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Abstract

Construction companies are heavily dependent on their heavy construction equipment fleets. These equipment fleets represent large capital investment by companies. Equipment managers must make complex decisions on their deployment, maintenance and retirement. They have finite physical and economic life and require replacement at some stage. However, different methodologies are employed in determining the time of construction equipment replacement. Among these decisions making approaches are optimization models. Which are relatively recent, and still need more researches to enhance them. This thesis investigates the mechanics of one of the most widely used replacement analysis theories, and how it can be implemented into a practical easy to use mathematical optimization model. Also, in this thesis, a Matlab code that can be used as a decision making aid tool was developed.

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COST MINIMIZATION MODEL FOR CONSTRUCTION EQUIPMENT REPLACEMENT POLICY

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This Thesis was submitted in Partial Fulfillment of the Requirements for the Master's Degree in Engineering Projects Management

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COMMITTEE DECISION

This Thesis (COST MINIMIZATION MODEL FOR CONSTRUCTION EQUIPMENT REPLACEMENT POLICY) Was Successfully Defended and Approved on 17 – January -2013.

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List of Abbreviations

EUAC	Equivalent uniform annual cost
ACG	Association of general contractors of America method
EGB	Equipment guide book method
IC	Initial capital cost
MV	Equipment market value
PW	Present worth value
E	Annual expenses
TC	Total marginal cost
MAPI	Machinery and Allied Products Institute model
CCM	Cumulative Cost Model
ERA	Equipment Replacement Analysis Model
FCP	Failure Cost Profile
P	Equipment Useful lifetime
i	Interest Rate
AFCF	Average Fuel Consumption Factor
S	Salvage Value
f	Operating Factor
Hp	Rated Horse Power
C	Crank Capacity
LRC	Lifetime Repair Cost
HOY	Hours Operated Yearly
RF	Repair Factor
D	Yearly Depreciation

HFC	Hourly Fuel Cost
FOG	Filter Oil and Grease Cost
TRC	Tires Cost
MRC	Maintenance and Replacement Cost
OWG	Operators' Wage
SPC	Special Items Cost
ETRL	Expected Tire Life
C_{FG}	Cost of Fuel Gallon
C_{OG}	Cost of Oil Gallon

Abstract

Construction companies are heavily dependent on their heavy construction equipment fleets. These equipment fleets represent large capital investment by companies. Equipment managers must make complex decisions on their deployment, maintenance and retirement. They have finite physical and economic life and require replacement at some stage. However, different methodologies are employed in determining the time of construction equipment replacement. Among these decisions making approaches are optimization models. Which are relatively recent, and still need more researches to enhance them. This thesis investigates the mechanics of one of the most widely used replacement analysis theories, and how it can be implemented into a practical easy to use mathematical optimization model. Also, in this thesis, a Matlab code that can be used as a decision making aid tool was developed.

Chapter 1

Introduction

1.1 Preface.

By the nature of the product, the construction contractor works under a unique set of production conditions that directly affect equipment management. Whereas most manufacturing companies have a permanent factory where raw materials flow in and finished products flow out in a repetitive, assembly-line process, a construction company carries its factory with it from job to job. At each new site, the company proceeds to set up and produce a one-of-a-kind project. If the construction work goes as planned, the job will be completed on time and with a profit.

For many years, there has been an underlying trend towards a greater use of machinery in construction projects. The scales of modern construction work, and the short construction times required, make the extensive use of plant essential.

Construction equipment generally represents the highest allocation of resources in the construction projects. The cost of incorrect decisions regarding equipment replacement can often exceed all the savings and cost reductions achieved in all other areas of production and planning. With age, both the failure rate and the corresponding maintenance cost increase considerably as deterioration due to wear and ageing of components sets in.

At some point of equipment useful lifetime, a decision has to be made, whether to continue to repair the equipment at ever increasing maintenance cost and risk of failure, or replace the item. This has created unique type of problems for equipment managers. This research was initiated to develop a mathematical optimization model to help construction managers and decision makers in determining the optimum replacement time for a piece of equipment.

1.2 Previous Research.

1.2.1 Classic Equipment Replacement Theories:

In this section, the classical equipment replacement theories are discussed. The next section focuses on replacement models developed specifically for construction equipment, before exploring the limitations of the theories and models.

Replacement theory seeks to answer the question: "What is the optimum economic life of a piece of equipment?" four early equipment replacement theories were proposed to answer this question for industrial equipment in general and not specifically for construction equipment [1].

Firstly, Taylor's cost minimization model defines the economic life of a piece of equipment as the period of time that minimizes the unit cost of production for the machine [20]. His model is graphically represented in Figure 1.1.

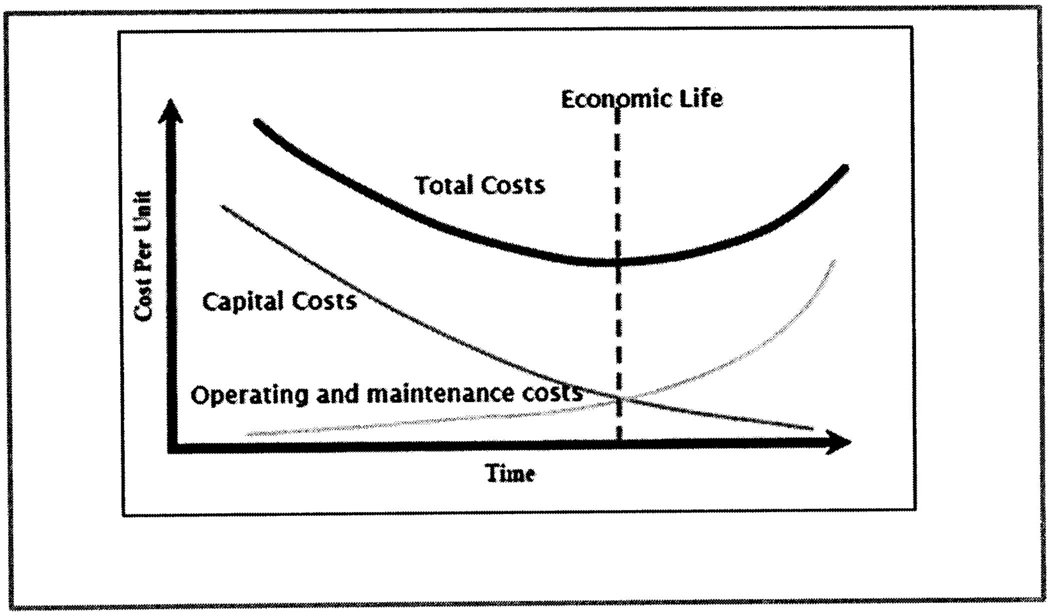

Fig. 1.1 Graphical Representation of Taylor's cost minimization model (1923)[20]

The owning costs of a piece of equipment decline with time, while the average operating and maintenance costs of equipment increase nonlinearly with time. By combining these two costs, the total cost of ownership for a piece of equipment can be obtained, which tends to have a u-shape. The economic life, and thus the optimal replacement age, corresponds to the minimum unit cost value.

Taylor's model, however, focuses on the existing machine only. It assumes that the existing machine is replaced with an identical unit and it does not allow for evaluations where replacement with a different machine occurs. Therefore, the performance improvement due to technological advances is ignored – this is termed machine obsolescence [10].

An alternative model is proposed by Hotelling, where instead of minimizing the costs, an attempt is made to maximize the present value of the equipment's output by using discounted cash flow techniques. In addition to the costs, this model also incorporates the revenues, and the average profit is shown over the age of the piece of equipment [10]. The optimum economic life occurs at the apex of the average profit curve and maximizes all future revenues minus the costs associated with the production, plus the expected salvage value of the equipment.

The model, however, does not recognize the existence of machine obsolescence due to technological improvements. Another disadvantage of this model is that the individual revenue generated per unit of equipment is often difficult to insulate and, in these instances, this model cannot be applied. Lastly, Jaafari and Mateffy highlight the fact that revenue estimation per unit for earthmoving equipment is generally very difficult to estimate and that the application of Hotelling's model to evaluate equipment replacements is therefore impractical. Preinrich developed and refined the earlier work by Taylor and Hotelling. He recognized that replacement problems are not only one machine being replaced by another of the same type. He identifies and categorizes five types of replacement decisions. Preinrich also addresses the problem of how to account for technological improvements. However, he does not provide a method for making the replacement decision [10].

Terborgh was the first person to define the concepts of the defender (the existing machine) and the challenger (the proposed replacement machine). He developed the Machinery and Allied Products Institute (MAPI) model, which was an extension of the cost minimization model [9]. He redefines obsolescence and introduces the concept of deterioration - a measurement of the decreased performance of the defender over time compared to the challenger. He also proposes that the sum of the owning and operating costs be converted into time-adjusted annual equivalents. His model then calculates an after-tax return for two alternatives: the first is to replace the defender machine immediately with the challenger, while the second alternative is to retain the defender and to postpone the replacement decision for one year.

Various criticisms have also been identified against the MAPI model. It does not allow for comparison beyond the first year and it is therefore not an optimization model. Other criticism of the model is that it requires an excessive amount of input information. Jaafari and Mateffy regard the MAPI model as "very academic and sophisticated" and not widely used [10].

Hasting provides an alternative replacement model called the repair limit replacement method. This method is only applicable when a machine requires repair. In such a case, the first step is to estimate the required repair costs. If the estimated cost exceeds a certain limit, called the repair limit, then the unit should not repaired but rather replaced. Dynamic programming methods are utilized to determine the repair limits. However, since the machine must require repair, this method has limited application in practice [20].

1.2.2 Construction Equipment replacement Models:

Replacement models of construction and mining equipment are largely based on the work done by the authors mentioned in the previous section. The most important replacement models and methods developed for construction equipment are discussed below

According to Mitchell, Douglas was the first person to dedicate a book to the management of construction equipment in 1975 [10]. In his book, Construction Equipment Policy, he describes three methods of making the replacement decision: intuition, cost minimization, and profit maximization. Intuition or "gut feel" relies on the judgment of the individual making the replacement decision. Douglas found that this is the most common method for making replacement decisions in the construction industry. However, he questions the use of this method, as it is not based on economic principles. He suggests that the individual making the replacement decision is often biased because of the high initial cost price of a new machine, without taking the long-term benefits of reduced operating costs and increased performance into account. Schexnayder states that although intuition could provide good insight into the relationships governing the replacement decision, but that it can be easily biased.

Douglas states: "decisions about heavy equipment replacement should be based on sound economic principles". He favors the profit maximization method above the cost minimization method and recommends that cost minimization should only be used when revenue or profits cannot be accurately determined [9].

The next model, called the geometric gradient-to-infinite-horizon model, was developed by Collier and Jacques. It describes how to perform calculations for different cost categories, while also accounting for the time value of money. The cost categories include acquisition costs, repair costs, maintenance costs, tire costs, downtime costs, obsolescence costs, taxes and insurance costs. Using their model, these costs are defined in terms of geometric gradients and the model is based on minimizing the total cost of existing equipment [20].

Collier and Jacques developed equations to find the net present value of all the costs associated with the defender [18], the first replacement challenger and all future replacement challengers. These net present costs are then added to find the overall net present value and once this value is minimized, it represents the optimal replacement age. This model is regarded as realistic and flexible in application.

Vorster and Sears regard the cumulative costs due to breakdown and downtime as the most important factor in the replacement decision in the earthmoving industries. In their cumulative cost model (CCM), they define the failure cost profile (FCP), which relates the total hourly cost of all resources in the production team to the number of hours the equipment is unavailable. In their model, the importance of realizing the difference between frequency and duration of equipment breakdowns is emphasized. According to Mitchell the cumulative cost model is the only replacement model that incorporates both classic economic replacement theory and repair limit theory [10].

The geometric gradient-to-infinite-horizon model developed by Collier and Jacques was further refined by Jaafari and Mateffy. Their model is called the equipment replacement analysis (ERA) model. They include inflation and flexibility in inputs to suit a variety of field applications [10]. A sample problem was used to illustrate their valuation model and they developed a computer program to implement it.

1.2.3 Age-Based Equipment Replacement:

Another equipment replacement strategy concerns age-based replacements, where replacement occurs once a certain predetermined fixed age is reached. An example of this replacement strategy is when a particular dozer reaches 50,000 hours, the dozer should be replaced with a new dozer. The replacement age can be determined by various means but is mostly based on minimization of the life cycle costing [5].

Although this replacement strategy is straightforward and easy to apply, age-based replacements have a potentially significant pitfall. The problem lies in the replacement rule that is applied. A stable environment is required to apply this rule optimally. Changes in the operating and maintenance environment occur regularly, which impacts on the equipment life cycle. The validity of the adopted rule must therefore be continuously reassessed by analysis of the inputs. This tends to negate the benefit of adopting the rule in the first place and the adopted rule tends to be a suboptimal solution, resulting in loss of shareholder value.

The literature review of previous construction equipment replacement models shows that these models do not take into consideration that the objective function should be a general function that can be used with any heavy construction equipment. Their objective functions are based on regression of historical data which in real practice are rarely found or not complete.

This research though, develops an objective function that can be used with any heavy construction equipment using data provided from the equipment manufacturers' data sheet.

1.3 Research Problem.

Previous research has shown that there is a need to develop models that are able to close the gap between theory and practice. By formulating objective function able to achieve the following:

1- The Models' objective function should be a realistic function that includes owning and operating costs incurred during the useful equipment lifetime.

2- Historical data for construction equipment are usually either hard to find or not complete. The proposed model therefore, should be developed with the lowest possible dependency on historical data.

3- The objective function should have the ability to be used with all heavy construction equipment, including new and old ones.

4- Time/Money factors should be taken into consideration.

1.4 Research objective.

To provide solutions to the research problem, the research has the following objectives:

1- Identify the main parameters that affect the replacement age of a construction equipment.

2- To develop a mathematical model with a realistic objective function that minimizes all costs incurred from owning and operating a piece of equipment.

3- Implement the developed model to reduce the dependency on historical data, yet it takes into consideration the time/money factors.

1.5 Relevance of Topic to the Construction Industry.

The motivation that drives any engineering research is the need to provide a solution or an explanation to a certain problem or phenomenon. The entire problem solving engineering methods were developed to search for the most perfect solution available. This search is no more needed if the mathematical optimization is applied. As it provides the optimum solution for the objective function. This research was initiated to obtain a realistic mathematical objective function that can be optimized to find the optimum solution for the replacement problem.

1.6 Research Methodology.

1.6.1 Theoretical Part.

A literature search was completed to gather information regarding equipment replacement optimization models. No effort was made to restrict this search to construction related articles as it was hypothesized that much of the information regarding replacement decisions would be available in other industry sectors. Literature related to optimization equipment replacement models was examined.

1.6.2 Practical Part.

In the next step, a mathematical model and its corresponding Matlab code were developed to optimize heavy construction equipment replacement decision. To achieve the research objectives, the objective function of this model was developed by implementing the caterpillar method of calculating owning and operating costs and the equivalent uniform annual cost method.

1.6.3 Achievements & Evaluation.

To illustrate the working of the proposed model, a 150 ton truck crane example was solved. The example results were analyzed in order to understand the model mechanics. Other examples were solved using the mathematical model and the results were analyzed.

1.7 Thesis Structure.

The structure of this thesis follows the traditional format. Chapter 2 supplies background information about the construction equipment economics and replacement analysis using equivalent uniform annual cost (EUAC) concept. This chapter also includes a brief discussion about the gap between academic models and applications in practice.

Chapter 3 is a more in-depth discussion of the research methodology and the formulation process of the models' objective function, including practical examples and analyzing there results.

Chapter 4 presents conclusions, recommendations and suggestions for future researches and developments of this model.

Chapter 2

Concepts of Economic Assessment of Construction Equipment

2.1 Introduction:

Once a piece of equipment is purchased and used, it eventually begins to wear out and to suffer mechanical problems. At some point, it reaches the end of its useful life and must be replaced. Thus, a major element of profitable fleet management is the process of making equipment replacement decision, which essentially involves determining when it is no longer economically feasible to retain a piece of machinery. Equipment life, replacement analysis and replacement equipment selection are the three components of the economics of equipment management decision making [18].

This chapter will provide standard definitions for equipment life time in terms of both theoretical and practical replacement methods and the associated owning and operating costs. As well as a review of the Equivalent Uniform Annual Cost (EUAC) concept.

2.2 Classification of Construction Equipment.

Construction equipment has been classified in various ways. The bases for classifying construction equipment are as follows:

1- Power Type:

a) Electrical. b) Diesel. c) Gasoline. d) Petrol.

2- Stationary type:

a) Stationed. b) Mobiled.

3- Operators' Cabinate Mounted:

a) Isolated. b) Combined.

4- Type of Work:

a) Concreting. b) Digging. c) Grading. d) Compacting. e) Generating. f) Lifting.

5- Way of Movement:

a) Crawling. b) Rubber tires. c) Rail. d) Floating.

6- Type of Acquisition:

a) Owned. b) Hired. c) Leased.

In this research the used classification method is based on the estimation category or the cost center the equipment will be listed under.

When estimating the cost for construction projects, equipment and tools used in construction operations are priced in the following three categories [5]:

1. Small tools and consumables: Hand tools up to a certain value together with blades, drill bits, and other consumables used in the project are priced as a percentage of the total labor price of the estimate.

2. Equipment usually shared by a number of work activities: These kinds of equipment items are usually kept at the site over a period of time and used in-progress activities.

3. Equipment used for specific tasks: These are capital items and used in projects such as digging trench or hoisting material into specified slots. This equipment is priced directly against the take-off quantities for the project it is to be used on. The equipment is not kept on-site for extended periods of time like those in the previous classification, but the equipment is shipped to the site, used for its particular task, and then immediately shipped back to its original location. Excavation equipment, cranes, hoisting equipment, highly specialized, and costly items such as concrete saws fall into this category.

This replacement model focus in making replacement decision of construction equipment of the third category by estimating the cost of owning and operating those equipment and, at the same time finding the time at which the equivalent uniform annual cost (EUAC) is at the lowest point. The concept of the EUAC will be discussed later on this chapter.

2.3 Construction Equipment Acquisition Policies.

The means of obtaining construction equipment may be broadly classified as follows [6]:

1- Owning all equipment. This policy recommends purchasing most of the equipment needed. Equipment availability is maintained thereby at all times with the added advantage of the prestige attached to demonstrating the use of owned equipment. However, much capital will be locked up in the equipment, which must become capable of generating a sufficient rate of return. A major disadvantage, however, of owning a large fleet of equipment is the problem of maintaining adequate levels of utilization.

2- Hiring all equipment. Many specialist equipment hiring firms are available in most countries for the supply of plant and equipment. The contractor who takes advantage of this facility avoids both the responsibility of maintenance and care of the plant and tying up his capital. The equipment may be hired for a specified periods and hire charges minimized by standing off-hire all unwanted equipment. In many instances the operator is also provided by the plant supplier.

The main disadvantage of hiring is that hire rates depends on market forces and are largely beyond the control of the contractor, except for limited negotiation between competing firms. This vulnerability to changes in the industry's economic climate could seriously affect a contractor's quoted price for work and the costs incurred later when work is carried out.

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