Chapter 14
The Asset Replacement Problem State of the Art

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Abstract This book chapter outlines the different modelling approaches for realising sustainable operations of asset replacement and studying the impact of the economic life, the repair-cost limit and comprehensive cost minimisation models. In particular it analyses in detail the parallel replacement models and suggests a new model that addresses some of the issues not yet solved in this area. Finally a discussion about the limitations of the current models from a theoretical and applied perspective is proposed and identifies some of the challenges still faced by academics and practitioners working on this topic.

14.1 Introduction

As assets age, they generally deteriorate, resulting in rising operating and maintenance (O&M) costs and decreasing salvage values. Moreover, newer assets that have a better performance and keep better their value may exist in the marketplace and be available for replacement. Therefore, public and private organisations that maintain fleets of vehicles, and/or specialised equipment, need to decide when to replace vehicles composing their fleet. These equipment replacement decisions are usually based on a desire to minimise fleet costs and are often motivated by the state of deterioration of the asset and by technological advances (Hartman 2005).

The general topic of equipment replacement models was first introduced in the 1950s (Bellman 1955). By using dynamic programming, Bellman developed a

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model in order to obtain the optimal age of replacement of the old machine with a new machine. Another important subject was the development of parallel replacement models in which management decisions are made for a group of assets instead of one asset at the time (Hartman and Lohmann 1997).

Vehicle replacement is a key role of fleet provisioning teams. Indeed field service operational planning and delivery primarily relies on the assumption that the whole engineering force can be furnished with the vehicle appropriate for the service, at any time. In practice, the choice of the adequate type, brand, and technology depends on internal factors (such as the engineer role and service environment, but not systematically mileage driven) and on external factors (such as fuel price variation, government carbon emission incentives, manufacturing costs, and maintenance costs). Moreover, in addition to risk and field force efficiency, the impact of vehicle replacement on customer experience needs to be considered as well. This suggests a twofold fleet planning problem that vehicle replacement aims to address: a planned fleet portfolio and a rental plan for jeopardy situations.

In addition, field service enterprises face increasing challenges on carbon emissions and cost reduction. This need to transform the way field services operate has an impact on the choice of vehicles within a business, affecting the vehicle replacement processes. When attempting to optimise the fleet composition, which is essential for achieving sustainability, we need to take into account several factors (some of which are stochastic and uncertain in nature), which need to be addressed before low-carbon vehicles are a feasible alternative for field service operations including the intangible reputation of sustainable energy investment, the evolution of market prices, strategic partnerships, and risk sharing.

This chapter aims at outlining the historical developments of the asset replacement problem, discussing the limitations of the models developed so far, and introducing a new model which overcomes some of these drawbacks. Section 14.2 presents a classification of different asset replacement models, which are broadly categorised into serial and parallel models. Section 14.3 describes the different approaches to modelling the asset replacement problem. Section 14.4 discusses the methods used to solve the parallel asset replacement problem and suggests a new formulation to address some of their drawbacks. Section 14.5 outlines our analysis from literature review, with Sect. 14.6 emphasizing the challenges from a practical service industry perspective. Section 14.7 concludes this chapter.

14.2 The General Classifications of Fleet (Asset) Replacement Models

The models generally can be categorised into two main groups based on different fleet (asset) characteristics: homogenous and heterogeneous models. In the homogeneous replacement models, a group of similar vehicles in terms of type and age, which form a cluster, have to be replaced simultaneously (each cluster or group cannot be decomposed into smaller clusters). On the other hand, in the heterogeneous model, multiple heterogeneous assets, such as fleets with different types of vehicle, have to be optimised simultaneously. For instance, vehicles of the same type and with the same age may be replaced in different periods (years) because of the restricted budget for procurement of new vehicles. The heterogeneous models are closer to the real-world commercial fleet replacing problem. These models are solved by integer programming, and, generally, the input variables are assumed to be deterministic (Hartman 1999, 2000, 2004; Simms et al. 1984; Karabakal et al. 1994).

The most popular methodology for solving homogenous models is dynamic programming. The advantage of the homogenous model is to take into account probabilistic distributions for input variables (Hartman 2001; Hartman and Murphy 2006; Oakford et al. 1984; Bean et al. 1984; Bellman 1955).

Another important classification of these models regards the nature of the replacement process: parallel vs. serial, e.g. Hartman and Lohmann (1997). The main difference between parallel replacement analysis and serial replacement analysis is that the former takes into account how any policy exercised over one particular asset affects the rest of the assets of the same fleet. An example of parallel replacement would be a fleet of trucks that service a distribution centre. In this case, the total available capacity is the sum of the individual capacities of the trucks. In the serial replacement model, the assets operate in series, and consequently, demand is satisfied by the group of assets which operate in sequence. An example of this case is a production line in which multiple machines must work together to meet a demand or service constraint. In general, the capacity of the system is defined by the smallest capacity in the production line (Hartman 2004).

The following definition of parallel replacement comes from (Hartman and Lohmann 1997). Parallel replacement deals with the replacement of a multitude of economically interdependent assets which operate in parallel. The reasons for this economic interdependence are:

1. Demand is generally a function of the assets as a group, such as when a fleet of assets are needed to meet a customer’s demands.
2. Economies of scale may exist due to purchasing assets and promoting large quantity of purchases.
3. Diseconomies of scale may exist with maintenance costs because assets which are purchased together tend to fail at the same time.
4. Budgeting constraints may require that assets compete for available funds. These characteristics, either alone or together, can cause the assets to be economically interdependent.

On the other hand, the serial replacement analysis assumes a certain utilisation level for an asset throughout its life cycle. Hartman (1999) mentioned that since utilisation levels affect operating and maintenance costs and salvage values (which in turn influence replacement schedules), a replacement solution is not optimal unless utilisation levels are also maximised. This suggests a strong dependency relationship between asset utilisation levels and the combination of demand requirements, the number of assets available, and the capacity of each asset.

Next section presents different approaches to modelling the asset replacement problem: the economic life cycle, the repair-cost limit, the comprehensive cost minimisation, and the issue of decreasing utilisation with age.

14.3 Approaches for Replacement Decisions

The goal driving a replacement decision consists of identifying replacement candidates among fleet or asset members so that the total costs are minimised in the long run. In this section we review different approaches for deciding the optimal time for candidate asset replacement.

14.3.1 Approaches Based on the "Economic Life"

An intuitive method for identifying replacement candidates is to use a replacement standard, such as the age of the equipment. For example, assets older than a standard threshold should be replaced. Additionally, a ranking profile can be used in order to sort the equipment units by how much they exceed the threshold. For example, Eilon et al. (1966) considered a model for the optimum replacement of forklift trucks. The parameters in their model were the purchase price, the resale value, and the maintenance costs of the equipment. The goal of their model was to derive the minimum average costs per equipment year, and the corresponding optimal equipment age policy, for a fleet of forklift trucks.

Let us now describe the model proposed by Eilon et al. (1966) in more detail. Let $TC(t)$ be the total average annual (or per period) cost of an existing truck, assuming it is replaced at age (time) t. Let A stand for the acquisition cost of new truck, $S(t)$ be the resale value of the existing truck at age t, $C(t)$ be the accumulated depreciation costs up to time t, τ be the rate of taxation, and $f(t)$ be the maintenance costs of a truck, t years after acquisition. Then the total average annual cost of an existing truck is represented by (14.1):

$$TC(t) = \frac{1}{t}(A - S(t) - C(t).\tau) + \frac{1}{t}\int_0^t f(t)dt \qquad (14.1)$$

The first term in (14.1) represents the average capital costs involved in the acquisition of the existing truck, taking into account the savings from resale value and tax savings from depreciation. The second term in (14.1) expresses the total average maintenance costs for the existing truck over the years up to the present time t. The minimum total average annual costs, as a function of t, determines the optimal replacement time.

The economic life of an asset (also known as service life or lifetime of the asset) is defined as the age which minimises the *equivalent annual cost* (EAC) of owning and operating the asset. The EAC includes purchase and *Operating and Maintenance* (O&M) costs minus salvage values. Generally, O&M costs increase with age while salvage values decrease with age. As a result, the optimal solution represents a trade-off between the high costs of replacement (purchase minus salvage) and increasing O&M costs over time.

The concept of economic life is easier to describe graphically. In Fig. 14.1, adapted from Hartman and Murphy (2006), it is assumed that the initial purchase cost is $100,000, with the salvage value declining 20 % per year. O&M costs are expected to increase 15 % per year after $11,500 in the first year. Figure 14.1 illustrates the annualised O&M and capital costs and their sum (EAC) for each possible of age assuming an annual interest rate 8 %. Once the optimal economic life is determined, the asset should be continuously replaced at this age, if we assume repeatability and stationary costs.

In order to obtain the EAC, when retaining an asset for n periods, all costs over the n periods must be converted into n equal and economically equivalent cash flows. Then, the economic life of an asset is typically computed by calculating the EAC of retaining an asset for each of its possible service lives, ages one through n, and the minimum is chosen from this set (Hartman 2005; Weissmann et al. 2003; Hartman and Murphy 2006).

Yatsenko and Hritonenko (2011) have also considered the economic life (EL) method of asset replacement taking into account the effects technological improvements which decrease maintenance costs, new asset cost, and salvage value. They have shown that, in general, the EL method renders an optimal replacement policy when the relative rate of technological change is less than one percent. However, for larger rates, they recommend annual cost minimisation over the two future replacement cycles, which was earlier proposed and implemented by Christer and Scarf (1994).

14.3.2 Approaches That Consider a Repair-Cost Limit

Another replacement criterion is the repair cost. When a unit requires repair, it is first inspected and the repair cost is estimated. If the estimated cost exceeds a threshold, which is known as “repair limit” then the unit is not repaired but, instead, is replaced. Repair limits have long been used and their values have often been based on the principle that no more should be spent on an item than it is worth. This criterion is indeed an important one. There is evidence that repair-cost limit policies have some advantages in comparison with economic age limit policies. For example, Drinkwater and Hastings (1967) analysed data for army vehicles. They obtained the repair limiting value in which the expected future cost per vehicle-

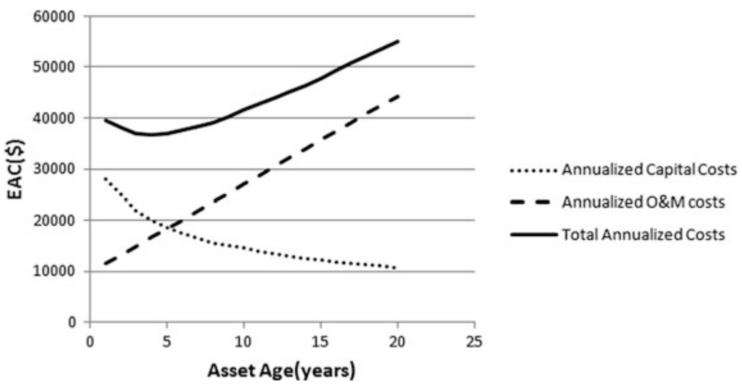

Fig. 14.1 Annualised purchase cost, O&M cost, and total (EAC) costs

year when the failed vehicle is repaired is equal to the cost in which the failed vehicle is scrapped and a new one is substituted. Specifically, they defined two options:

1. Repair the vehicle.
2. Scrap the vehicle and replace it by a new one. This is called a repair decision.

We now present the model used for the repair decision in more detail. We consider a vehicle at age t which requires repair. If we select option 1, to repair the vehicle, the future cost per vehicle-year is represented by (14.2) in which r is the present cost of repair, $c(t)$ is the expected total cost of future repairs, and $l(t)$ is the expected remaining life of the vehicle:

$$\frac{r + c(t)}{l(t)} \tag{14.2}$$

If we select option 2, scrapping the vehicle will incur an expected future cost per vehicle-year being δ, which is defined by the average cost per vehicle-year up to age t. Obviously, the repairing decision (option 1) will be selected if (14.3) holds; otherwise, the scrapping decision will be chosen. Therefore, the critical value of r is determined by (14.4) in which the future cost per vehicle-year equals the average cost per vehicle-year up to age t. As a result, the optimal repair limit at time t, $r^*(t)$, is determined by (14.5):

$$\frac{r + c(t)}{l(t)} < \delta \tag{14.3}$$

$$\frac{r^*(t) + c(t)}{l(t)} = \delta \tag{14.4}$$

$$r^*(t) = \delta l(t) - c(t) \tag{14.5}$$

Drinkwater and Hastings (1967) have shown that the repair-cost limit policy is better than the economic age policy. Nonetheless, there is a main drawback to the conventional repair-cost limit policy: the repair/replace decision is based only on the cost of one single repair. Under this condition, a system with frequent failures and, consequently, high accumulated repair costs will continue to be repaired rather than replaced. As a result, an improved policy making the repair/replace decision based on the entire repair history would be a better criterion. In order to address this issue, Chang et al. (2010) have developed a generalised model for determining the optimal replacement policy based on multiple factors such as the number of minimal repairs before replacement and the cumulative repair-cost limit. The main characteristic of their model is to consider the entire repair-cost history. Nakagawa and Osaki (1974) have also suggested an alternative approach which does not focus on repair costs but, instead, on repair time. If the repair process is not completed up to the fixed repair time limit, then the unit under repair is replaced by a new one. The repair time limit is obtained by minimising expected costs per unit of time over an infinite time horizon.

14.3.3 Comprehensive Cost Minimisation Models

There are other approaches that generalise the problem of optimal replacement by taking into account the optimal decisions for acquisition, operation, and replacement policies. For example, Simms et al. (1984) have analysed a transit bus fleet in which the equipment units in the fleet system were assigned to perform different tasks, at different levels, subject to changing capacity constraints. Their objective was to minimise the total discounted cost over a finite horizon.

14.3.3.1 Objective Function

The objective function is represented by (14.6), in which t and a are the indices for time periods (year) and age of the buses, respectively, and T is the length of the planning horizon, in years. The decision variables are the number of route kilometres travelled by a bus with age a, in year t, m_{ta}; the number of buses with age a, which operate in year t, x_{ta}; and the number of new buses which should be purchased, with an acquisition cost L_t, at the beginning of year t, denoted by p_t. In each year the price of selling a bus with age a is represented by S_{ta}, and C_{ta} (m_{ta}) is the cost of operating a bus with age a, in year t, for the associated kilometres travelled by m_{ta}. Finally, γ represents the discount factor. In (14.6) the first term represents the acquisition costs, the second term stands for the revenue received from selling the buses, and the third term denotes the cost of operating the buses.

Simms et al. (1984) computed the optimal acquisition, operation, and selling policies using dynamic programming:

$$\underset{m_{ta}, x_{ta}, p_t}{Min\,Z} = \sum_{t=0}^{T} \gamma^t p_t L_t - \sum_{t=0}^{T} \gamma^{t+1} \sum_{a} \left(x_{ta} - x_{t+1,a+1}\right) S_{t+1,a+1} + \sum_{t=0}^{T} \sum_{a} \gamma^i x_{ta} C_{ta}(m_{ta}) \tag{14.6}$$

On the same topic, Hartman (1999) has considered the replacement plan and corresponding utilisation levels for a multi-asset case in order to minimise the total cost. He generalised equipment replacement analysis as it explicitly considers utilisation as a decision variable. His model allows assets to be categorised according to age and cumulative utilisation while allowing their periodic utilisation to be determined through analysis. As a result, he has considered simultaneously tactical replacement and operational decisions, taking into account the trade-offs between capital expenses (replacement costs) and operating expenses (utilisation costs). The objective was to minimise the total cost of assets that operate in parallel. He solved the problem using linear programming. Furthermore, Hartman (2004) has generalised this same problem by incorporating a stochastic demand. He solved the problem using dynamic programming. Overall, none of these approaches introduced any special new replacement criteria and only presented optimisation methodologies in order to minimise the cost of corresponding fleets.

14.3.3.2 Modelling Fleet Life Conditions

Following the model proposed by Simms et al. (1984), the nonlinear constraint (14.7) requires the fleet to drive a minimum value of total kilometres per year, M_t. Constraint (14.8) expresses the boundary conditions for the decision variable m_{ta}, in which m_- and m_+ respectively denote the minimum and maximum number of kilometres that a single bus can drive in a given year. Constraint (14.9) represents the requirement that at least a minimum number of buses, N_t, in each year, should be in the fleet:

$$\sum_{a} x_{ta} m_{ta} \geq M_t \quad \forall\, t \in \{0, 1, 2, \ldots, T\} \tag{14.7}$$

$$m_- \leq m_{ta} \leq m_+ \tag{14.8}$$

$$\sum_{a} x_{ta} \geq N_t \quad \forall\, t \in \{0, 1, 2, \ldots, T\} \tag{14.9}$$

In inequality (10), Q is the minimum age for a bus to be considered for a sell decision and the left-hand side is equal to the number of buses which are sold at the beginning of the corresponding year. Therefore, inequality (10) stands for a consistency constraint, in the sense that it does not permit old buses to be bought:

$$x_{ta} - x_{t+1,a+1} \geq 0 \quad , a \geq Q - 1 \tag{14.10}$$

Equation 14.11 means that the buses are not eligible for sale until their reach to the minimum age Q. Equation 14.12 represents the boundary conditions, in which K_a are the initial numbers of buses for the different ages:

$$x_{ta} - x_{t+1,a+1} = 0 \quad , a < Q - 1 \tag{14.11}$$

$$x_{(-1)a} = K_a \ \ , x_{(T+1)j} = 0 \tag{14.12}$$

If budget constraints for capital acquisitions are also considered, then the constraint (14.13) are also required, in which B_t is the capital budget in period t. Furthermore, if there is also an operating budget constraint, then we also need to impose constraint (14.14) in which O_t is the operating budget in period t:

$$p_t \leq \frac{B_t}{L_t} \tag{14.13}$$

$$\sum_a x_{ta} C_{ta}(m_{ta}) \leq O_t \tag{14.14}$$

The model represented by (14.6–14.14) has a nonlinear objective function subject to a set of nonlinear constraints. By using dynamic programming, Simms et al. (1984) solved the problem. If we compare the two models proposed by Simms et al. (1984) and Keles and Hartman (2004), we understand that regardless of the solving methodology used, the main difference is considering the behaviour of utilisation as a function of age of the vehicles and assuming it as a decision variable by Simms et al. (1984). Another difference is that Simms et al. (1984) considered the same type of asset, whereas Keles and Hartman (2004) considered multiple types of asset. However, for the rest of the components of the two models, i.e. the goal of the objective function and the constraints, they are almost the same.

Another important issue that requires particular modelling attention is the relation between age and utilisation. The utilisation intensity (annual mileage) of vehicles exploited by transportation companies decreases with time of exploitation/cumulative mileage probably in real-life cases. The youngest vehicles are usually utilised more intensively than the oldest ones, because their unit exploitation costs are lower (e.g. fuel consumption is lower), and the depreciation costs could be ignored. Examples of the occurrence of such pattern can be found in Kim et al. (2004) and Simms et al. (1984), and it fits well with real-world situations. This pattern can cause an issue, in particular in bus fleet management (Simms et al. 1984), because if the relation associating utilisation with age is not considered, one would expect that the older buses would be replaced first and younger buses kept. However, in practice, this is not the case and does not appear systematically

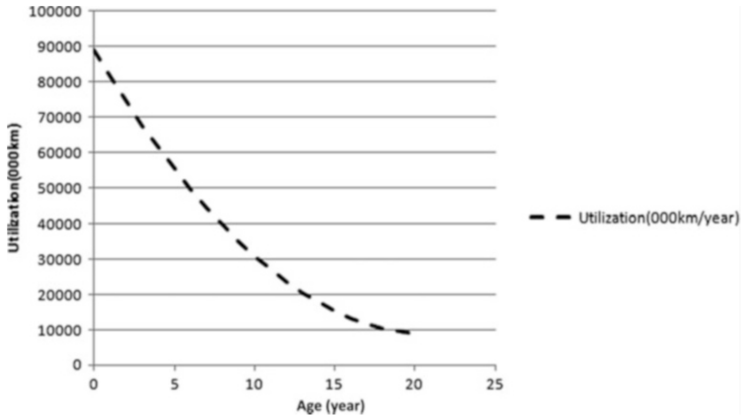

Fig. 14.2 Annual utilisation by age

suitable for two reasons. Firstly, older buses are usually kept only to meet peak daily demand and these buses accumulate only the minimum number of route kilometres during the year. Secondly, the resale value of younger buses is much higher than older buses. Therefore, even if the operating cost of older buses is higher, this is compensated by the fact that they do operate minimal route kilometres: the extra expense is lower than the gain obtained by selling younger buses. So, this suggests as a meaningful assumption to distinguish two levels of utilisation for an urban transit bus fleet with different ages. Simms et al. (1984) concluded that a high utilisation level is considered for buses with less than 10 years for satisfying the normal demand and a low utilisation level for buses more than 10 years in the case of peak demand. Figure 14.2 illustrates this vehicle utilisation pattern in a real-world field service situation.

Redmer (2009) has also considered the relationship between utilisation intensity and ageing by applying the minimal average cost replacement policy using the following considerations:

– The utilisation intensity (annual mileage) of vehicles for each year of their operational life has to be taken into account.
– The vehicles' exploitation costs have to be divided into fixed costs (independent of utilisation intensity but varying with time of exploitation/cumulative mileage), running costs (depending on utilisation intensity/mileage and varying with time of exploitation/cumulative mileage), and fuel costs (varying with time of exploitation/cumulative mileage).
– The total costs of exploitation and ownership have to be given per 1 km or mile.
– The technical durability of vehicles (e.g. maximal mileage) has to be taken into account.
– Different forms of financing the fleet investments (buying for cash, credit, leasing, and hiring) have to be considered.

Redmer (2009) also outlined the advantages and issues of solving different replacement strategies applied in parallel. Next section focuses on modelling the parallel replacement problem and proposes a new model for addressing the issues.

14.4 The General Parallel Replacement Problem

In this section we commonly refer to groups of assets as fleets. However, the model is general in the sense that cost functions are specified without operational details. Thus, this analysis may be applied to a manufacturing setting if the costs can be quantified. The parallel replacement models are usually difficult to solve due to their combinatorial nature as mentioned by Hartman (2000), leading to hypothesis making on the general statement. Jones et al. (1991) considered a parallel replacement problem on the condition of fixed replacement costs. Rajagopalan (1998) and Chand et al. (2000) have proposed dynamic programming algorithms that simultaneously consider the replacement and capacity expansion problems.

14.4.1 An Integer Programming Formulation of the Parallel Replacement Problem

Given the complex nature of the problem, the case of multiple alternatives within parallel replacement has been rarely considered in the literature. However, using an integer programming formulation, it is possible to deal with multiple choices under economies of scale and budgeting constraints (Keles and Hartman 2004).

- **Objective function**: The objective function represents the costs associated with each challenger's discounted cash flows which are purchasing, operating, and maintenance costs subtracting the revenue from salvage values. The objective function is summarised in (14.15). All costs in the model are assumed to be discounted to time zero using an appropriate discount rate. The fixed cost associated with asset buying is represented by f_t. The new asset acquisition cost per unit in each year is l_{it}. The operating and maintenance cost is shown by c_{iat}, and the salvage revenue is represented by r_{iat}. I represents the total number of challengers (i.e. available alternatives for assets) in each period. The maximum age of any asset associated with its type is shown by A_i, and the length of time horizon is assumed to be T—typically T is assumed to be less than 15 years:

$$\underset{X,S,Z}{Min}\sum_{i=1}^{I}\left[\sum_{t=0}^{T-1}\left(f_tZ_t+\sum_{a=0}^{A_i-1}l_{it}X_{i0t}\right)+\sum_{t=0}^{T-1}\sum_{a=0}^{A_i-1}c_{iat}X_{iat}-\sum_{t=0}^{T-1}\sum_{a=1}^{A_i}r_{iat}S_{iat}\right] \quad (14.15)$$

- **Decision variables**: The total number of assets which are currently used in the system is represented by X_{iat} ($a > 0$). The variable indices are a, t, and i which stand for the age of the assets (buses), time periods, and type of the assets, respectively. The decision variables are the number of the assets bought at the beginning of each year, X_{i0t}, the number of assets which are salvaged at the end of each year, S_{iat}, and a binary variable confirming an acquisition in year t, Z_t.
- **Constraints**: Constraint (14.16) states that enough assets (or capacity) have to be available to satisfy demand for buses at time t, d_t:

$$\sum_{i=1}^{I}\sum_{a=0}^{A_i-1}X_{iat}\geq d_t \qquad \forall\, t\in\{0,1,\,\ldots,T-1\} \quad (14.16)$$

- Equation 14.17 represents the capital budgeting constraint to limit the payment for new asset acquisitions with predetermined capital budget, b_t, in each year:

$$\sum_{i=1}^{I}\sum_{a=0}^{A_k-1}l_{it}X_{i0t}+f_tZ_t\leq b_t \qquad \forall\, t\in\{0,1,\,\ldots,T-1\} \quad (14.17)$$

- Constraint (14.18) describes that the initial number of assets, h_{ia} ($a > 0$), should be either used, X_{ia0}, or salvaged, S_{ia0}. Equation 14.19 shows that the number of used assets in 1 year should be either used or salvaged in the next year:

$$X_{ia0}+S_{ia0}=h_{ia} \qquad \forall\;\, a\in\{1,2,\ldots,A_k\},\,\forall\, i\in I \quad (14.18)$$

$$X_{i(a-1)(t-1)}=X_{iat}+S_{iat} \quad \forall\, i\in I,\,\forall\, a\in A_i,\forall t\in\{1,2,\ldots,T\} \quad (14.19)$$

- Constraint (14.20) requires that all assets should be sold in the last year of the planning horizon (T). Equation 14.21 presents that any asset that has reached its maximal age is not used anymore:

$$X_{iaT} = 0 \quad \forall\, a \in \{0, 1, 2, \ldots, A_i - 1\} \tag{14.20}$$

$$X_{iA_it} = 0 \quad \forall\, i \in I,\ \forall\, t \in \{0, 1, 2, \ldots, T\} \tag{14.21}$$

- Constraint (14.22) prohibits salvaging any new asset immediately. Indeed, for salvaging of any new purchased asset at least one year should be passed. Finally, constraint (14.23) requires non-negative, integer solutions:

$$S_{i0t} = 0 \quad \forall\, i \in I,\ \forall\, t \in \{0, 1, 2, \ldots, T\} \tag{14.22}$$

$$X_{iat}, S_{iat} \in \{0, 1, 2, \ldots\},\ Z_j \in \{0, 1\} \tag{14.23}$$

Solving the model represented in (14.15–14.23) provides quantitative data. An extensive sensitivity analysis, fed with this data, is generally required when we want to consider the impact of various parameters on the optimal policies and finally choose the appropriate type and timing for bus replacement.

The aforementioned papers on the parallel replacement problem were considered in a deterministic framework. Replacement models in the case of existence of uncertainty were focused mainly on single or serial replacement problems. For example, Ye (1990) presented a single replacement model in which operating costs and the rate of deterioration of equipment were stochastic and the optimal time for replacing was determined in a continuous-time setting. Dobbs (2004) developed a serial replacement model in which operating costs were modelled as a geometric Brownian motion and the optimal investment time was obtained. Rajagopalan et al. (1998) developed a dynamic programming algorithm for the case where a sequence of technological breakthroughs was anticipated but their magnitude and timing were uncertain. A firm, operating in such an environment, should decide how much capacity of the current technology to acquire to meet future demand growth.

Parallel replacement model has been very successful in other types of applications. Feng and Figliozzi (2013) have considered a fleet replacement framework for comparing the competitiveness of electrical with conventional diesel trucks. They adapted the model described above to scenarios with different fleet utilisation and fuel efficiency. By using sensitivity analysis of ten additional factors, they have shown that electrical vehicles are more cost effective when conventional diesel vehicles' fuel efficiency is low and daily utilisation is above some threshold. Breakeven values of some key economic and technological factors that separate the competitiveness between electrical vehicles and conventional diesel vehicles were calculated in all scenarios.

Typically, in the comparison of the performance of electrical and conventional vehicles, one takes into account the high capital costs associated with electrical engine vehicles. The replacement decision depends on the result of a complete economic and logistics evaluation of the competitiveness of the new vehicle type.

In addition, as vehicles age, their per-mile operating and maintenance costs increase and their salvage values decrease. So, when the O&M costs reach a relatively high level, it may become cost effective to replace fossil fuel vehicles since the savings from O&M costs may compensate the high capital cost of purchasing new engine vehicles. Moreover, if fleet managers are enthusiastic in replacing conventional vehicles with new electric vehicles, it is important to understand how the O&M costs and salvage values change over time. Conventional diesel and electric commercial vehicles have significantly different capital and O&M costs.

14.4.2 A General Parallel Heterogeneous Asset Leasing Replacement Model

In this subsection we introduce a general asset replacement model for obtaining optimal replacement decisions regarding K types of assets under leasing framework. Specifically, a heterogeneous model is developed in which the assets are bounded by common budget constraints, demand constraints, and a fixed cost that is charged in any period in which there exist a replacement. It is assumed that in any period, assets from any of K types can be leased in order to replace retired assets for meeting corresponding demand in that period. The section ends with a customised variant for vehicles fleet.

The notation and formulation to be presented is more easily described by the network in Fig. 14.3. For the sake of simplicity, this figure represents the case of two asset types that are available to meet the demand ($I = 2$). The age of the asset in years, a, is defined on the vertical axis (maximum A), and the end of the planning period in years, t, is defined on the horizontal axis (horizon T). Due to the fact that we are considering a commercial setting, the leasing period is assumed to be 4 years. So, based on this assumption, the model is represented with $A = 3$ and $T = 6$. Indeed, at the end of time horizon $T = 6$, all the assets are retired.

Each node is defined according to the pair (a,t). The flow between these nodes, noted X_{iat}, represents an asset of age a in use from the end of time period t to the end of period $t + 1$, in which the asset is of age $a + 1$. Assets are either provided from the initial fleet, represented as flow from supply nodes n_{ia}, or must be leased, represented as X_{i0t} flow in each period t. An asset when reaches age A must be retired. All assets are retired at the end of the horizon. For meeting the associated demand in each period, the retired assets should be replaced by leasing new assets. In Fig. 14.3, the two types of assets are represented by different arcs (dashed or solid).

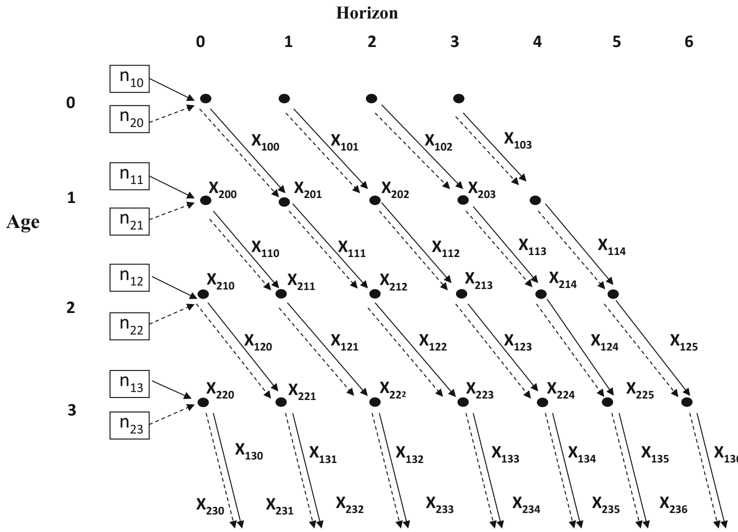

Fig. 14.3 Challengers are denoted by different arcs and different source (initial fleet) nodes. Nodes are labelled (a, t) with a being the age of the asset and t the time period. Flow X_{iat} represents asset leased ($a = 0$) and assets in use ($a > 0$)

14.4.2.1 Exploiting Asset Portfolio for Fleet Replacement

Let us adapt the introduced model for fleet replacement. We consider two types of technologies: the fossil fuel technology (defender) and the new engine technology (challenger). Moreover, we take into account the leasing option for financing the commercial fleet investments, which is seen as the best option in the commercial setting by Redmer (2009). This leads to a deterministic model. Future economic and technical factors and costs, such as lease prices, fuel prices, fuel, and electricity consumption rates, are assumed to be known functions of time and vehicle type.

The indices in the model are the types of vehicle, $i \in \{1, 2\}$, the maximum age of vehicles in years, $a \in A$; $A = \{1, 2,\ldots, A\}$, and the time periods (year), $t \in T$; $T = \{0, 1,\ldots, T\}$. The decision variables include the number of type i, age a vehicles which are currently leased in year t, X_{iat}, and the number of type i vehicles which are leased at the beginning of year t, P_{it}. The parameters are:

- **The expected utilisation** (miles travelled per year) of a type i, age a vehicle in year t (miles/year), u_{iat}
- **The expected demand** (miles need to be travelled by all vehicles) in year t (miles), d_t
- **The available budget** (money available for leasing new vehicles) in the beginning of year t, b_t
- **The initial number of vehicles** of type i, age a at the beginning of first year, h_{ia}
- **The lease cost** of a type i vehicle, l_i

- **The expected operating (running) cost** – per mile – of a type i , age a vehicle in year t, o_{iat}
- **The emissions cost** – per mile – of a type i , age a vehicle, e_{ia}

The objective function which we want to minimise (14.24) is the sum of leasing costs for the period (T-3) and the operating (running) cost for the entire horizon to the end of year T:

$$Min \sum_{i=0}^{I} \sum_{t=0}^{T-3} (l_i P_{it}) + \sum_{i=0}^{I} \sum_{a=0}^{A} \sum_{t=0}^{T} [o_{iat} + e_{ia}] u_{iat} X_{iat} \tag{14.24}$$

Equation 14.25 shows that the leasing costs cannot exceed the annual budget. Equation 14.26 requires that the total miles travelled by all used vehicles meet the annual demand:

$$\sum_{i=i}^{I} l_i . P_{it} \leq b_t \qquad \forall\, t \in \{0, 1, 2, \ldots, T-3\} \tag{14.25}$$

$$\sum_{a=0}^{A} \sum_{i=}^{I} X_{iat} u_{iat} \geq d_t \quad \forall\, t \in \{0, 1, 2, .., T-3\} \tag{14.26}$$

Equation 14.27 describes that the total number of the vehicles with different ages and types in the first year should be equal to the initial condition of the system:

$$X_{ia0} = h_{ia} \qquad \forall\, i \in I, \forall\, a \in A \tag{14.27}$$

In addition, (14.28) shows that in the last 4 years of the planning horizon, there is no leasing of new cars. In (14.29) the number of new leased cars at the beginning of each year is determined:

$$P_{it} = 0 \qquad \forall\, i \in I, \forall\, t \in \{T-3, \ldots, T\} \tag{14.28}$$

$$P_{it} = X_{i0t} \quad \forall\, i \in I\, , \forall\, t \in \{0, 1, 2, \ldots, T-3\} \tag{14.29}$$

Equation 14.30 represents the flow equation in which the number of the cars at each year equals to the number of new leased cars plus the number of cars belonged to the previous year. Finally, expression (14.31) is the constraint for non-negative numbers of decision variables:

$$X_{iat} = P_{it} + X_{i(a-1)(t-1)} \quad \forall\, i \in I, \forall\, a \in A, \forall\, t \in T \tag{14.30}$$

$$X_{iat}, P_{it} \in Z^{+} \tag{14.31}$$

Having analysed extensively the different models in the literature and identified some of their limitations, next, in Sect. 14.5, we summarise the main insights from our review of these different approaches.

14.5 Insights from the Literature on Fleet Replacement Models

The aforementioned replacement policies and methods represent only a small part of all efforts that have been done to solve the equipment replacement problem in general (Nakagawa 1984; Ritchken and Wilson 1990) and the vehicle replacement problem in particular (Eilon et al. 1966). The vehicle replacement policy has a prominent role in transportation companies and belongs to an important class of the fleet strategic management problems that have been extensively considered in the literature during last 50 years (Dejax and Crainic 1987). Nevertheless, there are many obstacles for applying the existing methods. Such obstacles exist from the following features of the existing replacement methods:

- Most of the methods are assumed to be applied in a stable environment which is not the case for most of the vehicles in under operational conditions, for example, the way those vehicles are utilised and the loads carried, the climate, and other factors from road conditions which can have impact on fuel economy of the vehicles.
- Focused on a given group (type) of vehicles, they do not go to the granularity of single vehicle.
- Assumptions taken such as a constant utilisation rate of the equipment during its operational life may be too far from field service real-world situations.

In practice, the existing models have at least one of the mentioned drawbacks. For instance, Eilon et al. (1966) consider particular vehicles but assume a fixed utilisation pattern, whereas Simms et al. (1984) relax the assumption of the constant utilisation but constrain an age to the replacement problem by placing a lower bound of 15 years. Suzuki and Pautsch (2005) constrain an age to the replacement model by putting an upper bound of 5 years and conclude that vehicles of age 6 or beyond may not be suitable for business operations: that contradicts the assumption of Simms et al. (1984). Moreover, the significant part of the vehicle replacement models assumes budget constraints (Simms et al. 1984). This part is actually important when replacement policy is defined for fleet of vehicles but not for particular vehicles. However, such constraints generally result in replacement of the limited group of the oldest vehicles (Redmer 2009). Because of the drawbacks of the existing replacement methods, a direct application of them to the vehicles deployed by freight transportation companies remains uncertain.

14.6 Practical Challenges for the Fleet Replacement Problem

Typically fleet management for field services requires finding the right vehicle, of the right capacity, for the right business, and fitting the required features into the serviced work type. In practice, these decisions are twofold:

- First, decision aims at identifying the vehicles portfolio needs in terms of volume capacity, driving features (speed and driving wheels, for instance).
- Second, decision requires a system for calculating a replacement plan, from 1 to 5 years. This aims at ensuring the provision of the right brand, model, and vehicle asset supplier for each identified fleet item.

The second step can be modelled as a multi-objective combinatorial optimisation problem. However, there is not a single solution; as a matter of fact, the solution is in the form of a ranking of the technology and brands available based on the most economical and ecological choice. The accuracy of such a ranking is generally limited to a number of years; due to high variations in energy prices market, fleet managers generally are advised to plan 1 year in advance. Therefore, there is an important practical challenge: to increase the planning horizon to the full 4 years, taking into account all the uncertainties.

The combinatorial aspect of the operation is complicated by the fact that the matching of vehicle types and running technology depends both on the driver's behaviour and on the variation of usage over days, months, or years. For instance, a simple analysis suggests that the petrol engine tends to be cost effective when dealing with short annual mileage usage, and a mixed diesel and hybrid technology are suitable for normal distances while affording a risk exposure reduction. Moreover, the electric engine tends to be the optimal choice, from both risk and cost minimisation perspectives, when the annual mileage usage is high.

The following are some of the challenges faced by fleet provisioning:

- **The fleet provisioning needs to consider the mileage driven by the vehicles**. Thus, in the process of constructing a replacement tactical plan, we need to implement a method for forecasting annual mileage with a granularity at the vehicle type or service operations type level.
- **The length of equipment life is not fixed**. Even though the rental duration can be used as working hypothesis, in practice the replacement decision may happen before the planned end of life, depending on the maintenance cost, fuel prices variation forecast, electric energy recharge constraints, geography, and volume of the field service demand.
- **We need to find a balance between risk exposure and O&M cost minimisation**, taking into consideration the utilisation of vehicles and the frequency of long, medium, or short distance driven by each vehicle. A fine granularity analysis of mileage, fuel consumption, and geographical information

monitoring data will help in adjusting the approach for realising sustainable field operations.

– **There is a need to consider fuel price uncertainty**, the **variation of real fuel consumption** in each technology, leasing costs, and the accessibility of vehicles based on the data for accidents.
– **Robustness of the replacement plan**. If we consider a larger number of aspects in the model, then the analysis will be more accurate. If you want to introduce manufacturing costs into the model, you will require quote information from the enterprise processes; if you consider customer experience (service commitment delivered, number of visits before completing the task, asset missing, for instance), you will need to analyse the robustness of the replacement plan when environment or service engineering variables change. Furthermore, an analysis of the impact of the average speed of the vehicles on the fleet management decisions seems to be one of the other direction of research; however, this variable suffers generally from data quality issues, due to lack of links between tactical planning and the travel feedback from field workers: the use of an electronic box embedded in vehicles is an interesting alternative to improve the flow of information from operations to strategic planning, one of which should be considered if the improvements in fleet management outweigh the costs of installing and maintaining the system.

Additionally, the vehicle utilisation governance within a firm also has an important impact on fleet management. We can consider this issue if we analyse the fleet portfolio life cycle at an organisational level. In this framework, a vehicle is seen as an item that can be swapped across business units: in this case, the transfer of an unused vehicle from a line of business to another one would be a better alternative to rent a new vehicle. If we consider this new framework, several questions arise: Which option leads to the best cost risk and customer experience trade-off? How can the cost of vehicle reuse option be recorded?

This governance structure at a global level, when transforming the fleet portfolio and the impact on environment, requires support at a tactical level by:

- Planning the number of vehicles per technology (source of energy), capacity, and various mileages, in the short, medium, and long term
- Analysing risk exposure (taking into account the forecasted demand and supply life cycle)
- Considering the impact of such decisions on the customer experience

14.7 Conclusions

In this chapter, we provided a comprehensive literature review for different approaches regarding the asset replacement problem and its particular case of field service fleet. Specifically, if we consider the conventional vehicle replacement decisions that exist among fleet managers of the companies and the impact of emerging new technologies on adoption of optimal replacement policies, the main questions that should be addressed for the fleet manager are:

– First, what kind of vehicle technologies has a better performance in terms of cost efficiency?
– Second, what is the impact of market uncertainties on vehicle replacement decisions?
– Third, what are the best practices for replacing vehicles in the future?

The model suggested in Sect. 14.4.2 has the potential to address most of the drawbacks in the existing replacement methods. First, it takes into account the variability of vehicles' operational (running) costs. Indeed, the majority of the parameters of the model depend on time, and fixed and variable aspects are distinguished in cost parameters. In particular, the expected utilisation (annual mileage driven) per year is assumed as a variable in each year. In addition, CO_2 emissions costs are also taken into account.

Moreover, unlike most of the papers in the literature, the leasing option is considered as a way for financing the vehicles in the fleet system which is commonplace in the most of the commercial logistics systems. By taking into account leasing of the new vehicles at the beginning of each year for a finite time horizon (4–5 years), many issues regarding the optimal age (economic life) of vehicles and relation with age and utilisation will be resolved, due to young structure of the fleet system.

Nevertheless, the model assumes the availability of a certain number of historical inputs and of forecasted data such as fuel prices, fuel consumption, CO_2 prices and the utilisation trend of the vehicles along years. This data should be collected, updated, and processed with the application of a modern database. This database combined with the suggested model provides a decision support system for a strategic fleet management in any transportation company.

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