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# Equipment Costs Associated With Downtime and Lack Of Availability

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## ABSTRACT

**This paper presents a model that has the capability to quantify the Consequential costs of downtime and lack of availability in four categories. The first, associated resource impact costs, deals with the costs that arise when failure in one machine impacts on the productivity and cost effectiveness of other machines working in close association with it. The second category, lack-of-readiness costs, addresses the cost that may be incurred when a capital asset is rendered idle by the downtime resulting from a prior failure. The third cost category, service level impact costs, deals with the situation that arises when one machine in a pool of resources fails to the extent that other machines in the pool must work in an uneconomical manner to maintain a given service level. The fourth cost category, alternative method impact costs, deals with the consequential costs that arise when failure causes a change in the method of operations. The methodology developed represents a significant step toward the rational quantification of consequential costs. An understanding of the philosophy behind each category, as well as the methodology used for quantification, should make it possible to model most situations, given a little thought and creativity in applying the model.**

**KEY WORDS :** Equipment Downtime Cost, Downtime cost.

## I. INTRODUCTION

The costs that arise when an item of equipment or a vehicle fails can be divided into two broad categories. The first of these includes the tangible cost of the labor, materials, and other resources needed to repair the machine. The second category includes all the intangible, or consequential, costs that arise from the failure and that impact the organization as a whole. Tangible costs are fairly easy to record and estimate using normal cost-accounting methods. Consequential costs present an entirely different problem in that they cannot be assessed with any degree of certainty except under very rigid, well-defined circumstances. The need to quantify consequential costs and include them in equipment, decisions has been recognized by researchers and practitioners since the earliest days, when Terborgh (1949) indicated that the basic trade-off in equipment management lies between capital costs and operating inferiority. Terborgh's definition of operating inferiority included both the direct costs of repair as well as the consequential costs arising from the failure.

Years later, Cox (1971) presented one approach to the problem when he defined the annual cost of interruption caused by component failure as being the product of the annual frequency, the average duration of a failure, and the downtime cost per unit. This approach is suited to situations where the equipment working on a particular task is configured as a single rigid system and where failure in one component causes the whole system to go down. Subsequently, Nunnally (1977) described a method that assigned downtime costs to a particular year of equipment life on the basis of an estimated percentage of downtime multiplied by the planned hours of operation for the machine and the hourly cost of a replacement or rental machine. This is at the other end of the spectrum from the method described by Cox in that it focuses on the failed machine alone and disregards any effect the failure may have on the production system as a whole. An attempt at steering a middle course between Cox and Nunnally was made by Vorster (1980) when he developed a model that defined consequential costs as being the product of the hourly cost of the resources affected by a failure, the time necessary to react to a failure, and the frequency of failure. This approach drew criticism because it relied too heavily on the frequency of failure. This model was later modified (Vorster and Sears 1987) to define consequential costs as being dependent on a failure-cost profile reflecting both the environment within which the machine operates as well as the manner in which the situation changes as the failure duration increases.

The progression from the simple, rigid, and almost dogmatic approach favored by Cox to the profile-based approach developed by Vorster and Sears reflects a growing concern for the problem of quantifying consequential costs. Despite this concern, the concept is inherently subjective; and any approach does little more than assess the dollar value of an intangible cost.

## II. VALUE OF SOLUTION

The search for an effective or at least consistent methodology to access the dollar value of consequential costs is important because success will bring some rigor to many aspects of equipment management that remain subjective despite advances in recording and processing data pertaining to tangible costs. Quantifying consequential costs with a reasonable degree of accuracy can influence equipment decision making in three ways. At the first and most basic level, consequential costs can be taken on their own as a measure representing the impact that less-than-perfect performance in a particular machine has on the organization as a whole. This can be used to compare one machine with another and identify members of a fleet that merit special attention.

At the next level, consequential costs can be used to assess the effectiveness of maintenance policies and procedures. This stems from the fact that effective maintenance operations should keep the mechanical quality of equipment at a high level and thus ensure that consequential costs remain low. The balance between maintenance expenditures and consequential costs is thus a good measure of maintenance effectiveness.

At the third level, consequential costs can be used as an input to an economic replacement model. Under these conditions they would be added to normal owning and operating costs to give a better assessment of economic life. Consequential costs can thus play an important part in economic life studies, because they highlight the neither fact that neither costs nor economic life are independent of the consequential impact associated with downtime and the lack of availability.

## III. LAD Cost

LAD costs occur when a machine breaks down during use and is unable to meet expectations. LAD costs seldom, if ever, give rise to costs that can be measured, recorded, and allocated using normal costing systems. LAD costs cannot in fact be quantified in the true sense of the word. Instead, they must be estimated using the most rigorous technique available. Estimating tools rely heavily on the grouping of work items and the classification of costs in order to streamline procedures. The model described in this paper is no exception. It relies heavily on the following.

1. The classification of the fleet into LAD groups according to the type of and main application of the vehicles and equipment involved.
2. The description of the task being performed when a failure occurs by articulating a number of possible failure scenarios.
3. The definition of LAD-cost categories that reflect the impacts those are likely to occur under given circumstances. The roles of LAD groups, scenarios, and LAD-cost categories in providing a framework for estimating LAD costs are depicted in Fig. 1. These three concepts are discussed in the following subsections as a prerequisite to the description of the model.

## IV. ARI-Cost Procedure

This procedure is used to assist in estimating the parameters needed to calculate the ARI costs. The parameters apply to a given LAD group working under a given scenario. Fig. 2 shows the domain within which they occur as being somewhere along a time line that stretches from the point where the failure occurs and normal operations cease (C) to the point where normal operations resume (R). Each of the associated resources impacted by a failure is affected differently and thus each has its own impact lag (CL) to represent the period that elapses from the time of the failure to the start of the impact on the resource.

For certain types of resources, such as the driver of a failed truck, this lag period may be very short; for other resources this lag may be relatively long, as it is in the case when a dozer fails and impacts a loader loading material stockpiled by the dozer.

Each of the associated resources also has its impact duration (CD) to define the time from the failure to the end of the impact on the resource. The impact duration can be equal to the total duration of the impact (CR) if replanning is not possible. On the other hand, it can be substantially shorter if resources can be reassigned during the period affected by the failure. The impact period, the period in which the impacts and thus their associated costs actually occur, is given by LD.

The rate at which the impact cost of an associated resource accumulates with the increasing failure duration is shown in the rectangle above the time line in Fig. 4.1 This also varies from impacted resource to impacted resource and thus it is necessary to define a cost-accumulation method for each of the impacted resources. The cost-accumulation method is used to generate a cumulative-cost profile (LMNO) that reflects the way in which cumulative cost of the impact on a particular resource grows over time. The

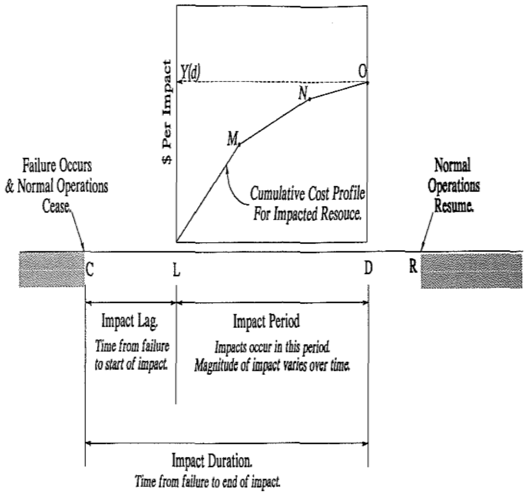

FIG. 4.1. Time Line of Occurrence of ARI Costs

profile in Fig. 4.1 shows that an impact of duration LD yields a cumulative cost of *$Y(d).*
The ARI cost for a given machine in a given period is determined by multiplying the total ARI cost per impact by the number of failures suffered by the machine in the period.

## V. LOR-Cost Procedure

This procedure is used to assist in estimating the parameters needed to calculate lack-of-readiness costs. LOR costs have been defined as the penalty costs that could or should be levied because of the expectation that resources representing capital investments in productive assets should be kept in a ready condition as far as possible. They are based on the concept that there should be some charging or penalty mechanism that motivates managers to ensure that as much of the fleet as possible is ready for deployment when needed.

These costs are in many ways analogous to ongoing depreciation and interest charges. The methodology used to quantify LOR costs for a machine belonging to a particular LAD group is essentially similar to that used for ARI costs, and is set out in Fig. 3. Point C identifies the time when failures occur and normal operations cease. The impact lag reflects the fact that the penalty should only be applied after a reasonable period defined by the time CL. The impact duration is given by CD, which in this case equals the period of the downtime. Penalties should stop when the machine is repaired and able to resume work, whether it is needed or not. Normal operations resume at point R.

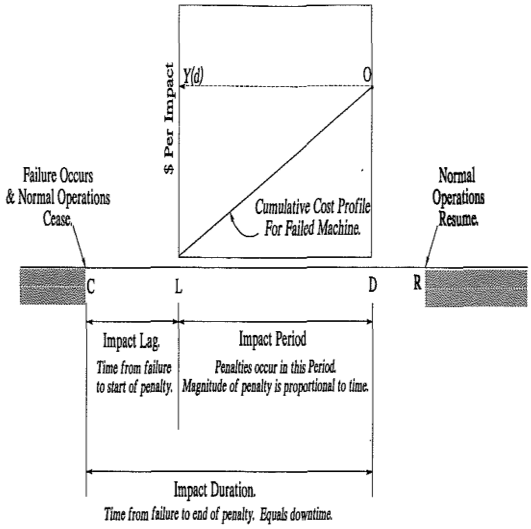

FIG. 5.1. Time Line of Occurrence of LOR Costs.

The cumulative-cost profile is fairly straightforward in that LOR costs relate only to units in the LAD group under study and have nothing to do with any other resources. The profile starts at point L and has a uniform slope proportional to the penalty cost per hour.

The fact that the cumulative cost profile is linear makes it possible to calculate the LOR costs on a monthly basis using the following form:
$LOR = P[D - (V\text{-}L)]$ ……………………….(1)
where LOR = lack-of-readiness costs for a machine in a month; $P$ = the lack of readiness penalty cost in \$/hr; $D$ = the number of hours a particular unit is broken down and unable to respond to operational demands in a month;
$V$ = the number of times a machine breaks down and disrupts planned operations in the month; and $L$ = the impact lag in hours.

## VI. SLI Cost Procedure

This procedure assists in estimating the parameters needed to quantify service level impact (SLI) costs. SLI costs occur when groups of similar vehicles form a common pool of resources to perform a certain service. They are incurred because the lack of reliability in one or more vehicles in the pool causes other vehicles in the pool to work in a more costly manner to maintain the required level of service.

The common pool of resources, from which a certain level of service is demanded, corresponds to a LAD group. The problem of quantifying SLI costs for a member of the group must take the following factors into account.

1. The operational demands placed on the LAD group in terms of the number of vehicles needed to satisfy operational demands under normal conditions.

2. The overall work capacity of the LAD group is defined by the probability that a certain number of vehicles will be available in any one day given the overall availability of each member in the LAD group.

3. The cost of the action that will be taken to ensure that the service level is maintained when the work capacity of the LAD group falls below the number required to satisfy operational demands.

This is an extremely complex problem that has been addressed by developing a Monte Carlo simulation model that performs the following five functions.

1. The down ratio for each of the members of the LAD group listed as units *X = A, B, C, ... N is* calculated for the month under study using the following form:

$$Z = \frac{D}{D + W} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where Z = down ratio; *D* = the number of hours a particular unit is broken down and unable to respond to operational demands in a month; and *W* = hours worked by the machine in the month.

2. The down ratio of each individual machine in the LAD group (machines *X = A, B, C, ... N) is* used in a simulation model to produce the following two results: the probability *P(q)* of having *q* = 0, 1, 2, 3, . . . m units in the LAD group down and incapable of working in any one day; and the frequency with which unit *X = A, B, C, ... N is* listed as down on the days when the number of units down equals *q* = 0, 1, 2, 3, . . . *m.*

3. The two results of the simulation are used to calculate the joint probability *P(X, q)* that *q* units in the LAD group are down in a given day and that unit *X* = *A, B, C, ... N* will be included among the down units.

4. A monthly charge reflecting the additional expenditure needed to maintain the service level *if q* = 0, 1, 2, 3, . . . *m* units are down on a particular day is calculated from a series of user inputs.

5. The SLI costs for the particular machine in a month are calculated by multiplying the monthly charge by the joint probabilities *P(X,q)* for the machine and summing over all values of *q.*

## VII. AMI-Cost Procedure

This procedure is used to estimate the parameters needed to quantify alternative method impact costs (AMI). AMI costs are costs that occur when the failure and continuing downtime of a machine in a LAD group forces a change in the method used to carry out the work described in the scenario.

The change is assumed to be from an optimum to a less-than-optimum method and thus the organization suffers a consequential cost proportional to the cost differential between the methods and the quantity of work done under the less-favorable circumstances.

The rationale developed to quantify ARI costs in Fig. 2 is used for the third time, as can be seen in Fig. 4. C and R again represent the points where normal operations cease and resume; CL shows the lag from failure to, in this case, the introduction of the alternative method, CD shows the impact duration, and LD shows the impact period. The cumulative-cost profile is essentially the same as that for the LOR cost module with the following three exceptions.

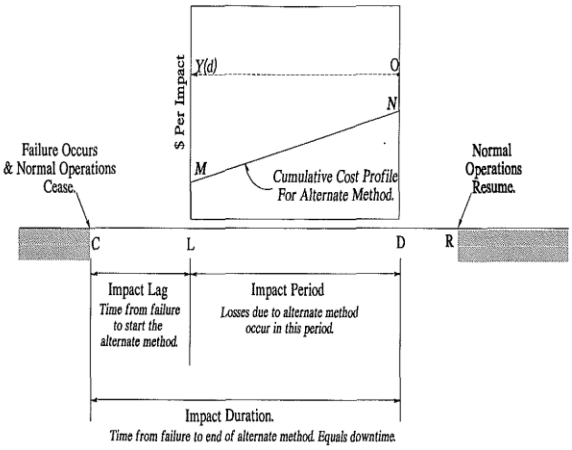

FIG. 7.1, Time Line of Occurrence of AMI Costs

1. There is a vertical step *(LM)* right at the beginning to reflect the setup costs associated with mobilizing the new method.

2. The slope of the profile in the range *M* to A' is proportional to the cost and production differential between the methods.

3. There is a second vertical step *(NO)* at the end to reflect the cost of breaking down or demobilizing the new method.

The cumulative-cost profile and simplicity of the concept hide a critical problem; the AMI cost for a given machine in a given period cannot be obtained by multiplying the total AMI cost per impact *Y(d)* by the number of failures the machine experiences in the period, because the mobilization and demobilization costs are only incurred in a limited number of severe failures. It is thus necessary to define a mobilization percentage that reflects the proportion of severe failures relative to all failures and that is used to scale down the effect of the mobilization and demobilization estimates.

The linear nature of the cumulative-cost profile between $M$ and $N$ and the use of a mobilization percentage makes it possible to calculate AMI costs on a monthly basis using the following form:

$$AMI = S\text{-}Q\text{-}\{D - (V\text{-}L)] + V\text{-}MP(MZ + Dz). \quad \ldots\ldots(3)$$

where AMI = alternative method impact costs for a machine in a month; $S$ = the cost surcharge in \$/unit caused by the alternative method; $Q$ = quantity produced in units per hour by the alternative method; $D$ = the number of hours a particular unit is broken down and unable to respond to operational demands in a month; $V$ = the number of times a machine breaks down and disrupts planned operations in the month; $L$ = the impact lag in hours; $Mp$ = mobilization percentage; Mz = cost of mobilization; and $Dz$ — cost of demobilization.

### 7.2Remarks

The foregoing four subsections have conceptually described the procedures that must be followed in order to define the parameters needed to estimate LAD costs in each of the four LAD-cost categories.

Actual cost-estimating functions have been developed for a prototype proof-of-concept computer program. These functions are used to estimate the four LAD cost categories and define the way in which the LAD costs are weighted and aggregated to form a single estimate for a particular unit in a particular month. A detailed description of the computer program is beyond the scope of this paper; its information-flow model is presented in the following section.

## VIII. LAD COMPUTER MODEL

A prototype proof-of-concept computer program was developed as part of the research to ensure that the conceptual and descriptive work done could be computerized and practically implemented. The structure of the computer model is given diagrammatically in Fig. 5, which shows three sets of routines, their main functions, and their interrelationships.

The administrative routines would normally be used once to enter the units under study into the system, divide them into LAD groups, and define relevant scenarios. The parameter-input routines would be used infrequently, as the parameters needed to estimate a particular category of LAD costs for a particular LAD group and scenario are somewhat static and do not vary with time. The operating routines would be used frequently, as they are needed whenever periodic (monthly) data are to be entered and outputs are to be produced.

Outputs unique to a particular unit and period are developed using the following sequence, which is also depicted in Fig. 6.

1. Units are allocated uniquely to LAD groups.
2. Scenarios are uniquely linked to LAD groups.
3. Input parameters unique to a particular LAD-cost category, LAD group, and scenario are estimated.

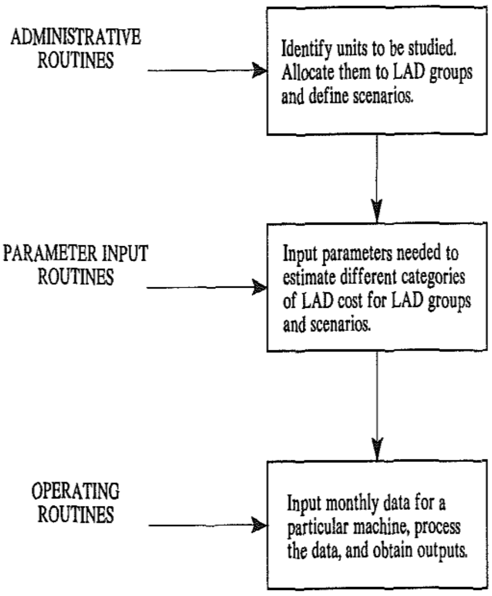

FIG. 8.1. Structure of Model

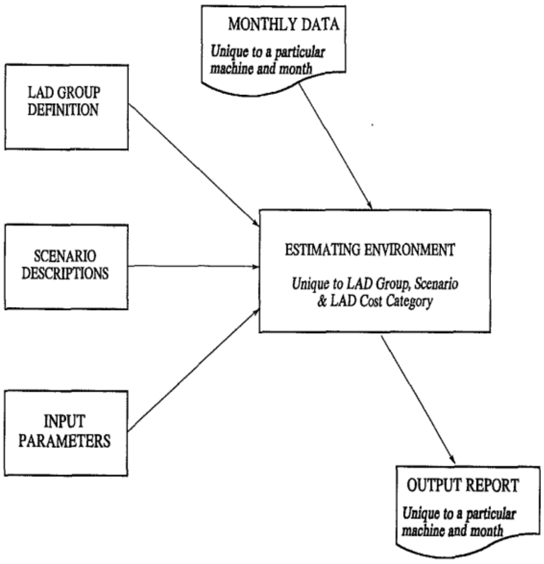

FIG. 8.2. Input Parameters and Monthly Data

4. Monthly data unique to a particular unit and period are entered.
5. Periodic estimates of LAD costs for each unit and LAD-cost category are obtained by bringing data unique to the unit and period together with estimating parameters unique to the cost category, LAD group, and scenario.

## IX. CONCLUSIONS

The development of the LAD cost model has advanced the state of the practice in the following important ways.

1. The model is specifically designed to quantify the consequential costs associated with lack of availability and downtime in a particular operating environment (e.g., the DEH fleet). It thus gives focus to many of the generalities that plague prior work.
2. The model acknowledges that consequential costs take many forms and therefore it comprises four interlinked modules able to model any combination of four very different consequential-cost categories.

The four categories defined in the development of the model reflect different ways in which consequential costs are incurred. An understanding of the philosophy behind each category as well as the methodology used for quantification should make it possible to model most situations given a little thought and creativity.

Because the model provides the conceptual mechanisms needed to quantify consequential costs in all four categories, it has the potential to be accurate, or at least relevant, in a number of situations. It also means that the model's actual implementation must be complex.

Discussion regarding the level of complexity of the model must be blendedwith discussion regarding the level at which the complexity in the model is implemented in the field. Three possible implementation strategies are the following.

1. Implementation in breadth, where certain parameters are neglected and LAD costs are estimated for a large portion of a fleet by implementing the model at a low level of complexity.
2. Implementation in depth, where a high level of accuracy is required in a relatively small portion of the fleet.
3. Total implementation, where implementation is affected at a high level of detail for all or most of the fleet.

This model can accommodate any of these three implementation strategies. Choice of strategy will depend on the use and value of the information obtainable from implementing the model, the ability to quantify the required estimating parameters, and the availability of the monthly data. The estimating parameters required for each LAD-cost category and each scenario appear numerous and complex. This may be so, but in many cases values repeat themselves, as the impact remains unchanged from scenario to scenario. The complexity of the input parameters and the overall structure of the model has resulted in a situation in which the monthly data requirements are limited to the following elements: $V$ = number of times a machine breaks down and disrupts planned operations in the month; $D$ = number of hours a machine is broken down and unable to respond to operational demands in the month; and $W$ = number of hours the machine works during the month.

This is not an extensive requirement, but monthly data must be available in order to implement the model. Further extensions to the model's concepts should include the development of a mechanism to record and input the actual duration of each and every failure on each machine. These data will eliminate a number of difficult parameter estimates and assumptions currently required to determine the LAD costs. This practice will also, however, increase data collection, storage, and processing effort. In short, a signficant step has been taken toward the rational quantification of consequential costs, although the reader must bear in mind that the whole concept of consequential cost is not amenable to exact solution. Implementation and further development will result in worthwhile information; use of this information on a routine basis through its integration with other systems will result in a better understanding of the many dilemmas facing equipment managers.

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