{fi}^{2})\right\} \tag{17}$$

$$s.t. \left\{S_{fi+1}\right\} = \left\{S_{fi}\right\} + \left\{d_{fi}^{\theta}\right\}, \quad i = 0, \ldots, T; f = 1, \ldots, k \tag{18}$$

$$R_{f^*ti} \geq r_{f^*}^{\min} \tag{19}$$

$$\sum_{f^p} W_{f^p i} \leq t^w \tag{20}$$

$$\max\{T_i^p, T_i^b\} \leq t^d \tag{21}$$

$$\sum_{f^{**}=1}^{k-k^*} Z_{f^{**}i0} \leq M_i + \sum_{i=0}^{i-1}(M_i - \sum_{f=1}^{k} Z_{fi0}) - \sum_{f^*=1}^{k^*} Z_{f^*i0} \tag{22}$$

where $C_{fi}(S_{fi}, d_{fi}^{\theta})$ represent the decision cost, where S_{fi} and d_{fi}^{θ} are the set of facility f and the set of decision at period i, respectively. Eq. (17) is an objective function that minimizes the total costs of all facilities. The decisions $\theta = 0$, $\theta = 1$ and $\theta = 2$ represent to remain unchanged, purchase additional facilities, and replace existing facilities, respectively. The reliability of facilities related to aviation safety is restricted to maintain at least higher than a minimum level as Eq. (19) to secure aviation safety of airport. Eq. (20) and Eq. (21) constrain the waiting time of passengers and the delay time of flight not exceeding an acceptable service level. Eq. (22) prevents the airport authority from financial woe while ensuring aviation safety.

The decision cost, $C_{fi}(S_{fi}, d_{fi}^{\theta})$, can be formulated further as:

$$C_{fi}(S_{fi}, d_{fi}^{0}) = \sum_{t=1}^{E_{fi}} (C_{fit}^{s} + C_{fit}^{o} + C_{fit}^{m} + C_{fit}^{d}) + C_{fi}^{d'} \quad , \quad \left\{d_{fi}^{0}\right\} = 0 \tag{23}$$

$$C_{fi}(S_{fi}, d_{fi}^{1}) = \sum_{t=0}^{E_{fi}} (C_{fit}^{s} + C_{fit}^{o} + C_{fit}^{m} + C_{fit}^{d}) + C_{fi}^{d'} \quad , \quad \left\{d_{fi}^{1}\right\} = F_{fi0} \tag{24}$$

$$C_{fi}(S_{fi}, d_{fi}^{2}) = \sum_{t=0}^{h-1} (C_{fit}^{s} + C_{fit}^{o} + C_{fit}^{m} + C_{fit}^{d}) + C_{fi}^{d'} + \sum_{t=h}^{E_{fi}} C_{fit}^{r} \quad , \quad \left\{d_{fi}^{2}\right\} = F_{fi0} - \sum_{t=h}^{E_{fi}} F_{fit} \tag{25}$$

where E_{fi} is the largest service age of all facilities f at period i. If $\theta = 0$, the facilities remain unchanged and decision cost, $C_{fi}(S_{fi}, d_{fi}^{0})$, is shown by Eq. (23). If $\theta = 1$, in the set of facilities, an additional F numbers of facility f with service age 0, F_{fi0}, are added and the decision cost, $C_{fi}(S_{fi}, d^1_{fi})$, is shown by Eq. (24). If $\theta=2$, the decisions not only replace those facilities f with service age larger than h, $\sum_{t=h}^{E_{fi}} F_{fit}$, but also add an equivalent number of F_{fi0} and the decision cost, $C_{fi}(S_{fi}, d^2_{fi})$, is shown by Eq. (25).

4.CASE STUDY

Chiang Kai-shek International Airport (CKS) is located in Taoyuan, Taiwan, ROC, about 40 km from Taipei. With an area of 1,223 hectares, CKS has two terminals and two runways. Currently, 36 airlines operate at this airport. In 2002, the passenger volume of CKS was 19,228,411.This study uses CKS international airport as an example to demonstrate the feasibility and usefulness of the constructed models for scheduling the purchase and replacement of facilities. Due to data availability, we merely discuss departure-process related major facilities that include check-in, immigration, security and boarding gate. The study period is 15 years beginning from 1991, which is denoted by i=0 in the model. Table 2 lists the parameter values of these facilities which were estimated from the previous data. To simplify the analysis, the following assumptions were made.

1. Passenger volume is an exogenous variable and given. The value of 2003 passenger volume is the actual value while those of 2004 and 2005 were estimated using the average annual growth rate.
2. The study focuses on hardware facilities and does not consider software facilities.
3. At the initial year, i=0, all facilities are new (service age=0), the same type of facilities purchased at different time periods have the same functions and price.
4. When purchase and replacement is decided, all facilities with the same age will be purchased.
5. Purchase and replacement will be appropriately completed at the same year to avoid service interruption.

Table 2. Parameter Values of Major Facilities

Facilities (f)	Set-up Cost	e	K_f	α_f	β_f	δ_f	ϕ_f	a_f
Check-in	600	8	7060	5	19.2	1.2	1817	5
Immigration	15	8	1765	0.02	0.48	0.03	454	5
Security	250	10	1176	0.015	16	1	950	5
Boarding Gate	1000	20	1412	0.06	32	2	550	2

The study then applies the models formulated in Section 3 to schedule purchase and replacement for departure facilities at CKS. The results indicate that the optimal numbers of facilities for check-in, immigration, security and boarding gates at period 0 were 3, 9, 2 and 14, respectively. Since maintenance cost and delay cost will increase with increasing service age, when facility failure rates exceed a certain level, maintenance cost and delay cost become greater than depreciation and replacement costs, then new facilities should be purchased to replace the old ones. Take check-in counters for example, beyond the service age of 10 years, the cost of using these old facilities may exceed that of new ones, thus necessitating replacement. Table 3 shows the optimal purchase and replacement decisions regarding various facilities at different time periods and the optimal sets of various facilities. As shown in the table, the optimal values change over time depending on both service age and passenger volume. Take year 1990 (i=9) as an example. The optimal decision on check-in counters remains unchanged and the service ages of all existing check-in counters are added one more year. The set of check-in counters changes from $\{3_{1,8,8}, 1_{1,8,7}, 1_{1,8,4}, 1_{1,8,0}\}$ to $\{3_{1,9,9}, 1_{1,9,8}, 1_{1,9,5}, 1_{1,9,1}\}$. On the other hand, the optimal decision on immigration counters is to replace 19 counters with service age 9 and purchase additionally 4 new counters. The new sets of immigration and security counters, i.e. $\{23_{2,9,0}\}$ and $\{1_{3,9,0}\}$, are added at this period, respectively. The decision on boarding gate remains unchanged.

Table 3.The Optimal Decision and Set of Facilities at Each Period

Period(i)	Facilities (f)	Optimal Decision	Set of Facilities
0	Check-in	$3_{1,0,0}$	$3_{1,0,0}$
	Immigration	$19_{2,0,0}$	$19_{2,0,0}$
	Security	$2_{3,0,0}$	$2_{3,0,0}$
	Boarding Gate	$14_{4,0,0}$	$14_{4,0,0}$
1	Check-in	$1_{1,1,0}$	$3_{1,1,1}$, $1_{1,1,0}$
	Immigration	$3_{2,1,0}$	$19_{2,1,1}$, $3_{2,1,0}$
	Security		$2_{3,1,1}$
	Boarding Gate		$14_{4,1,1}$
2	Check-in		$3_{1,2,2}$, $1_{1,2,1}$
	Immigration		$19_{2,2,2}$, $3_{2,2,1}$
	Security		$2_{3,2,2}$
	Boarding Gate		$14_{4,2,2}$
3	Check-in		$3_{1,3,3}$, $1_{1,3,2}$
	Immigration		$19_{2,3,3}$, $3_{2,3,2}$
	Security		$2_{3,3,3}$
	Boarding Gate	$2_{4,3,0}$	$14_{4,3,3}$, $2_{4,3,0}$
4	Check-in	$1_{1,4,0}$	$3_{1,4,4}$, $1_{1,4,3}$, $1_{1,4,0}$
	Immigration	$4_{2,4,0}$	$19_{2,4,4}$, $3_{2,4,3}$, $4_{2,4,0}$
	Security	$1_{3,4,0}$	$2_{3,4,4}$, $1_{3,4,0}$
	Boarding Gate		$14_{4,4,4}$, $2_{4,4,1}$
5	Check-in		$3_{1,5,5}$, $1_{1,5,4}$, $1_{1,5,1}$
	Immigration		$19_{2,5,5}$, $3_{2,5,4}$, $4_{2,5,1}$
	Security		$2_{3,5,5}$, $1_{3,5,1}$
	Boarding Gate	$3_{4,5,0}$	$14_{4,5,5}$, $2_{4,5,2}$, $3_{4,5,0}$
6	Check-in		$3_{1,6,6}$, $1_{1,6,5}$, $1_{1,6,2}$
	Immigration	$3_{2,6,0}$	$19_{2,6,6}$, $3_{2,6,5}$, $4_{2,6,2}$, $3_{2,6,0}$
	Security		$2_{3,6,6}$, $1_{3,6,2}$
	Boarding Gate		$14_{4,6,6}$, $2_{4,6,3}$, $3_{4,6,1}$
7	Check-in		$3_{1,7,7}$, $1_{1,7,6}$, $1_{1,7,3}$
	Immigration		$19_{2,7,7}$, $3_{2,7,6}$, $4_{2,7,3}$, $3_{2,7,1}$
	Security		$2_{3,7,7}$, $1_{3,7,3}$
	Boarding Gate		$14_{4,7,7}$, $2_{4,7,4}$, $3_{4,7,2}$
8	Check-in	$1_{1,8,0}$	$3_{1,8,8}$, $1_{1,8,7}$, $1_{1,8,4}$, $1_{1,8,0}$
	Immigration		$19_{2,8,8}$, $3_{2,8,7}$, $4_{2,8,4}$, $3_{2,8,2}$
	Security		$2_{3,8,8}$, $1_{3,8,4}$
	Boarding Gate	$3_{4,8,0}$	$14_{4,8,8}$, $2_{4,8,5}$, $3_{4,8,3}$, $3_{4,8,0}$
9	Check-in		$3_{1,9,9}$, $1_{1,9,8}$, $1_{1,9,5}$, $1_{1,9,1}$
	Immigration	$-19_{2,9,9}$, $23_{2,9,0}$	$3_{2,9,8}$, $4_{2,9,5}$, $3_{2,9,3}$, $23_{2,9,0}$
	Security	$1_{3,9,0}$	$2_{3,9,9}$, $1_{3,9,5}$, $1_{3,9,0}$
	Boarding Gate		$14_{4,9,9}$, $2_{4,9,6}$, $3_{4,9,4}$, $3_{4,9,1}$
10	Check-in	$-3_{1,10,10}$, $3_{1,10,0}$	$1_{1,10,9}$, $1_{1,10,6}$, $1_{1,10,2}$, $3_{1,10,0}$
	Immigration	$-3_{2,10,9}$, $3_{2,10,0}$	$4_{2,10,6}$, $3_{2,10,4}$, $23_{2,10,1}$, $3_{2,10,0}$
	Security		$2_{3,10,10}$, $1_{3,10,6}$, $1_{3,10,1}$
	Boarding Gate		$14_{4,10,10}$, $2_{4,10,7}$, $3_{4,10,5}$, $3_{4,10,2}$
11	Check-in	$-1_{1,11,10}$, $1_{1,11,0}$	$1_{1,11,7}$, $1_{1,11,3}$, $3_{1,11,1}$, $1_{1,11,0}$
	Immigration		$4_{2,11,7}$, $3_{2,11,5}$, $23_{2,11,2}$, $3_{2,11,1}$
	Security		$2_{3,11,11}$, $1_{3,11,7}$, $1_{3,11,2}$
	Boarding Gate	$4_{4,11,0}$	$14_{4,11,11}$, $2_{4,11,8}$, $3_{4,11,6}$, $3_{4,11,3}$, $4_{4,11,0}$
12	Check-in	$1_{1,12,0}$	$1_{1,12,8}$, $1_{1,12,4}$, $3_{1,12,2}$, $1_{1,12,1}$, $1_{1,12,0}$
	Immigration	$7_{2,12,0}$	$4_{2,12,8}$, $3_{2,12,6}$, $23_{2,12,3}$, $3_{2,12,2}$, $7_{2,12,0}$
	Security	$-2_{3,12,12}$, $2_{3,12,0}$	$1_{3,12,8}$, $1_{3,12,3}$, $2_{3,12,0}$
	Boarding Gate		$14_{4,12,12}$, $2_{4,12,9}$, $3_{4,12,7}$, $3_{4,12,4}$, $4_{4,12,1}$
13	Check-in		$1_{1,13,9}$, $1_{1,13,5}$, $3_{1,13,3}$, $1_{1,13,2}$, $1_{1,13,1}$
	Immigration	$-4_{2,13,9}$, $4_{2,13,0}$	$3_{2,13,7}$, $23_{2,13,4}$, $3_{2,13,3}$, $7_{2,13,1}$, $4_{2,13,0}$
	Security	$1_{3,13,0}$	$1_{3,13,9}$, $1_{3,13,4}$, $2_{3,13,1}$, $1_{3,13,0}$
	Boarding Gate	$3_{4,13,0}$	$14_{4,13,13}$, $2_{4,13,10}$, $3_{4,13,8}$, $3_{4,13,5}$, $4_{4,13,2}$, $3_{4,13,0}$
14	Check-in	$-1_{1,14,10}$, $2_{1,14,0}$	$1_{1,14,6}$, $3_{1,14,4}$, $1_{1,14,3}$, $1_{1,14,2}$, $2_{1,14,0}$
	Immigration	$2_{2,14,0}$	$3_{2,14,8}$, $23_{2,14,5}$, $3_{2,14,4}$, $7_{2,14,2}$, $4_{2,14,1}$, $2_{2,14,0}$
	Security		$1_{3,14,10}$, $1_{3,14,5}$, $2_{3,14,2}$, $1_{3,14,1}$
	Boarding Gate		$14_{4,14,14}$, $2_{4,14,11}$, $3_{4,14,9}$, $3_{4,14,6}$, $4_{4,14,3}$, $3_{4,14,1}$

The results of the model in the case study yield the minimum total cost of NT$ 3,772,626,094 for all facilities over the study period. Various costs of different facilities at each period are further shown in Table 4. The results show that maintenance and delay cost functions vary with respect to different equipments, among which, the maintenance cost for boarding gates increases with a higher rate than that for check-in counters as equipment reliability decreases, as shown in Figure 2. And equipments with a longer operating time also incur a higher delay cost than those with a shorter operating time as equipment reliability declines. Figure 3 shows that check-in is the highest, immigration is the second and security is the lowest.

The reliability of facilities deteriorates with the increase in service age, which further leads to higher maintenance cost and delay cost. The rate of deterioration accelerates when service age exceeds the expected life. Therefore, maintenance cost and delay cost increase rapidly in 10 and 11 periods. The optimal service lives of check-in and immigration counters are 10 and 9 year, respectively, if passenger volume grows continuously. The study further analyzes how various costs are affected by the numbers of different facilities. Assume annual departure passenger volume is 7 million persons and use check-in counters as an example to explore variations in various costs due to different numbers of counters. The results are shown in Figure 4 and indicate that, a smaller number of facilities though reduce depreciation and maintenance costs, will greatly increase the delay cost. The total cost of inadequate facilities is larger than that with the optimum facilities. On the other hand, though excess facilities decrease the delay cost but will increase depreciation and maintenance costs. Because the amount of increased cost is larger than those of the decreased cost for either inadequate or excess facilities, consequently, the optimal number of a facility will yield the minimum total cost, as shown in Figure 4.

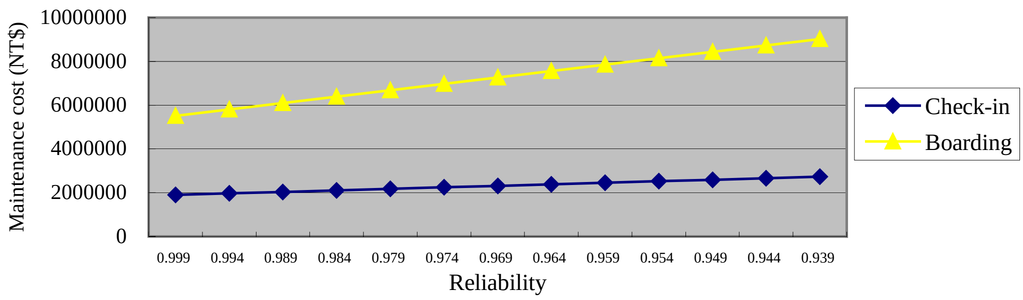


Figure 2. Maintenance Cost versus Reliability

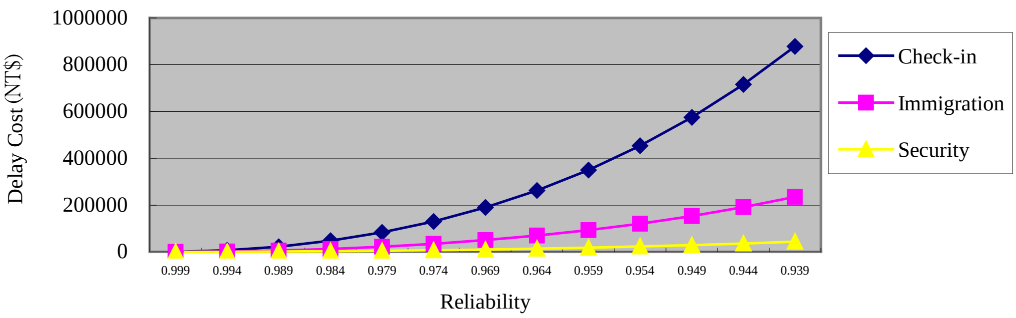
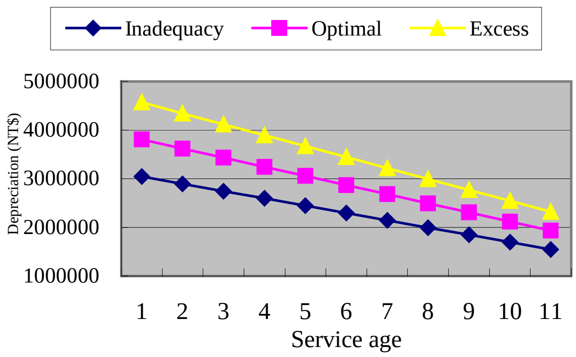


Figure 3. Delay Cost versus Reliability

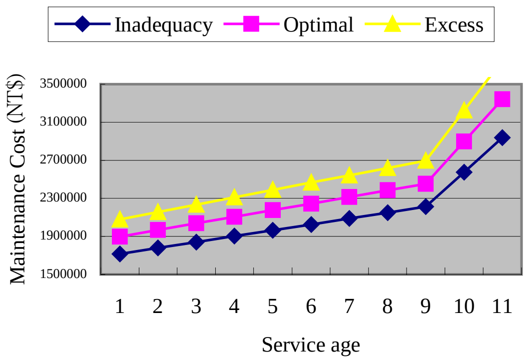
Table 4. Various Costs of Facilities under the Optimal Decision at Each Period

Unit：NT$

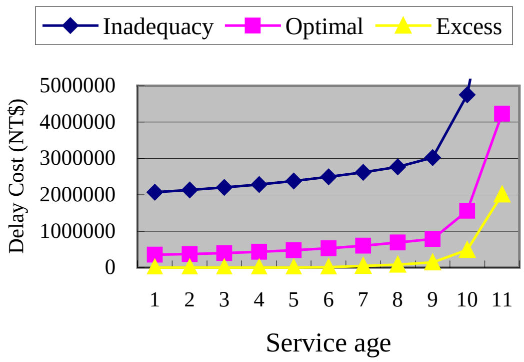
Period (i)	Facilities (f)	Depreciation	Maintenance	Operating	Delay	Total
0	Check-in	3,150,000	1,210,808	94,142,820	796,371	99,299,999
	Immigration	498,750	175,054	17,749,922	3	18,419,728
	Security	750,000	288,513	11,838,460	213,124	13,090,097
	Boarding Gate	14,000,000	3,062,671	14,403,851	0	31,466,523
1	Check-in	4,087,500	1,534,323	108,609,722	110378	114,341,924
	Immigration	559,688	201,789	20,436,490	606	21,198,572
	Security	725,000	325,752	13,633,738	384,366	15,068,857
	Boarding Gate	13,650,000	3,631,038	16,592,693	0	33,873,731
2	Check-in	3,937,500	1,607,638	111,374,461	251,568	117,171,167
	Immigration	539,063	211,543	20,906,770	22,110	21,679,486
	Security	700,000	351,135	13,947,659	432,822	15,431,615
	Boarding Gate	13,300,000	3,920,064	16,979,373	0	34,199,436
3	Check-in	3,787,500	1,701,241	116,654,504	558,046	122,701,291
	Immigration	518,438	223,856	21,845,865	98,820	22,686,979
	Security	675,000	380,301	14,574,355	522,938	16,152,594
	Boarding Gate	14,950,000	4,332,406	17,744,519	0	37,026,925
4	Check-in	4,687,500	1,997,750	126,901,939	14,671	133,601,861
	Immigration	602,813	249,827	23,751,179	8,851	24,612,669
	Security	1,025,000	496,757	15,844,164	211,557	17,577,478
	Boarding Gate	14,550,000	4,874,422	19,298,856	0	38,723,278
5	Check-in	4,500,000	2,144,676	137,412,823	253,367	144,310,866
	Immigration	578,438	268,134	25,657,475	120,426	26,624,472
	Security	987,500	540,824	17,116,060	327,150	18,971,534
	Boarding Gate	17,150,000	5,460,825	20,847,795	0	43,458,620
6	Check-in	4,312,500	2,263,130	143,899,052	661,784	151,136,466
	Immigration	632,813	289,454	26,803,523	26,482	27,752,272
	Security	950,000	580,814	17,881,855	418,252	19,830,921
	Boarding Gate	16,675,000	5,936,958	21,786,485	0	44,398,443
7	Check-in	4,125,000	2,299,416	140,209,705	489,319	147,123,440
	Immigration	605,625	295,391	26,054,760	31,104	26,986,879
	Security	912,500	606,016	17,382,550	400,010	19,301,076
	Boarding Gate	16,200,000	6,096,481	21,183,916	0	43,480,397
8	Check-in	2,737,500	2,612,174	152,098,034	113,255	157,560,963
	Immigration	222,188	316,701	28,278,539	153,133	28,970,560
	Security	875,000	656,945	18,866,403	585,258	20,983,605
	Boarding Gate	18,725,000	6,743,507	22,990,068	0	48,458,575
9	Check-in	1,875,000	3,062,287	169,650,782	1,518,489	176,106,558
	Immigration	760,313	292,925	31,447,395	37,817	32,538,450
	Security	1,212,500	783,784	20,989,645	347,477	23,333,406
	Boarding Gate	18,175,000	7,649,773	25,590,194	0	51,414,972
10	Check-in	4,950,000	2,569,296	166,592,813	453,861	174,565,970
	Immigration	810,938	293,863	31,187,789	20,587	32,313,176
	Security	662,500	821,321	20,818,450	371,055	22,673,325
	Boarding Gate	17,625,000	7,941,335	25,388,376	0	50,954,711
11	Check-in	5,812,500	2,474,916	171,070,218	599,780	179,957,414
	Immigration	780,000	309,033	32,082,494	93,998	33,265,525
	Security	637,500	869,490	21,415,964	459,427	23,382,381
	Boarding Gate	21,075,000	8,323,906	26,110,085	0	55,508,990
12	Check-in	5,887,500	2,814,367	183,294,380	512,218	192,508,465
	Immigration	857,813	350,418	34,329,496	0	35,537,727
	Security	1,362,500	684,138	22,901,427	419,354	25,367,419
	Boarding Gate	20,425,000	9,132,425	27,948,714	0	57,506,141
13	Check-in	5,662,500	3,084,438	196,611,986	687,587	206,046,511
	Immigration	929,063	361,945	36,732,949	14,403	38,038,360
	Security	1,687,500	824,441	24,505,256	269235	27,286,432
	Boarding Gate	22,775,000	9,880,908	29,401,430	0	62,057,338
14	Check-in	7,537,500	3,236,574	209,937,478	46,830	220,758,381
	Immigration	887,813	392,374	39,307,586	31,135	40,618,908
	Security	1,375,000	892,431	26,223,751	374,550	28,865,731
	Boarding Gate	22,050,000	10,824,461	31,472,037	0	64,346,498



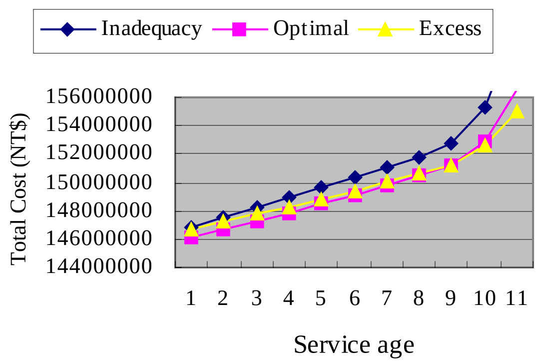
(a) Depreciation vs. Service Age



(b) Maintenance Cost vs. Service Age



(c) Delay Cost vs. Service Age



(d) Total Cost vs. Service Age

Figure 4. Various Costs versus Service Age under Different Numbers of Check-in Counters

5.CONCLUSIONS

This study formulates a dynamic programming model to determine the optimal facility purchase and replacement scheduling for departure related facilities for international airports by considering facility renewal costs, aviation safety, passenger service level, and airport finance. The study constructs various cost functions on depreciation, operation, maintenance and delay for different facilities at different time stages according to passenger volume, facility reliability and utilization. Operating costs include energy, labor and material cost, which vary as passenger volume changes, and maintenance costs include preventive maintenance and repair costs due to malfunction, which is related to equipment age, utilization, and reliability. Delay cost function deals with departure related facilities such as check-in, immigration, and security being out of order or insufficient and includes the cost of delay time for passengers, the decrease in the concession revenue and compensation paid to passengers for meals, accommodations and trip delay expenses due to the delay of departure flights. According to these cost functions, the study further investigates variations in various costs for different facilities with various service ages and passenger volumes and analyzes the optimal purchase and replacement decision.

Moreover, this study uses CKS international airport departure related facilities including check-in counters, immigration counters, security checks, and boarding gates as an example to demonstrate the application of the model. Moreover, with a declining reliability, equipment with a longer service age also incurs a greater delay cost than that with a shorter service age. When the malfunction rate of a equipment is above a certain level, such that the sum of maintenance and delay costs exceed the sum of depreciation cost for purchasing new facility and the loss of replacing old facility, then replacement must be done. The optimal service lives of check-in and immigration counters are 10 and 9 years, respectively. The results also show that the optimal quantities and timing of facility purchase and replacement depend on the net benefit, which is the decrease in delay and operating costs minus the depreciation and maintenance costs of the facilities. In case of insufficient facilities, despite less depreciation and lower maintenance cost incurred, the total cost will be higher than that with the optimum facilities. On the other hand, excess facilities though reduce delay cost but at the same time increase depreciation and maintenance costs. Consequently, the total cost of the optimal facilities is the lowest among all. The application of the model formulated in this study provides the airport authority with the optimal strategic decision on the purchase and replacement of various facilities in terms of quantities and timing.

ACKNOWLEDGEMENTS

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 93-2211-E-009-031.

REFERENCES

Bellman, R. (1995) Equipment Replacement Policy, **Journal of the Society for Industrial and Applied Mathematics, Vol. 3, No. 3,** 133-136.

Chan, J. K. and Shaw, L. (1993) Modeling Repairable Systems with Failure Rates that Depend on Age and Maintenance, **IEEE Transactions on Reliability, Vol. 42, No. 4,** 566-571.

Dedopoulos, I. T. and Smeers, Y. (1998) An Age Reduction Approach fur Finite Horizon Optimization of Preventive Maintenance for Single Units Subject to Random Failures, **Computers ind. Engng, Vol. 34, No. 3,** 643-654.

Dhillon, B. S. (1981) Life Distributions, **IEEE Transactions on Reliability, Vol. R-30, No. 5,** 457-459.

Hartman, J. C. (2001) An Economic Replacement Model with Probabilistic Asset Utilization, **IIE Transactions, Vol. 33, No. 9,** 717-727.

Jayabalan, V. and Chaudhuri, D. (1992) Optimal Maintenance-Replacement Policy under Imperfect Maintenance, **Reliability Engineering and System Safety, Vol. 36, No. 2,** 165-169.

Lam, Y. (1997) An optimal maintenance model using a number of different actions, **Microelectronics and Reliability, Vol. 37, No. 4,** 615-622.

Lie, C. H., and Chun, T, H. (1986) An Algorithm for Preventive Maintenance Policy, **IEEE Transactions on Reliability, Vol. R-35, No. 1,** 71-75.

MIL-STD-2173 (1986) Reliability Centered Maintenance Requirements for Naval Aircraft Weapons Systems and Support Equipment, 21-23.

Park, D. H., Jung, G. M., and Yum, J. K. (2000) Cost Minimization for Periodic Maintenance Policy of a System Subject to Slow Degradation, **Reliability Engineering and System Safety, Vol. 68, No. 2,** 105-112.

Pham, H., and Wang, H. (1996) Optimal Maintenance Policies for Several Imperfect Maintenance Model, **International Journal of Systems Science, Vol. 27, No. 6,** 543-551.

Sherif, Y. S. and Smith, M. L. (1981) Optimal Maintenance Models for Systems Subject to Failure – A Review, **Naval Research Logistics Quarterly, Vol. 28, No. 1,** 47-74.

Smith, R. M., and Bain, L. J. (1975) An Exponential Power Life-testing Distribution, **Communications in Statistics, Vol. 4, No. 5,** 469-481.

Tsai, Y. T., Wang, K. S., and Teng, H. Y. (2001) Optimizing Preventive Maintenance for Mechanical Components Using Genetic Algorithms, **Reliability Engineering and System Safety, Vol. 74, No. 1,** 89-97.