A cost analysis model for heavy equipment

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\section*{A B S T R A C T}

Total cost is one of the most important factors for a heavy equipment product purchase decision. However, the different cost views and perspectives of performance expectations between the different involved stakeholders may cause customer relation problems between the manufacturers and customers. Beginning with the conventional manufacturers’ cost view, this paper presents the necessity and importance of expanding the heavy equipment manufacturers’ cost scope to include the post-manufacturing customer stage of their products. Then, this paper narrates a general mathematics Post-Manufacturing Product Cost (PMPC) model to analyze the total costs of heavy equipment in its utilization stage. A major emphasis of the PMPC model is placed on the strategy of improving the manufacturers product cost management and the strategy of customers purchasing decisions cost management and their interdependencies as related to their specific different perspectives on the product utilization patterns.

\section*{1. Introduction}

In the last century, new product development in the manufacturing environment has changed significantly to meet the challenge of global competition. To survive internationally, manufacturing firms must strategically examine customer needs and values in all their served market segments. Increasing complexity and costs of new products place an increased importance on a system life-cycle cost analysis by the vendors and customers. Furthermore, this life-cycle cost view is of particular importance for revenue generator products. For instance, Hitachi Construction Truck Manufacturing, Ltd. is a multi-international manufacturer for off-highway, rigid dump trucks. Its products consist of 30 to over 300 ton rigid haulers with typical life spans of approximately 10 years. The initial cost of rigid haulers can be over one million dollars and corresponding operating costs approximately three to four times of the initial cost. Under these circumstances, a proper cost-evaluating model becomes extremely important.

The traditional cost analysis models can be classified into three categories: manufacturer-oriented cost analysis models, end-user-oriented cost analysis models, and life-cycle cost models.

The typical manufacturer-oriented cost analysis models include productivity hour rate costing, process costing, activity-based costing, and precision engineered costing system. Ostwald’s Productive Hour Rate Costing Model calculates the productive hourly rate by adding the machine hourly rate and the direct labor hourly rate (Sims, 1995). Woods’s Process Costing Model assigns costs to process by accounting for the degree to which the processes cause costs to be incurred (Clark & Lorenzoni, 1978). Activity-Based Costing (ABC) solves the cost accounting precision problem by assigning “cost drivers” to the various sources or elements of manufacturing expense. Sims’s Precision Engineered Costing System is a cost method for both piece part and continuous process manufacturing operations. Sims’s System focuses on the cost-finding impact of capital intensive and high tech operations.

Manufacturer-oriented cost analysis models are deployed by manufacturers to analyze product manufacturing and warranty cost. The major problem with those models is that they can only be applied to manufacturing cost analysis. In other words, they are not total cost analysis models. Therefore, those models can not provide the total cost data to meet customer needs.

The typical end-user-oriented cost analysis models include Benefit-Cost Analysis (BCA) and Total Cost Analysis (TCA). Benefit-cost analysis, which is also known as Cost-benefit analysis, was first demonstrated by Benjamin Franklin in one of his letters from the 1770s. Since its conception, Cost-benefit analysis has been widely deployed in the fields of health and community services, defense and R&D, natural resources, transport, and investment problems (Berliner, Brimson, & James, 1988; Gramlich, 1981). BCA includes two topics: the formulation of alternatives; and the enumeration, quantification, and (when possible) valuation of the relevant costs and benefits of each decision algorithm and preference function (Turvey, 1971). The Total Cost Analysis (TCA) approach suggested by DeCorla-Souza, Everett, Gardner, and Culp (1997) is an alternative to Benefit-Cost Analysis (BCA) for evaluating transportation alternatives. In the TCA approach, benefits involving “cost savings”
are automatically considered on the “cost” side of the equation and not the “benefits” side. In BCA, most or all monetized benefits are really cost savings.

The main problem with end-user-oriented models is that the product most likely will play a static role in the analysis process. End-user-oriented models, which are deployed by end-users and not manufacturers, attempt to make general criteria for computing operating cost. Regardless of the performance variation among the same type of products from different manufacturers, end-user-oriented models only consider the variation of the product’s quantity and functionality. Once the quantity and functionality are determined, the operating cost of the equipment is determined. The best interest of those models is to pick an optimal solution from a group of candidates on the method/path level. In other words, they do not really analyze the cost of different entities performing the same task. For instance, the TCA model for transportation cost analysis classifies the transportation tools into three different categories: private vehicle, public bus, and rail. Upon selecting the “private vehicle” category, the TCA model will not help in picking a kind of “private vehicle”. The result of those models helps people make high level decisions, but it does not help manufacturers or customers when promoting the product or making the purchase decision.

Fig. 1 presents a typical product/system life-cycle economic model from the manufacturer perspective as described by Chen and Keys (2003). It demonstrates the costs incurred to the manufacturer from marketing’s conceptual development through prototype design, development into production, and field costs. Keys (1991) identifies field costs as including manufacturer covered post-manufacturing cost items, such as warrantee optimization, associated dealer/customer allowances, and customer service. More details on these costing can also be found in Keys (1990), Locascio (2000), Sheldon, Huang, and Perks (1991), Keys, Balmer, and Creswell (1987), and Menezes (1990).

In general, the utilization costs of heavy equipment contain two parts: ownership costs and operating costs. The operating costs are normally much bigger than the ownership costs. There is now a clear understanding between manufacturers and customers. One of the fundamental cost problems so-called “lack of total cost visibility” as reported by Blanchard (2003) in Fig. 2 has been well recognized after introducing the principle of the system life-cycle cost. However, when investigating those visible and invisible costs in detail, manufacturers and customers start to show their significantly different interests, perspectives and concerns. These differences are the issues of the typical life-cycle cost model.

First, different concerns will be presented regarding costs. While all costs are integrated, the typical system life-cycle cost view does not clearly distinguish the different cost “partner” responsibilities, (i.e., the different detailed cost concerns). Traditionally, a major concern of manufacturers is all about the Product Manufacturing Cost (PMC). On the other hand, customers could care less about the PMC. Their focus is on the costs to own/lease the machine and keep it running (i.e., the total product utilization cost or the Post-Manufacturing Product Cost (PMPC) as reported by Chen (2002)). Fig. 3 depicts PMC and PMPC cost curves based on the system life-cycle cost view. Neither of these two cost concerns are completed because PMC and PMPC are interrelated. In order to create a long-term relationship with its customers, a heavy equipment manufacturer has to realize the trade-off between PMC and PMPC. Hence, the cost interests of a manufacturer should include both PMC and PMPC. Manufacturers can reduce PMC by using less expensive components or materials without considering the possibility of increasing the PMPC on the customer side.

Second, differences in cost definitions will be presented. In a mining job site, cost data is collected on a regular basis so that the mine managers have a clear idea about the overall costs on the fleet. However, problems and disagreements will come out regarding how to properly allocate and analyze those costs. The collected cost data presents what is really happening in the field. However, this does not necessarily indicate the optical performance for the machine. Furthermore, not all machine costs are ultimately related to a manufacturer's responsibilities. For example, manufacturers are not responsible for the costs of delay in repairs due to lack of required parts. Therefore, it is in the manufacturers’ best interests to separate the true machine cost factors away from the noise cost factors. In other words, manufacturers need to generate their cost models to identify the truly best economical performance of their machine by implementing a better understanding and a better technical knowledge of their products. While the ownership costs are more explicit in general, operating costs generally can be much more confusing and cause disagreements between manufacturers and customers.

![Fig. 1. System production/technology economic life cycles.](image)

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**References**


**Fig. 1.** System production/technology economic life cycles.
Finally, the best method for evaluating or comparing costs will be presented. There are three basic cost measurement methods: absolute costs ($), cost/time unit ($/h), and cost/productivity unit ($/ton). All three methods present different economic aspects of a machine. Absolute costs can be used to determine the overall investment. Cost/time unit can be used to determine the required budget for each year. However, when we are doing costs comparison between different products, cost/productivity unit ($/ton) is the only fair method. Furthermore, since heavy equipment is a profit-making machine, the ultimate goal for heavy equipment customers is maximizing the high gain–loss ratio. Therefore, the cost/productivity unit is the most common method to show a machine’s economic performance.

In today’s business world, most people realize the importance of equipment operating costs impact their businesses (Waeyenbergh & Pintelon, 2004). This paper will first present a general cost structure for heavy equipment. Then, it narrates a general mathematics Post-Manufacturing Product Cost (PMPC) model to analyze the total costs of heavy equipment in its utilization stage. The concept presented in this paper is that manufacturers should extend their cost views to include their product utilization phases (i.e., having an integrated cost view). In addition, the cost model proposed in this paper intends to provide heavy equipment manufacturers a way to present their future machine total utilization costs to their potential customers.

2. Total cost structure for heavy equipment

The Post-Manufacturing Product Cost (PMPC) is the total cost of an operating cost-related product system throughout its lifetime. PMPC is usually paid for by the customer. The total product cost contains two major elements: ownership cost and operating cost. Fig. 4 illustrates the general cost structure and elements for heavy equipment.

Ownership costs are the costs that the owner has on equipment on his job. They include two major parts: Delivered Price/Depreciation and Facilities Capital Cost of Money (FCCM). Delivered Price is the initial capital investment, and depreciation is
the distribution of the initial capital investment throughout its depreciation period. FCCM is the cost of holding the equipment year after year. Due to depreciation, the value of machine changes each year. Therefore, FCCM varies from year to year. In most cases, there are some indirect ownership costs related to a machine besides Delivered Price/Depreciation and FCCM. These indirect ownership costs can include license fees, property taxes, etc. We classify these indirect cost elements as miscellaneous ownership costs.

Operating costs are the owner’s costs to have the equipment operating on his job site. Explicit operating costs, which include energy sources and operator’s wage, are costs directly applicable to operation of equipment. For instance, energy sources consumption, or fuel consumption for trucks, only occurs when the machine is running. On the other hand, implicit operating costs are costs that actually take place when the machine is down. However, these costs are essential factors related to machine operation. For example, maintenance costs and wearing-parts costs are the costs that keep the equipment under operable condition. On the other hand, out-of-service lost revenue is the cost that is caused by the downtime of equipment awaiting the completion of unplanned overhaul and repair.

### 3. Ownership costs analysis

#### 3.1. Delivered costs/depreciation

Delivered costs should include all costs of putting a machine to work at the user’s job site. Actual extra cost items on top of the base machine price are case based. However, all these items can be classified into major extra cost categories as follows:

- **Machine base price cost (Group I):** This cost includes sales taxes, market-share discount, customs duty, etc. This cost is defined as:
  \[ C_I = p_i \times B \]
  where \( B \) is the machines base price and \( p_i \) is the coefficient.

- **Time-related cost (Group J):** This cost includes labor costs for machine setup. This cost is defined as:
  \[ C_J = h_j \times r_j \]
  where \( h_j \) is the number of hours and \( r_j \) is the hourly rate.

- **Weight-related cost (Group K):** This cost includes freight charge. This cost is defined as:
  \[ C_K = W \times f_k \]
  where \( W \) is the weight of the machine and \( f_k \) is the weight-cost rate.

- **Fixed amount cost (Group L):** This cost is not dependent on the machine’s base price or any other variable factors and could include a documentation fee. This cost is defined \( C_L \) and is denoted as Group L.

Based on these four additional cost types, one can calculate the delivered price using the following formula:

\[
DP = \text{Based-Price} + \sum \text{Costs of } (\text{Group } I + \text{Group } J + \text{Group } K + \text{Group } L) \tag{1}
\]

Therefore,

\[
DP = \left( 1 + \sum_{i=1}^{l} p_i \right) \times B + \sum_{j=1}^{l} h_j r_j + \sum_{k=1}^{m} W f_k + \sum_{l=1}^{n} C_L \tag{2}
\]

where

- \( DP \) Delivered Price.

During the equipment’s useful life, its capital value decreases. In other words, its capital is consumed. When the capital cost is combined together with the product lifetime, it becomes capital consumption or depreciation. Capital consumption concerns a product’s useful and economic life and the loss of resale value for a machine (i.e., the equipment’s delivered price less the equipment’s resale price).

For many owners, the potential resale or trade-in value is a key factor in their purchasing decisions. This is a means of reducing the net investment cost they must recover through depreciation charges. The high resale value can reduce hourly depreciation charges, lower total hourly owning costs, and improve the equipment’s competitive position. And, if a machine is traded early before the end of its useful life, resale value becomes even more significant (Thuesen & Fabrycky, 2001). Although the actual resale value for equipment at trade-in time is determined by used equipment auction prices at the local market, one can use some depreciation techniques to estimate the equipment’s resale value at the end of each year during its useful life. There are several commonly used depreciation techniques, which include straight-line, double-declining balance and sum-of-years-digits methods. The double-declining balance method is selected to demonstrate how to calculate Ownership costs. However, one can select any other depreciation method to generate a model by following the same steps below.
The formula below is used to calculate $R_n$, the estimated trade-in value at year $n$:

$$R_n = B \times \left(1 - \frac{2}{T}ight)^n$$  \hspace{1cm} (3)

$L$ as machines useful life in year.

Hence, by considering the machine's trade-in value, the actual capital loss should equal to:

Total Capital Cost to Yr. $n = \text{Machine's Delivered Price-Resale Price @ Yr. } n$

Now, let us take the inflation rate for consideration. Denoting the general inflation rate as $\lambda$, the above equation can be expressed mathematically as

$$TCC_N = \left(1 - \left(\frac{L - 2}{L(1 + \lambda)}\right)^N + \sum_{i=1}^{I} p_i\right) \times B + \sum_{j=1}^{J} h_j + \sum_{k=1}^{K} W_k + \sum_{l=1}^{L} C_l$$  \hspace{1cm} (4)

where

$TCC_N$ Total capital cost to time $N$ present value.

3.2. Facilities Capital Cost of Money (FCCM)

FCCM is the other core element of ownership costs. The Department of the Treasury adjusts the Cost-of-Money Rate (CMR) on or around January 1 and July 1 of each year. This CMR is a guideline. Based on this published CMR, an Adjusted CMR (ACMR) will be specified by customers. Expressed as a formula, FCCM at time $n$ equals the following:

$$\text{FCCM}_n = \text{Equipment's Current Value} \times \text{ACMR}_n$$

Since the CMR will be adjusted each year, ACMR will be changed correspondingly. The actual FCCM should use the CMR according to the actual period that the equipment is used. However, for the estimated purpose, it is impossible to get the CMR during each time period in advance. Therefore, we will use a general estimated ACMR in the formula below by applying the inflation rate and converting the future value to present value:

$$\text{FCCM}_n = \left(1 - \frac{2}{T}\right)^{n-1} \times \frac{1}{(1 + \lambda)^{n-1}} \times B \times \text{ACMR}_n$$  \hspace{1cm} (5)

To sum up the total cost of the FCCM from year 1 to year $n$, we use the following formula:

$$\text{TFCCM}_n = \sum_{m=1}^{N} \text{FCCM}_m = B \times \text{ACMR} \times \frac{L^N(1 + \lambda)^N - (L - 2)^N}{(2 + L\lambda)(1 + \lambda)^N + (1 + \lambda)^N}$$  \hspace{1cm} (6)

where

$\text{TFCCM}_n$ the total cost of the FCCM from year 1 to year $N$ at present value.

3.3. Miscellaneous ownership costs

Besides the delivered cost and FCCM, some other miscellaneous cost items may also apply to a machine based on certain circumstances. There are two types of miscellaneous costs:

- Costs based on the equipment's present value: This includes property taxes, property insurance, etc. This cost is defined as Group MI.
- Costs not directly related to the equipment’s present value but are determined by equipment’s other features: This includes license fees. This cost is defined as Group MII.

The Group MII is similar to the FCCM cost. To generalize the formula applied for FCCM to apply to the cost items in Group MII, replace the ACMR with a $\partial_i$, which is the coefficient of cost item $i$ versus the machine present value. Then, you have the following formula:

$$\text{TMIC}_N = \sum_{i=1}^{N} \text{TMIC}_N = \frac{L^N(1 + \lambda)^N - (L - 2)^N}{(2 + L\lambda)(1 + \lambda)^N + (1 + \lambda)^N} \times B \times \partial_i$$  \hspace{1cm} (7)

where

$\text{TMIC}_N$ the total cost of the Group MII from year 1 to year $N$.

For comparison purposes, the total absolute cost, TAC, should be converted into forms of cost rate, time-cost rate TCR, or productivity cost rate PCR. The estimated economic life is denoted as EL. Assuming the hour is defined as the basic unit of the EL, then EL is converted to designed operating hours (DOH), which results in:

$$\text{TCR} = \frac{\text{TAC} \times \text{DOH}}{\text{EL}}$$  \hspace{1cm} (10)

where

$\text{TCR}$ is the total ownership cost rate.

$\text{TCR}^* \text{ is the total ownership cost rate for the manufacturer's responsibility. However, end-users do not always schedule the machine to its maximum availability. Therefore, the scheduled operating hours (SOH) do not necessarily equal the DOH. In this case, TCR}^* \text{ is not the end-user's final cost. The additional cost of unused capacity should be addressed and added to the TCR}^*$. Denoting the UOH as unused operating hours, we have the following formula:

$$\text{DOH} = \text{SOH} + \text{UOH}$$  \hspace{1cm} (11)

To calculate the time-cost rate of unused capacity, we use the following formula:

$$\text{TCR}^* = \frac{\text{DOH} - \text{SOH}}{\text{DOH}} \times \text{TCR}^*$$  \hspace{1cm} (12)

where

$\text{TCR}^*$ TCR of unused capacity

Therefore, the total ownership cost/h for the end-user’s aspect is equivalent to:

$$\text{TCR}^* = \frac{\text{DOH} \times \text{TCR}^*}{\text{SOH}}$$  \hspace{1cm} (13)

where

$\text{TCR}^*$ the total ownership cost rate on the end-user's aspect.
If TCROS\textsubscript{M} is the final cost to the end-users, then why is it necessary to calculate TCROS\textsubscript{UC} and TCROS\textsubscript{OS} separately, and then sum them up. In other words, what is the point to introduce the concept of unused capacity? The answer is that TCROS\textsubscript{OS} and TCROS\textsubscript{UC} represent different cost concerns, and both of these concerns are important under different circumstances. For example, machine A’s ownership cost is $160,000 with designed service time of 80,000 h, and machine B’s ownership cost is $120,000 with designed service time of 50,000 h. The customer is going to schedule the machine for 20 h/day, 20 days/month in 10 years. The following table shows different TCR results based on different scenarios of total operating hours.

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Designated service hours</th>
<th>Scheduled service hours</th>
<th>Unused capacity</th>
<th>TCROS\textsubscript{OS} (h)</th>
<th>TCROS\textsubscript{UC} (h)</th>
<th>TCROS\textsubscript{M} (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$160,000</td>
<td>80,000</td>
<td>48,000</td>
<td>32,000</td>
<td>$2.00</td>
<td>$3.33</td>
</tr>
<tr>
<td>B</td>
<td>$120,000</td>
<td>50,000</td>
<td>48,000</td>
<td>2000</td>
<td>$2.4</td>
<td>$2.5</td>
</tr>
</tbody>
</table>

From the end-user aspect, it seems that machine B is better than machine A since its TCROS\textsubscript{OS} is less than the machine B’s. However, if we draw a conclusion that machine B has better economic performance than machine A, it will be unfair and wrong. Unfortunately, this kind of wrong conclusion does happen during the operation of the heavy equipment market from time to time. As demonstrated in formula (13), the TCROS\textsubscript{M} contains two parts: TCROS\textsubscript{UC} and TCROS\textsubscript{OS}. Only TCROS\textsubscript{M} represents the true economic performance of the machine. In other words, we should use TCROS\textsubscript{M}, not TCROS\textsubscript{OS} to compare two different equipment apple-to-apple. On the other hand, TCR\textsubscript{UC} should be considered as the utilization problem or loss rather than cost on the end-users side. Therefore, it should be totally eliminated in an ideal situation. There are two ways to achieve this goal:

- The end-users should reexamine their scheduling strategies in order to use machines up to their maximum available capacities.
- The manufactures should reevaluate their marketing target. If the majority of field customers in expect the machine with less operating hours, then they need to consider if there is over-design issue and make the corresponding changes.

After obtaining the TCR value based on the operating hours and productivity/h, the PCR value can be calculated. The productivity rate is operating related and will be discussed in detail in the following pages.

4. Operating costs analysis

While the ownership costs can be used by manufacturers to demonstrate their product price advantage over other manufacturers’ products, the operating costs are dynamically influenced by economic-indicators, which are based on the product’s quality, performance, and functionality.

4.1. Use-case study

Operating costs are much more complicated issues than ownership costs due to their uncertainty. When a machine is operating at a particular user job site, numerous factors influence and determine its actual operating costs. Therefore, a use-case study based on the specified job site parameters needs to be established in order to effectively study the operating costs. For example, a study for a mining job site is defined as the unique combination of equipment, road profile, material, and fixed times from which production and costs can be predicted. Fig. 5 is the use-case model described by UML.

Such a study needs to be further broken down into detailed segments for the actual calculations to be performed. A machine works in relatively the same use pattern as in a segment. For example, in order to study the fuel consumption of a hauler running on one whole cycle, a breakdown into segments is needed. This breakdown is shown below:

- **Wait for loading**: Engine is idle.
- **Run on the haul road with load**: Segments are created based on the road profile. If there is a significant change of the road, such as changing of grade or a turn, then a new segment is created because the engine speed/load has changed.
- **Dump**: Engine is idle.
- **Return with empty load**: This is identical to “Run on the haul road with load”.

Obtaining the required data shown in Fig. 5 can be very difficult, and it normally is one of the major tasks during the purchasing process. It is a joint effect of the manufacturer and the potential buyer. Generally, heavy equipment users will have a detailed financial and productivity plan laid out before they begin searching for proper equipment. In other words, they will not keep millions of dollars worth of equipment as inventory for some uncertain future use. Hence, once the customers decide to buy equipment, they almost always have a very clear plan for the placement of the equipment (the job site) and the equipment’s expectation (the productivity requirement). When it comes to collecting data for the study, the customers will need the manufacturers’ assistance. On the other hand, the manufacturers are often willing to offer their help even on their own costs because the accurate analysis result will benefit both sides. For example, the potential customer has the elevation map of the mining job site. However, the elevation map is not good enough to create a detailed road profile. When the manufacturers conduct field tests for their equipment, they know the essential parameters needed for creating a road profile in order to achieve an accurate speed and fuel analysis. Moreover, different manufacturers might require different parameters since their analysis models vary. All of these technical details and knowledge are impossible for the customers to understand and utilize, and they should not be required to do so. Therefore, a manufacturer is normally working very closely with its potential customers to create the case studies. They will send out engineers to customers’ job sites. Since manufacturers possess the deep knowledge of their products and the rich experience of dealing with similar situations, the accuracy of parameters of the job study is guaranteed within a certain tolerance level. After the case study is created, the data is normally only available for the manufacturer and the customer because it contains a significant amount of business sensitive information.

There are two major outputs from the use-case study. One is the operating costs’ items, which will be discussed in later sections.
The other one is productivity. For heavy equipment, it is the volume of material that a fleet can move in a specified timeframe.

4.2. Energy sources consumption

Almost all heavy equipment needs to consume certain forms of energy resources in addition to manpower. Typically, the energy sources consumption (ESC) is heavy use-case based.

For example, a rigid hauler is selected to calculate its fuel consumption. Many detailed parameters of major related components and job site, such as engine BSFC rating, fuel map, machine weight, body size, and haul road, need to be known. After determining these parameters, a study on how the truck will perform and consume each job segment should be completed. This study consists of applying corresponding physical, mechanic and mathematics theories and formulas. Finally, an accumulation of fuel consumption on all segments is completed to get the total ESC for that particular use-case.

Simulation is an extremely complicated process. It requires the combined knowledge of general engineering philosophy and the unique machine features/parameters. Therefore, in order to get accurate results, design/product development engineers, not the customers, need to take the responsibility of carrying out such simulation tasks. These simulations should be part of the product development process (Keys, 1990).

To generalize, the TCR for ESC can be calculated by the following formula:

$$\text{TCROP}_{\text{ESC}} = \frac{\sum SC_{i}^{\text{ESC}} \cdot \phi_{i}^{\text{ESC}}}{\sum ST_{i}^{\text{ESC}}}$$

(14)

where

- $\text{TCROP}_{\text{ESC}}$ the TCR for ESC
- $SC_{i}^{\text{ESC}}$ the standard ESC for segment $i$
- $ST_{i}^{\text{ESC}}$ the standard required time for segment $i$
- $\phi_{i}^{\text{ESC}}$ the environment-human adjustment factor

4.3. Operators' wages

The operator’s wage (OW) depends on the customers' local labor conditions. For instance, in the USA, the final cost to a company for an operator includes the annual salary and additional benefits. These benefits include Social Security, unemployment compensation, taxes (state and federal), workmen's compensation insurance, a retirement plan, etc.

The additional costs can be broken into two categories A and B. Type A is dependent on the operator's basic salary (i.e., a certain percentage of the base salary, such as Social Security, taxes, etc.). Type B is a fixed amount regardless of the operator's base salary.

Therefore, one can use the following formula to calculate the TCR of an operator's wage based on the operator's annual salary:

$$\text{TCROP}_{\text{OW},i} = \frac{\text{BS}_{i} \cdot (1 + \sum \eta_{j}) + \sum \text{FA}_{k}}{\text{PH}_{i} \cdot \text{WD}_{i}}$$

(15)

where

- $\text{TCROP}_{\text{OW},i}$ the wage rate for operator type $i$
- $\text{BS}_{i}$ the basic annual salary for operator type $i$
- $\eta_{j}$ the salary adjustment coefficient $j$
- $\text{FA}_{k}$ the fixed adjustment $k$
- $\text{PH}_{i}$ work time per day for operator type $i$
- $\text{WD}_{i}$ work days per year for operator type $i$

To calculate the total TCR of OW for specified equipment, a use-case study again is needed. Under special circumstances, different numbers and different types of operators may be involved. For each operator, the number, types, and work time of each operators required by each job segment should be defined.
The TCR of OW for the whole system can be calculated by using the following formula:

\[
TCROP_{\text{NOW}} = \frac{\sum L_{i}^{\text{NOW}}T_{i}^{\text{OW}}}{\sum S_{i}^{\text{RT}}}
\]  

(16)

where

- \(TCROP_{\text{NOW}}\) the total wage rate for the system
- \(L_{i}^{\text{NOW}}\) the number of required operators of type \(i\)
- \(T_{i}^{\text{OW}}\) the required time for each type \(i\) operator
- \(S_{i}^{\text{RT}}\) the standard required time for the segment \(j\)

### 4.4. Service maintenance costs

Service maintenance refers to basic maintenance tasks. This includes cleaning, lubrication, and retightening. Each service maintenance event contains a group of tasks based on specified maintenance time intervals. The Service Maintenance Cost (SMC) includes two basic parts: labor costs and parts costs. Although a service event may involve the replacement of some minor and wearing parts, labor costs are the major cost element of SMC. The overhaul or replacement of major components will be considered as repair maintenance, which will be discussed in the next section.

The labor costs are determined by the manpower-hours required for a specified task and the labor cost per unit time. Manufacturers can list the suggested manpower-hours for a certain maintenance activity. However, under most circumstances, customers do the service maintenance using their own mechanics on the job site. Therefore, the actual manpower-hours are heavily dependent on the maintenance personnel's efficiency and their experience with that type of machine. Hence, some leading manufacturers are providing training programs not only for operators but also mechanics for job-site maintenance purpose.

The other cost variable is the hourly cost rate of labor. There are two different rates: one is the rate during the regular working hours and the other is the rate before or after the regular working hours (overtime). Since all service maintenance events are performed based on a fixed time interval, we can simplify the problem by assuming that end-users can manage the maintenance personnel's schedule to match the service schedule in advance (i.e., no overtime charge will be applied). Hence, we can calculate the SMC by the following formula:

\[
SMC_{i} = \delta \sum_{j} l_{ij}^{\text{SM}} \times rlr + \sum_{j} p_{ij}^{\text{SM}}
\]

(17)

- \(SMC_{i}\) the costs for accomplishing service maintenance event \(i\) once
- \(l_{ij}^{\text{SM}}\) the standard required manpower-hours for the task \(j\) of the event \(i\)
- \(rlr\) the regular labor rate
- \(p_{ij}^{\text{SM}}\) the part cost for task \(j\) of the event \(i\)
- \(\delta\) the efficiency and proficient adjust factor

Therefore, the Total-Cost-Rate (TCR) of a service maintenance event \(i\) can be expressed as follows:

\[
TCROP_{\text{SMi}} = \frac{\sum_{j} \left( \delta \sum_{j} l_{ij}^{\text{SM}} \times rlr + \sum_{j} p_{ij}^{\text{SM}} \right)}{\sum_{j} S_{i}^{\text{SM}}}
\]

(18)

- \(TCROP_{\text{SMi}}\) the time-cost rate for delivering event \(i\) during the product lifetime
- \(TCROP_{\text{SM}}\) the time-cost rate for total SMC

### 4.5. System view for repair maintenance costs

Repair Maintenance Costs (RMC) include all parts and direct labor chargeable to repair/maintain a product during its lifetime. This kind of cost calculation is based on the system view of a complex product.

A system is a set of interrelated components working together toward some common objective or purpose. Based on the system view, a complex product can be structured as an upside-down tree. A product’s architecture is composed of modules, and each module can be broken down into smaller sub-components. The root of the tree is the product itself, which is on the top level. Then, from top down, the product is broken down into different levels of individual components/sub-components based on the functionality or characteristics (Blanchard, 2003; Keys, 1990).

There are two approaches to estimate/analyze the RMC: one is the component-driven method and the other is the event-driven method.

The component-driven method uses each individual component as a base point to estimate the total RMC. Depending on the reliability, component life, and other influential factors, the estimated RMC of a single component during the product’s economic life can be computed. By summing up the costs of all components, the total RMC of the product is calculated.

The event-driven method combines the repair activities and the involved components together as events. An event is composed of tasks. Each task involves several related components. The cost calculation is completed bottom-up. From the related components and manpower requirement, the cost to perform a certain task is calculated. By adding up all task costs together, the cost for a specified event is obtained. From the event interval and the estimated product lifetime, the number of the occurrences of a specific event can be obtained. Therefore, the total cost of an event can be calculated. Finally, the total RMC is the sum of all events’ costs.

The advantages of the component-driven approach are its distinct system view and independency. It is very simple to track the costs on a specified component during the product’s lifetime based on this method. Therefore, the manufacturers and the end-users can have a clear picture about the cost allocation. On the manufacturers’ side, it helps to better understand the costs’ weakest point. On the end-users’ side, it helps to determine their parts’ supplement and inventory strategy. On the other hand, in the event-driven approach, the cost focus is on the event rather than on the component. Despite being difficult, it is possible for this method to provide the cost view based on the system’s breakdown structure. Furthermore, the component’s life is a variable determined by the working conditions, working stress, etc.

In the component-driven method, the adjustment of one component’s life will not affect other components. Contrasting the event-driven method, the adjustment of one component’s life will affect the task and the event as well. An old task or event may be removed according to the change of a component’s life. On the other hand, a new task or event referring to the new time interval will be created for that changed component. Therefore, a simple adjustment of one component’s life may cause a lot more complex changes of the whole event list.

One advantage of the event-driven approach is that it is more operable realistically than the component-driven approach. The system view based on components is a logic structure. In reality, the scheduled events are the standards to be carried out. In addition to the component-oriented costs, there are some fixed event-oriented...
costs, which do not vary based on the number of activities or components involved. These fixed event-oriented costs can include the required manpower and costs to send the equipment to the workshop for repairing/maintenance, the administration cost of recording each machine down event, etc. It is impossible to use the component-driven method to reflect those kinds of costs. Furthermore, after considering those fixed costs, optimization of the components’ overhaul time intervals, which involves merging some events together, should be done. Therefore, the total event number and total costs will be reduced, and the equipment’s availability will be increased.

In the ongoing discussion, the method that will be used is a combination of the component-driven and event-driven method. First, the focus will be on calculating the RMC for a particular component. Then, a discussion will be reviewed on deploying the event cost view, adding those neglected costs back, and optimizing the components’ overhaul intervals to reduce the total RMC.

4.6. Repair maintenance costs

Based on its characteristics, repair maintenance can be broken down into two categories: preventive-overhaul maintenance and failure-corrective maintenance. Failure-corrective maintenance is unscheduled maintenance resulting from component failure during equipment operation. Preventive-overhaul maintenance is scheduled maintenance to prevent a component from failure during the equipment operation time. This includes providing systematic inspection, detection, component rebuilding or replacement based on a specified time interval. Preventive-overhaul maintenance can be classified further into two more detailed categories: rebuild maintenance and replacement maintenance. Rebuild maintenance retains a component at a specified level of performance by rebuilding it based on a certain time period. Replacement maintenance replaces a specified component with a new one in order to retain the satisfaction of the machine’s overall performance. Generally, a component cannot be rebuilt indefinitely. In other words, a component has to be replaced with a new one after a certain number of rebuilds. Ideally, the failure-corrective maintenance should be totally eliminated by a properly scheduled preventive-overhaul dictated by the machine’s cost and downtime.

Since the failure-corrective repairs are unscheduled and unpredictable, the general method to estimate these costs is to reference the scheduled preventive maintenance costs as a baseline, then multiply by a predicated coefficient. The coefficient can be acquired by analyzing the historical data collected from practice.

\[
\text{RMC}_i = (1 + 2^{FC}) \text{PM}_i \tag{19}
\]

where
- \(\text{RMC}_i\) the RMC for the component \(i\)
- \(\text{PM}^{RM}_i\) the preventive-overhaul portion of RMC
- \(2^{FC}\) the estimated coefficient of failure-corrective costs

Therefore, considering the replacement cost as a full cost cycle for a specified component, the total preventive-overhaul costs during one replacement cycle can be calculated by the following formula:

\[
\text{PM}^{RM}_i = \sum_j \text{RB}^{PM}_{ij} \text{PR}^{PM}_i \tag{20}
\]

where
- \(\text{RB}^{PM}_{ij}\) the cost of the rebuild activity \(j\) of the component \(i\)
- \(\text{PR}^{PM}_i\) the replacement cost of component \(i\)

The replacement cost is composed of two elements: the component cost and the labor cost to remove the old component from the system and install the new component into the system. For the same reason stated in the service maintenance costs section, the overtime factor will not be considered in the labor cost.

The rebuild cost contains three elements: the parts replacement cost, the rebuild labor cost (the bench cost), and the removal and reinstallation labor costs. As stated previously, not every rebuild activity requires removing and reinstalling the specified component. If it is required, the related hours should equal the RR hours in the replacement cost formula. Otherwise, the R&R cost for this particular activity is 0. Furthermore, a rebuild activity will be replaced periodically based on the time interval before the component is replaced with a new one.

If we denote \(AT\) as the number of the rebuild activity to be performed before a replacement, assume the replacement activity, the rebuild activities are subject to the following constraints:

Assume \(T_{ij}\) is the time interval for the rebuild activity \(j\) for the component \(i\), and \(T_{i1} < \ldots < T_{i,n}\). Then \(T_{i,n} = C_{i,n-1}\ T_{i,n-1} = C_{i,n} - 1\ T_{i,n} = C_{i,n}\)

where \(C_{i,1} < \ldots < C_{i,n-1}\) are integer numbers and greater than 1. For example, if the component \(i\) has three rebuild activities \(A, B,\) and \(C\) and \(A < B < C\), then \(A, B,\) and \(C\) will satisfy: \(B = N \times A\) and \(C = M \times B\). In other words, when \(B\) occurs, \(C\) will occur. When \(A\) occurs, \(B\) will occur.

1. Assume \(T_{ij}\) is the time interval for the replacement for the component \(i\). Then \(T_{ip} = C_{i,n} - T_{i,n}\), where \(C_{i,n}\) is an integer and greater than 1.

2. Assume \(P_{ij}\) is the set of sub-components to be replaced in the rebuild activity \(j\) for the component \(i\). Then: \(P_{ij} = P_{ij} + 1\), i.e., the activity \(j + 1\) will cover everything in activity \(j\) and some extra work and parts.

The above assumptions are based on common industry practices. As a matter of fact, most components will have three or less different rebuild activities: minor, intermediate, and major.

We can calculate the ATs using the following formula.

\[
\text{AT}^{PM}_{i,j} = \prod_{k=1}^{i-1} C_{i-k} - \prod_{l=1}^{j-1} C_{l} - 1\prod_{j=1}^{i+1} C_{l} \tag{21}
\]

where
- \(\text{AT}^{PM}_{i,j}\) the number of the rebuild activity \(j\) be performed before total replacement \(C_{i,n+1} = 1\)

The time interval \(Ts\) for rebuild and replace activities are specified by manufacturers based on the component’s reliability and the experience gained from practice. In general, this data results from the joint efforts of the engineering department, marketing department, and warranty parts department of manufacturers and their components suppliers. When designing a new component, the engineers will provide estimates based on the scientific computing and lab testing. The marketing department and the warranty parts department will work together to collect and analyze the feedback from the field and adjust the data to become more accurate. The raw data is considered as highly classified business intelligence data for a manufacturer. Normally, this data is only available to the related internal departments and personals. The analysis result based on this raw data will be provided to interested parties (i.e., the current and the potential customers).

Based on the standard data, the actual \(Ts\) are heavily dependent on real working conditions and working stress. Therefore, a corresponding adjustment factor, which combines all influence parameters, needs to be added to the equation. However, since the time intervals for a component are adjusted simultaneously and equally, the \(ATs\) will remain the same.
Therefore, the TCR of RM of the whole product system is shown below:

$$\text{TCR}_{RM} = \sum_i \text{TCR}_{RM}^i = \sum_i \left( \frac{1}{\lambda_i^{TC}} \left( p_{i}^{RP} + RR_{i}^{RM} * rlr \right) + \left( \sum_k p_{i,k}^{RB} + \left( RR_{i}^{PM} * \beta_i + BH_{i,j}^{RB} * rlr \right) * \left( C_{ij} - 1 \right) \prod_{l=j}^{n} C_{il} \right) \right)$$

(22)

where

- $\lambda_i^{RP}$ the adjusted coefficient of the replacement time interval for component $i$
- $p_{i}^{RP}$ the cost of a new component $i$
- $RR_{i}^{RM}$ the manpower-hours required to remove and reinstall (R&R) $i$
- $rlr$ the labor rate
- $p_{i,k}^{RB}$ the part cost for item $k$ required by the rebuild activity $j$
- $\beta_i$ the coefficient of R&R manpower requirement. 1: if R&R is required, 0: otherwise
- $BH_{i,j}^{RB}$ the required bench manpower required the rebuild activity $j$

The adjustment factor $\lambda$ is determined by the use-case study. For example, a hauler running on a most flat/straight haul roads will have less maintenance costs versus the same hauler running on mostly severe grade/turn haul roads. For major components, $\lambda$ can be obtained from the component life table (i.e., stress versus life curve).

### 4.7. Total maintenance costs

Previously, we discussed service maintenance costs and repair maintenance costs separately. However, these two kinds of maintenance activities need to be consolidated. As stated previously, all maintenance activities will be organized as events to be carried out. Those activities which share the same time interval will be considered as a series of tasks in one event. The purpose of introducing the concept of an event is to address and reduce the event fixed cost.

To generate the event list based on the time intervals for SM and RM, we can classify the SM and RM activities into different groups with activities in the same group have the same time interval. Denote the intervals for different groups as:

$EI_1, EI_2, \ldots, EI_m$

In order to calculate the total event fixed cost, the total number of none-duplication event occurrences is needed. For example, there are two events: one event’s interval is 1000 h and the other event’s interval is 3000 h. At 3000 h, both events will be performed. However, since these two events are carried out at the same time, the none-duplication event occurrence should be counted only once. In other words, the fixed event cost should only be counted once, not twice. The following flow chart in Fig. 6 illustrates the algorithm used to calculate the Total Event Number (TEN) of none-duplication occurrences. Denote $H$ as the accumulated operating hours, $E$ as the total estimated operating hours, and $S$ as the largest common integer factor of all $EI_i$

![Flow Chart](image-url)
The TEN is applied for all scheduled activities. The actual down event number should also be considered in the accident breakdown. The general method to estimate the accident breakdown number is to use the equipment’s operating hours as a baseline, and then adjust it by a coefficient.

The TCR of the fixed event cost can be mathematically expressed as follows:

\[ \text{TEN}_c = \frac{(\text{MTBR} + \text{MTA}) \times \text{EPC}}{\text{SEOH}} \]

where

\( \text{MTBR} \) the accident breakdown coefficient

Therefore, the consolidated TCR of all maintenance activities can be calculated as follows:

\[ \text{TCR}_{MC} = \text{TCR}_{NM} + \text{TCR}_{SM} + \text{TCR}_{RE} \]

4.8. Out of Service Lost Revenue (OSLR)

Out-of-service lost revenue costs are known as unscheduled downtime costs.

OSLR costs are typically either hidden or attributed to operations. Sometimes, OSLR costs are not explicit costs by strict cost definition. In other words, it is not the actual expense paid by the customer. Rather it is a loss that a user will get less pay back. However, in order to accurately evaluate the true cost performance of equipment, OSLR cost is very important and should be considered separately as an essential cost item. This is because it may significantly impact the gain/loss ratio, which is the most cared about outcome for users. As mentioned in the beginning of this paper, the ultimate goal for analyzing total equipment costs is not how much the machines will cost but how much the machine will bring. Hence, OSLR is a cost and not a loss.

When a machine is accidentally broken, there are three case scenarios as follows:

- Wait until the machine is being repaired. The company will lose its production and may consequently face potential penalties because of insufficient delivery to its customers.
- Use the standby unit(s) to cover the broken-down machine. The company will keep up with its production schedule. However, the company will have to purchase or lease extra unit(s) from the manufacturer at a special, cheaper price with certain utilization restrictions (e.g., only use the unit(s) to keep the overall availability to a specified level). These utilization restrictions are based on the experience gained from historical data and anticipate the possible availability shortage.
- Contract other companies to catch up with the lost production. In general, it will cost a company more to use a contracting company to produce products than to produce products on its own.

The formula below illustrates this case scenario:

\[ \text{TAC}^\text{OP}_{OSLR} = \begin{cases} (\alpha + \beta) \times P \times T_{\text{TUDT}} & \text{(i)} \\ \text{TCR}^* \times T_{\text{TUDT}} + \text{TAC}_{\text{standby}} & \text{(ii)} \\ \text{PCR}_{\text{contract}} \times P \times T_{\text{TUDT}} & \text{(iii)} \end{cases} \]

\( \alpha \) the profit/product

\( \beta \) the penalty cost/product

\( P \) the equipment productivity rate

\( T_{\text{TUDT}} \) the total unschedule out-of-service time

\( \text{PCR}_{\text{contract}} \) the cost rate of the contract company

The total unscheduled downtime is difficult to predicate due to its uncertainty. For existing products, the manufacturer can estimate downtime from historical data by assuming the unscheduled failure follows certain exponential distribution with MTBF. For new products, this figure becomes more difficult to forecast.

Assume all the three aforementioned methods are available for users, then the optimal TAC for OSLR will be:

\[ \text{TAC}^\text{OSLR} = \min \left( (\alpha + \beta) \times P \times T_{\text{TUDT}}, + \text{TCR}^* \times T_{\text{TUDT}} + \text{TAC}_{\text{standby}}, \text{PCR}_{\text{contract}} \times P \times T_{\text{TUDT}} \right) \]

Therefore,

\[ \text{TAC}^\text{OP}_{OSLR} = \min \left( (\alpha + \beta) \times P \times T_{\text{TUDT}} \text{TCR}^* \times T_{\text{TUDT}} + \text{TAC}_{\text{standby}}, \text{PCR}_{\text{contract}} \times P \times T_{\text{TUDT}} \right) \]

4.9. Other operating costs

Besides the previously discussed general operating cost items, there are some other items which must be applied under certain circumstances.

For example, tires are considered as wearing parts for most rubber tire equipment. Therefore, the repair and replacement costs for tires are separated from all other components and considered as an individual operating cost item, which is defined as “wearing-parts costs”. It is very obvious that job factors are also involved in the calculation. The calculation can then be expressed by the formula as below:

\[ \text{TCR}^\text{OP}_{MS} = \sum_i \frac{C_{i,\text{MS}}}{T_i} \times \mu_{i,\text{MS}} \]

where

\( \text{TCR}^\text{OP}_{MS} \) the total TCR of miscellaneous costs

\( C_{i,\text{MS}} \) the one-cycle cost for item \( i \)

\( T_i \) the time of one-cycle for item \( i \)

\( \mu_{i,\text{MS}} \) the job adjustment coefficient for item \( i \)

4.10. Total operating costs

The total TCR of operating costs for a product system can be expressed by the following formula:

\[ \text{TCR}^\text{OP} = \text{TCR}^\text{OP}_{MC} + \text{TCR}^\text{OP}_{NM} + \text{TCR}^\text{OP}_{SM} + \text{TCR}^\text{OP}_{OSLR} + \text{TCR}^\text{OP}_{MS} \]

where

\( \text{TCR}^\text{OP} \) the total operating TCR for the system

Hence the TAC of operating costs is defined as:

\[ \text{TAC}^\text{OP} = \text{TCR}^\text{OP} \times \text{SOH} \]

In conclusion, the operating costs for heavy equipment are use-case related and the general costing analysis procedure is as follows:

- Define a job study for the particular project.
- Study each job segment to obtain the power consumption, time consumption, and effect factors for components’ life and other required coefficients.
- Analyze each cost item.
- Integrate all cost items into the total operating cost.

5. Integrated PMPC

To calculate the total equipment costs, ownership costs, and operating costs need to be consolidated. There are three different types of cost figures: TAC, TCR, and PCR.
The TCR was discussed in the previous sections. The integrated TCR for the whole product system is given in the following equation:

\[
TCR = \frac{DOH}{SOH} + TCR_{SOH}^{OP} + TCR_{STES}^{OP} + TCR_{MS}^{OP} + TCR_{MOS}^{OP}
\]  

(31)

The integrated TAC for the whole product system can be calculated as:

\[
TAC = DOH \times TCR_{SOH}^{OP} + \left( TCR_{STES}^{OP} + TCR_{MS}^{OP} + TCR_{MOS}^{OP} \right) \times SOH
\]  

(32)

In order to compute the PCR, the productivity \( P \) yielded by each working cycle needs to be known. As previously mentioned, \( P \) is one of the essential outputs from a use-case study. Hence, the PCR can be expressed by the following formula:

\[
PCR = TCR \times \frac{\sum STES}{P}
\]  

(33)

6. Conclusion

This paper presents an approach to define the total cost structure and an analysis method for using heavy equipment in general. The PMPC model is not an alternative solution for the LLC model because they are aiming on different subjects.

From the high level cost view, LLC and PMPC have different research scopes. LLC includes all the costs for a product from the very beginning to the very end. On the other hand, PMPC focuses on the product's costs in its utilization stage with the cost responsibilities clearly defined. Therefore, PMPC can establish a set of costs to present the true economic performance of the product accurately. By defining the cost responsibilities, it comprises a serious difference between PMPC and LLC.

With the different cost responsibilities defined, some new elements are not being accounted. For example, the profit for the manufacturer is never a cost item in LLC. However, it is a cost for the end-user in PMPC by including itself into the purchase price. Moreover, some elements that are either hidden or not considered as cost in LLC, which includes OSLR and unused capacity cost, become very important in the PMPC. For instance, OSLR is the potential economic performance losses and not the actual cost. However, it must be included if we want to compare the products' economic performance on an “apple-to-apple” basis.

Although PMPC is used to analyze the utilization costs, it suggests that the manufacturers should deploy the PMPC as a part of their manufacturing and marketing strategy in order to make their products more competitive. By implementing the concept, the heavy equipment manufacturers can create their own detailed cost models for their products. Such a model should be verified by the specific manufacturer's historic data and real feedback from the field. For example, as described above, the predication of fuel consumption of a hauler is dependent on the simulation of a use-case study. Therefore, the simulation method has to be accurate in order to get precise results of fuel consumption. In Hitachi Construction Machinery organization, there is a software called CONSULT to perform these job studies. With the verification from the field tests, CONSULT's results are in the satisfied tolerance range.

There are two ultimate goals of the total cost analysis. One is to indicate the complete economic performance of a product. The other is to find solutions to reduce the total cost at the product design and development stages and not only effective manufacturing costs (Barton, Love, & Taylor, 2001). While the first goal is well recognized by the sales and marketing departments of companies, the second goal still needs to be emphasized through all departments in heavy equipment manufacturing. In fact, decisions made early in the design/development cycle (maybe only 20%) can “freeze” (effect) 75–80% of the total life-cycle costs as illustrated in Fig. 7. Details can be found in Goel and Singh (1999), Woodward (1997), Keys (1997), and Blanchard and Fabrycky (2000).

To summarize, the PMPC model proposed in this paper can be used by manufacturers to analyze the costs of the current products. Additionally, it can be used to predicate the costs of products when they are still in the design and development stages. For example, once the proper PMPC model is in place, the design engineer will be able to do “What-If” cost analysis on a component by component basis. By considering its part cost (PMC) and future operating and maintenance costs (PMPC), the design engineer will be able to make the most cost-effective decision. For their best interest, manufacturers should be responsible to provide the estimation of the total machines' costs to potential customers. In order to accom-
lish this task, a successful manufacturer should distinguish its products from others and help equipment buyers to lower their future operating costs (i.e., scheduling properly, optimizing maintenance events, etc.). Based on the same philosophy, the concept of this paper can be transferred into a variety of operating cost-related products, such as super electric systems, passenger cars, and telecomm-equipment.

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