A METHODOLOGY FOR COMPARING AGE-BASED MAINTENANCE AND CONDITION-BASED MAINTENANCE USING ECONOMIC MEASURES OF PERFORMANCE

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NOMENCLATURE

ABM	Age-Based Maintenance
beta, β	The shape parameter of the Weibull Distribution
$C_{ABM} = C_p$	The cost performing age-based maintenance
$\overline{C}_{ABM}$	The long run average cost of performing age-based maintenance
C_{CBM}	The cost of performing condition-based maintenance
$\overline{C}_{CBM}$	The long run average cost of performing condition-based maintenance
$C_{CM} = C_u$	The cost of asset failure including lost production costs
$\overline{C}_{CM} = \overline{C}_u$	The long run average failure costs
$C_{IC\text{-}CBM}$	The implementation and continuation costs of implementing a CBM strategy
$C_{IC\text{-}p}$	The implementation and continuation costs of implementing an ABM strategy
CBM	Condition-Based Maintenance
CCb	$\dfrac{C_u / C_{CBM}}{\text{Beta}}$
CCBLB	$\dfrac{C_u / C_{CBM}}{\text{Beta}} + \log(C_{CBM}) + \log(C_u) + \text{Beta}$
CM	Corrective Maintenance (Run-to-Failure)

CuCcbm	$\frac{C_u}{C_{CBM}}$
F(t)	Cumulative failure probability
$\overline{F}(t)$	1 – F(t), The survival probability, reliability
h(t)	Hazard rate function
LB	$\log(C_{CBM}) + \log(C_u) + \text{Beta}$
LBLC	$\log(C_{CBM}) + \log(C_u) + \text{Beta} - (\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right))$
LL	$\frac{\log(C_{CBM}) + \log(C_u) + \text{Beta}}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$
LLC	$\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$
LLCCB	$\frac{C_u / C_{CBM}}{\text{Beta}} * \frac{\log(C_{CBM}) + \log(C_u) + \text{Beta}}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$
MMI	Measuring/Monitoring/Inspecting or Measurement/Monitoring/ Inspection
MTTF	Mean time to failure
MVLR	Multivariate Linear Regression
PHM	Proportional Hazards Model
PM	Preventive Maintenance
TBM	Time-Based Maintenance
theta, θ	The scale parameter of the Weibull Distribution
VTTF	Variance time to failure

CHAPTER I

INTRODUCTION

1.1 Overview

Effectively maintaining production equipment is a constant battle for maintenance departments because if not maintained all operated systems eventually fail. Jiang [2001] states that in eleven Canadian industries, for every dollar spent on new assets, $0.58 is spent on maintaining existing assets. The key to an effective maintenance strategy is to develop a maintenance plan that maximizes, as much as possible, the profitability of the organization. To do this, a manager must consider the current state of the organization in addition to the current state of the specific production (sub) system.

The current generation of production strategies, such as lean and agile manufacturing, are forcing organizations to reduce inventory levels to enable faster response to changing demands in the marketplace [McKone, 1996]. The effect of these production strategies, from a maintenance viewpoint, is that system downtime is more costly to the organization. Consequently, the maintenance manager strives to maximize equipment uptime. While this goal may seem worthwhile, the cost of this "diligent maintenance" can be high.

The objective of this research is to provide the maintenance planner a set of maintenance strategy selection decision variables and a maintenance strategy selection decision framework. This framework provides the maintenance planner a methodology for selecting the economically preferred maintenance strategy for specific (sub) systems within the production environment.

This chapter introduces the topic of this research (Sections 1.1, 1.2, and 1.3). Next, this chapter presents the problem and the research questions of this research (Sections 1.5 and 1.6). Sections 1.7 and 1.8 present the anticipated challenges and methodological approach of this research. Sections 1.9 and 1.10 discuss the research boundaries and assumptions. Finally, Sections 1.11 and 1.12 present an overview and summary of the remainder of this dissertation.

1.2 Maintenance Strategies

In general, there are three maintenance strategies in use in industry. In implementation order from simple to complex, they are Corrective or Reactive Maintenance (CM), Preventive Maintenance (PM), and Condition-Based Maintenance (CBM).

During the initial stages of this research, a literature review for maintenance strategies revealed many inconsistencies regarding the definition of preventive maintenance and condition-based maintenance. For example, one researcher defined preventive maintenance as that maintenance that excludes general repairs, overhauls, replacement, inspections, and lubrication [Al-Sultan and Duffuaa, 1995]. Another researcher defined preventive maintenance as maintenance that includes preplanned and scheduled adjustments, major overhauls, inspection, and lubrication [Ashayeri, Teelan, and Selen, 1996].

Bahrami-G, Price, and Matthew [2000] separated preventive maintenance into two categories, age-based and constant interval-based (time-based maintenance). Age-based preventive maintenance is that maintenance that is performed every *x* units of asset use. Constant interval-based preventive maintenance is that maintenance that is performed every *y* units of calendar time. McCall [1965] described preventive maintenance as that maintenance that is applicable when equipment fails stochastically and the state of the system is always known with certainty. Mann, Saxena, and Knapp [1995] subdivided preventive maintenance into that maintenance that uses statistical and reliability analysis and that maintenance that utilizes sensors to monitor an asset's operational state.

The purpose of the following three subsections is twofold. First, these sections define, as explicitly as possible, the three major maintenance strategies as they are used throughout this research. Second, these sub-sections present a list of the minimum implementation knowledge requirements for each strategy.

1.2.1 Corrective or Reactive Maintenance

A corrective maintenance strategy describes maintenance performed on an asset after failure [Gits, 1994]. Corrective maintenance (CM) is also referred to as emergency maintenance [Al-Sultan and Duffuaa, 1995], breakdown maintenance [Al-Najjar, 1999], reactive maintenance [Bahrami-G, Price, and Matthew, 2000], failure-based maintenance [Gits, 1994], and/or operate-to-failure (run-to-failure) maintenance [Sherwin, 2000]. This maintenance strategy is the least complex and least expensive to implement of the three general maintenance strategies because no system maintenance is performed until a failure occurs. However, the total cost of this strategy may be very high if the cost of asset failure is high.

There are two primary disadvantages to this strategy [Campbell and Jardine, 2001]. First, the organization has no control over the time of repair/replacement of the asset. Consequently, corrective maintenance cannot be planned. Second, asset failure can be more costly and take more time to repair than the cost and time required to perform maintenance before failure.

1.2.2 Preventive Maintenance

The discussion in the introduction of this dissertation shows that there is no universally accepted definition of preventive maintenance. To avoid this problem, this research defines (and consistently uses) two terms: time-based maintenance (TBM) and age-based maintenance (ABM).

Time-based maintenance is that maintenance performed at calendar time intervals. The selection of the length of the maintenance event interval is based on expert knowledge, vendor recommendations and/or historical operational data (estimates of the Mean-Time-to-Failure (MTTF), Variance-Time-to-Failure (VTTF), and/or failure distribution ($F(t)$). An implicit assumption of time-based maintenance is that an asset may fail during an idle state.

Age-based maintenance is a maintenance strategy that incorporates knowledge (expert and/or historical) of asset use, such as actual operational time or output volume, to estimate the interval between maintenance events. The important difference between time-based maintenance and age-based maintenance is the implied decrease in uncertainty to which the MTTF, VTTF, and/or F(t) is known. This decrease in uncertainty is based on the premise that more in-depth knowledge is known about the asset if the parameters and/or distribution are derived from specific asset level data. In addition, an age-based maintenance strategy ties asset failure with asset operation.

For example, a car owner can schedule an engine oil change interval using either of these strategies. Under a TBM strategy, the owner changes the engine oil after a specified length of time (e.g., 3 months). Conversely, under an ABM strategy the owner changes the oil after a specified number of miles (e.g., 3,000 miles). Historically, these two maintenance strategies are the most widely used forms of maintenance [Campbell and Jardine, 2001]. However, in recent times there has been a push toward condition-based maintenance (discussed in the next section).

1.2.3 Condition-Based Maintenance

Conceptually, a CBM strategy involves measuring/monitoring/ inspecting[1] (MMI) the condition of an asset to assess/predict whether the asset is likely to fail during some specified future period [Moubray, 1997]. The condition of an asset may be obtainable

- by measuring equipment parameters (e.g., temperature, vibration, pressure, and/or flow),
- with statistical process control techniques, by monitoring equipment performance (e.g., capacity, energy usage, and/or efficiency) and/or
- using human senses [Moubray, 1997].

[1] This research will use MMI to represent either measuring/monitoring/inspecting or measurement/monitoring/inspection.

Condition-based maintenance is also referred to as maintenance on demand [Pate-Cornell, Lee, and Tagaras, 1987] and predictive maintenance [Paz and Leigh, 1994]. However, Riis, Luxhoj, and Thorsteinsson [1997] classified condition-based maintenance and predictive maintenance separately. Sherwin [2000] divided condition-based maintenance based on whether the asset's MMI process occurs while the asset is in operation or while the asset is stopped.

This research follows Riis, Luxhoj, and Thorsteinsson's [1997] and Sherwin's [2000] lead and defines four levels of CBM. The distinguishing difference between the levels is the implied level of certainty regarding the true state of the asset that the decision maker achieves.

1.2.3.1 Indirect Offline Condition-Based Maintenance

The first level of CBM is a maintenance strategy based on offline MMI of the asset's performance (e.g., production quality or resource use). This is the lowest level of CBM because the asset's condition MMI process only provides information concerning the recent, past performance of the asset.

1.2.3.2 Direct Non-Operating Condition-Based Maintenance

The second level of a CBM inspects the asset while the asset is not operating. This strategy provides the lowest level of direct knowledge of an asset's current state. However, the current state described is that of a non-operating asset. Therefore, operating conditions such as dynamic fluid pressure or operating vibration level are not observable/measurable.

1.2.3.3 Direct Periodic Online Condition-Based Maintenance

The third level of CBM is periodic MMI of the asset while it is in operation. This strategy gives a description about the current state of the asset at each periodic interval.

1.2.3.4 Direct Continuous Online Condition-Based Maintenance

The fourth, and highest, level of CBM is continuous MMI of the asset while it is in operation. This strategy can provide a measure of the real time state of the asset.

1.2.4 Minimum Required Practioner Knowledge at each Level of Maintenance

The preceding sub-sections described several possible maintenance strategies. Table I shows the possible maintenance strategies in order of increasing required knowledge.

TABLE I

MAINTENANCE STRATEGIES IN ORDER OF INCREASING ASSET KNOWLEDGE

Maintenance Strategy	Asset Knowledge Level
Corrective maintenance	None
Time-based maintenance	Qualitative Asset Knowledge
Age-based maintenance	Quantitative Asset Knowledge
Indirect Offline CBM	Indirect Asset Performance Knowledge
Direct Non-operating CBM	Direct Non-Operating Asset Condition Knowledge
Direct Periodic Online CBM	Direct Periodic Asset Condition Knowledge
Direct Continuous Online CBM	Direct Continuous Asset Knowledge

The purpose of this sub-section is to identify the minimum level of knowledge a practitioner has at each level. The goal is to show qualitatively that at each subsequent level, the practitioner has more knowledge regarding the true time of failure of an asset [Andersen and Rasmussen, 1999].

The practitioner requires no asset knowledge to implement a CM strategy. The strategy is to run the asset until failure.

For a TBM strategy, the practitioner must establish a basis for the selection of the length of the maintenance event interval. This basis may be expert knowledge, vendor recommendations and/or historical operational data. For example, a time-based maintenance strategy may be developed from vendor recommendations or from estimates of MTTF, VTTF, and/or F(t) developed from historical, chronological maintenance data.

As with TBM, the practitioner must establish the interval schedule for the past performance of ABM. However, in an ABM strategy, the practitioner has the additional knowledge gained from operational performance data of the specific asset as a function of asset run time. This increased knowledge leads to a decrease in the uncertainty in the estimates for the MTTF, VTTF, and/or F(t), which allows the practitioner to make a more informed decision regarding the appropriate interval for the performance of a maintenance event.

The important distinction between the knowledge required for TBM/ABM and knowledge required for CBM is that the estimates for MTTF, VTTF, and F(t), used in TBM/ABM strategies describe the average failure characteristics of the asset [Aven and Sandve, 1999; Lu, Lu, and Kolarik, 2001; Mann, Saxena, and Knapp, 1995]. In CBM, the practitioner has recent or current, direct or indirect knowledge concerning the recent performance or operational state of the asset.

For example, consider the activity of a person who drives a fixed route every day. Assume that a log is kept of the average departure and return time of all the drivers who have driven the route in the past. The current driver could estimate his own mean return time based on an average of the past averages. This is analogous to a TBM strategy. Alternatively, if a log of the current driver's departure and return time is kept the current driver could estimate his return time based on an average of his own departure and return times. This is analogous to an ABM strategy. In both cases, if at any point in the route the person wishes to estimate the return time of the route, the only estimate available is the estimated mean return time.

Now consider the situation where not only the departure and return time are recorded, but also the current driver's arrival and departure time at each stop is recorded. With this additional information, the person can estimate the mean return time conditioned on each stop for the trip. Therefore, an estimate of the return time for the current route is the conditional mean estimate based on the current time and location.

At the first level of CBM, the practitioner has knowledge (either direct or indirect) of the recent past performance of the asset. With regard to the route driver example above, this level of CBM is analogous to the driver estimating the return time conditioned on the number and average time of deliveries completed.

The second level of a CBM is inspection of the asset while the asset idle. Returning to the route driver example, this level is analogous to the person estimating the return time conditioned on the departure time from the last delivery. The distinction between level one and level two CBM is, that in level one the estimate for the return time is conditioned on the recent past performance measure (number of deliveries) of the asset and the level two estimate of the return time is based a value of the parameter, time, itself. More concisely, the difference is whether the asset performance results are measured or whether asset operational variables are measured.

The third level of CBM is periodic MMI of an asset's condition while it is in operation. In the route driver example, this level is analogous to the driver periodically estimating the return time conditioned on a periodic reading showing on the dash clock and the average rate of completion of the remaining stops.

The fourth, and highest, level of CBM is based on the continuous MMI of the asset's condition while it is in operation. Staying with the automotive theme, this strategy is the one preferred by the children in the back seat while on a long trip. Specifically, they want to continually know when they will arrive. With regard to the route driver example, this strategy is analogous to continuously monitoring time and readjusting the average rate of the completion of the remaining stops so that, the return time can be continuously estimated. In the ideal situation, this level of maintenance provides the decision maker with certain knowledge of the state of an asset during every moment of operation.

1.2.5 Summary

In a global view, each "next" step in maintenance strategy requires the practitioner to have more knowledge about the state of an asset. The underlying assumption in the above discussion is that as knowledge about the operation of an asset increases, the practitioner's ability to predict the nature of asset failure increases. This in turn, increases the practitioner's certainty regarding when an asset will fail or will fail to perform at a satisfactory level.

1.3 Variables Affecting Maintenance Strategy Selection

Section 1.2 discussed several maintenance strategies that are available to a practitioner. The thrust of the ordered listing of these strategies is that more knowledge leads to more informed maintenance strategy selection decisions. Therefore, one might assume that more knowledge is better than less knowledge in every situation. This is not necessarily the case, however.

The two issues neglected in this "more is better" reasoning are the cost required to gain the additional knowledge and the expected cost of the anticipated maintenance events. The following two subsections discuss these issues.

1.3.1 Cost of Knowledge

The total cost of knowledge, with regard to maintenance, is encompassed in three general costs; administrative costs, technological costs, and safety costs [Al-Sultan and Duffuaa, 1995; Al-Najjar, 1999]. Administrative costs are those organizational costs required to implement and maintain a maintenance system. Technological costs relate to the cost of specialized tools, inspection, and monitoring equipment necessary to perform a maintenance event. Safety costs are incurred if the performance of the maintenance event poses a safety hazard to personnel, the environment or to the organization.

It is important to note that these costs of knowledge are affected by the nature of the asset in question. For example, in a continuously operated process, performing stopped CBM may be much more expensive than performing periodic offline CBM. The result is that there is not necessarily a direct relationship between the knowledge and the cost of knowledge.

1.3.2 Expected Cost of the Maintenance Events

What is the cost of performing maintenance? In general, it is the sum of the expected cost of the maintenance action and the expected cost of failure. Unlike the maintenance strategy definition issue, the descriptions of the costs incurred during a maintenance event are standard in the literature. The following list is compiled from the work of Al-Sultan and Duffuaa [1995], Al-Najjar [1999], Andersen and Rasmussen [1999], Ben-Daya and Alghamdi [2000], Cavalier and Knapp [1996], Dohi, Kaio, and Osaki [1998], Duffuaa and Ben-Daya [1995], Gits, [1994], Kumar and Westberg [1997] and Mann, Saxena, and Knapp. [1995].

1. Planned maintenance costs (Time-based, Age-based or Condition-based)
    a. Personnel
    b. Materials
    c. Tools and equipment
    d. Spare parts
    e. Production losses at the maintained asset
    f. Administrative
2. Unplanned maintenance costs (Corrective or Run-to-Failure)
    a. All of those listed for planned maintenance (note that these costs are usually higher for unplanned maintenance)

b. Consequential damage to surrounding assets
c. Production losses at the surrounding assets
d. Delivery delays
e. Personnel safety costs
f. Environmental cost

Much of the literature in the last decade has focused on the interaction between time-based maintenance and age-based maintenance strategies, and production [Rishel and Christy, 1996; Weinstein, 1996; McKone, 1996; Ashayeri, Teelan, and Selan, 1996]. However, there are still avenues of research available regarding the relationship between condition-based maintenance and production.

1.4 Major Literature Reviews

Between 1965 and 1997, there were six major maintenance literature reviews. The focus of this section is not to discuss the research surveyed in each review but to present what each review article foresaw as the areas of future work. The next section discusses the problem with the current maintenance models.

In the first review paper, McCall [1965, p. 519] stated that time-based and age-based maintenance models "have been the topics of a thorough and exhaustive analysis." However, the existing studies (circa 1965) only considered single-unit assets. Therefore, it was suggested that future work should concern multi-unit assets that have stochastic and economic dependencies. The next area suggested for research was that of sequential age-based maintenance models. A sequential model allows a decision maker to change the interval for the next maintenance event based on information gained from the current maintenance event.

Another suggested area for research was the relation between the inventory policy and the maintenance policy. The question posed was how an optimal time/age-based maintenance strategy is derived when it is connected with a particular inventory policy.

Deteriorating single-unit maintenance models began appearing in the maintenance literature after 1965 [Pierskalla and Voelker, 1976]. These models were based on a Markov chain approach. With regard to single-unit assets, these researchers believed that the underlying model was sound and few practical improvements were achievable. The suggestion was that future work should concentrate on adding more system constraints and developing more efficient solution algorithms. The area believed to need future work, was in the area of multi-echelon multi-part maintenance models.

The review by Sherif and Smith [1981] was a biographical review and did not contain future work recommendations. The review by Valdez-Flores and Feldman [1989] also did not include future work recommendations. However, there were two conclusions that relate directly to this dissertation's research. The first conclusion was that the current inspection maintenance models (circa 1989) are all very similar to the model discussed by Barlow, Hunter, and Proschan in 1963. The second conclusion concerning minimal repair models was that the current studies (circa 1989) were based on Barlow and Hunter's [1965] presentation. The apparent major contribution to maintenance research occurring over this survey's review period was that of the maintenance shock model.

Maintenance shock models describe a system that is randomly subjected to shocks. These shocks cause a random amount of damage to the system. The damage accumulates until either the system is replaced or it fails.

The Cho and Parlar [1991] review presented research concerning multi-unit systems. This review stated that the areas of asset repair models and group/block/ cannibalistic/opportunistic maintenance and replacement models were well developed (circa 1991). The recommended area for future research concerned the study of multi-unit repairable item inventory-maintenance models. This area was recommended even though the focus of 40% of the 129 listed references were on these models.

Dekker, van der Duyn Schouten, and Wildeman [1997] reviewed multi-component maintenance models that have economic dependence. While this review did not have a recommended future work section, it did provide the following information. First, the interactions between the components in a multi-component system were classified as either economic, structural, and/or stochastic. Economic interactions relate to the idea that it may be more economical to perform maintenance on several components at a time, as opposed to scheduling and performing maintenance on each component independently. Structural interactions relate to components that are physically connected to each other. Stochastic interactions occur if the state of one component affects the state of one or more of the other components. Most multi-component maintenance models incorporate only one of these interactions because the model becomes too complicated to solve or analyze otherwise. Finally, most multi-component maintenance optimization models in the literature assume complete information with regard to the cost structure and the lifetime distributions.

To summarize, there were 1190 references in the combined reviews. Theoretical time-based and age-based maintenance models were well defined for single-unit assets by 1965. Theoretical deteriorating single-unit time/age based models were well defined by 1976. As of 1989, theoretical inspection maintenance models were still based on work presented in 1963 and minimal repair maintenance models were still based on work presented in the early 1960's. The 1980's saw the maturation of theoretical work concerning maintenance shock models and multi-component repair, and group/block/ cannibalistic/opportunistic replacement maintenance models. By 1997, there was significant theoretical work concerning multi-component maintenance models with economic dependence.

1.5 The Problem

Dekker [1996] identified three reasons why the maintenance optimization models developed by theoreticians have seen limited application to real problems. First, there is a lack of application tools utilizing these models. Second, there is a lack of data and knowledge regarding the modeling of the deterioration process and the occurrence of failures in a system over time. In addition, there is a lack of data and knowledge regarding the direct and indirect costs associated with these parameters. Third, there is a gap between theory and practice. Dekker [1996] explained this gap by presenting the following issues.

1. Maintenance optimization models are frequently complex and the average maintenance engineer is not experienced in dealing with these types of models.
2. Many models are set up for mathematical convenience.

3. Maintenance problems are complex and diverse, and therefore difficult to model.

4. Not all maintenance decisions are worth optimizing.

5. Models are said to concentrate on the wrong type of maintenance.

Dekker is not the only researcher, nor the first, who has voiced concern about these issues. Tukey [1962] stated that maintenance models that fail to account for the practical aspects of maintenance are transient and doomed to be forgotten. Scarf [1997] stated that too much attention is focused on new models. Modelers should consider "restricting attention to simple models, and approximate solutions to problems of interest to decision-makers" [Scarf, 1997 p. 494]. Thorstensen and Rasmussen [1999] stated that despite the huge and constantly growing amount of literature in this area, the models are of little value to the practitioner. The real problem is that researchers pay little attention to data collection and to the consideration of the usefulness of the models for solving real problems [Thorstensen and Rasmussen, 1999].

Lu, Lu, and Kolarik [2001] and Mann, Saxena, and Knapp [1995] discussed the use of time to failure distributions in traditional reliability approaches.

> Traditional reliability approaches are based on probability distributions of time to failure. The distributions are usually obtained through analysis of life test data sampled from test populations. Such approaches yield statistical results that reflect 'average' characteristics of the same kind of systems, under the same conditions, as those constituted in the data. In reality, however, system reliability characteristics are strongly affected by application and operating conditions. Variations also exist among individual systems. Therefore, traditional reliability methods, although widely used, are limited in estimating individual system reliability under dynamic operating and environmental conditions. Considering all

> possible system failure modes, each failure mode may be correlated to one or more physical performance measures [Lu, Lu, and Kolarik, 2001, p.1].
>
> The primary disadvantage is that the results of the calculations...are based on the use of the mean value as the measure of central tendency. If the standard deviations of these means are large, then the probability of ascertaining the maintenance interval with accuracy is small. In many of these cases, the plant is over-maintained. Other disadvantages include more emergency maintenance, more overtime, and less equipment utilization" [Mann, Saxena, and Knapp, 1995. p. 49].

While both of these arguments may seen intuitive, criticism of using time to failure distributions must be weighed against the cost of obtaining more certain knowledge.

The next section discusses the problem with current maintenance models. As seen, the trend in research has been to develop maintenance models that have more academic appeal than practical usability. The problem, and the area of focus of this dissertation, is how does the maintenance practitioner use the wealth of academic maintenance research to solve their specific maintenance strategy selection problem.

1.6 Research Questions

As stated Section 1.5, the problem studied in this research is how does the maintenance practitioner use the wealth of academic maintenance research to solve his maintenance strategy selection problem. To solve this problem, this research will answer the following research questions.

1. At what level of failure cost is an age-based maintenance strategy economically preferable to corrective maintenance?

2. At what level of failure cost and the cost of performing condition-based maintenance is a condition-based maintenance strategy economically preferable to an age-based maintenance strategy?
3. At what level of failure cost and the cost of performing condition-based maintenance is a condition-based maintenance strategy preferable to a corrective maintenance strategy?
4. At what level of condition-based maintenance implementation and continuation costs is a condition-based maintenance strategy economically preferable to an age-based maintenance strategy?
5. What level of accuracy is necessary to make a condition-based maintenance strategy an economically preferred maintenance strategy?

Answers to these questions will provide the maintenance practitioner with a means to select an economically preferred maintenance strategy based on economic and asset operational decision variables. The next section discusses the specific challenges faced by this research that must be addressed before the research questions can be answered.

1.7 The Challenges

There are six challenges (presented as questions to answer) to overcome to answer the research questions stated above.

1. What are the basic decision variables regarding the selection of an economically preferred maintenance strategy?
2. How can the "recent/current operational parameters " of an asset be incorporated into the maintenance strategy selection model?

3. What models are available to compare the different maintenance strategies?
4. How does the literature compare time/age-based maintenance and CBM?
5. What conceptually and computationally simple and comparable maintenance cost models are available for corrective, time/age-based and CBM.
6. What maintenance strategy selection methodologies have been developed that provide a maintenance practitioner the means to economically discriminate between different maintenance strategies?

This research addresses these challenges with the research methodology presented in the next section.

1.8 Methodology

This research divides the research methodology into five phases; preparation, analysis, synthesis, answer the research questions, and conclusions/contributions.

1.8.1 Preparation

This research begins, as does all research, with a collection/review of the current literature. The focus of the literature review (Chapter II) is to supply the solid theoretical foundation necessary to answer the challenge questions presented in Section 1.7 and ultimately, to answer the research questions presented in Section 1.6.

1.8.2 Analysis

During this phase (Chapter III), the literature gathered in the preparation stage is studied in detail. The focus of this phase is to answer the first five challenge questions (Section

1.7). This information is used to accomplish phase three of this methodology.

1.8.3 Synthesis

This phase (Chapter IV) uses the results of the analysis phase to develop/present maintenance costs models for corrective maintenance, age-based maintenance, and condition-based maintenance strategies. The major focus of these models is that they are formulated such that direct economic comparisons are achievable between the strategies. In addition, these models should reasonably satisfy Scarf's [1997] recommendation that current research focus on simple maintenance models, i.e., models with few decision variables.

1.8.4 Answer the Research Questions

This research uses the maintenance models obtained from the synthesis phase to determine the expected cost of corrective, age-based, and condition based maintenance, for various levels of the decision variables. This phase (Chapter IV) addresses the challenge identified in challenge question 6, in Section 1.7 and answers the research questions presented in Section 1.6.

1.8.5 Conclusions/Contributions

The most significant contribution of this research is the maintenance strategy selection decision methodology produced from the results of the preceding phase (Answer the Research Questions). Ideally, this methodology should allow a practitioner to determine the economically preferred maintenance strategy given the values of the defined decision variables.

The deliverables for this research are a maintenance strategy selection methodology for corrective, age-based, and condition-based maintenance strategies, a maintenance strategy taxonomy, and the required minimum knowledge for each level of maintenance strategy.

1.9 Research Boundaries

As with any research effort there must be scope and limitations, else there can be no reasonably defined end. To this end, this research will adhere to the following criteria.

This research is only concerned with corrective, age-based, and condition based maintenance strategies. This research does not distinguish between the different levels of condition-based maintenance. This research will only study single component assets or assets that can be described using single component analyses. The intent is that this research will form the basis for more exhaustive future comparisons.

The focus of the degradation model is to represent asset degradation in a general manner. Therefore, this research avoids specific failure mode degradation models. Additionally, because of the need to compare age-based maintenance with condition-based maintenance, this research does not consider models that preclude such a comparison.

1.10 Assumptions

This research makes the following assumptions. This researcher believes that each assumption is reasonable and does not detract from this research's objectives or its general applicability.

1. The repair of an asset returns the asset to as-good-as-new condition. This assumption implies condition equivalence between repair and replacement of an asset.
2. This research assumes an infinite planning horizon for the cost models.
3. This research assumes that a Weibull failure distribution can be used to describe an asset's failure distribution.
4. This research assumes that failure costs are proportional to age-based maintenance costs.
5. This research assumes that the implementation and continuation cost for condition-based maintenance is proportional to the implementation and continuation cost for age-based maintenance.

The next section presents an overview of the organization of this dissertation.

1.11 Organization of the Dissertation

This dissertation is organized into three distinct, but interrelated parts.

1.11.1 Part 1: Understanding the Challenge

Part I provides a frame of reference and context for the dissertation. It consists of the first two chapters of the dissertation.

- Chapter I is the introduction.
- Chapter II is the literature review. The literature review focuses on 1) the basic maintenance strategy decision variables, 2) asset degradation models,

3) maintenance strategy comparisons, and 4) maintenance cost models for corrective, time/age-based, and condition-based maintenance.

Part I provides a basis and path for the remainder of this dissertation.

1.11.2 Part II: Obtaining and Analyzing Total Maintenance Costs for Each Maintenance Strategy

Part II uses the results of Part I to generate total maintenance strategy costs, for each of the three selected maintenance strategies, under varying levels of the decision variables. Part II consists of two chapters.

- Chapter III synthesizes the discoveries/findings of Chapter II, and presents the methodology that this research uses to answer the research questions.
- Chapter IV presents the quantitative results of the methodology presented in Chapter III.

Part II will provide the basis for the theoretical contribution of this research

1.11.3 Part III: Summary of Research

Part III (Chapter V) presents a summary of this dissertation. This includes the a discussion of the results of this research, a review of the contributions to the existing body of knowledge and research weaknesses, and a discussion of anticipated future research.

1.12 Summary

This purpose of this chapter is to serve as an introduction and roadmap for the research presented in this dissertation. The focus of this chapter is to provide a broad overview of the research questions and the general solution methodology. It is expected, that any questions concerning the specifics of this research are answered in the following chapters.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Forty years of maintenance modeling research has provided a wealth of information. However, industry practitioners still contend that there are few models applicable to real-world maintenance scheduling and implementation [Dekker, van der Duyn Schouten, and Wilderman, 1997]. The problem revolves around the complexity of the maintenance process. Real assets have several components that have different modes of failure. Additionally, the term failure has a duel meaning, that is, there are two forms of failure. A failure can occur when an asset fails to operate or when it fails to operate at a specified performance level.

The objective of this research is to provide a maintenance practitioner with a methodology to select an economically preferred maintenance strategy. This objective serves as a guidepost for this literature review chapter.

The following literature review for this research is divided into four sections. The first section is this introduction. The second section focuses on maintenance models for time/age-based maintenance and condition-based maintenance. The third section focuses on the comparison between time/age-based maintenance and condition-based maintenance. The final section summarizes the findings of this literature review.

2.2 Maintenance Models

Even a casual study of Sherif and Smith's [1981] review paper shows that a researcher has a very broad range of maintenance models from which to choose. Adding to this review, the reviews of Valdez-Flores and Feldman [1989], Cho and Parlar [1991] and Dekker, van der Duyn Schouten and Wilderman [1997] provide an even broader range of possibilities. However, this research only focuses on those models Scarf [1997] classifies as simple maintenance models, i.e., models that have a small number of decision variables (parameters). The motivation for this restriction is that...

> ...(m)ore complex models with a large number of parameters usually posses the characteristic of high correlation between parameter estimates; this indicates that the data is unable to distinguish between equally plausible parameter combinations. Such models are difficult to resolve, and have low predictive power [Scarf, 1997 p.495].

This section uses the following classification for this literature survey. The first subsection discusses single component replacement/repair models. The second subsection discusses inspection models with the focus on recent models. The last section discusses condition-based maintenance models.

2.2.1 Age-Based Replacement and As-Good-As-New Repair Models

An age replacement maintenance model prescribes replacement of the asset at a fixed operational age, T, or at failure, whichever occurs first. If T is a random variable then the model is referred to as a random age replacement model.

The measures of merit for age replacement models are, generally, the distribution and expected value of the number of planned replacements, the number of failures, and the total number of removals due to either failure or planned replacement during the replacement time, T [Barlow and Proschan, 1965]. The usual assumption regarding age replacement models is that the asset's failure rate increases with time (the asset wears at an increasing rate). If an asset's failure rate is constant or decreasing, asset replacement provides either no improvement or a worsening of the asset's failure potential, respectively.

Under an increasing failure rate assumption and a replacement schedule of every T operating hours, the probability that an asset does not fail in service before time t, $\overline{S}_T(t)$, is shown in Equation 1 [Barlow and Proschan, 1965; Ebeling, 1997].

$$\overline{S}_T(t) = [\overline{F}(T)]^n \overline{F}(t - nT) \text{ for } nT \leq t < (n+1)T \qquad (1)$$

where

$F(t)$	= the cumulative failure probability,
$1 - F(t) = \overline{F}(t)$ [1]	= the survival probability without a replacement policy,
$[\overline{F}(T)]^n$	= the probability of surviving n maintenance intervals and
$\overline{F}(t - nT)$	= the probability of surviving (t – nT) time units past the last maintenance event.

Therefore, the mean time to failure of the interval (0 – T), assuming a replacement every T operating hours (MTTF(T)), over an infinite time span and under an age-based maintenance strategy is derived as follows (Equations 2-5) [Ebeling, 1997].

[1] The overscore bar above the variable in this specific case represents one minus the value of the variable. This method is used to remain consistent with literature under study. Later in this dissertation, the bar above the variable will be used in the more traditional way to represent an average.

$$MTTF(T) = \int_0^{\infty} \overline{S}_T(t)dt = \sum_{n=0}^{\infty} \int_{nT}^{(n+1)T} \overline{S}_T(t)dt \tag{2}$$

$$= \sum_{n=0}^{\infty} \int_{nT}^{(n+1)T} \overline{F}(T)^n \overline{F}(t - nT)dt \tag{3}$$

$$= \sum_{n=0}^{\infty} \overline{F}(T)^n \int_{nT}^{(n+1)T} \overline{F}(t - nT)dt \tag{4}$$

$$= \sum_{n=0}^{\infty} \overline{F}(T)^n \int_0^{T} \overline{F}(t`)dt` \text{ where, } t` = t - nT \tag{5}$$

However since the term $\sum_{n=0}^{\infty} \overline{F}(T)^n$ is an infinite geometric series equal to $\frac{1}{1-\overline{F}(T)}$ the MTTF(T) can be found using Equation 6.

$$MTTF(T) = \frac{\int_0^{T} \overline{F}(t)dt}{1-\overline{F}(T)} \tag{6}$$

Note that as the maintenance interval increases to infinity, the MTTF(T) approaches the mean of f(t), the probability density function. The cost model[2] under an age replacement strategy and over an infinite time span is (Equation 7) [Barlow and Proschan, 1965].

$$\overline{C}_{ABM}(T) = \lim_{t\to\infty}\left\{\frac{C_p N_p(t)}{t} + \frac{C_u N_u(t)}{t}\right\} = \frac{C_p[1-F(T)] + C_u F(T)}{\int_0^{T} [1-F(t)]dt} \tag{7}$$

[2] As stated in footnote 1, the overscore bar in this case represents the long run average cost of the variable.

where

$\overline{C}_{ABM}(T)$ = the asymptotic cost per unit time of operating the asset when the asset is replaced at failure or at age T, which ever comes first,

C_u = the cost of replacing a failed asset,

C_p = the cost of performing maintenance before asset failure,

$N_p(t)$ = the expected number of preventive maintenance events in the interval (0, t),

$N_u(t)$ = the expected number of failures in the interval (0, t),

T = replacement interval,

F(T) = probability of failure by time T, and

$\int_0^T [1 - F(t)]dt$ = the expected time horizon.

Al-Najjar [1999] incorporates the long run average implementation cost per unit time (C_{IC-p}) with the infinite time span age replacement model as shown in Equation 8.

$$\overline{C}_{ABM}(T) = \frac{C_p[1 - F(T)] + C_u F(T)}{\int_0^T [1 - F(t)]dt} + C_{IC-p} \tag{8}$$

Another approach to the age-based model is to assume that the conditional mean time to failure in the interval [0, T], $MTTF(t|t \leq T)$, is equal to the sum of the expected time for replacement, $E[T_r]$, and the expected time to failure, $E[T_f]$, in the interval [0, T] [Jardine, 1973] (Equation 9).

$$\overline{C}_{ABM}(T) = \frac{C_p\overline{F}(T) + C_u[1-\overline{F}(T)]}{E[T_r] + E[T_f]} = \frac{C_p\overline{F}(T) + C_u[1-\overline{F}(T)]}{T \cdot \overline{F}(T) + MMTF(t \mid t \leq T) \cdot [1-\overline{F}(T)]} \quad (9)$$

However, if the MTTF(t|t ≤ T) is defined as Equation 10 [Jardine, 1973], Equations 8 and 9 are equivalent. Consider the following derivation.

$$MTTF(t \mid t \leq T) = \frac{\int_0^T t \cdot f(t)dt}{1-\overline{F}(T)} \quad (10)$$

$$MTTF(t \mid t \leq T) = \frac{\int_0^T -\frac{dR(t)}{dt} tdt}{F(T)} \quad (11)$$

Integrating the numerator, $\int_0^T -\frac{dR(t)}{dt} tdt$, by parts gives (u = t, dv = -dR(t)/dt)

$$MTTF(t \mid t \leq T) = \frac{-T\,\overline{F}(T) + \int_0^T \overline{F}(t)dt}{F(T)} \quad (12)$$

Solving for the integral term, gives Equation 13.

$$\int_0^T \overline{F}(t)dt = MTTF(t \mid t \leq T) \cdot F(T) + T \cdot \overline{F}(T). \quad (13)$$

Equation 9 results when this result is substituted into the denominator of Equation 7.

Setting the derivative of $\overline{C}_{ABM}(T)$ (Equation 7, repeated here as Equation 14) equal to zero and solving for T gives the optimal interval for minimizing $\overline{C}_{ABM}(T)$. Equation 15 shows the expression for this derivative [Barlow and Proschan, 1965].

$$\overline{C}_{ABM}(T) = \lim_{t\to\infty}\left\{\frac{C_pN_p(t)}{t} + \frac{C_uN_u(t)}{t}\right\} = \frac{C_p[1-F(T)] + C_uF(T)}{\int_0^T [1-F(t)]dt} \tag{14}$$

$$h(T)\int_0^T [1-F(t)]dt - F(T) = \frac{C_p}{C_u - C_p} \tag{15}$$

where

h(T) = the hazard rate of f(t) calculated at time T.

If the hazard rate is continuous and increasing, the left side of Equation 15 is continuous and increasing and an optimum interval, T, exists [Barlow and Proschan, 1965]. If the optimum interval is infinite then the optimal maintenance policy is to replace an asset only at failure [McCall, 1965]. If T is finite, then the Weibull distribution with a shape parameter greater than one is a reasonable model [McCall, 1965]. Finally, assuming that T uniquely satisfies Equation 15 and minimizes Equation 14, the resulting minimum cost is calculated using Equation 16 [Barlow and Proschan, 1965].

$$\overline{C}_{ABM}(T) = (C_u - C_p)h(T) \tag{16}$$

The above discussion represents the age-based maintenance model under replacement or under as-good-as-new repair, and an infinite time span. The following discussion highlights some modifications researchers have proposed to this simple model.

If the time span is finite, a sequential replacement strategy is preferred [Barlow and Proschan, 1962]. Under a sequential replacement policy, the next maintenance interval is based on the preceding maintenance interval, whereas under a periodic replacement interval the intervals are preset initially and remain unchanged regardless of when the preceding interval occurred. Barlow and Proschan [1962] show that the expected cost of an optimal sequential strategy over the interval (0, t) is always less than or equal to the expected cost of an optimal periodic strategy.

If instead of as-good-as-new repair, the assumption is as-good-as-old (minimal repair), the long run average cost is shown in Equation 17 [Barlow and Proschan, 1965].

$$\overline{C}(T) = \lim_{t\to\infty}\left\{\frac{C_p N_p(t)}{t} + \frac{C_u N_u(t)}{t}\right\} = \frac{C_u \int_0^T h(u)du + C_p}{T} \quad (17)$$

where

h(u) = the hazard rate of f(t).

The optimal maintenance interval is shown in Equation 18.

$$\int_0^T [h(T) - h(u)]du = \frac{C_p}{C_u} \quad (18)$$

The optimal value for T satisfies Equation 19.

$$C(T) = C_u h(T) \quad (19)$$

Additionally variations of the basic age replacement or minimal replacement maintenance models include [Pierskalla and Voelker, 1976]

- the addition of an age dependent cost (either discretely or continuously) to the age replacement model that reflects the increase in maintenance cost as asset age increases, and
- the assumption, under the minimal repair model, that the minimal repairs do not continue indefinitely, but only for a finite number of minimal repairs. The asset is replaced after the $(k-1)^{th}$ repair.

2.2.2 Inspection Maintenance Models

Inspection maintenance models assume that an asset degrades with age and that this degradation is observable through inspection. The pure inspection model also assumes that

1. the inspection time is negligible,
2. there is no preventive maintenance; the asset is replaced only upon failure,
3. the inspection process does not degrade the asset,
4. the asset cannot fail during inspection,
5. the cost of each inspection is c_1 and the cost of not detecting a failure is c_2 per unit time, and
6. inspection stops upon asset failure [Barlow and Proschan, 1965].

If assumption 6 is replaced with 'at failure, the repair/replacement occurs at an average cost of c_3 and inspection continues', the model represents an inspection model over an infinite time span [Barlow and Proschan, 1965]. The following discussion presents this last model and a discussion of the delay time, inspection model as suggested by Scarf [1997].

2.2.2.1 Inspection Model Assuming Renewal at Detection of Failure

The long run average cost of an inspection maintenance model assuming renewal at the detection of failure is developed similar to the age replacement model [Barlow and Proschan, 1965]. Specifically, the long run average cost is equal to the expected cost per cycle, $C(\mathbf{x})$, divided by the expected maintenance cycle time, $T(\mathbf{x})$ (Equation 20).

$$R(\mathbf{x}) = \frac{C(\mathbf{x})}{T(\mathbf{x})} \tag{20}$$

Let the set of inspection times be the set $\mathbf{x}$, where $\mathbf{x} = (x_1, x_2, \ldots | \, x_1 < x_2 < \ldots) =$ the inspection time after a repair/replacement. The long run average cost is then shown in Equation 21.

$$R(x) = \frac{\sum_{k=0}^{\infty} \int_{x_k}^{x_{k+1}} [c_1(k+1) + c_2(x_{k+1} - t)] dF(t) + c_3}{\mu + \sum_{k=0}^{\infty} \int_{x_k}^{x_{k+1}} (x_{k+1} - t) dF(t)} \tag{21}$$

where

k = the k^{th} inspection event,

x_k = the inspection time of the k^{th} inspection event,

$F(t)$ = the cumulative probability distribution of the asset,

c_1 = the cost of each inspection,

c_2 = the cost of not detecting a failure,

c_3 = the cost of repair/replacement of the asset, and

μ = the mean failure time.

The optimal solution is the set of inspection times, **x**, that minimize Equation 19 (see [Barlow and Proschan, 1965 p. 116] for the solution algorithm).

2.2.2.2 Delay Time Inspection Model

The delay time inspection model incorporates a two stage stochastic process. The first stage is the initiation phase of a defect[3]. The second stage is failure. The time between the observable initiation of a defect and failure is defined as the delay time [Wang, 1997]. Christer and Waller [1984, page 401] state that using the delay time concept "represents a considerable advance over (the) current knowledge" required for an age-based maintenance strategy.

The simplest of the delay time models is that of a Poisson process of defect arrivals with a rate α, exponentially distributed delay times with a mean $1/\gamma$ and perfect inspection [Scarf, 1997]. For an asset where inspections are equally spaced at Δ time units apart over a time interval [0, T], the maximum likelihood estimate satisfies Equations 22 and 23 [Scarf, 1997].

$$\hat{\alpha} = \frac{n}{T} \tag{22}$$

$$\frac{(n-k)\hat{\gamma}\Delta}{e^{\hat{\gamma}\Delta}-1} + \frac{\sum \hat{\gamma} t_i}{e^{\hat{\gamma} t_i}-1} = (n-k) \tag{23}$$

where

[3] The term defect is used as a generic term. The idea is that an asset begins to degrade immediately, but it is undetectable until some time in the future

k = number of failures observed at time, t_i, ($i = 1, 2, \ldots, k$), from the last inspection, and

n – k = the number of defects found at inspection.

Note that there are a total of n defects. However, because failure occurred k times the inspection process must have failed to detect k defects. Therefore, the number of defects detected at inspection is n – k. The cost per unit time is (Equation 24)

$$D = \frac{c_I}{\Delta} + \alpha c_f (1 - P_D), \tag{24}$$

where

c_I = the cost of inspection,

c_f = the cost of failure, and

$1 - P_D$ = the fraction of defects that result in failures.

The optimum inspection interval satisfies Equation 25.

$$(1 + \gamma\Delta) \cdot e^{-\gamma\Delta} = 1 - \frac{\gamma c_1}{\alpha c_2} \tag{25}$$

Scarf [1997] states that the data required for more complex delay time models (NHPP and/or imperfect inspection), generally does not exit. Therefore, it may be more sensible to derive a rough estimate using the simple model, rather than an "optimum inspection interval" using highly variable data.

2.2.3 Condition-Based Maintenance Models

Recent years have seen a rapid increase in the use of condition based maintenance techniques [Scarf, 1997]. The generally accepted reason for this is that the demand for production performance has increased, technological advances have increased the complexity and cost of operations, and the available downtime for maintenance events has decreased [Scarf, 1997].

This section is divided into two major subsections. The first subsection departs from the traditional academic literature review by presenting a technical discussion concerning condition-based maintenance. The second subsection returns to the academic literature and discusses theoretical approaches to condition based maintenance.

2.2.3.1 A Practical View of Condition-Based Maintenance

During operation, physical assets are under a variety of stresses. Furthermore, while not all failures are age related, most failures give a warning (which may or may not be easily identified) before failure occurs [Moubray, 1997]. This insight is the motivation for concept of P-F (potential failure-functional failure) curves.

Figure 1 shows a generic P-F curve. Note that there are two identifiable points on the curve. Point P is the point where the potential for failure is detectable. Point F is the point where failure occurs.

The time span between point P and point F is the available time for prevention of the failure (P-F interval) [Moubray, 1997]. If the asset is degrading rapidly, this time is generally small. If the asset is degrading slowly, this time is generally large. An important observation concerning the P-F curve is that MMI must occur at intervals smaller than the P-F interval; otherwise, it is possible that a potential failure will not be detected until failure occurs.

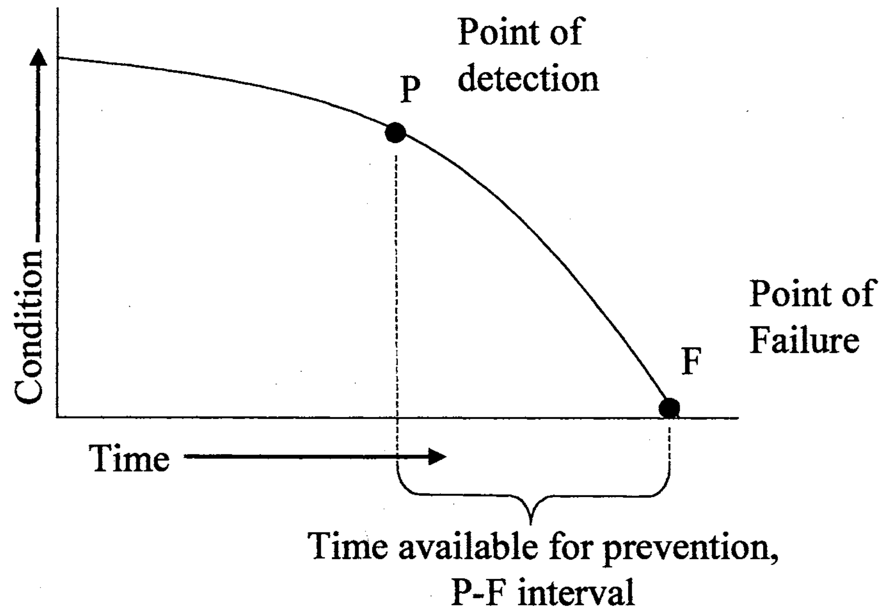

Figure 1. Generic P-F curve [Moubray, 1997]

Figure 1 shows a P-F curve for a single failure mode and one detection point. However, consider the P-F curve in Figure 2, which describes the possible detection points for bearing failure. The conclusion is that there may be many measurable condition parameters. As seen, however, some parameters provide more reaction time than others do.

Returning to Figure 1, one can note that the P-F curve is decreasing at an increasing rate. Is this a reasonable assumption for most asset degradation? Moubray [1997] believes it is and states that degradation accelerates as the time to failure decreases in most cases. However, in some cases the degradation can be linear. A linear degradation occurs generally when the failure mechanism is intrinsically related to age (auto tire wear for example) [Moubray, 1997].

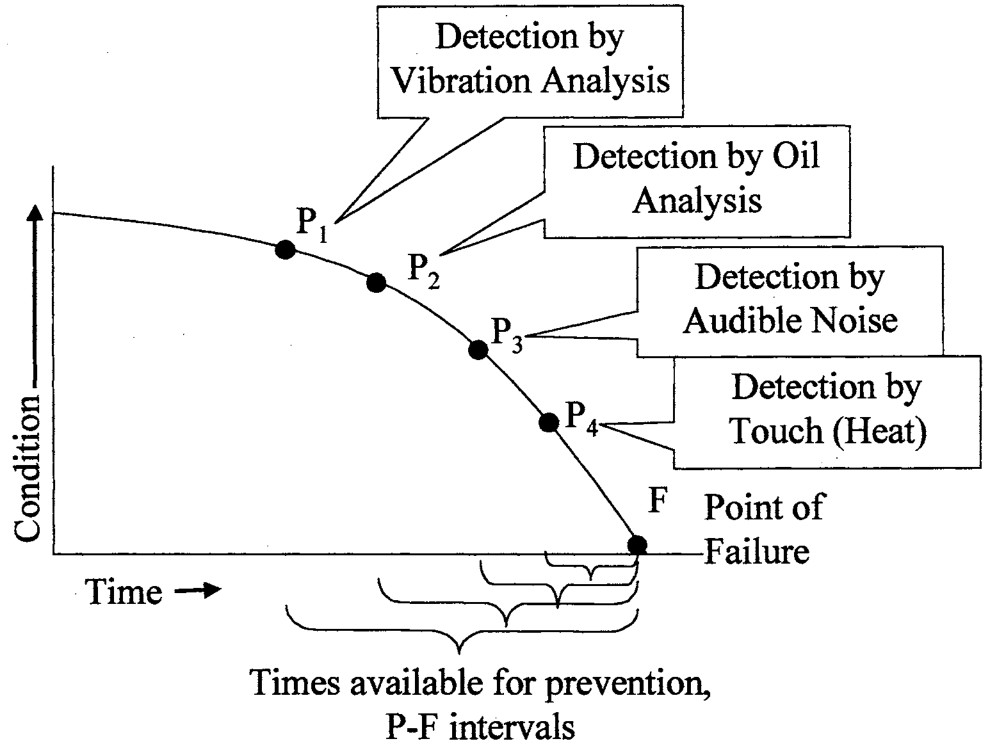

Figure 2. Possible detection points for bearing failure [Moubray, 1997]

An interesting note concerning P-F curves is that the focus is on the point of first detection and the point of failure. The time interval between these two points is the starting point for determining the condition monitoring interval. The path taken by the asset from the point of detection to the point of failure is not critical to the implementation of condition-based maintenance on a practical level.

2.2.3.2 Theoretical Approaches to Condition-Based Maintenance

This subsection discusses theoretical approaches to condition-based maintenance. The literature presents four general approaches to condition-based maintenance modeling.

The first approach uses the proportional hazard model. The second approach uses a modified form of Barlow and Proschan's age replacement maintenance model (presented in Section 2.2.1). The third approach uses a two part empirical model to represent asset degradation. The fourth approach used a condition state model such as a Markov chain model.

2.2.3.2.1 Proportional Hazards Model

D. R. Cox [1972] introduced the Proportional Hazards Model (PHM) model in the 1970's for use in the area of lifetime data analysis. One advantage of this model is that it incorporates the current age and the current condition of an asset [Jardine et al, 1998]. This subsection discusses the hazard rate function and the PHM.

Reliability theory describes the hazard rate function, h(t), as the instantaneous rate of failure [Ebeling, 1997]. The failure density function uniquely describes the hazard rate function as shown in Equation 26.

$$h(t) = \frac{f(t)}{\int_t^{\infty} f(t)dt} = \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)} \tag{26}$$

In the mid 1980's, reliability researchers began studying the applicability of the PHM to condition-based maintenance on assets that have an increasing hazard rate. Dhananjay and Dlefsjo [1994] provide a review of this research.

The concept of the PHM model is that the failure rate function of an asset is decomposable into a baseline failure rate function and a function dependent on covariates resulting from a multiple regression analysis of historical data [Ansell and Phillips, 1994]. In general, the failure rate function is expressed as Equation 27.

$$h(t \mid z) = \psi[h_o(t), \phi(z;\beta)] \tag{27}$$

where

ψ = is an arbitrary function,

$h_o(t)$ = the baseline failure rate function,

ϕ = an arbitrary function of covariates, and

z, β = parameters of the function ϕ.

Cox [1972] suggests that ψ be a multiplicative function and that ϕ be an exponential function with a linear argument. Jardine et al. [1998] defines the failure rate function for the PHM in this manner. Equation 28 is the composite of a baseline failure rate function, $h_o(t)$, and a degradation function, $e^{\sum \gamma_i Z_i(t)}$, which is based on the current condition parameters of an asset. Essentially, the degradation function serves as an acceleration factor for the baseline hazard function.

$$h(t, Z(t)) = h_o(t) e^{\sum \gamma_i Z_i(t)} \tag{28}$$

where

γ_i = constants where, if $\gamma_i = 0$, then $Z_i(t)$ has no influence on asset degradation (also called importance factors),

$Z_i(t)$ = observed variables values at time t and are assumed to be factors for accelerating the failure rate of an asset [Mann, Saxena, and Knapp, 1995], and

$h_o(t)$ = baseline failure rate function.

The variables, $Z_i(t)$, may be measurements of asset condition, such as metallic particulate contamination in oil, or the vibration level. Increases in $Z_i(t)$ lead to reduced estimates of asset survival time [Mann, Saxena, and Knapp, 1995].

To use the PHM, the first step is to define a stopping rule (the interval for maintenance) as T_d, where d > zero and is equal to the value of the PHM at $t = T_d$ [Jardine, Banjevic, and Makis, 1997]. To find the optimum value of d, (d*), the cost model shown in Equation 9 (repeated as Equation 29) is used with Equation 28 to recursively determine an optimal maintenance event time by minimizing the expected maintenance cost (Equation 30).

$$\overline{C}(T) = \frac{C_p\overline{F}(T) + C_u[1-\overline{F}(T)]}{E[T_r] + E[T_f]} = \frac{C_p\overline{F}(T) + C_u[1-\overline{F}(T)]}{T\cdot\overline{F}(T) + MMTF(t \mid t \le T)\cdot[1-\overline{F}(T)]} \tag{29}$$

$$\overline{C}(d^*) = \frac{C_p[1-Q(d^*)] + C_f[Q(d^*)]}{W(d^*)} = \frac{C_p\left[\dfrac{f(t)}{d^*\cdot e^{-\sum\gamma_i Z_i(t)}}\right] + C_f\left[1-\dfrac{f(t)}{d^*\cdot e^{-\sum\gamma_i Z_i(t)}}\right]}{t\cdot\dfrac{f(t)}{d^*\cdot e^{-\sum\gamma_i Z_i(t)}} + \displaystyle\int_0^t \frac{f(t')}{d^*\cdot e^{-\sum\gamma_i Z_i(t')}}dt'\cdot\left[1-\dfrac{f(t)}{d^*\cdot e^{-\sum\gamma_i Z_i(t)}}\right]} \tag{30}$$

where

Q(d*) = the probability that an asset will fail before maintenance and

W(d*) = the expected time between two consecutive replacements (regardless of whether replacement results from maintenance or failure).

Operators perform maintenance on the asset when the current asset condition level exceeds d*. Note that variables such as temperature, frequency and particulate level are being measured. The assumption is made that as these levels increase the condition level of an asset decreases.

Consider the following model (Equation 31) developed from oil analysis records of certain diesel engines [Jardine et al., 1998].

$$h(t,z)=\frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}e^{\sum \gamma_i z_i(t)}=\frac{4.166}{43560}\left(\frac{t}{43560}\right)^{3.166}e^{0.1467z_1(t)+0.012z_2(t)} \qquad (31)$$

where

β = 4.166,

θ = 43,560,

$z_1(t)$ = accumulated ppm iron,

$z_2(t)$ = accumulated ppm copper,

$\gamma 1$ = 0.1467, and

$\gamma 2$ = 0.012.

The point of interest regarding Equation 31 is that the estimated mean time to failure for the engines is 6,000 – 7,000 hours. If the estimated values for the parameters β and θ, in Equation 31, are used to calculate the meantime to failure, the result is 39,575 hours (Equation 32) [Ebeling, 1997].

$$\text{MTTF}=\theta\Gamma\left(1+\frac{1}{\beta}\right)=39{,}575 \text{ hours} \qquad (32)$$

The explanation for this discrepancy [Jardine et al., 1998] is that the large value of θ in Equation 31 compensates for the strong influence of covariates on the asset's underlying hazard rate. However, consider the following substitution of variables (Equation 33).

$$\theta^{\beta} = \theta^{\beta}_{f(t)} \cdot e^{-k} \tag{33}$$

where, $\theta_{f(t)}$ is the scale parameter for the asset's probability density function. Equation 31 then becomes (Equation 34)

$$h(t,z) = \frac{\beta}{\theta_{f(t)}}\left(\frac{t}{\theta_{f(t)}}\right)^{\beta-1} e^{k+\sum \gamma_i z_i(t)} = \frac{4.166}{7155}\left(\frac{t}{7155}\right)^{3.166} e^{-7.53+0.1467 z_1(t)+0.012 z_2(t)} \tag{34}$$

However, even with this linkage between the asset's density function and the condition variables it is difficult to make general comparison between age-based and condition based maintenance strategies. The difficulty arises because there is no general form for the covariate values. These values must be estimated for each specific asset.

Additionally, the model has an unstated assumption that hinders its general acceptance in industry. First, it uses historical data to develop a single covariate model. This covariate model is then used with current covariant variable values to estimate the current state of a system. The major problem with this approach is that there is an assumption that the history of the current values matches that of the historical values. This may be an acceptable assumption, but in general, many researchers do not agree that there is sufficient evidence to make such a generalization. Scarf [1997, p. 501] explains this problem as follows.

The main criticism of the work to date on proportional hazards modeling in condition-based maintenance is that the conditional residual life is determined by the current hazard, that is, the current values of the condition related variables (and the full condition history is not used). Thus, this does not capture the essence of the problem as illustrated in Fig. 1.

Either it is necessary to forecast the hazard to date, or the condition-related covariates must reflect recent history, that is for example $X_{t-} = \{Z_t^1, Z_{t-1}^1, Z_t^2, Z_{t-1}^2, ...\}$, say where Z^1, Z^2, Z^3,... are condition related variables.

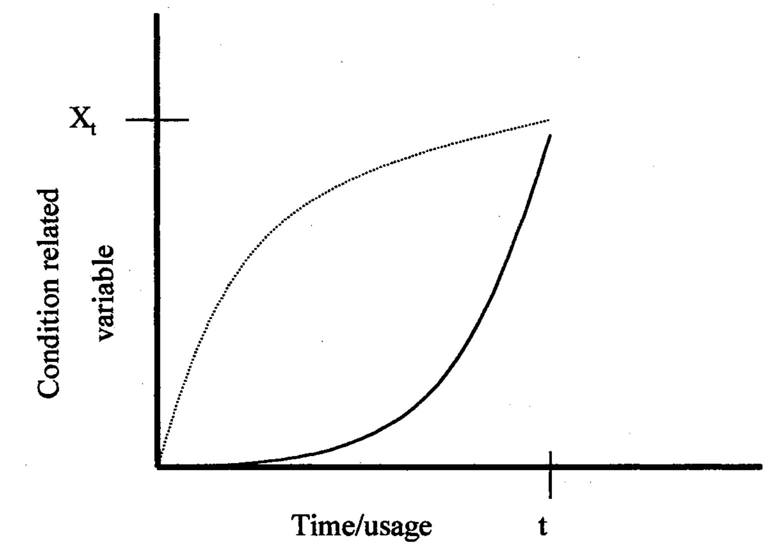

Figure 1. Conceptual view of two different condition histories: condition history 1, with large expected residual life (....); and condition history 2 with small expected residual life (____).

However, if we recall the discussion concerning the shape of the P-F curve and we assume that the condition related variables are proportional to the condition of an asset, the above criticism may not be significant. Specifically, the P-F curve (condition level versus age) can be assumed to be a function that decreases at an increasing rate. Therefore, it seems reasonable that if the variables that are being measured are proportional to the condition of an asset then the measured variables will increase at an increasing rate.

2.2.3.2.2 Modifications to Barlow and Proschan's Infinite Time Span Age Replacement Model

McKone's [1996] doctoral work focuses on the implementation of Total Productive Maintenance, which endeavors to marry production requirements with maintenance requirements. To model the maintenance activity, McKone modifies Barlow and Proschan's [1965] infinite time span age replacement maintenance model as shown conceptually in Equation 35.

$$E[C_t] = \frac{E[C_{CBM}/t + C_u/t + C_p/t]}{E[t]} \tag{35}$$

where

C_{CBM} = the cost of a condition-based maintenance event,

C_u = the cost of asset failure,

C_p = the cost of an age-based maintenance event, and

T = time horizon.

Equation 36 shows the general formulation.

$$E[C_t] = \frac{M_{pd}\left[\int_0^N\int_0^x f(s,x)\partial s\partial x + \int_N^\infty\int_0^N f(s,x)\partial s\partial x\right] + M_b\int_o^N\int_x^\infty f(s,x)\partial s\partial x + M_p\int_N^\infty\int_N^\infty f(s,x)\partial s\partial x}{\left[\int_0^N\int_0^N sf(s,x)\partial s\partial x + \int_N^\infty\int_0^N sf(s,x)\partial s\partial x\right] + \int_0^N\int_x^N xf(s,x)\partial s\partial x + \int_N^\infty\int_N^\infty Nf(s,x)\partial s\partial x} \tag{36}$$

where

M_{pd} = cost of a condition-based maintenance event,

M_b = cost of asset failure,

M_p = cost of an age-based maintenance event,

s = time of the potential failure prediction signal,

x = time of equipment failure without intervention,

f(s, x) = joint density of the prediction signal and equipment failure, f(s/x)f(x), and

N = time of planned replacement.

The first two terms in the numerator of this model are noteworthy concerning the current research. The first term in the numerator, $\int_0^N \int_0^x f(s,x) \partial s \partial x$, represents the joint probability that a signal for CBM will occur before failure and the probability of failure before the age replacement maintenance interval. The second term in the numerator, $\int_N^\infty \int_0^N f(s,x) \partial s \partial x$, represents the joint probability that a CBM signal will occur before the age replacement maintenance interval and the probability of survival given the system survives the age replacement maintenance interval.

These two terms do appear to follow the same logic as the original model presented by Barlow and Proschan [1965] (i.e., they both consider the probability that an asset will fail before maintenance and the probability that an as will survive until maintenance). However, the results of this research are very limited (see Section 2.3)

2.2.3.2.3 General Empirical Model

Another approach to condition-based maintenance starts with an estimate of the degradation function of an asset and then incorporates a stochastic component to represent the failure potential of the system. This approach is generally found in the literature under the topic of "degrading assets under random shock," where the random shock component is related, tightly or loosely, to the failure probability of the system.

Chikte and Deshmukh [1981] presented such an approach. Their model describes the state of an asset as a function of system's cumulative damage level, which randomly increases with time and is affected by the maintenance strategy. The damage accumulation level, while always increasing, is an inversely related function of the level of maintenance performed (i.e., the more maintenance performed the slower damage accumulates in the system).

Thorstensen and Rasmussen [1999] define a two component, empirical asset degradation model (Equation 37).

$$d(t) = g(t) + b\sqrt{t}\,U \qquad U \sim N(0,1) \tag{37}$$

The first component, g(t), represents the deterministic degradation of an asset. The second component, $b\sqrt{t}\,U$, represents the stochastic nature of an asset's degradation. Figure 3 shows a graphical representation of this model.

This model is appealing because of its simplicity. However, it is not apparent how a CBM strategy using this model would be compared to an ABM strategy.

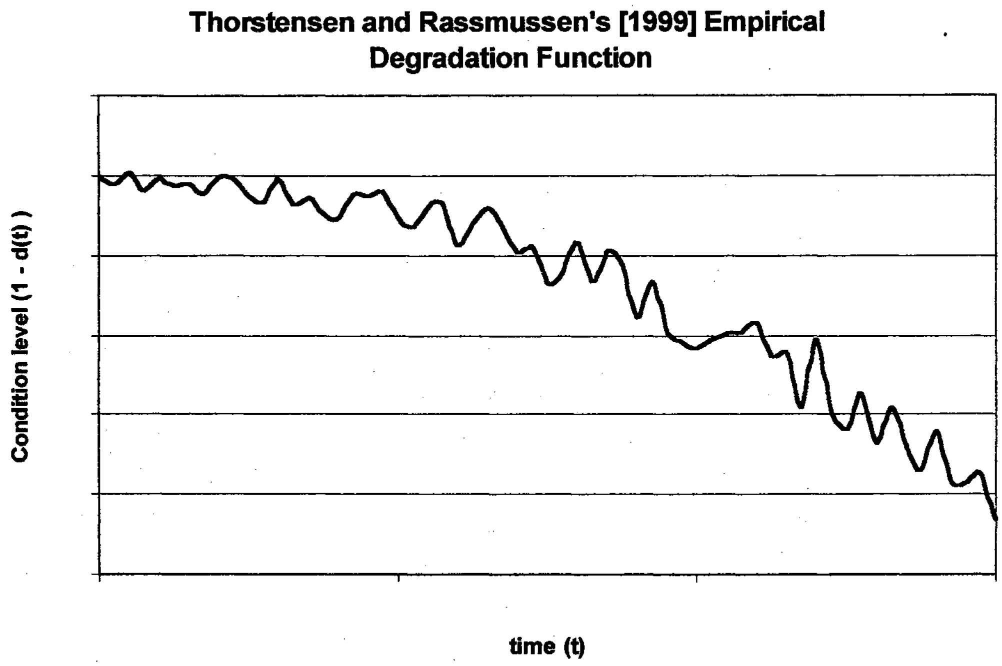

Figure 3. Graphical representation of Thorstensen and Rasmussen's [1999] empirical degradation function

2.2.3.2.4 Condition State Model

Another approach is the condition state models, e.g., Markov chain models (see [Pierskalla and Voelker, 1976] for a review of the literature). Figure 4 shows the general approach.

At any time, the asset can fail, degrade to the next state or remain in its current state. The level of degradation at each degraded state can be either constant or a stochastic function of the state and/or time. Maintenance can be performed in any of the degraded states. However, maintenance may not bring the system back to as-good-as-new condition.

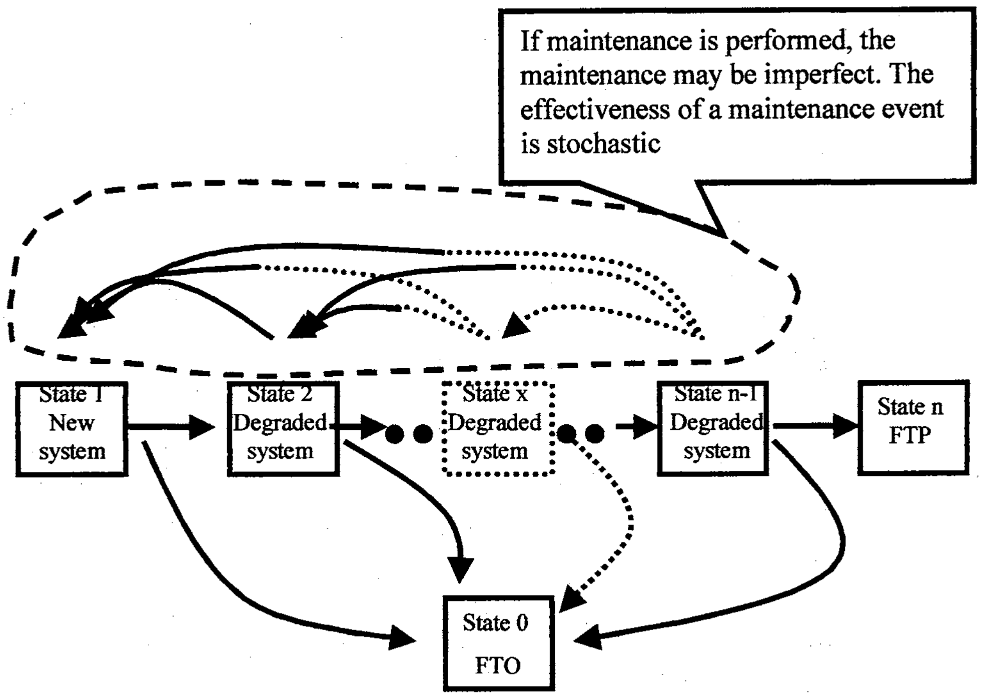

Figure 4. General approach for a condition state type of analysis

This approach has seen a large amount of support in the theoretical literature [Pierskalla and Voelker, 1976]. However, the data requirements for determining the state transition probabilities are generally large [Scarf, 1997].

Van Noortwijk [1998] stated that a generalized gamma function is the appropriate distribution to describe asset deterioration (degradation). However, this approach focuses on age-based maintenance. In a methodological sense, this approach is, in concept, similar to the condition state approach.

2.3 Time/Age-Based versus Condition-Based Maintenance

There is only one quantitative comparison paper for ABM versus CBM in the literature

[McKone, 1996]. The apparent reason is that it is a difficult comparison to make. McKone's [1996] model and the condition state model should allow such comparisons. However, only a comparison using McKone's model is presented in the literature. As a result, this section is restricted to a discussion of McKone's results.

McKone's [1996] analysis phase began with descriptions of the decision variables (Table II). Table III shows the ranges for these decision variables (DV).

TABLE II

DESCRIPTION OF DECISION VARIABLES USED IN MCKONE [1996]

Decision variable	Description
β	Shape parameter of the Weibull distribution
θ	Characteristic life of the Weibull distribution
M_p/M_b	Ratio of age-based cost to corrective cost
M_{pd}/M_b	Ratio of CBM cost to corrective cost
α	Prediction accuracy of CBM signal
n	Prediction precision of CBM signal

TABLE III

VARIABLE SETTINGS FOR THE ANALYSIS PHASE

Experiment #	Variable	Description	Variable Range				
1, 2, 3	M_p/M_b	Ratio of age-based cost to corrective cost	0.499	0.823	1.000	1.180	1.501
1, 2, 3	M_{pd}/M_b	Ratio of CBM cost to corrective cost	1.000	3.910	5.500	7.090	10.000
1, 2, 3	θ	Characteristic life of the Weibull dist.	2.141	1.176	1.333	1.176	0.970
1	β	Shape parameter of the Weibull dist.	0.576	0.850	1.000	1.150	1.425
2	β	Shape parameter of the Weibull dist.	1.226	1.500	1.650	1.800	2.075
3	β	Shape parameter of the Weibull dist.	0.076	0.350	0.500	0.650	0.925

Justification for the experimental ranges for the decision variables relied on personal experience. A careful study of the DV ranges shows that the ranges restrict the research to the point of providing limited results. Specifically, it is unclear why M_p/M_b ratios greater than one should be tested, since this result is shown in the literature [e.g., Barlow and Prochan, 1965]. If the cost of age-based maintenance is greater than the cost of failure, then the appropriate strategy is a corrective strategy [McCall, 1965]. The range for M_{pd}/M_b is even more questionable, however. In this case, the range selected restricts the cost of condition-based maintenance to be always greater than or equal to the cost of failure. It is unclear, why a practitioner would choose a CBM strategy over a corrective maintenance strategy in this situation.

However, McKone does provide a list of general classification guidelines regarding maintenance strategy selection. These guidelines, while not quantitatively specific, will allow for a reasonableness check for the maintenance models used in the current research. The guidelines are as follows.

- When the Weibull shape parameter, beta, is less than or equal to one, CM is preferred over ABM.
- When beta is less than one, CBM is preferred if the cost of CBM is significantly less than the cost of failure and the precision of the CBM signal is good.
- When beta is greater than one, the decision to use CBM is over ABM and CM is based on the failure cost, the ABM cost, the CBM cost and the precision of the CBM signal.

As stated previously, this list does not provide quantitative discrimination levels for the maintenance strategies. That is the focus of the current research.

In summary, there are two reasons why this direction of research needs further study.

- The ranges assumed for the decision variables, and the even smaller range of practical values, limits generalization of the results beyond the current literature.
- The general model is complex and computationally difficult to solve, making its acceptance to a practitioner limited.

The next section presents a summary of the findings of this literature review.

2.4 Summary

The literature review presented in this chapter highlights the fundamental concepts of maintenance as developed over the last 40 years ago. Even though condition based maintenance is generally regarded as a recent area of study, the general concepts/ formulations promoted today were first presented in the late 1960's (inspection models). However, as stated by Dekker [1996] there remains a gap between the academic research of maintenance and the practical application of maintenance strategy selection methodology.

The specific conclusions resulting from this chapter's literature review are listed below.

1. There is no consensus in the literature regarding the best method of incorporating the cost of condition-based maintenance into maintenance strategy selection decision theory.

2. There is no consensus in the literature regarding the appropriate method of describing the degradation of an asset under a condition-based maintenance strategy, in such a way that a comparison can be made to an age-based maintenance strategy.
3. The literature is nearly void of studies that directly compare corrective maintenance, age-based maintenance and condition-based maintenance. This probably results from conclusion two.
4. Beyond the generalizations provided by Barlow and Proschan [1965] and their contemporary researchers, the literature provides little assistance to the practitioner regarding which maintenance strategy (corrective, age-based, condition-based) is preferable under general conditions.
5. Because of the lack of consensus regarding the asset degradation formulation, the literature provides the practitioner little surety regarding the appropriate decision variables when condition based maintenance is an alternative.
6. The complexity of the existing models dissuades industry practitioners from embracing them.
7. In general, asset condition can be modeled as a function that decreases at an increasing rate.

The task of current researchers is to either

- provide industry practitioners with less computationally difficult, but still theoretically sound, models or
- provide industry practitioners with a set of decision variables and a decision methodology that does not require the practitioner to carry out the

complex and data intensive computations for every maintenance strategy selection decision.

This research takes up the second task because it has had the least support in the literature. The Chapter III uses the knowledge gained from this literature review to develop the research methodology used for this dissertation.

CHAPTER III

ANALYSIS AND SYNTHESIS OF LITERATURE REVIEW

3.1 Introduction

Section 1.8 states that this research is accomplished in five phases; Preparation, Analysis, Synthesis, Answer Research Questions, and Conclusions/Contributions. The purpose of the literature review, as stated in section 1.8.1, was to gather sufficient literature to answer challenge questions 1 through 5. Therefore, Chapter II constitutes the Preparation phase of this research's methodology. This chapter presents an analysis of the literature review and answers challenge questions 1 through 5. This chapter then uses the results of the analysis phase to develop/present maintenance costs models for corrective maintenance, age-based maintenance and condition-based maintenance strategies, which will address challenge: question six. Therefore, this chapter constitutes the Analysis and Synthesis phase of this research's methodology.

The major focus of these models is that they are formulated such that direct economic comparisons are achievable between the maintenance strategies. In addition, it is the intent of this research that these models should reasonably satisfy Scarf's [1997] recommendation that current research focus on simple maintenance models, i.e., models with few decision variables.

3.2 Challenge Questions 1 through 5 Answered

This section re-states challenge questions one through five. Each question is then followed by a discussion of the findings resulting from an analysis of the literature review presented in Chapter II.

What are the basic decision variables regarding the selection of an economically preferred maintenance strategy? Barlow and Proschan [1965] stated that the cost of failure, the cost of performing age-based maintenance and the failure density function are required for an age-based maintenance model. Al-Najjar [1999] stated that the cost of performing condition-based maintenance, the implementation and continuation costs of an age-based, and a condition-based strategy should be included in a maintenance model. Scarf [1997], Wang[1997], and Moubray [1997] indicated the importance of the delay-time (P-F interval) when considering condition-based maintenance.

How can the "recent/current operational parameters " of an asset be incorporated into the maintenance strategy selection model? Cox [1972], and later Jardine et al. [1998], shows that the proportional hazards model can incorporate the historical/current operational parameters of an asset into a condition-based maintenance model.

What models are available to compare the different maintenance strategies? McKone [1996] presents a condition-based maintenance model (a modified form of Barlow and Proschan, 1965) that allows comparison between corrective, age-based, and condition based maintenance strategies. The important note concerning McKone's formulation is that the major issue for determining the cost of condition-based maintenance is accuracy of an asset's condition MMI process.

How does the literature compare time/age-based maintenance and condition-based maintenance? The literature is sparse in this regard. McKone's work is the only quantitative research in this area and the results are of limited value with regard to developing a general decision methodology.

What conceptually and computationally simple and comparable maintenance cost models are available for corrective, time/age-based and condition-based maintenance? Although, McKone presents a comparison that is conceptually simple, the method is computationally difficult and not likely to be embraced by industry users.

The remaining sections synthesize the findings of this chapter into a quantitative procedure that can be used to answer the research questions of this study. The next section presents a discussion of the measurement/monitoring/inspection (MMI) process for CBM.

3.3 The Condition-Based Maintenance Measurement/Monitoring/Inspection Process

An ideal condition-based maintenance strategy would prevent all failures and allow maximum asset usage before maintenance. However, an asset's condition MMI process measures parameters that a maintenance practitioner believes represents the actual state of the asset. The extent to which asset condition is predicted by these parameters determines the user's ability to predict asset failure. The less predictive power the measured parameters have toward describing the future state of an asset, the higher the probability that a failure may occur before maintenance is performed. In a sense, this uncertainty creates a window for failure. This window for failure is the P-F interval concept, as discussed by Moubray [1997], and the delay time concept as discussed by Scarf [1997] and Wang [1997].

As seen above, in practice an asset's condition MMI process does not eliminate the possibility of failure. This, therefore, begs the question, "Why should I use condition-based maintenance?" The answer to this question is that condition MMI reduces a user's uncertainty regarding when a failure may occur.

For example, suppose that a user has installed a MMI process that can detect a 25% change in an asset's condition. Assuming the MMI process's signal has no error, the user will receive a signal when the asset is at its 75%, 50%, and 25% condition level. The 0% condition level will coincide with asset failure. Effectively, the user is now able to predict with certainty that asset failure will occur some time after the 25% condition level signal. In general, increasing the precision of the detection capability of the MMI process allows for better and better estimates of asset failure.

The next subsection presents the decision variables used in this research. The preceding discussion serves as justification for one of these decision variables.

3.4 Decision Variables

The first decision variable concerns the failure distribution. This research uses the Weibull failure distribution because of its nearly unanimous support in the asset failure literature. Initial trials are conducted by varying the shape parameter, β, of the Weibull distribution. A beta value of one indicates a constant failure rate, in which case the performance of maintenance has no effect on the probability of failure during an arbitrary "next" maintenance period. A beta value of approximately two indicates a relatively linear increase in the probability of failure over time. A beta value between approximately three and four indicates an increasing probability of failure over time. Cavalier and Knapp [1996] state that many mechanical failures have beta values less than four. Assets that have beta values of greater than four are generally exhibiting rapid old-age wear out and should be replaced or extensively refurbished rather than maintained.

The goal of the initial trials is to determine the boundaries for the remaining decision variables. In later trials, the Weibull scale parameter is varied to determine whether changing the scale parameter results in a different maintenance strategy selection decision. This research initially makes the assumption that the scale parameter, θ, will have little effect on the maintenance strategy selection process. However, this assumption will be tested in Chapter IV.

The next three decision variables have broad support within the literature. They are the cost of CBM (C_{CBM}), the cost of ABM (C_p) and the cost of failure (C_u, corrective maintenance costs). This research will generically define these costs as the cost of performing a CBM event, the cost of performing an ABM event and the cost of replacing a failed asset. This failure cost is meant to include the cost of lost production.

The next decision variables are the result of the recent CBM research [Al-Najjar, 1999, for example]. Specifically, these decision variables ($C_{IC\text{-}CBM}$ and $C_{IC\text{-}p}$) represent the cost per unit time of implementing and continuing a maintenance strategy. These costs are different from C_{CBM}, C_p, and C_u in that the costs $C_{IC\text{-}CBM}$ and $C_{IC\text{-}p}$, represent the initial cost of implementing and the annual administrative cost of maintaining a specific strategy (CBM and ABM, respectively). This research does not delve deeply into these costs, but it does provide a solid starting point for a future researcher.

The last decision variable is motivated by the conceptual discussion in Section 3.3. This decision variable represents the discriminatory ability of the asset's condition MMI process. The purpose of this decision variable is to represent inaccuracy of the MMI process in predicting the true condition level of an asset. In summary, the decision variables for this research are

- β = the shape parameter of the Weibull distribution,
- θ = the scale parameter of the Weibull distribution,
- C_{CBM} = the cost of condition-based maintenance,
- C_p = the cost of age-based maintenance,
- C_u = the cost of asset failure,
- $C_{IC\text{-}CBM}$ = the initial cost of implementing and the annual administrative cost of maintaining a condition-based maintenance strategy,
- $C_{IC\text{-}p}$ = the initial cost of implementing and the annual administrative cost of maintaining an age-based maintenance strategy, and
- D_L = discrimination ability of the condition monitoring/inspection process.

The next three subsections presents maintenance models used in this research. The CBM model is presented first, followed by the ABM and the CM.

3.5 Condition-Based Maintenance Model

One difficulty encountered when modeling CBM is how to model the condition level of the asset. In general, the idea is to select a set of parameters that, as a group, reliably represent the current condition level (performance level) of the asset and then monitor these parameters. However, as seen in the Chapter II the literature does not agree as to the best method to accomplish this task. Each method presented may be acceptable for many or few specific assets.

Recall that the focus of this research is to predict in a general sense, under what conditions CM, ABM or CBM is economically preferred. To accomplish this task the following reasoning is used to construct a generic asset degradation model to represent the deterioration of an asset's condition level over time/use.

3.5.1 Degradation Function

After a study of failure and operational data (using an approach similar to the PHM approach), the user discovers that increasing levels of stress (percentage utilization, abuse, instantaneous throughput, temperature variation, etc.) result in accelerated degradation of the asset. The user may identify several degradation paths. However, this discussion (and this research) assumes that only one average path is identified. The specific approach used to identify this path is not the focus of this research but it is anticipated that this topic will be in the forefront of future research.

Further, assume that the termination point of this path corresponds to the MTTF of the asset's failure density function. Next, recalling that Moubray [1997] stated that most mechanical systems degrade at an increasing rate, we could superimpose the distinguishable degradation path over the failure density function (Figure 5).

How is the specified degradation path related to the failure density function and the condition parameters? The theoretical and technical literature, while not in agreement on the specific form, is in agreement as to the general shape of an asset's degradation function. Specifically, asset condition decreases at an increasing rate. The challenge is how to define this decreasing function in such a way that it models, at least approximately, a wide range of degradation functions. To this end, this research takes the following approach.

Recall the generic P-F curve presented by Moubray [1997] (Figure 6).

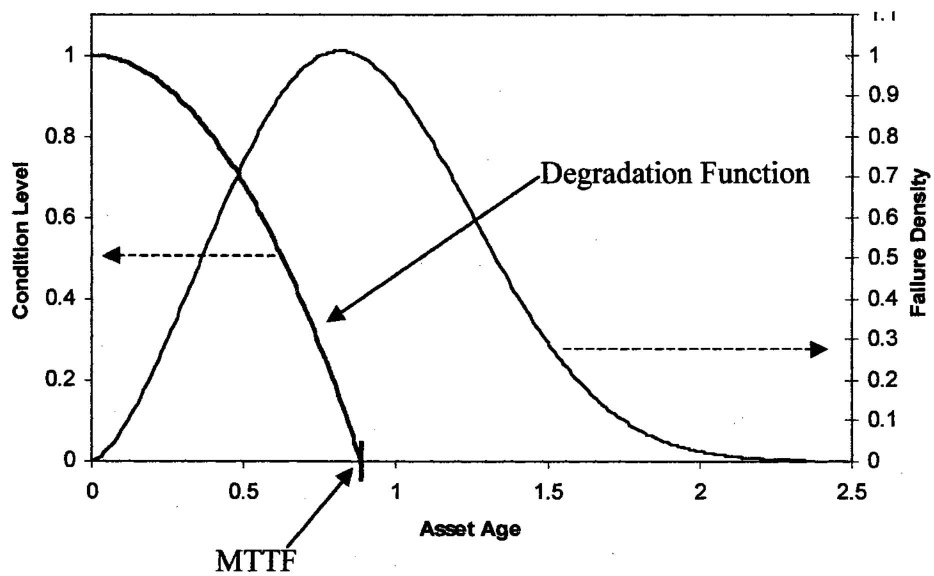

Figure 5. Failure density function with superimposed degradation function

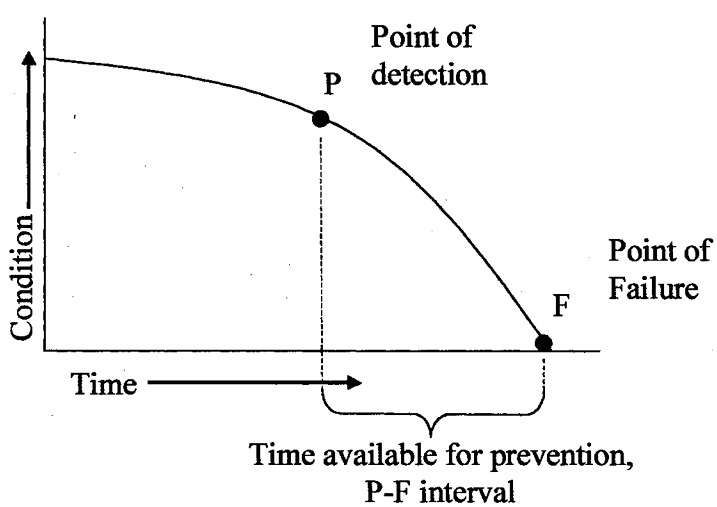

Figure 6. Generic P-F curve

There are two points of interest on this curve, P and F, the first point of detection (P) and the point of failure (F). In addition, recall, that in practice the path from P to F is not as critical as the time duration between the points (see also the discussion on delay time in section 2.2.2.2). Consequently, a general function that approximately represents the curve should provide a reasonable approximation of the degradation process (Equation 38).

$$d(t) = 1 - \frac{1}{h(t)} t^2 \tag{38}$$

where

h(t) = the hazard rate of the failure density function at a specific time and

t = the age of the asset.

This formulation is appealing because of the inclusion of the hazard rate function, which allows a link to be made between the proportional hazards model, the degradation function, and practical knowledge. This link potentially eliminates the criticism voiced by Scarf [1997].

Future research will search for specific methods of incorporating an asset's hazard rate into this equation and incorporating multiple degradation functions into the analysis of CBM modeling. The current research, however, assumes that there is one degradation function that represents the average of all the possible distinguishable degradation functions of a specific asset. Consequently, in this research, the function, h(t), is approximated as the $(MTTF)^2$ of the asset. The next subsection presents the decision variables that are used in this research.

3.5.2 Condition-Based Maintenance Model

Two approaches may be used to formulate an analytical model for CBM. The first approach is to perform CBM immediately after the last expected CBM signal (i.e., the last signal BEFORE failure). The second approach is similar to the ABM model in that it incorporates the cost of failure and optimizes the maintenance schedule by minimizing the expected maintenance cost. This research uses the first approach with the intent that it will serve as the baseline for future work. A brief preliminary presentation of the second approach is presented in Appendix A.

The long run average cost of performing CBM ($\overline{C}_{CBM}$) is equal to the cost of performing each CBM event divided by the expected time of each CBM event (Equation 39).

$$\overline{C}_{CBM} = \frac{C_{CBM}}{t_s} \tag{39}$$

where

C_{CBM} = the cost of performing a CBM event and

t_s = the expected time of each CBM event which, in this research, is assumed to be equal the time of the last signal BEFORE failure.

3.6 Age-Based Maintenance Model

This research uses Barlow and Proschan's [1965] infinite time span age replacement maintenance model (Equation 40) to calculate the cost for an ABM strategy. The motivation for using this simple model is due to the expository nature of this research. Specifically, since the literature is sparse concerning comparisons between age-based and condition-based maintenance, this simple model will provide a solid starting point for more detailed future research.

$$\overline{C}(T) = \frac{C_p[1 - F(T)] + C_u F(T)}{\int_0^T [1 - F(t)]dt} \tag{40}$$

3.7 Corrective Maintenance Model

As stated previously, a CM strategy is a run-to-failure maintenance strategy. Therefore, the long run average cost of implementing a CM strategy ($\overline{C}_u$) is the cost of asset failure divided by the expected time to asset failure (Equation 41).

$$\overline{C}_u = \frac{C_u}{MTTF} \tag{41}$$

where

C_u = the cost of repairing/replacing a failed asset and

MTTF = the mean time to failure of the asset.

The last component to add to the cost equation is the implementation/continuation cost of age-based and condition-based maintenance, $C_{IC\text{-}p}$ and $C_{IC\text{-}CBM}$, respectively. This research incorporates these costs by following the approach presented by Al-Najjar [1999]. Specifically, the continuation and implementation cost for an age-based maintenance strategy and a condition-based maintenance strategy is the expected cost per unit time. The age-based maintenance cost model with implementation and continuation cost is shown in Equation 42.

$$\overline{C}(T) = \frac{C_p[1 - F(T)] + C_u F(T)}{\int_0^T [1 - F(t)]dt} + C_{IC-p} \tag{42}$$

The condition-based maintenance cost model with implementation and continuation cost is shown in Equation 43.

$$\overline{C}_{CBM} = \frac{C_{CBM}}{t_s} + C_{IC-CBM} \tag{43}$$

3.8 Comparing Corrective, Age-Based and Condition-Based Maintenance

This research compares CM, ABM, and CBM strategies in two phases. In the first phase the scale parameter, θ, of the Weibull failure density function is arbitrarily set equal to one. Additionally, the implementation and continuation costs are ignored. Table IV shows the ranges of remaining decision variables used in this research for phase one. The range for the Weibull shape parameter, β, is chosen to include constant and increasing failure rates. The ranges for C_{CBM}, C_u, and D_L are chosen to provide a broad coverage of the possible ranges. The variables C_{CBM} and C_u are standardized relative to C_p.

Phase two studies the effect of changing the scale parameter θ and incorporating the implementation and continuation costs into the ABM and CBM models. The scale parameter is tested at twice the original value ($\theta = 2$). The implementation and continuation cost for ABM is arbitrarily set equal to 0.01 and the implementation and continuation cost for CBM is set equal to $1*C_{IC\text{-}CP}$, $10*C_{IC\text{-}CP}$, $100*C_{IC\text{-}CP}$, $1000*C_{IC\text{-}CP}$, and $10000*C_{IC\text{-}CP}$. Future research will explore this issue further.

In general, this research calculates the cost of CM, ABM, and CBM under comparable conditions. Next, this research chooses the lowest long run average cost of the three strategies, for each practical combination of decision variables, as the economically preferred strategy.

TABLE IV

PROPOSED RANGES FOR THE VARYING DECISION VARIABLES IN PHASE ONE

beta, β	Theta, θ	C_p	C_{cbm}	C_u	D_L
1.0	1	1	1	1	0.500
1.5			10	10	0.250
2.5			100	100	0.125
3.5			1000	1000	0.063
4.5			10000	10000	0.031
5.5					0.016
					7.81E-03
					3.91E-03
					1.95E-03
					9.76E-05
					9.76E-06
					9.76E-07
					9.76E-08
					9.76E-09

Those decision variable combinations that specify C_{CBM} to be greater than the cost of failure are ignored. If the cost of CBM was greater than the cost of failure, why would a practitioner implement a CBM strategy? The remainder of this section presents the systematic methodology used by this research.

Given a set of decision variable values and recalling that a corrective maintenance strategy is a run to failure strategy, the long run average cost of corrective maintenance is computed using Equation 44.

$$\overline{C}_{CM} = \frac{C_u}{MTTF} = \frac{C_u}{\int_0^\infty t \cdot f(t)dt} \tag{44}$$

Given the same set of decision variable values, the long rung average cost of an age-based maintenance strategy is computed by minimizing Equation 45 for T the optimized maintenance interval.

$$\overline{C}_{ABM}(T) = \frac{C_p[1-F(T)] + C_u F(T)}{\int_0^T [1-F(t)]dt} \tag{45}$$

In this research, this minimization process is accomplished using MathCad®, Version 8.

The long run average cost of condition-based maintenance, again using the same set of decision variable values as above, is computed using Equation.

$$\overline{C}_{CBM} = \frac{C_{CBM}}{t_s} \tag{46}$$

The next chapter presents the results of this quantitative procedure.

CHAPTER IV

RESULTS AND ANALYSIS

4.1 Introduction

This chapter constitutes the fourth phase of this research's methodology. Specifically, this chapter presents the results of the experimental methodology presented in Chapter III. This chapter then uses these results to answer the research questions posed in Chapter I.

4.2 Initial Results of Phase One

This section presents the quantitative results for Phase One of the methodology presented in Chapter III. Table V shows the economically preferred maintenance strategy for the combinations of decision variables when the scale parameter θ is equal to one, the implementation and continuation costs are equal to zero and the cost of performing CBM is greater than or equal to the cost of asset failure. The implementation and continuation costs are ignored in this presentation because it presents a picture of the "best possible" feasibility of ABM and CBM. The complete data set for Phase One that includes the implementation and continuation costs are presented in Appendix B.

A study of the results show that the maintenance cost models presented/proposed in this research are in agreement with the list of maintenance strategy selection guidelines presented Chapter II. Specifically, the first guideline states that when the failure rate is constant, ABM maintenance is never the preferred strategy. This is shown in trials 16 through 30.

TABLE V

ECONOMICALLY PREFERRED MAINTENANCE STRATEGY

Trial	beta	C_{CBM}	C_u	Economically Preferred Strategy	Trial	beta	C_{CBM}	C_u	Economically Preferred Strategy
16	1	1	1	CM	61	3.5	1	1	CM
17	1	1	10	CBM	62	3.5	1	10	CBM
18	1	1	100	CBM	63	3.5	1	100	CBM
19	1	1	1000	CBM	64	3.5	1	1000	CBM
20	1	1	10000	CBM	65	3.5	1	10000	CBM
21	1	10	10	CM	66	3.5	10	10	ABM
22	1	10	100	CBM	67	3.5	10	100	ABM
23	1	10	1000	CBM	68	3.5	10	1000	CBM
24	1	10	10000	CBM	69	3.5	10	10000	CBM
25	1	100	100	CM	70	3.5	100	100	ABM
26	1	100	1000	CBM	71	3.5	100	1000	ABM
27	1	100	10000	CBM	72	3.5	100	10000	ABM
28	1	1000	1000	CM	73	3.5	1000	1000	ABM
29	1	1000	10000	CBM	74	3.5	1000	10000	ABM
30	1	10000	10000	CM	75	3.5	10000	10000	ABM
31	1.5	1	1	CM	76	4.5	1	1	CM
32	1.5	1	10	CBM	77	4.5	1	10	CBM
33	1.5	1	100	CBM	78	4.5	1	100	CBM
34	1.5	1	1000	CBM	79	4.5	1	1000	CBM
35	1.5	1	10000	CBM	80	4.5	1	10000	CBM
36	1.5	10	10	ABM	81	4.5	10	10	ABM
37	1.5	10	100	CBM	82	4.5	10	100	ABM
38	1.5	10	1000	CBM	83	4.5	10	1000	ABM
39	1.5	10	10000	CBM	84	4.5	10	10000	CBM
40	1.5	100	100	ABM	85	4.5	100	100	ABM
41	1.5	100	1000	CBM	86	4.5	100	1000	ABM
42	1.5	100	10000	CBM	87	4.5	100	10000	ABM
43	1.5	1000	1000	ABM	88	4.5	1000	1000	ABM
44	1.5	1000	10000	ABM	89	4.5	1000	10000	ABM
45	1.5	10000	10000	ABM	90	4.5	10000	10000	ABM
46	2.5	1	1	CM	91	5.5	1	1	CM
47	2.5	1	10	CBM	92	5.5	1	10	CBM
48	2.5	1	100	CBM	93	5.5	1	100	CBM
49	2.5	1	1000	CBM	94	5.5	1	1000	CBM
50	2.5	1	10000	CBM	95	5.5	1	10000	CBM
51	2.5	10	10	ABM	96	5.5	10	10	ABM
52	2.5	10	100	CBM	97	5.5	10	100	ABM
53	2.5	10	1000	CBM	98	5.5	10	1000	ABM
54	2.5	10	10000	CBM	99	5.5	10	10000	ABM
55	2.5	100	100	ABM	100	5.5	100	100	ABM
56	2.5	100	1000	ABM	101	5.5	100	1000	ABM
57	2.5	100	10000	ABM	102	5.5	100	10000	ABM
58	2.5	1000	1000	ABM	103	5.5	1000	1000	ABM
59	2.5	1000	10000	ABM	104	5.5	1000	10000	ABM
60	2.5	10000	10000	ABM	105	5.5	10000	10000	ABM

The next guideline states that when beta is greater than one (trials 31- 105), the decision to use CBM over ABM and CM, is based on the failure cost, the ABM cost (equal to one in this research), and the CBM cost. Again, this guideline appears to be supported by these initial results (i.e., as the failure cost (C_u) increases the ABM tends to be the preferred strategy).

The agreement between the general guidelines presented in Chapter II and the initial results serve as a reasonableness check for the maintenance models used in this research. Specifically, and most importantly, this reasonableness check supports the CBM cost model proposed by this research.

4.3 Using Phase One Results to Build a Maintenance Strategy Selection Decision Model

This subsection details the evolutionary approach used in this research to develop a maintenance strategy selection decision model for CM, ABM and CBM. The first step in this model building process was to perform a multivariate linear regression analysis on the data shown in Table V (minus the trials where beta is equal to one). To perform the regression analysis, the classification variables of the data set (CM, ABM, and CBM) were set to 0, 1 and –1, respectively. If the regression model produces a result less than -0.33, CBM is selected. If the regression model produces a result greater than 0.33, ABM is selected. Otherwise, CM is selected. These boundaries were set to obtain three equally sized intervals between –1.0 and 1.0.

The results (shown in Appendix C) show that only the shape parameter β and the cost of CBM are significant. A comparison of the regression model against the original data shows that only 19 out of 75 results were predicted correctly. A second regression analysis was performed using the logarithm of the cost of failure and the cost of CBM values to determine if the order of magnitude differences between the values of the three decision variables were adversely affecting the regression results. The results are shown in Appendix C.

The second regression analysis correctly predicted 56 of the original 75 data combination results. This is a significant improvement over the results of the first regression analysis but still unimpressive considering that the regression model was being fit to the original data and not new data. However, these initial regression analyses indicate that beta, C_{CBM} and C_u are probably not a set of fundamental decision variables for determining the economically preferred maintenance strategy. Moreover, it seems possible that logarithmic functions of these variables will provide a preferred set of decision variables. Therefore, the next step in the process for developing a maintenance strategy selection decision model searches for a set of decision variables that are functions of beta, C_{CBM} and C_u and will accurately predict the economically preferred maintenance strategy. This is accomplished through a trial and error approach.
The following ordered list of decision rules (Table VI) accurately predicts the economically preferred maintenance strategy for all 90 decisions of the original data set. Appendix D presents a detailed discussion of the evolutionary development of the decision rules shown in Table VI.

To test this set of decision rules, a validation data set (Validation Set #1, VS1) was generated using MS Excel's random number generator. The validation sets discussed in this chapter are shown in Appendix E. Table VII (page 75) shows the criteria used to generate VS1.

TABLE VI

DECISION RULES TO TEST VALIDATION SET #1

Order of Use	Decision Rules
1	If beta is less than or equal to one and the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose CM.
2	If the cost of CBM (C_{CBM}) is equal to one and the cost of failure (C_u) is equal to one then choose CM.
3	If $\left(\frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)} \right)$ is less than 1.06 and beta is less than or equal to one then choose CBM.
4	If the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose ABM.
5	If $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 9.6 then choose ABM.
6	If $\frac{C_u / C_{CBM}}{beta} + \log(C_{CBM}) + \log(C_u) + beta$ is greater than 75 then choose CBM.
7	If $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 7.9 then choose ABM.
8	If $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is greater than or equal to 5.5, then choose CBM.
9	If $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 6.42, then choose ABM.

TABLE VII

VALIDATION SET #1

Trial Number	Criteria
1 - 10	$1 < beta < 6$ $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 10000$
11 - 20	$1 < beta < 6$ $0 < C_{CBM} <= 100$ $C_{CBM} <= C_u <= 10000$
21 - 30	$1 < beta < 6$ $0 < C_{CBM} <= 1000$ $C_{CBM} <= C_u <= 10000$
31 – 40	$1 < beta < 6$ $0 < C_{CBM} <= 10000$ $C_{CBM} <= C_u <= 10000$
41 - 50	$1 < beta < 6$ $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 10$

The validation results tables shown in the chapter only lists the misclassified/non-classified trials. The assumption made is that all of the remaining trials were correctly classified. Table VIII shows the results of using the decision rules shown in Table VI to test VS1. As is seen, no trials were misclassified. However, two trials were unclassified by the decision rule model.

TABLE VIII

RESULTS OF VALIDATION SET #1

Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
41	4.62	2	6	CBM	Unclassified
42	3.38	2	9	CBM	Unclassified

To properly classify the two non-classified strategies, three additional decision rules were added to the existing decision rule set (see Table IX). The added decision rules have asterisks on their "order of use" number.

TABLE IX

DECISION RULES TO TEST VALIDATION SET #1

Order of Use	Decision Rules
1	If beta is less than or equal to one and the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose CM.
2	If the cost of CBM (C_{CBM}) is equal to one and the cost of failure (C_u) is equal to one then choose CM.
3	If the function $\left(\frac{\log(C_{CBM})+\log(C_u)+\text{beta}}{\log(C_{CBM})+\log(C_u)+\log\left(\frac{C_u}{C_{CBM}}\right)}\right)$ is less than 1.06 and beta is less than or equal to one then choose CBM.
4	If the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose ABM.
5	If the function $\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 9.6 then choose ABM.
6	If the function $\frac{C_u/C_{CBM}}{\text{beta}}+\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 75 then choose CBM.
7	If the function $\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 7.9 then choose ABM.
8*	If the function $\frac{C_u/C_{CBM}}{\text{beta}} * \frac{\log(C_{CBM})+\log(C_u)+\text{beta}}{\log(C_{CBM})+\log(C_u)+\log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 1.53, then choose ABM.

TABLE IX continued

Order of Use	Decision Rules
9	If the function $\dfrac{C_u / C_{CBM}}{beta} * \dfrac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\dfrac{C_u}{C_{CBM}}\right)}$ is greater than or equal to 5.5, then choose CBM.
10	If the function $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 6.42, then choose ABM.
11*	If the function $\dfrac{C_u / C_{CBM}}{beta} * \dfrac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\dfrac{C_u}{C_{CBM}}\right)}$ is less than 2.65, then choose CBM.
12*	If the function $\log(C_{CBM}) + \log(C_u) + \log\left(\dfrac{C_u}{C_{CBM}}\right)$ is less than 3, then choose CBM.

Validation Set #2 was generated using the same criteria used to create VS1. This new validation set was then used to test the new decision rule set shown in Table IX.

Table X shows that two trials were misclassified and four trials were non-classified. The economically preferred strategy for trials 21, and 45 were ABM but the decision rules misclassified these trials as CBM. Three decision rules were added to properly classify the four non-classified trials (Table XI). The added decision rules have asterisks on their “order of use” number.

TABLE X

RESULTS OF VALIDATION SET #2

Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
21	2.04	185	2019	ABM	CBM
41	1.16	9	10	CBM	Unclassified
43	1.47	2	8	CBM	Unclassified
45	4.96	2	5	ABM	CBM
47	3.16	4	9	ABM	Unclassified
49	2.89	4	8	ABM	Unclassified

TABLE XI

DECISION RULES TO TEST VALIDATION SET #3

Order of Use	Decision Rules
1	If beta is less than or equal to one and the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose CM.
2	If the cost of CBM (C_{CBM}) is equal to one and the cost of failure (C_u) is equal to one then choose CM.
3	If the function $\left(\frac{\log(C_{CBM})+\log(C_u)+\text{beta}}{\log(C_{CBM})+\log(C_u)+\log\left(\frac{C_u}{C_{CBM}}\right)}\right)$ is less than 1.06 and beta is less than or equal to one then choose CBM.
4	If the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose ABM.
5	If the function $\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 9.6 then choose ABM.

TABLE XI continued

Order of Use	Decision Rules
6	If the function $\frac{C_u / C_{CBM}}{beta} + \log(C_{CBM}) + \log(C_u) + beta$ is greater than 75 then choose CBM.
7	If the function $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 7.9 then choose ABM.
8*	If beta is less than 1.26, then choose CBM.
9	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 1.53, then choose ABM.
10	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is greater than or equal to 5.5, then choose CBM.
11*	If the function $\log(C_{CBM}) + \log(C_u) + beta$ is less than 3.87, then choose CBM.
12	If the function $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 6.42, then choose ABM.
13	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 2.65, then choose CBM.
14*	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 1.95, then choose ABM.
15	If the function $\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$ is less than 3, then choose CBM.

Validation Set #3 was generated to test the revised decision rules shown in Table XI when the beta parameter was restricted to be greater than 1.0 and less than 1.5 (Table XII). This was done to explore transition range where ABM may be preferred and where ABM will never be preferred. Traditional thought indicates that the transition point is occurs when the beta parameter is equal to one ([McKone, 1996], for example).

TABLE XII

VALIDATION SET #3

Trial Number	Criteria
1 - 10	1 < beta < 1.5 $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 10000$
11 - 20	1 < beta < 1.5 $0 < C_{CBM} <= 100$ $C_{CBM} <= C_u <= 10000$
21 - 30	1 < beta < 1.5 $0 < C_{CBM} <= 1000$ $C_{CBM} <= C_u <= 10000$
31 – 40	1 < beta < 1.5 $0 < C_{CBM} <= 10000$ $C_{CBM} <= C_u <= 10000$
41 - 50	1 < beta < 1.5 $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 10$

The decision rules shown in Table XI neither misclassified nor failed to classify any of the trials in VS3. VS4 was generated using the criteria shown in Table XIII. In this criteria set the beta parameter is restricted to be greater than one and less than two. Additionally, C_u is restricted to greater than or equal to C_{CBM} and less than or equal to four times C_{CBM}. The focus of this validation set was to study what this researcher perceived as a problem area for the decision model.

TABLE XIII

VALIDATION SET #4

Trial Number	Criteria
1 - 10	1 < beta < 2 $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 4*C_{CBM}$
11 - 20	1 < beta < 2 $0 < C_{CBM} <= 100$ $C_{CBM} <= C_u <= 4*C_{CBM}$
21 - 30	1 < beta < 2 $0 < C_{CBM} <= 1000$ $C_{CBM} <= C_u <= 4*C_{CBM}$
31 – 40	1 < beta < 2 $0 < C_{CBM} <= 10000$ $C_{CBM} <= C_u <= 4*C_{CBM}$
41 - 50	1 < beta < 2 $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 4*C_{CBM}$

Table XIV shows that the decision rules shown in Table XI (page 78) did not misclassify any of the trials. However, the decision rules did fail to classify three trials (Trials 11, 15, and 39)

Decision Rule 16 (noted with an asterisk) was added to the decision rules shown in Table XI (page 78) to correctly classify the non-classified trials (Shown in Table XV).

TABLE XIV

RESULTS OF VALIDATION SET #4

Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
11	1.91194	41	148	ABM	Unclassified
15	1.94446	18	63	ABM	Unclassified
39	1.82195	78	224	ABM	Unclassified

TABLE XV

DECISION RULES TO TEST VALIDATION SET #5

Order of Use	Decision Rules
1	If beta is less than or equal to one and the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose CM.
2	If the cost of CBM (C_{CBM}) is equal to one and the cost of failure (C_u) is equal to one then choose CM.
3	If the function $\left(\frac{\log(C_{CBM})+\log(C_u)+\text{beta}}{\log(C_{CBM})+\log(C_u)+\log\left(\frac{C_u}{C_{CBM}}\right)}\right)$ is less than 1.06 and beta is less than or equal to one then choose CBM.
4	If the ratio $\frac{C_u}{C_{CBM}}$ is equal to one then choose ABM.
5	If the function $\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 9.6 then choose ABM.
6	If the function $\frac{C_u/C_{CBM}}{\text{beta}}+\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 75 then choose CBM.
7	If the function $\log(C_{CBM})+\log(C_u)+\text{beta}$ is greater than 7.9 then choose ABM.
8	If beta is less than 1.26, then choose CBM.

TABLE XV continued

Order of Use	Decision Rules
9	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 1.53, then choose ABM.
10	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is greater than or equal to 5.5, then choose CBM.
11	If the function $\log(C_{CBM}) + \log(C_u) + beta$ is less than 3.87, then choose CBM.
12	If the function $\log(C_{CBM}) + \log(C_u) + beta$ is greater than 6.42, then choose ABM.
13	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 2.65, then choose CBM.
14	If the function $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 1.95, then choose ABM.
15	If the function $\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$ is less than 3, then choose CBM.
16	If the function $\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$ is greater than or equal to 3, then choose ABM.

The criteria used to generate VS5 are the same as for VS1 and VS2. Table XVI shows that the revised decision rules shown in Table XV misclassified one trial (Trial 41).

Validation Set #6 was generated using the criteria shown in Table XVII. Note that the C_u is defined as being three times the C_{CBM}. Again, the decision rules shown in Table XV were used.

TABLE XVI

RESULTS OF VALIDATION SET #5

Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
41	3.59	3	9	ABM	CBM

TABLE XVII

VALIDATION SET #6

Trial Number	Criteria
1 - 10	$1 < beta < 6$ $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 3*C_{CBM}$
11 - 20	$1 < beta < 6$ $0 < C_{CBM} <= 100$ $C_{CBM} <= C_u <= 3*C_{CBM}$
21 - 30	$1 < beta < 6$ $0 < C_{CBM} <= 1000$ $C_{CBM} <= C_u <= 3*C_{CBM}$
31 – 40	$1 < beta < 6$ $0 < C_{CBM} <= 10000$ $C_{CBM} <= C_u <= 3*C_{CBM}$
41 - 50	$1 < beta < 6$ $0 < C_{CBM} <= 10$ $C_{CBM} <= C_u <= 3*C_{CBM}$

Two trials in VS6 were misclassified (Table XVIII)

TABLE XVIII

RESULTS OF VALIDATION SET #6

Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
8	3.57555	4	12	ABM	CBM
49	4.38021	3	9	ABM	CBM

If the original data set (90 trials) and the six validation sets are combined and tested using the decision rules shown in Table XV (page 82), Table XIX shows that four trials are misclassified.

TABLE XIX

TOTAL NUMBER OF MISCLASSIFICATIONS

Validation Set	Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
vs2	21	2.04	185	2019	ABM	CBM
vs5	41	3.59	3	9	ABM	CBM
vs6	8	3.58	4	12	ABM	CBM
vs6	49	4.38	3	9	ABM	CBM

What is different about these four trials? Trial 21 from VS2 has a beta parameter of approximately two and a $\frac{C_u}{C_{CBM}}$ ratio of approximately 10. The most evident characteristics of trials 41, 8 and 49 (from VS5, VS6 and VS6, respectively) are that the $\frac{C_u}{C_{CBM}}$ ratio is equal to three and the beta parameter values are between approximately 3.5 and 4.5. These characteristics do not indicate why these trials are not classified properly by the decision rules since other trials with these characteristics were properly classified in one or more of the previous validation sets. However, the decision rules did accurately classify 386 out of a total 390 trials.

The last set of decision rules (Table XV, page 82) shows 16 steps are required to obtained the results shown in Table XIX. Generally, the larger the order of use number a rule has, the smaller the number of trials predicted by the rule. This research believes that the "point of diminishing returns" has been reached with regard to adding additional rules. Therefore, this experimental methodology will return to MVLR analysis to attempt to explain those trials that are difficult to classify using the decision rules.

Similar to the multivariate linear regression (MVLR) performed at the beginning of this experimental methodology, a MVLR was performed (Appendix F) on the 428 trials plus 50 additional trials (VS6a) that were generated using the criteria shown in Table XX. There are only 428 trials instead of 440 because those trials that specified CM were omitted. Corrective maintenance is considered separately. The purpose for this additional data set was to give the MVLR model more information concerning values similar to trial number 21 in VS2 (beta parameter of approximately 2 and a $\frac{C_u}{C_{CBM}}$ ratio of approximately 10).

The MVLR model accurately predicted 223 out 248 ABM trials and 160 out of 180 CBM trials (Table XXI). The linear equation is shown in Appendix F.

TABLE XX

VALIDATION SET #6A

Trial Number	Criteria
1 - 10	1.5 < beta < 2.5 $0 < C_{CBM} <= 10$ $9*C_{CBM} <= C_u <= 11*C_{CBM}$
11 - 20	1.5 < beta < 2.5 $0 < C_{CBM} <= 100$ $9*C_{CBM} <= C_u <= 11*C_{CBM}$
21 - 30	1.5 < beta < 2.5 $0 < C_{CBM} <= 1000$ $9*C_{CBM} <= C_u <= 11*C_{CBM}$
31 – 40	1.5 < beta < 2.5 $0 < C_{CBM} <= 10000$ $9*C_{CBM} <= C_u <= 11*C_{CBM}$
41 - 50	1.5 < beta < 2.5 $0 < C_{CBM} <= 10$ $9*C_{CBM} <= C_u <= 11*C_{CBM}$

TABLE XXI

RESULTS OF MULTIVARIATE LINEAR REGRESSION ANALYSIS

		Predicted		
		ABM	CBM	Total
Actual	ABM	222	26	248
	CBM	20	160	180

The next subsection studies the results presented above and presents a recommended maintenance strategy selection decision model.

4.4 Analysis of the Results of Phase One

The first step in this analysis is to compare the trials that were misclassified by the decision rule model and that were misclassified by the regression model. If VS6a is included, the decision rule model misclassified seventeen trials (Table XXII).

TABLE XXII

MISCLASSIFICATIONS FOR DECISION RULE MODEL

	Validation Set	Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
1	vs2	21	2.04	185	2019	ABM	CBM
2	vs5	41	3.59	3	9	ABM	CBM
3	vs6	8	3.58	4	12	ABM	CBM
4	vs6	49	4.38	3	9	ABM	CBM
5	vs6a	11	2.05	71	746	ABM	CBM
6	vs6a	12	2.31	30	324	ABM	CBM
7	vs6a	13	2.12	98	1000	ABM	CBM
8	vs6a	14	2.27	19	194	ABM	CBM
9	vs6a	15	2.22	92	978	ABM	CBM
10	vs6a	16	2.01	46	432	ABM	CBM
11	vs6a	17	2.41	40	434	ABM	CBM
12	vs6a	19	1.92	50	455	ABM	CBM
13	vs6a	24	1.89	138	1272	ABM	CBM
14	vs6a	25	1.68	281	2813	ABM	CBM
15	vs6a	29	1.86	208	2103	ABM	CBM
16	vs6a	32	1.50	9241	94284	ABM	CBM
17	vs6a	39	1.56	3450	37795	ABM	CBM

An interesting note concerning the decision rules' misclassifications is that only ABM strategies were misclassified. The regression model misclassified 46 trials (Table XXIII).

TABLE XXIII

TOTAL NUMBER OF MISCLASSIFICATIONS FOR REGRESSION MODEL

Validation Set	Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
Original	57	2.50	100.00	10000.00	ABM	CBM
Original	83	4.50	10.00	1000.00	ABM	CBM
Original	99	5.50	10.00	10000.00	ABM	CBM
VS1	16	2.69	68.00	4973.00	ABM	CBM
VS1	49	1.48	7.00	7.00	ABM	CBM
VS1	50	1.43	10.00	10.00	ABM	CBM
VS2	15	3.63	24.00	1954.00	ABM	CBM
VS2	18	2.24	94.00	9854.00	ABM	CBM
VS2	44	1.42	3.00	3.00	ABM	CBM
VS3	42	1.31	8.00	9.00	ABM	CBM
VS3	47	1.30	9.00	9.00	ABM	CBM
VS3	48	1.36	7.00	8.00	ABM	CBM
VS3	49	1.28	10.00	10.00	ABM	CBM
VS3	50	1.41	8.00	8.00	ABM	CBM
VS4	2	1.79	8.00	15.00	ABM	CBM
VS4	15	1.94	18.00	63.00	ABM	CBM
VS4	41	1.79	8	10.00	ABM	CBM
VS4	44	1.83	10.00	23.00	ABM	CBM
VS5	11	4.77	25.00	9573.00	ABM	CBM
VS5	43	1.56	8.00	10.00	ABM	CBM
VS5	46	1.87	6.00	9.00	ABM	CBM
VS6	20	1.81	18.00	54.00	ABM	CBM
VS6A	12	2.31	30.00	324.00	ABM	CBM
VS6A	14	2.27	19.00	194.00	ABM	CBM
VS6A	16	2.01	46.00	432.00	ABM	CBM
VS6A	19	1.92	50.00	455.00	ABM	CBM
Original	29	1.00	1000.00	10000.00	CBM	ABM
Original	41	1.50	100.00	1000.00	CBM	ABM
Original	92	5.50	1.00	10.00	CBM	ABM
VS1	21	1.21	313.00	5744.00	CBM	ABM
VS1	41	4.62	2.00	6.00	CBM	ABM
VS2	23	1.10	655.00	3459.00	CBM	ABM
VS3	21	1.05	851.00	2228.00	CBM	ABM
VS3	23	1.44	316.00	5963.00	CBM	ABM
VS3	25	1.25	342.00	1136.00	CBM	ABM
VS3	28	1.08	475.00	7072.00	CBM	ABM
VS3	31	1.10	269.00	7088.00	CBM	ABM
VS3	35	1.08	476.00	8891.00	CBM	ABM
VS4	12	1.41	50.00	175.00	CBM	ABM
VS4	19	1.26	92.00	357.00	CBM	ABM
VS4	20	1.14	75.00	198.00	CBM	ABM
VS4	26	1.02	661.00	1302.00	CBM	ABM
VS4	27	1.09	107.00	376.00	CBM	ABM
VS6	11	1.05	65.00	195.00	CBM	ABM
VS6	50	5.34	2.00	6.00	CBM	ABM
VS6A	28	1.69	72.00	694.00	CBM	ABM

The regression model results are more difficult to analyze. There appears to be small sets of commonality within the data, however, broad generalizations are not evident. Consequently, the approach taken by this research is to combine the results of the decision rules model and a MVLR model. Specifically, a regression analysis, shown in Appendix G, was performed on VS6a (1.5 > beta > 2.5, $9*C_{CBM} < C_u < 11*C_{CBM}$). This regression model will then be used to prescreen for the decision rule model. Specifically, if beta is between the values 1.5 and 2.5 and the cost of failure is between nine and 10 times the cost of performing CBM then the regression model will be applied before the decision rules.

The linear regression model is shown in Equation 47. The decision rule is to select ABM when M_s is greater than zero, otherwise choose CBM.

$$M_s = 7.3089 + 2.48305 * \text{beta} - 10.3378* \left(\frac{\log(C_{CBM}) + \log(C_u) + \text{beta}}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)} \right) \quad (47)$$

where

M_s = ABM if $M_S > 0$ or CBM is $M_S \leq 0$

Table XXIV shows the regression analysis results. The regression results show that all of the specified ABM trials were predicted accurately and only one of the specified CBM trials were misclassified. Using this combined decision methodology, the total number of misclassifications is shown in Table XXV. The first four trials listed are the result of misclassification by the decision rules. The last trial is a result of misclassification by the regression model.

TABLE XXIV

RESULTS OF MVLR ANALYSIS ON VS6A

		Predicted ABM	Predicted CBM	Total
Actual	ABM	29	0	29
	CBM	1	20	21

TABLE XXV

MISCLASSIFIED TRIALS USING THE COMBINED METHODOLOGY

Validation Set	Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
vs2	21	2.04	185	2019	ABM	CBM
vs5	41	3.59	3	9	ABM	CBM
vs6	8	3.58	4	12	ABM	CBM
vs6	49	4.38	3	9	ABM	CBM

What is the impact of making the misclassifications shown in Table XXV? Table XXVI shows the calculated long run average cost and the expected maintenance interval for the misclassified trials shown in Table XXV. Note that there are two columns for CBM. Column “CBM Cost (50)” represents the cost of performing CBM under a 50% discrimination level. Column “CBM Cost (min)” represents the cost of performing CBM under a 9.76E-07% discrimination level. The maintenance interval times are interpreted similarly.

The cost data for trials 8, 41 and 49 (from VS6, VS5 and VS6, respectively) show that cost of performing CBM versus ABM is less than a factor of two. Admittedly, this difference could be significant. However, each of these three misclassifications occur when the cost of performing CBM is only 3 to 4 times greater than the cost of performing ABM. Furthermore, the cost of failure is only three times greater than the cost of performing CBM. Therefore, unless the cost of performing ABM is large these costs differences are likely not large. Table XXVI also shows that in trial 28 (from VS6a) the cost of performing ABM is between the two values shown for performing CBM. Therefore, the discriminatory ability of the CBM MMI process will determine if CBM is economically preferred. A discussion of the maintenance interval times will be presented at the end of this chapter.

TABLE XXVI

COSTS AND MAINTENANCE INTERVAL OF MISCLASSIFIED TRIALS USING THE COMBINED METHODOLOGY

Validation Set	Trial	Economically Preferred Strategy	CM Cost	CM Time	ABM Cost	ABM Time	CBM Cost (50)	CBM Cost (min)	CBM Time (50)	CBM Time (min)
VS5	41	ABM	9.99	0.90	3.24	0.43	4.71	3.33	0.64	0.90
VS6	8	ABM	13.32	0.90	3.54	0.39	6.28	4.44	0.64	0.90
VS6	49	ABM	9.88	0.91	2.76	0.47	4.66	3.29	0.64	0.91
VS6A	28	CBM	777.50	0.89	94.33	0.03	114.07	80.66	0.63	0.89

To test the combined decision methodology, two new validation sets (VS7 and VS8) were generated. The criteria used for VS7 limited the maximum beta value to seven, otherwise the criteria used for VS7 andVS8 were the same as those used for VS1. Table XXVII shows the three trials that were misclassified out of 100 trials.

Table XXIII shows that the cost of performing ABM maintenance is, at most, less than four times greater than performing CBM. Again noting that the cost of performing CBM is only two to four times greater than performing ABM, in a practical sense the difference is likely minimal.

TABLE XXVII

TRIALS MISCLASSIFIED USING THE COMBINED METHODOLOGY

Validation Set	Trial Number	beta	C_{CBM}	C_u	Economically Preferred Strategy	Predicted Strategy
VS7	1	6.98	2.00	8792.00	CBM	ABM
VS7	3	5.56	2.00	5916.00	CBM	ABM
VS8	2	5.89	4.00	9794.00	CBM	ABM

TABLE XXVIII

COSTS AND MAINTENANCE INTERVAL OF MISCLASSIFIED TRIALS USING THE COMBINED METHODOLOGY

Validation Set	Trial	Economically Preferred Strategy	CM Cost	CM Time	ABM Cost	ABM Time	CBM Cost (50)	CBM Cost (min)	CBM Time (50)	CBM Time (min)
VS7	1	CBM	9400.00	0.94	5.54	0.21	3.02	2.14	0.66	0.94
VS7	3	CBM	6404.00	0.92	7.64	0.16	3.06	2.17	0.65	0.92
VS8	2	CBM	10570.00	0.93	7.51	0.16	6.10	4.32	0.66	0.93

4.5 Summary of Phase One

Phase one of this research methodology focused on developing a maintenance strategy selection decision model. As might be expected the first half of the decision rules predict the majority of the trials. For example, the regression model combined with the first five decision rules correctly predicts 72% of the trials.

Two specific areas are difficult to predict. The first area occurs when beta is between 3.5 and 4.5 and the ratio C_u/C_{CBM} is approximately equal to three. However, this area does not appear to pose a significant problem with regard to the applicability of this decision model. The reason is that the decision model only has prediction difficulties when the cost of performing ABM is of the same magnitude as the cost of performing CBM. Therefore, a prediction error by the model is likely not significant on a practical level.

The other area that is difficult to predict occurs when beta is between 1.5 and 2.5, and the ratio C_u/C_{CBM} is between 9 and 11. The need to accurately predict this area was the major reason that a regression component was added to the decision model. It appears that even though the set of decision rules developed using the defined decision variables performed satisfactorily for the majority of the trials studied, these decision rules did not perform well in this problem area. This would indicate that the defined decision variables do not constitute a complete decision variables set. Unfortunately, this researcher was unable to identify any additional variable(s). The search for this/these variable(s) will be left to future work. The regression, however, performs well in this problem area. It is interesting to note that even though all of the defined decision variables were used in the regression analysis, only two decision variables were found to be significant. They were the beta parameter and the functional relationship

$$\frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}.$$

4.6 Results of Phase Two

The purpose of phase two of the research is to comment on the effects of the Weibull scale parameter θ and the implementation and continuation costs on the maintenance strategy selection decision process. Doubling the scale parameter θ did not change the economically preferred maintenance strategy decision for any of the trials (Appendix H)

The effects of the implementation and continuation costs on the maintenance strategy selection process when the implementation and continuation cost for ABM is equal to 0.01 times the cost of performing ABM was explored (see Appendix B). This value was arbitrarily chosen. The implementation and continuation costs for CBM were defined as order of magnitude changes of the implementation and continuation cost for ABM and range from 1 to 10000 times the ABM implementation and continuation cost. Future work will study a broad range of implementation and continuation costs. A more complete discussion concerning the implementation and continuation costs is presented in the next subsection.

4.7 The Research Questions

This research, as in all research, asked questions and searched for answers or more insight into the questions. Specifically, this research asked five questions. The goal of these questions was to better understand and to ultimately predict an economically preferred maintenance strategy when the choices are between CM, ABM and CBM. The following discussion addresses each of the five research questions.

1. At what level of failure cost is an age-based maintenance strategy economically preferable to corrective maintenance?

Table XXIX shows that CM is preferred over ABM when beta is equal to one or when the cost of failure is equal to the cost of performing ABM.

TABLE XXIX

TRIALS WHERE CM IS THE ECONOMICALLY PREFERRED MAINTENANCE STRATEGY

Data Set	Trial	beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
Original	16	1.00	1	1	CM
Original	31	1.50	1	1	CM
Original	46	2.50	1	1	CM
Original	61	3.50	1	1	CM
Original	76	4.50	1	1	CM
Original	91	5.50	1	1	CM
VS1	48	5.57	1	1	CM
Original	21	1.00	10	10	CM
Original	25	1.00	100	100	CM
Original	28	1.00	1000	1000	CM
Original	30	1.00	10000	10000	CM

2. At what level of failure cost and condition-based maintenance event cost is a condition-based maintenance strategy economically preferable to an age-based maintenance strategy?

The approach taken to gain an understanding of when CBM is preferred over ABM was to perform two Principal Component analyses. The first analysis was performed on those trials that resulted in a CBM selection. The second analysis was performed on those trials that resulted in an ABM selection. Appendix I shows the complete results of these analyses.

Table XXX shows the first four principal components that explain 94% of the variation in the data when CBM is the preferred maintenance strategy. If the two largest contributors[1] (including ties) to each principal component are selected it is seen that the variables first principal component is described by the variables CCb, CCBLB and LLCCB describe the first principal component (Table XXXI). The variables beta and LL describe the second principal component. The variables beta and LB describe the third principal component. The variable Ccbm describes the fourth principal component. Only Ccbm was selected for the fourth principal component since it is significantly larger than the other variables. Table XXXII (page 100) shows the definition of the variables used in the principal component analysis.

Table XXXIII (page 101) shows that the first four principal components explain 95% of the variation in the data when ABM is the preferred maintenance strategy. The first four principal components are listed in Table XXXIV (page 102). Again, if the two largest contributors (including ties) to each principal component are selected it is seen that the variables first principal component is described by the variables CCb, CCBLB, CuCcbm and LLCCB describe the first principal component.

[1] There is no exact approach to choosing the major contributors when using a principal component analysis. The focus of a principal component analysis is to gain insight into the minimum number of independent, but unknown, variables underlying a process [Johnson, 1998]. In general, the fewer contributors used the better.

TABLE XXX

PRINCIPAL COMPONENT ANALYSIS RESULTS ON THE CBM SELECTED TRIALS

CBM Selected

	Eigenvalue	Difference	Proportion	Cumulative
Prin 1	5.11	2.79	0.46	0.46
Prin 2	2.32	0.27	0.21	0.68
Prin 3	2.05	1.16	0.19	0.86
Prin 4	0.89	0.58	0.08	0.94
Prin 5	0.31	0.11	0.03	0.97
Prin 6	0.19	0.11	0.02	0.99
Prin 7	0.08	0.03	0.01	1.00
Prin 8	0.05	0.05	0.00	1.00
Prin 9	0.00	0.00	0.00	1.00
Prin 10	0.00	0.00	0.00	1.00
Prin 11	0.00	0.00	0.00	1.00

TABLE XXXI

THE FOUR LARGEST PRINCIPAL COMPONENTS FOR THE CBM SELECTED TRIALS

CBM Selected

	Prin1	Prin2	Prin3	Prin4
beta	0.00	0.38	0.54	-0.17
Ccbm	0.02	-0.33	0.14	0.89
Cu	0.35	-0.18	0.25	-0.05
CuCcbm	0.36	0.29	0.01	0.05
CCb	0.38	0.26	-0.18	0.15
LL	-0.26	0.42	0.16	0.26
LB	0.21	-0.13	0.59	-0.02
LCC	0.33	-0.31	0.29	-0.13
LBLC	-0.29	0.36	0.31	0.19
CCBLB	0.38	0.26	-0.18	0.15
LLCCB	0.39	0.27	-0.12	0.11

TABLE XXXII

DEFINITION OF VARIABLES USED IN THE PRINCIPAL COMPONENT ANALYSIS

Variable Name	Variable Definition
beta	The beta parameter of the Weibull distribution
Ccbm	The cost of performing CBM
Cu	The cost of failure
CuCcbm	$\frac{C_u}{C_{CBM}}$
CCb	$\frac{C_u / C_{CBM}}{beta}$
LL	$\frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$
LB	$\log(C_{CBM}) + \log(C_u) + beta$
LLC	$\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$
LBLC	$\log(C_{CBM}) + \log(C_u) + beta - (\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right))$
CCBLB	$\frac{C_u / C_{CBM}}{beta} + \log(C_{CBM}) + \log(C_u) + beta$
LLCCB	$\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$

Four variables where chosen for the first principal component because of their nearly equal weighting within the principal component. The variables LL and Ccbm describe the second principal component. The variables beta and LBLC describe the third principal component. The variable Cu describes the fourth principal component. Only Cu was selected for the fourth principal component since it is significantly larger than the other variables.

Table XXXIII

PRINCIPAL COMPONENT ANALYSIS RESULTS ON THE ABM SELECTED TRIALS

ABM Selected	Eigenvalue	Difference	Proportion	Cumulative
Prin 1	4.24	1.18	0.39	0.39
Prin 2	3.06	0.71	0.28	0.66
Prin 3	2.35	1.53	0.21	0.88
Prin 4	0.82	0.42	0.07	0.95
Prin 5	0.40	0.29	0.04	0.99
Prin 6	0.10	0.08	0.01	1.00
Prin 7	0.03	0.02	0.00	1.00
Prin 8	0.01	0.01	0.00	1.00
Prin 9	0.00	0.00	0.00	1.00
Prin 10	0.00	0.00	0.00	1.00
Prin 11	0.00	0.00	0.00	1.00

Table XXXV summarizes the results shown in Table XXXIV. A significant note regarding these results is that the ration C_u/C_{CBM} is not listed in the CBM selected column of Table XXXV. The same is true for the variable LBLC, which is the difference between beta and the logarithm of C_u/C_{CBM}.

TABLE XXXIV

THE FOUR LARGEST PRINCIPAL COMPONENTS FOR THE ABM SELECTED TRIALS

ABM Selected	Prin1	Prin2	Prin3	Prin4
beta	0.07	0.31	0.52	-0.12
Ccbm	0.06	-0.39	0.26	0.44
Cu	0.14	-0.36	0.13	0.62
CuCcbm	0.45	0.19	-0.09	0.08
CCb	0.46	0.16	-0.12	0.07
LL	-0.18	0.43	0.18	0.47
LB	0.20	-0.23	0.50	-0.28
LCC	0.24	-0.43	0.19	-0.29
LBLC	-0.05	0.30	0.54	0.00
CCBLB	0.47	0.11	-0.03	0.02
LLCCB	0.45	0.18	-0.11	0.07

TABLE XXXV

SUMMARY OF PRINCIPAL COMPONENT ANALYSES

	CBM Selected	ABM Selected
Prin 1	CCb, CCBLB and LLCCB	CCb, CCBLB, CuCcbm and LLCCB
Prin 2	Beta and LL	LL and Ccbm
Prin 3	Beta and LB	Beta and LBLC
Prin 4	Ccbm	Cu

Figure 7 shows a scatter plot of the logarithm of C_u/C_{CBM} versus beta, for the trials of either the original data set or VS1 to VS6a, where either CBM or ABM was preferred. The dashed line shows an approximation of the boundary for determining CBM is preferred over ABM (i.e., CBM is always preferred above the dashed line). Note that the lower left hand corner of the data plot corresponds to C_u/C_{CBM} ratios of approximately 10 or less. This was also identified as an area that was difficult to predict in the preceding subsection. Consequently, the decision model required the use of a MVLR model to describe this area.

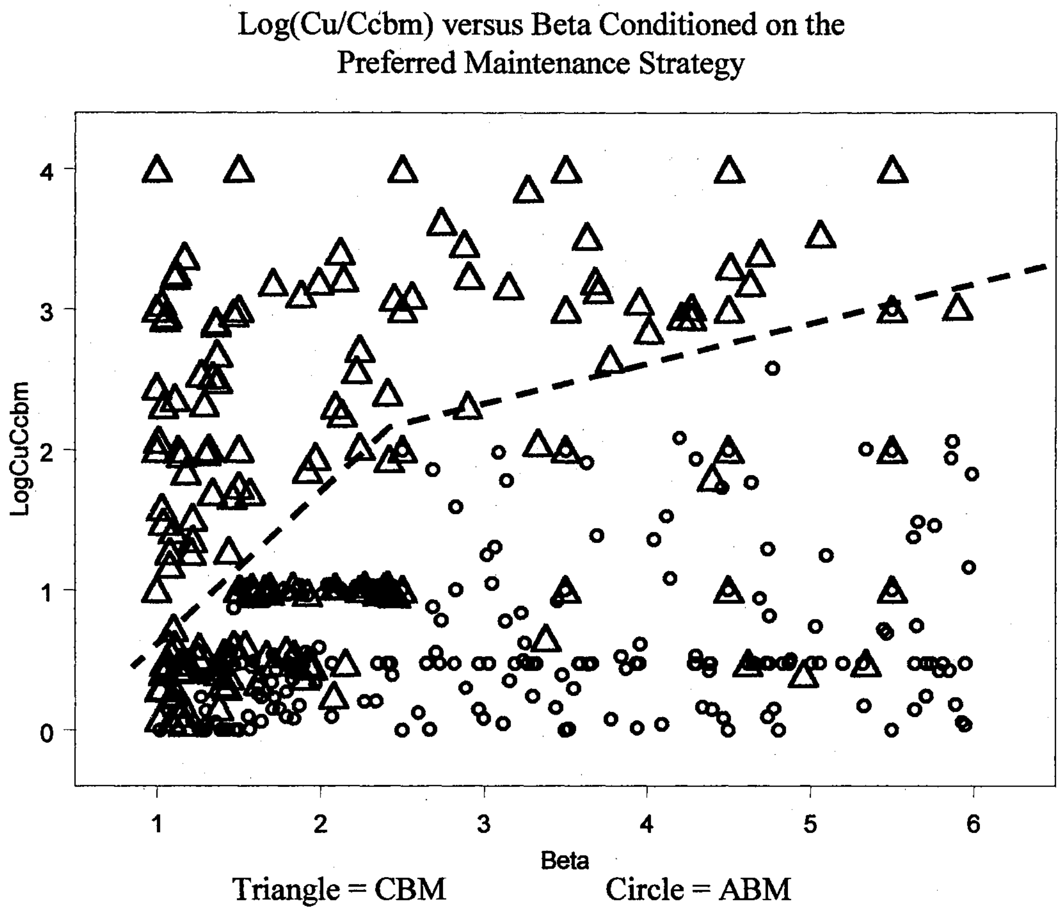

Figure 7. Scatter plot of the logarithm of Cu/CCBM versus beta conditioned on the preferred maintenance strategy

3. At what level of failure cost and condition-based maintenance event cost is a condition-based maintenance strategy preferable to a corrective maintenance strategy?

The answer to this research question is the same as stated for research question number one.

4. At what level of condition-based maintenance implementation and continuation costs is a condition based maintenance strategy economically preferable to an age-based maintenance strategy?

This research question is answered by assuming a worst-case approach because the discriminatory ability of the CBM MMI process affects the flexibility that a practitioner has regarding the acceptable level of implementation and continuation costs. Specifically, it is assumed that the discriminatory ability of the CBM MMI process is the largest level possible such that CBM is still the economically preferred maintenance strategy.

Figure 8 shows a plot of the cost difference between the cost of ABM and the cost of CBM, when CBM is preferred, divided by the ratio C_u/C_{CBM} versus beta (see Appendix J for the data set). Therefore, given values for beta and the ratio C_u/C_{CBM} a practitioner can determine the possible range of acceptable implementation and continuation costs when CBM is to be preferred over ABM.

For example, suppose that a practitioner has an asset that has a Weibull failure density function beta parameter of two, a C_u/C_{CBM} ratio of 100 and the combined decision methodology predicts a CBM strategy. Figure 9 indicates that difference between the cost of ABM and the cost of CBM is approximately 100 or less. Therefore, if the implementation and continuation cost per unit time for CBM is not more than \$100, then CBM is the preferred maintenance strategy.

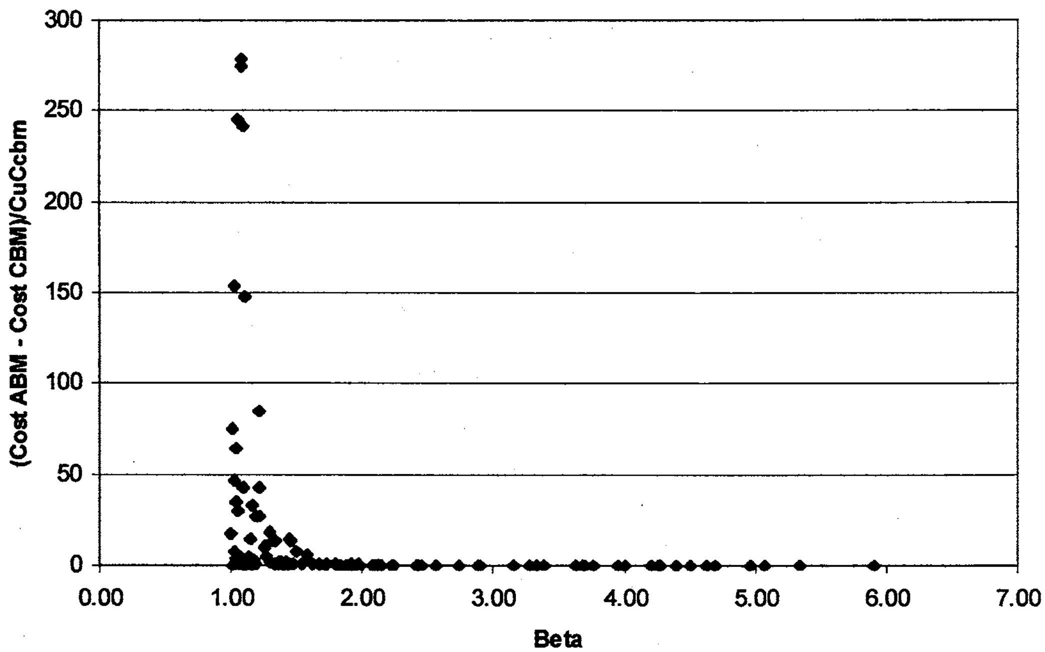

Figure 8. Plot of the cost difference between the cost of ABM and the cost of CBM, when CBM is preferred, divided by the ratio C_u/C_{CBM} versus beta

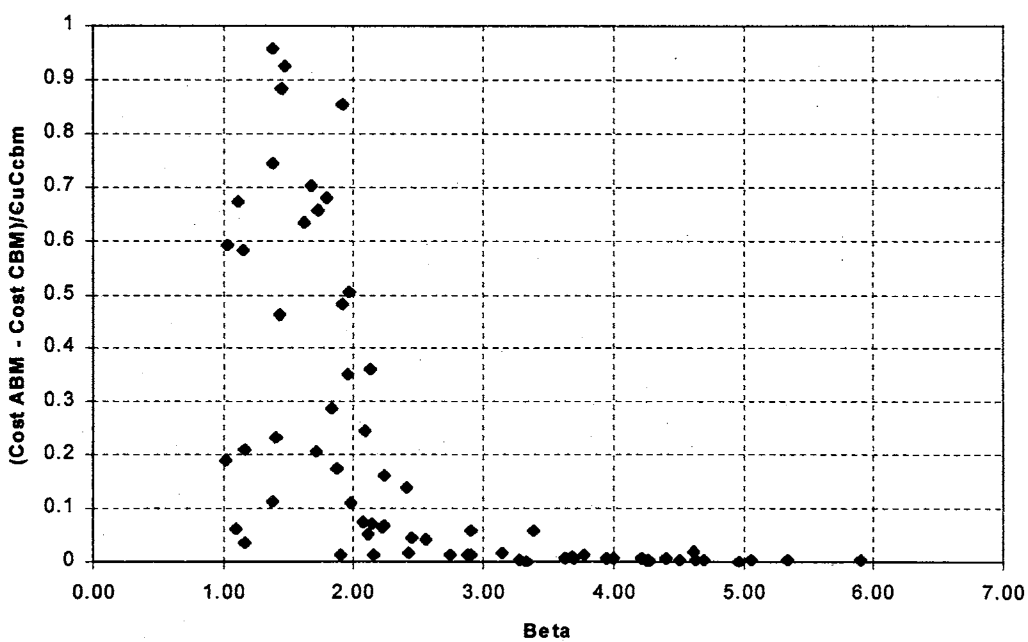

Figure 9. Enlargement of the lower portion of Figure 8

5. What level of accuracy is necessary to make a condition-based maintenance strategy an economically preferred maintenance strategy?

Table XXXVI (page 108) shows the necessary discrimination level for selecting CBM using the combined decision methodology presented in this chapter and using VS1 – VS6. The values shown in the discrimination level columns are the difference between the cost of ABM and the selected discrimination level cost of CBM. The "boxed" values indicate the worst case (but acceptable) level of discrimination.

This researcher attempted to classify the discrimination levels using both MVLR analysis and decision rules. However, both of these approaches failed to predict the correct discrimination level effectively. This leads this researcher to propose that there are other factors that remain to be determined before an accurate classification process is determined. In general, the table shows that a 50% discrimination level is acceptable for a majority of the trials.

4.8 Summary

This chapter presented the result and analysis of the experimental methodology presented in Chapter 3. The focus of this research was to explore the conditions under which corrective maintenance, age-based maintenance, and condition-based maintenance are economically preferred.

The result of this exploration was a maintenance strategy selection decision model that incorporates a multivariate linear regression model and a set of ordered decision rules. This decision model should be useful on a practical level to maintenance practitioners.

The development of the decision model led to the discovery that the traditional decision variables – beta, the cost of CBM, the cost of failure, and the cost of ABM – are not sufficient to classify the economically preferred maintenance strategy using simple linear models.

TABLE XXXVI

DISCRIMINATION LEVEL NECESSARY TO CHOOSE CBM

DataSet	Trial	beta	Ccbm	Cu	Discrimination Level = 50%	Discrimination Level = 25%	Discrimination Level = 12.5%	Discrimination Level = 6.25%	Discrimination Level = 3.125%	Discrimination Level = 1.625%
vs2	45	4.96	2	5	-0.89	-0.32	-0.14	-0.06	-0.02	0.00
vs6	50	5.34	2	6	-0.87	-0.31	-0.12	-0.04	-0.01	0.01
vs4	4	1.90	8	19	-3.56	-1.22	-0.45	-0.12	0.03	0.10
vs6	10	2.15	7	21	-3.11	-1.06	-0.38	-0.10	0.04	0.10
vs1	19	3.33	15	1666	-6.55	-2.21	-0.78	-0.17	0.11	0.25
vs5	45	2.08	4	7	-1.59	-0.42	-0.04	0.13	0.20	0.24
vs1	18	2.42	54	4614	-21.79	-5.98	-0.77	1.44	2.46	2.96
vs2	41	1.16	9	10	-3.23	-0.77	0.04	0.38	0.54	0.62
vs1	41	4.62	2	6	-0.70	-0.13	0.06	0.14	0.18	0.19
vs5	2	4.40	5	317	-1.44	-0.01	0.46	0.66	0.75	0.79
vs2	18	2.24	94	9854	-29.48	-1.94	7.15	11.00	12.78	13.64
vs4	3	1.09	6	7	-1.54	0.07	0.60	0.83	0.93	0.98
vs4	43	1.38	7	10	-1.83	0.16	0.82	1.09	1.22	1.29
vs3	43	1.02	5	6	-108	0.23	0.66	0.84	0.93	0.97
vs3	46	1.15	7	9	-1.16	0.75	1.38	1.65	1.77	1.83
vs4	1	1.95	5	14	-0.48	0.99	1.47	1.68	1.77	1.82
vs4	47	1.84	9	31	-1.63	0.99	1.86	2.23	2.40	2.48
vs4	46	1.62	6	13	-0.37	1.37	1.95	2.19	2.30	2.36
vs6	45	1.92	5	15	-0.02	1.44	1.92	2.13	2.22	2.27
vs4	18	1.67	12	41	-1.09	2.40	3.55	4.03	4.26	4.37
vs4	12	1.41	50	175	-6.67	7.58	12.28	14.27	15.20	15.64
vs3	25	1.25	342	1136	-60.74	34.55	66.00	79.31	85.48	88.45
vs5	3	4.27	9	7908	0.11	2.68	3.53	3.89	4.05	4.13
vs1	42	3.38	2	9	0.26	0.84	1.03	1.11	1.15	1.17
vs4	13	1.16	4	6	0.31	1.41	1.77	1.92	1.99	2.03
vs4	8	1.40	9	19	0.49	3.06	3.90	4.26	4.42	4.50
vs3	44	1.43	5	10	0.93	2.35	2.83	3.03	3.12	3.16
vs4	7	1.03	2	4	1.19	1.71	1.88	1.96	1.99	2.01
vs1	6	4.27	8	8205	1.79	4.07	4.82	5.14	5.29	5.36
vs6	5	1.72	2	6	1.97	2.55	2.74	2.83	2.86	2.88
vs4	45	1.44	5	12	2.12	3.55	4.03	4.22	4.32	4.36
vs4	48	1.12	6	11	2.40	4.03	4.56	4.79	4.89	4.94
vs4	49	1.79	3	11	2.49	3.37	3.66	3.78	3.84	3.86
vs4	42	1.09	8	14	2.57	4.72	5.42	5.72	5.86	5.93
vs4	10	1.11	1	4	2.69	2.96	3.05	3.08	3.10	3.11
vs4	17	1.38	11	28	2.71	5.83	6.87	7.30	7.50	7.60
vs2	2	4.63	6	9214	2.82	4.52	5.09	5.32	5.43	5.49
vs3	41	1.38	2	6	2.88	3.44	3.63	3.71	3.75	3.76
vs4	6	1.07	2	6	3.26	3.79	3.97	4.04	4.07	4.09

TABLE XXXVI continued

DataSet	Trial	beta	Ccbm	Cu	Discrimination Level = 50%	Discrimination Level = 25%	Discrimination Level = 12.5%	Discrimination Level = 6.25%	Discrimination Level = 3.125%	Discrimination Level = 1.625%
vs6	43	1.19	2	6	3.27	3.82	4.00	4.08	4.12	4.13
vs5	10	5.90	1	1037	3.59	3.87	3.96	4.00	4.02	4.03
vs2	43	1.47	2	8	4.05	4.62	4.81	4.89	4.93	4.95
vs2	8	4.01	6	4246	4.72	6.44	7.01	7.25	7.36	7.41
vs5	9	3.77	6	2642	5.02	6.75	7.32	7.56	7.67	7.72
vs4	50	1.54	5	20	5.17	6.61	7.08	7.28	7.38	7.42
vs2	1	4.21	4	3558	5.84	6.99	7.36	7.52	7.60	7.63
vs1	1	4.51	4	8052	6.27	7.41	7.78	-2.33	-2.26	8.05
vs1	10	5.06	2	6914	6.36	6.92	7.11	7.19	7.22	7.24
vs1	7	4.69	3	7553	6.63	7.48	7.76	7.88	7.94	7.97
vs4	9	1.18	7	19	7.48	9.40	10.03	10.30	10.43	10.49
vs6	6	1.14	5	15	7.52	8.88	9.33	9.52	9.60	9.65
vs1	4	3.95	4	4539	8.60	9.74	10.12	10.28	10.36	10.39
vs4	5	1.04	9	23	10.36	12.73	13.52	13.85	14.00	14.08
vs2	5	3.70	7	9590	10.39	12.40	13.07	13.35	13.48	13.54
vs2	7	2.90	7	1445	12.30	14.34	15.01	15.30	15.43	15.49
vs5	4	3.68	4	6294	13.07	14.22	14.60	14.76	14.83	14.87
vs6	46	1.05	9	27	14.26	16.64	17.42	17.76	17.91	17.99
vs1	3	3.63	2	6585	17.00	17.57	17.76	17.84	17.88	17.90
vs2	6	3.15	4	5841	23.00	24.16	24.54	24.70	24.78	24.81
vs2	4	2.91	1	1726	23.06	23.35	23.45	23.49	23.51	23.52
vs5	1	2.22	7	2560	23.43	25.48	26.15	26.44	26.57	26.63
vs1	5	3.27	1	7205	26.42	26.71	26.80	26.84	26.86	26.87
vs2	17	2.41	24	6089	35.01	42.03	44.35	45.33	45.79	46.00
vs4	19	1.26	92	357	36.36	62.04	70.52	74.11	75.77	76.57
vs4	20	1.14	75	198	38.43	58.83	65.56	68.41	69.73	70.37
vs1	11	2.88	3	8783	39.88	40.76	41.04	41.17	41.22	41.25
vs2	20	1.97	96	8540	44.83	72.94	82.21	86.14	87.96	88.83
vs2	3	2.74	2	8401	48.97	49.55	49.74	49.82	49.86	49.88
vs2	10	2.09	6	1227	50.46	52.21	52.79	53.04	53.15	53.21
vs5	8	2.56	6	7472	54.06	55.82	56.40	56.64	56.75	56.81
vs1	8	2.45	4	4813	56.23	57.40	57.79	57.95	58.03	58.07
vs5	16	1.92	56	4001	60.95	77.33	82.74	85.02	86.08	86.60
vs5	18	2.13	33	5905	64.99	74.66	77.85	79.20	79.83	80.13
vs5	14	2.24	15	7759	84.45	88.85	90.30	90.91	91.19	91.33
vs6	11	1.05	65	195	89.31	106.51	112.18	114.59	115.70	116.24
vs2	11	2.14	4	6599	115.20	116.37	116.76	116.92	117.00	117.03
vs1	2	2.12	3	7712	131.32	132.20	132.49	132.61	132.67	132.69
vs4	27	1.09	107	376	149.52	178.21	187.68	191.68	193.54	194.43
vs1	9	1.99	5	7816	172.85	174.32	174.80	175.01	175.10	175.15
vs5	5	1.88	6	7636	222.43	224.19	224.77	225.01	225.13	225.18

TABLE XXXVI continued

DataSet	Trial	beta	Ccbm	Cu	Discrimination Level = 50%	Discrimination Level = 25%	Discrimination Level = 12.5%	Discrimination Level = 6.25%	Discrimination Level = 3.125%	Discrimination Level = 1.625%
vs3	23	1.44	316	5963	282.28	372.64	402.46	415.08	420.93	423.75
vs4	26	1.02	661	1302	302.54	475.49	532.57	556.73	567.92	573.31
vs2	29	1.57	125	6210	304.93	341.04	352.96	358.01	360.35	361.47
vs5	6	1.71	4	6108	316.28	317.45	317.83	317.99	318.07	318.10
vs3	6	1.37	3	1436	356.48	357.34	357.62	357.74	357.79	357.82
vs3	19	1.29	6	1274	425.69	427.37	427.92	428.16	428.27	428.32
vs2	13	1.50	100	5515	433.21	461.96	471.45	475.46	477.32	478.22
vs3	4	1.34	5	1662	438.25	439.66	440.13	440.33	440.42	440.46
vs3	10	1.13	8	798	516.36	518.53	519.25	519.55	519.69	519.76
vs3	13	1.22	77	1744	611.18	632.51	639.55	642.53	643.91	644.57
vs3	3	1.37	10	3103	618.41	621.25	622.19	622.58	622.77	622.85
vs3	22	1.46	179	8308	622.47	673.75	690.67	697.83	701.15	702.75
vs3	7	1.11	4	920	639.89	640.96	641.32	641.47	641.54	641.57
vs3	21	1.05	851	2228	642.00	867.00	941.43	972.88	987.45	994.48
vs1	13	1.34	71	3517	671.03	691.10	697.72	700.53	701.82	702.45
vs2	9	1.47	9	8314	854.23	856.81	857.66	858.02	858.19	858.27
vs3	12	1.36	6	4683	881.68	883.38	883.94	884.18	884.29	884.34
vs2	23	1.10	655	3459	1276.01	1452.17	1510.31	1534.92	1546.32	1551.82
vs3	27	1.32	72	7312	1361.42	1381.71	1388.41	1391.24	1392.56	1393.19
vs3	32	1.22	140	4570	1391.64	1430.43	1443.23	1448.65	1451.16	1452.37
vs3	17	1.36	12	9721	1505.47	1508.87	1509.99	1510.47	1510.69	1510.79
vs1	21	1.21	313	5744	1556.43	1642.97	1671.53	1683.61	1689.21	1691.91
vs3	20	1.27	19	6550	1668.05	1673.36	1675.12	1675.86	1676.20	1676.37
vs3	30	1.03	53	2044	1791.14	1805.06	1809.65	1811.60	1812.50	1812.93
vs3	14	1.30	99	9445	1809.41	1837.23	1846.41	1850.29	1852.09	1852.96
vs5	13	1.18	67	4690	1879.72	1898.12	1904.19	1906.76	1907.95	1908.53
vs3	11	1.04	78	2355	1943.94	1964.50	1971.29	1974.16	1975.49	1976.13
vs3	5	1.05	4	3416	2801.23	2802.29	2802.64	2802.79	2802.86	2802.89
vs3	26	1.15	74	6818	3065.04	3085.22	3091.88	3094.69	3096.00	3096.63
vs5	7	1.17	4	9496	3792.03	3793.12	3793.49	3793.64	3793.71	3793.74
vs3	31	1.10	269	7088	3898.74	3971.09	3994.97	4005.08	4009.76	4012.01
vs3	2	1.12	4	7293	3946.10	3947.19	3947.54	3947.69	3947.76	3947.80
vs3	28	1.08	475	7072	4084.12	4211.09	4252.99	4270.72	4278.94	4282.90
vs3	9	1.11	5	8554	4809.65	4811.00	4811.44	4811.63	4811.72	4811.76
vs3	18	1.00	18	4998	4972.54	4977.22	4978.76	4979.41	4979.71	4979.86
vs3	35	1.08	476	8891	5209.67	5336.90	5378.89	5396.66	5404.89	5408.86
vs3	1	1.06	8	7166	5377.42	5379.55	5380.25	5380.55	5380.68	5380.75
vs3	16	1.04	42	8611	7092.66	7103.73	7107.39	7108.93	7109.65	7110.00
vs3	8	1.03	9	9897	8623.12	8625.48	8626.26	8626.59	8626.75	8626.82
vs3	15	1.01	79	9168	8741.81	8762.40	8769.19	8772.07	8773.40	8774.04

CHAPTER V

CONCLUSION

5.1 Summary

The broad goal of the dissertation was to develop a methodology for comparing age-based maintenance and condition-based maintenance using economic measures of performance. There has been significant research in both of these maintenance strategy areas separately. However, the literature is nearly void of comparative research between ABM and CBM. Consequently, a maintenance practitioner is given little support with regard to whether he/she should implement a CBM strategy.

This dissertation approached this problem by first compiling a literature review of various maintenance models and theories. This led to the discovery that not every researcher defines maintenance in the same way. For example, the term Preventive Maintenance (PM) can mean time-base maintenance, age-based maintenance and/or condition-based maintenance. Therefore, the first step in this research's process was to explicitly define the maintenance strategies used research. This resulted in using the term age-based maintenance for an asset use based maintenance strategy and condition-based maintenance for the situation where the condition of a specific asset is monitored or measures (directly or indirectly).

It was also during this step that the discovery was made that maintenance strategies could be classified according to the required knowledge necessary to implement each strategy. For example, a corrective maintenance (CM) strategy requires no knowledge about an asset to implement. However, if a practitioner is to implement a CBM strategy, he/she must have specific operational knowledge about the specific asset of concern.

The concluding analysis of the literature review was that the models for CM and ABM were well known and accepted. Additionally, the literature presented several models for CBM. However, only one of the models allowed for a comparative analysis between CBM and ABM. The solution techniques required to solve this model are complex. Therefore, this researcher searched for a simpler model for CBM. The conclusion resulting from the literature review was that the Weibull failure distribution is almost universally accepted as the asset failure distribution of choice. Therefore, this research uses the Weibull failure distribution exclusively.

The final CBM model resulted from a synthesis of concepts of the P-F curve used in industry, the delay time concept presented in the literature, and the PHM used to describe the relationship between measured parameters of an asset and its operational condition level. The conclusion of this synthesis was the development of the asset degradation function. This degradation function became the pivotal point for the completion of this research because it allowed the condition level of an asset to be "connected" to the failure density function that describes the failure potential of an asset. The CBM also incorporated a discrimination term that specified the ability of a CBM measuring process to determine the actual condition level of an asset.

With the models determined for CM, ABM, and CBM, this research then developed a methodology to compare the long run average cost of each maintenance strategy. The results of the methodology was a table of costs for each strategy for a broad range of values for the decision variable – the cost of failure, the cost of performing CBM, the shape parameter of the Weibull failure distribution, and the cost of performing ABM. The most economical cost for each set of decision variable conditions was then chosen as the economically preferred cost and the maintenance strategy corresponding to the cost was chosen that the economically preferred maintenance strategy.

The task of the researcher was then to use this data to answer the defined research questions and to develop a maintenance strategy selection methodology. The task of finding the decision methodology was tackled first.

The process of developing a decision methodology led to the discovery that the initial set of decision variables were unable to predict the correct maintenance strategy when used in simple linear models. Consequently, several derived decision variables were developed.

The first approach taken to develop a decision model was to use a rule-based approach. In conjunction with the initial and derived decision variables, this approach resulted in a decision model with 16 rules. The decision rule model predicted the economically preferred maintenance strategy accurately for all the ranges tested except for the situation when the beta parameter was between 3.5 and 4.5 and the ratio of C_u/C_{CBM} was approximately equal to 3 and when the beta parameter was between approximately 1.5 and 2.5 and the ratio C_u/C_{CBM} was between 9 and 11.

The next approach taken was to attempt to develop a model using multivariate linear regression, again using the initial and derived decision variables. This approach failed to predict the economically preferred maintenance strategy with accuracy. Ultimately, the MVLR approach was used to predict one of the problems areas identified by the decision rule approach. Specifically, a regression model was used to predict the economically preferred maintenance strategy when the beta parameter was between approximately 1.5 and 2.5, and the ratio C_u/C_{CBM} was between 9 and 11. The regression model performed poorly with regard to predicting the economically preferred maintenance strategy for the situation where the beta parameter was between 3.5 and 4.5, and the ratio of C_u/C_{CBM} was approximately equal to three. However, a study of the cost data showed that misclassification under these conditions would not likely be significant. Additionally, Cavalier and Knapp [1996] state that many mechanical failures have beta values less than four. Assets that have beta values of greater than four are generally exhibiting rapid old-age wear out and should be replaced or extensively refurbished rather than maintained. Therefore, no further attempt was made to classify this problem area. Figure 10 shows the hazard rate function plotted against time for varying beta values.

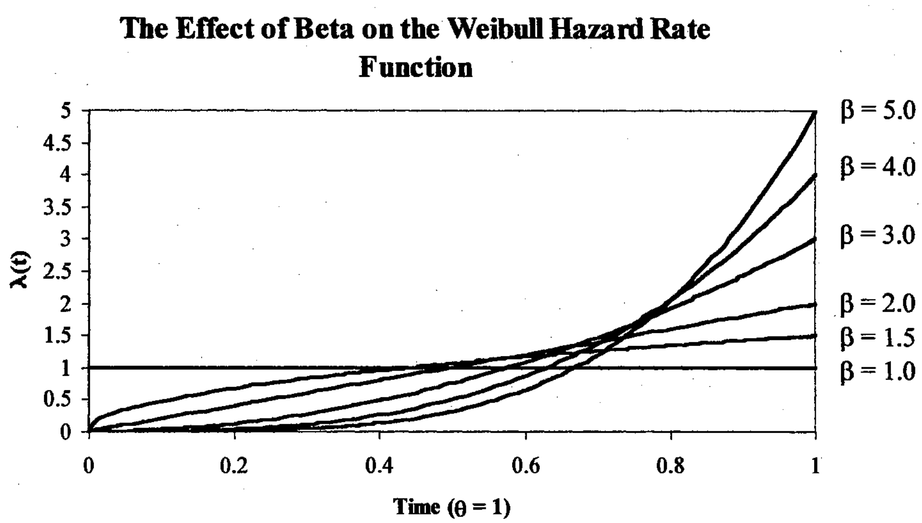

Figure 10. The hazard rate function plotted against time for varying beta values

The results of this decision methodology development process was a decision model that used a linear regression model to "weed out" the major problem area encountered by the decision rule model, prior to the use of the decision rule model. The result is a decision model that performed very well with regard to predicting the economically preferred maintenance strategy for the initial data set and subsequent validation data sets.

5.1.1 Research Questions

This research effort, as all research efforts must, asked questions and searched for answers and insights. The question asked by this research focused on the cost of maintenance and the level of knowledge required to implement a CBM strategy. The research questions are repeated below. Note that research questions one and three have the same answer.

1. At what level of failure cost is an ABM strategy economically preferable to CM?
2. At what level of failure cost and CBM event cost is a CBM strategy economically preferable to an ABM?
3. At what level of failure cost and CBM event cost is a CBM strategy preferable to a CM strategy?
4. At what level of CBM implementation and continuation costs is a CBM strategy economically preferable to an ABM strategy?
5. What level of accuracy is necessary to make a CBM strategy an economically preferred maintenance strategy?

Corrective maintenance is preferred over ABM and CBM when beta is equal to one or when the cost of failure is equal to the cost of performing ABM or CBM. No exact exhaustive answers were discovered for research questions two or four. However, graphical aids (repeated again as Figures 11, page 116 and 12, page 117) were developed to help a practitioner better understand how changes in the value of the cost of failure, the cost of performing CBM and the implementation and continuation cost of CBM can change the economically preferred maintenance strategy selection. Figure 11 indicates that for all plotted points of the ordered pairs of (beta, $\log(C_u/C_{CBM})$) that lie approximately above the dashed line, CBM is the economically preferred maintenance strategy.

As discussed in Section 4.7, Figure 12 indicates the approximate range for acceptable values for the implementation and continuation costs for CBM.
All attempts to classify the discrimination levels, given CBM is the selected maintenance strategy, failed to predict the correct discrimination level effectively. The only generalization made is that a 50% discrimination level is acceptable for the majority of the situations

The presented answers to the research questions of this dissertation, while not exhaustive, should lay the groundwork for much future research. The next subsection presents the decision model developed in this research.

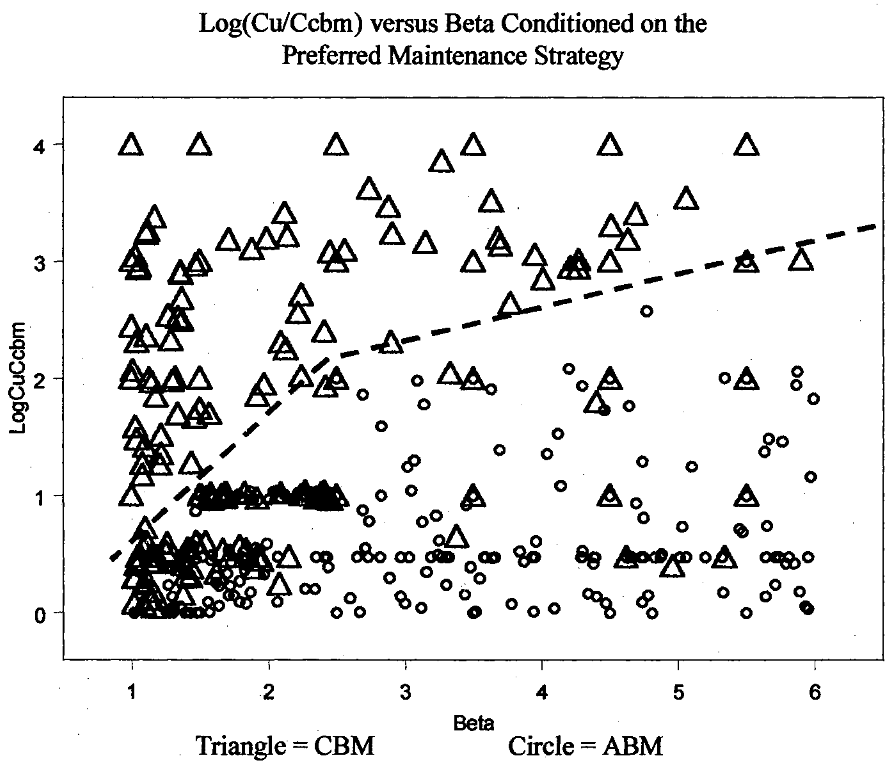

Figure 11. Scatter plot of the logarithm of Cu/CCBM versus beta conditioned on the preferred maintenance strategy

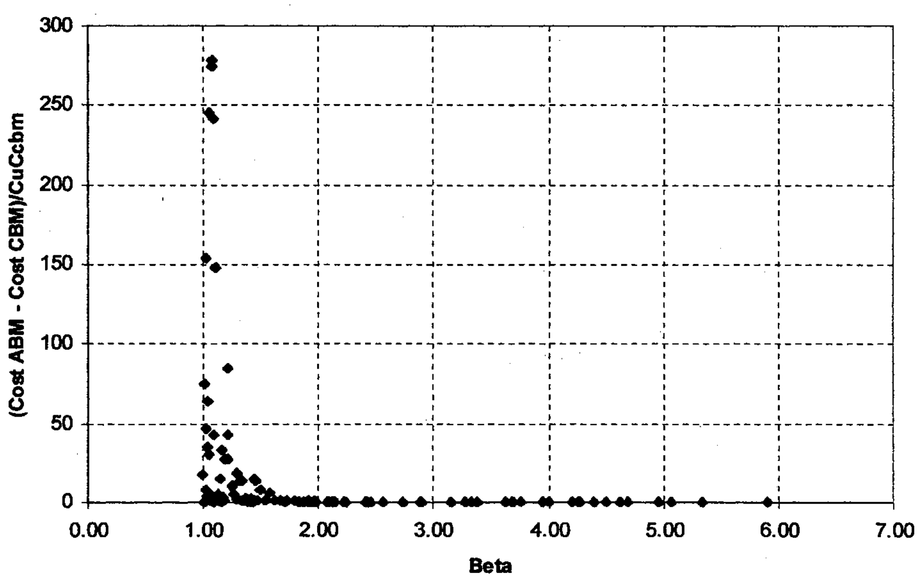

Figure 12. Plot of the cost difference between the cost of ABM and the cost of CBM, when CBM is preferred, divided by the ratio C_u/C_{CBM} versus beta

5.1.2 Decision Model

The decision model developed in this research has two components. The first component is a multivariate linear regression model that is used to predict the economically preferred maintenance strategy when the beta parameter is between approximately 1.5 and 2.5 and the ratio C_u/C_{CBM} is between 9 and 11 (Equation 48). The decision rule is to select ABM if M_s is greater than zero, otherwise choose CBM.

$$M_s = 7.3089 + 2.48305 * \text{beta} - 10.3378 * \left(\frac{\log(C_{CBM}) + \log(C_u) + \text{beta}}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)} \right) \quad (48)$$

If the ranges for beta and the ratio C_u/C_{CBM} do not satisfy the requirements for the regression model then the ordered decision rules shown in Table XXXVII are used to select the economically preferred maintenance strategy.

TABLE XXXVII

DECISION RULES

Order of Use	Decision Rules
1	If beta is less than or equal to one and the ratios $\frac{C_u}{C_{CBM}}$ is equal to one then choose CM.
2	If the cost of CBM (C_{CBM}) is equal to one and the cost of failure (C_u) is equal to one then choose CM.

TABLE XXXVII continued

Order of Use	Decision Rules
3	If $\left(\dfrac{\log(C_{CBM})+\log(C_u)+beta}{\log(C_{CBM})+\log(C_u)+\log\left(\dfrac{C_u}{C_{CBM}}\right)}\right)$ is less than 1.06 and beta is less than or equal to one then choose CBM
4	If the ratio $\dfrac{C_u}{C_{CBM}}$ is equal to one then choose ABM.
5	If $\log(C_{CBM})+\log(C_u)+beta$ is greater than 9.6 then choose ABM.
6	If $\dfrac{C_u/C_{CBM}}{beta}+\log(C_{CBM})+\log(C_u)+beta$ is greater than 75 then choose CBM.
7	If $\log(C_{CBM})+\log(C_u)+beta$ is greater than 7.9 then choose ABM.
8	If beta is less than 1.26, then choose CBM.
9	If $\dfrac{C_u/C_{CBM}}{beta}*\dfrac{\log(C_{CBM})+\log(C_u)+beta}{\log(C_{CBM})+\log(C_u)+\log\left(\dfrac{C_u}{C_{CBM}}\right)}$ is less than 1.53, then choose ABM.
10	If $\dfrac{C_u/C_{CBM}}{beta}*\dfrac{\log(C_{CBM})+\log(C_u)+beta}{\log(C_{CBM})+\log(C_u)+\log\left(\dfrac{C_u}{C_{CBM}}\right)}$ is greater than or equal to 5.5, then choose CBM.
11	If $\log(C_{CBM})+\log(C_u)+beta$ is less than 3.87, then choose CBM.
12	If $\log(C_{CBM})+\log(C_u)+beta$ is greater than 6.42, then choose ABM.

TABLE XXXVII continued

Order of Use	Decision Rules
13	If $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 2.65, then choose CBM.
14	If $\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$ is less than 1.95, then choose ABM.
15	If $\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$ is less than 3, then choose CBM.
16	If $\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$ is greater than or equal to 3, then choose ABM.

The weakness of the decision rule lies in the area where the beta parameter is between 3.5 and 4.5 and the ratio of C_u/C_{CBM} is approximately equal to three. However, the data sets generated in this research indicate that the economic penalty for misclassification in this area is not great. The next subsection discusses the assumptions used in this research.

5.1.3 Revisiting the Research Assumptions

This research made the following assumptions. The purpose of this subsection is to discuss the impact of making these assumptions.

1. The repair of an asset returns the asset to as-good-as-new condition. This assumption implies condition equivalence between repair and replacement of an asset.
2. This research assumes an infinite planning horizon for the cost models.
3. This research assumes that a Weibull failure distribution can be used to describe an asset's failure distribution.
4. This research assumes that failure costs are proportional to ABM costs.
5. This research assumes that the implementation and continuation cost for condition-based maintenance is proportional to the implementation and continuation cost for age-based maintenance.

The first two assumptions are likely contradictory to nearly all assets. When an asset is repaired, even with new parts, a practitioner is still left with used asset that is not as-good-as-new. Additionally, few assets can be assumed to survive an infinite time span. However, given lack of literature regarding comparative research with regard to ABM and CBM, it is felt that these two assumptions were justified. The third assumption is not so much as an assumption as it is a concession to 40 years of maintenance research. This researcher believes that the last two assumptions had no impact on the results of this research. They did however ease the computational requirements. The next subsection discusses this research's weaknesses and contributions to existing body of knowledge.

5.2 Contributions and Research Weaknesses

It is thought that this research will provide the starting point for further research in the area of comparative analysis between CBM and ABM. The defined decision variables presented in this dissertation should foster further study regarding the interaction between the traditional maintenance decision variables and the affect these interaction have on future maintenance methodologies. The major contributions of this research are the decision methodology, the development of an asset degradation function that incorporates an assets failure density function, the insight gained regarding the conditions under which CBM is preferred, and the insight gained regarding the maximum acceptable values for the implementation and continuation costs.

The decision methodology fills a void in the current literature. It should provide maintenance practitioners with a theoretically sound "best guess" as to whether a CBM strategy should be attempted. The development of the asset degradation function is seen as an important next step in the development of CBM theory. The degradation function takes the next step beyond the proportional hazards model approach and ties asset condition to condition variable measurements and an asset's failure density function (albeit, abstractly at this point). The insights regarding the implementation and continuation costs of CBM should provide even more justification to a maintenance practitioner with regard to whether a CBM strategy should be attempted. The insight regarding the conditions under which CBM is preferred should provide a solid starting point for future research.

This research has also made two minor contributions to the existing body of knowledge. The first is the all inclusive maintenance taxonomy with minimum knowledge requirements (Chapter I). The second is the open discussion regarding the non standard use of maintenance terminology (Chapter I).

While this research provides significant results and makes a valid contribution to the existing body of knowledge, this research also has its weaknesses. Admittedly, many of the weaknesses of this research concern the same issues that were listed as contributions. The first concerns the decision methodology. It seems apparent that the decision methodology is not perfect (i.e., it does misclassify some maintenance strategies). This would indicate that there are yet to be discovered interactions between the decision variable or additional variables. The second weakness concerns the proposed degradation function. No attempt has been made in this research to define the appropriate methodology to determine the specific degradation function for a specific asset. It is thought that the process would be similar to that used to develop a proportional hazards model. The third weakness is the results shown in Figure 11. While the figure does provide valuable insights, it does not give a practitioner definitive boundaries. The fourth weakness concerns this research's inability to classify the necessary discrimination level for CBM. Finally, this research in general does not address the difficulties a practitioner may have in obtaining the necessary data to use the methodology presented.

5.3 Future Research

During the course of this research, several areas were identified as potential future research areas. One area of great interest to this researcher involves the further exploration of the degradation function. Specifically, how is a specific degradation function developed for a specific asset? Do assets have multiple degradation functions? Can the PHM approach be used to determine the degradation function? How is the condition level of an asset related to measured operational parameters? Finally, can an asset with multiple degradation paths be optimizes to account for a "make it last till shutdown" approach?

Another area involves the implementation and continuation costs. Specifically, how are these costs estimated in practice? What is the proper method of incorporating these costs into a maintenance cost model? The next area involves the CBM model itself. Specifically, the question is how is the discriminatory ability best included in the CBM model? How does a practitioner know what level of discriminatory ability is required to ensure that a CBM strategy is economically advantageous?

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APPENDICES

APPENDIX A – CBM MODEL FOR OPTIMIZED MAINTENANANCE INTERVAL USING THE DEGRADATION FUNCTION

Consider Figure A - 1 below. This figure shows an arbitrary degradation function superimposed on a failure density plot. Suppose that there is uncertainty with regard to the degradation function. Assume that the bounds for this uncertainty are represented by the labeled upper and lower bound curves. What is the long run average cost of CBM if there are an infinite number of possible curves?

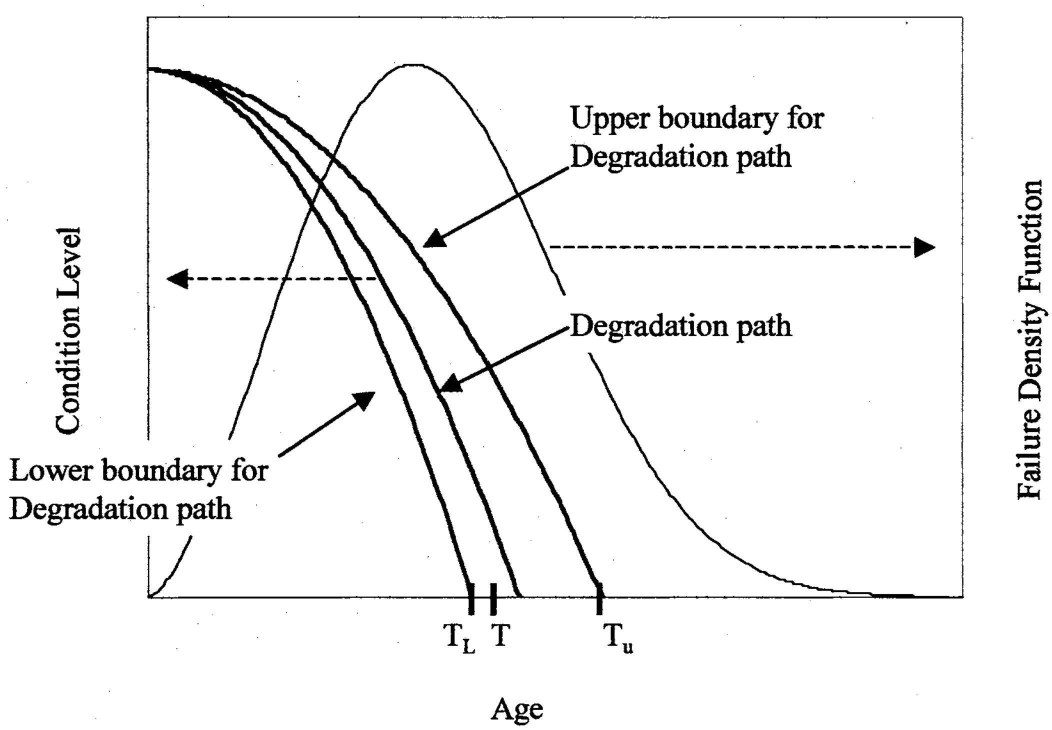

Figure A - 1. An arbitrary degradation curve superimposed on a failure density plot

Assume that a practitioner desires to optimize the maintenance interval under this policy. Let the optimized time be equal to T. Therefore, the goal is to minimize the long run average cost by optimizing the maintenance time T. A modification of Barlow and Proschan's [1965] ABM will allow a practitioner to achieve the desired results (Equation A – 1). Note that the three integral terms inside the overall integral are conditioned on the integral of the density function over the same range ($T_L - T_u$). Therefore, these integrals are left out of Equation A-1.

$$\overline{C}_{CBM} = \int_0^{\infty} \frac{C_{CBM} \int_T^{T_u} f(x)dx + C_u \int_{T_L}^{T} f(x)dx}{\int_{T_L}^{T} R(x)dx} dt \qquad \text{(A-1)}$$

APPENDIX B – COMPLETE ORIGINAL DATA SET WITH IC COSTS

NOMENCLATURE

Beta	The shape parameter of the Weibull distribution
Theta	The scale parameter of the Weibull distribution
Cp	The cost of performing ABM
Ccbm	The cost of performing CBM
Cu	The cost of asset failure
C icp	The implementation and continuation cost for ABM
Ciccbm	The implementation and continuation cost fro CBM
CM	The long run average cost for CM
Cabm	The long run average cost ABM
DL50	The long run average cost for CBM when the discriminatory ability is 50%
DL25	The long run average cost for CBM when the discriminatory ability is 25%
DL12.5	The long run average cost for CBM when the discriminatory ability is 12.50%
DL6.25	The long run average cost for CBM when the discriminatory ability is 6.25%
DL03125	The long run average cost for CBM when the discriminatory ability is 3.125%

DL015625	The long run average cost for CBM when the discriminatory ability is 1.5625%
DL_7812	The long run average cost for CBM when the discriminatory ability is 0.7812%
DL_3906	The long run average cost for CBM when the discriminatory ability is 0.3906%
DL_1953	The long run average cost for CBM when the discriminatory ability is 0.1953%
DL_097565	The long run average cost for CBM when the discriminatory ability is 0.097565%
DL_0097565	The long run average cost for CBM when the discriminatory ability is 0.0097565%
DL_00097565	The long run average cost for CBM when the discriminatory ability is 0.00097565%
DL_000097565	The long run average cost for CBM when the discriminatory ability is 0.000097565%

TABLE B – I
RESULTS: BETA EQUALS 1.0

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Clccbm	CM	ABM	Condition-Based Maintenance													Economically Preferred Strategy
								CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	
76	1	1	1	1	1	0.01	0.01	1.00	1.01	1.42	1.17	1.08	1.04	1.03	1.02	1.01	1.01	1.08	1.01	1.01	1.01	1.01	CM
77	1	1	1	1	1	0.01	0.1	1.00	1.01	1.51	1.26	1.17	1.13	1.12	1.11	1.10	1.10	1.17	1.10	1.10	1.10	1.10	CM
78	1	1	1	1	1	0.01	1	1.00	1.01	2.41	2.16	2.07	2.03	2.02	2.01	2.00	2.00	2.07	2.00	2.00	2.00	2.00	CM
79	1	1	1	1	1	0.01	10	1.00	1.01	11.41	11.16	11.07	11.03	11.02	11.01	11.00	11.00	11.07	11.00	11.00	11.00	11.00	CM
80	1	1	1	1	1	0.01	100	1.00	1.01	101.41	101.16	101.07	101.03	101.02	101.01	101.00	101.00	101.07	101.00	101.00	101.00	101.00	CM
81	1	1	1	1	10	0.01	0.01	10.00	10.00	1.42	1.17	1.08	1.04	1.03	1.02	1.01	1.01	1.08	1.01	1.01	1.01	1.01	CBM
82	1	1	1	1	10	0.01	0.1	10.00	10.00	1.51	1.26	1.17	1.13	1.12	1.11	1.10	1.10	1.17	1.10	1.10	1.10	1.10	CBM
83	1	1	1	1	10	0.01	1	10.00	10.00	2.41	2.16	2.07	2.03	2.02	2.01	2.00	2.00	2.07	2.00	2.00	2.00	2.00	CBM
84	1	1	1	1	10	0.01	10	10.00	10.00	11.41	11.16	11.07	11.03	11.02	11.01	11.00	11.00	11.07	11.00	11.00	11.00	11.00	CM
85	1	1	1	1	10	0.01	100	10.00	10.00	101.41	101.16	101.07	101.03	101.02	101.01	101.00	101.00	101.07	101.00	101.00	101.00	101.00	CM
86	1	1	1	1	100	0.01	0.01	100.00	100.00	1.42	1.17	1.08	1.04	1.03	1.02	1.01	1.01	1.08	1.01	1.01	1.01	1.01	CBM
87	1	1	1	1	100	0.01	0.1	100.00	100.00	1.51	1.26	1.17	1.13	1.12	1.11	1.10	1.10	1.17	1.10	1.10	1.10	1.10	CBM
88	1	1	1	1	100	0.01	1	100.00	100.00	2.41	2.16	2.07	2.03	2.02	2.01	2.00	2.00	2.07	2.00	2.00	2.00	2.00	CBM
89	1	1	1	1	100	0.01	10	100.00	100.00	11.41	11.16	11.07	11.03	11.02	11.01	11.00	11.00	11.07	11.00	11.00	11.00	11.00	CBM
90	1	1	1	1	100	0.01	100	100.00	100.00	101.41	101.16	101.07	101.03	101.02	101.01	101.00	101.00	101.07	101.00	101.00	101.00	101.00	CM
91	1	1	1	1	1000	0.01	0.01	1000.00	1000.00	1.42	1.17	1.08	1.04	1.03	1.02	1.01	1.01	1.08	1.01	1.01	1.01	1.01	CBM
92	1	1	1	1	1000	0.01	0.1	1000.00	1000.00	1.51	1.26	1.17	1.13	1.12	1.11	1.10	1.10	1.17	1.10	1.10	1.10	1.10	CBM
93	1	1	1	1	1000	0.01	1	1000.00	1000.00	2.41	2.16	2.07	2.03	2.02	2.01	2.00	2.00	2.07	2.00	2.00	2.00	2.00	CBM
94	1	1	1	1	1000	0.01	10	1000.00	1000.00	11.41	11.16	11.07	11.03	11.02	11.01	11.00	11.00	11.07	11.00	11.00	11.00	11.00	CBM
95	1	1	1	1	1000	0.01	100	1000.00	1000.00	101.41	101.16	101.07	101.03	101.02	101.01	101.00	101.00	101.07	101.00	101.00	101.00	101.00	CBM
96	1	1	1	1	10000	0.01	0.01	10000.00	10000.00	1.42	1.17	1.08	1.04	1.03	1.02	1.01	1.01	1.08	1.01	1.01	1.01	1.01	CBM
97	1	1	1	1	10000	0.01	0.1	10000.00	10000.00	1.51	1.26	1.17	1.13	1.12	1.11	1.10	1.10	1.17	1.10	1.10	1.10	1.10	CBM
98	1	1	1	1	10000	0.01	1	10000.00	10000.00	2.41	2.16	2.07	2.03	2.02	2.01	2.00	2.00	2.07	2.00	2.00	2.00	2.00	CBM
99	1	1	1	1	10000	0.01	10	10000.00	10000.00	11.41	11.16	11.07	11.03	11.02	11.01	11.00	11.00	11.07	11.00	11.00	11.00	11.00	CBM
100	1	1	1	1	10000	0.01	100	10000.00	10000.00	101.41	101.16	101.07	101.03	101.02	101.01	101.00	101.00	101.07	101.00	101.00	101.00	101.00	CBM
101	1	1	1	10	10	0.01	0.01	10.00	10.00	14.15	11.56	10.70	10.34	10.17	10.09	10.05	10.03	10.70	10.02	10.01	10.01	10.01	CM
102	1	1	1	10	10	0.01	0.1	10.00	10.00	14.24	11.65	10.79	10.43	10.26	10.18	10.14	10.12	10.79	10.11	10.10	10.10	10.10	CM
103	1	1	1	10	10	0.01	1	10.00	10.00	15.14	12.55	11.69	11.33	11.16	11.08	11.04	11.02	11.69	11.01	11.00	11.00	11.00	CM
104	1	1	1	10	10	0.01	10	10.00	10.00	24.14	21.55	20.69	20.33	20.16	20.08	20.04	20.02	20.69	20.01	20.00	20.00	20.00	CM
105	1	1	1	10	10	0.01	100	10.00	10.00	114.14	111.55	110.69	110.33	110.16	110.08	110.04	110.02	110.69	110.01	110.00	110.00	110.00	CM
106	1	1	1	10	100	0.01	0.01	100.00	100.00	14.15	11.56	10.70	10.34	10.17	10.09	10.05	10.03	10.70	10.02	10.01	10.01	10.01	CBM
107	1	1	1	10	100	0.01	0.1	100.00	100.00	14.24	11.65	10.79	10.43	10.26	10.18	10.14	10.12	10.79	10.11	10.10	10.10	10.10	CBM
108	1	1	1	10	100	0.01	1	100.00	100.00	15.14	12.55	11.69	11.33	11.16	11.08	11.04	11.02	11.69	11.01	11.00	11.00	11.00	CBM
109	1	1	1	10	100	0.01	10	100.00	100.00	24.14	21.55	20.69	20.33	20.16	20.08	20.04	20.02	20.69	20.01	20.00	20.00	20.00	CBM
110	1	1	1	10	100	0.01	100	100.00	100.00	114.14	111.55	110.69	110.33	110.16	110.08	110.04	110.02	110.69	110.01	110.00	110.00	110.00	CM
111	1	1	1	10	1000	0.01	0.01	1000.00	1000.00	14.15	11.56	10.70	10.34	10.17	10.09	10.05	10.03	10.70	10.02	10.01	10.01	10.01	CBM
112	1	1	1	10	1000	0.01	0.1	1000.00	1000.00	14.24	11.65	10.79	10.43	10.26	10.18	10.14	10.12	10.79	10.11	10.10	10.10	10.10	CBM
113	1	1	1	10	1000	0.01	1	1000.00	1000.00	15.14	12.55	11.69	11.33	11.16	11.08	11.04	11.02	11.69	11.01	11.00	11.00	11.00	CBM
114	1	1	1	10	1000	0.01	10	1000.00	1000.00	24.14	21.55	20.69	20.33	20.16	20.08	20.04	20.02	20.69	20.01	20.00	20.00	20.00	CBM
115	1	1	1	10	1000	0.01	100	1000.00	1000.00	114.14	111.55	110.69	110.33	110.16	110.08	110.04	110.02	110.69	110.01	110.00	110.00	110.00	CBM

TABLE B – I continued

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Clccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
116	1	1	1	10	10000	0.01	0.01	10000.00	10000.00	14.15	11.56	10.70	10.34	10.17	10.09	10.05	10.03	10.70	10.02	10.01	10.01	10.01	CBM
117	1	1	1	10	10000	0.01	0.1	10000.00	10000.00	14.24	11.65	10.79	10.43	10.26	10.18	10.14	10.12	10.79	10.11	10.10	10.10	10.10	CBM
118	1	1	1	10	10000	0.01	1	10000.00	10000.00	15.14	12.55	11.69	11.33	11.16	11.08	11.04	11.02	11.69	11.01	11.00	11.00	11.00	CBM
119	1	1	1	10	10000	0.01	10	10000.00	10000.00	24.14	21.55	20.69	20.33	20.16	20.08	20.04	20.02	20.69	20.01	20.00	20.00	20.00	CBM
120	1	1	1	10	10000	0.01	100	10000.00	10000.00	114.14	111.55	110.69	110.33	110.16	110.08	110.04	110.02	110.69	110.01	110.00	110.00	110.00	CBM
121	1	1	1	100	100	0.01	0.01	100.00	100.00	141.43	115.48	106.91	103.29	101.61	100.80	100.40	100.21	100.11	100.06	100.02	100.01	100.01	CM
122	1	1	1	100	100	0.01	0.1	100.00	100.00	141.52	115.57	107.00	103.38	101.70	100.89	100.49	100.30	100.20	100.15	100.11	100.10	100.10	CM
123	1	1	1	100	100	0.01	1	100.00	100.00	142.42	116.47	107.90	104.28	102.60	101.79	101.39	101.20	101.10	101.05	101.01	101.00	101.00	CM
124	1	1	1	100	100	0.01	10	100.00	100.00	151.42	125.47	116.90	113.28	111.60	110.79	110.39	110.20	110.10	110.05	110.01	110.00	110.00	CM
125	1	1	1	100	100	0.01	100	100.00	100.00	241.42	215.47	206.90	203.28	201.60	200.79	200.39	200.20	200.10	200.05	200.01	200.00	200.00	CM
126	1	1	1	100	1000	0.01	0.01	1000.00	1000.00	141.43	115.48	106.91	103.29	101.61	100.80	100.40	100.21	100.11	100.06	100.02	100.01	100.01	CBM
127	1	1	1	100	1000	0.01	0.1	1000.00	1000.00	141.52	115.57	107.00	103.38	101.70	100.89	100.49	100.30	100.20	100.15	100.11	100.10	100.10	CBM
128	1	1	1	100	1000	0.01	1	1000.00	1000.00	142.42	116.47	107.90	104.28	102.60	101.79	101.39	101.20	101.10	101.05	101.01	101.00	101.00	CBM
129	1	1	1	100	1000	0.01	10	1000.00	1000.00	151.42	125.47	116.90	113.28	111.60	110.79	110.39	110.20	110.10	110.05	110.01	110.00	110.00	CBM
130	1	1	1	100	1000	0.01	100	1000.00	1000.00	241.42	215.47	206.90	203.28	201.60	200.79	200.39	200.20	200.10	200.05	200.01	200.00	200.00	CBM
131	1	1	1	100	10000	0.01	0.01	10000.00	10000.00	141.43	115.48	106.91	103.29	101.61	100.80	100.40	100.21	100.11	100.06	100.02	100.01	100.01	CBM
132	1	1	1	100	10000	0.01	0.1	10000.00	10000.00	141.52	115.57	107.00	103.38	101.70	100.89	100.49	100.30	100.20	100.15	100.11	100.10	100.10	CBM
133	1	1	1	100	10000	0.01	1	10000.00	10000.00	142.42	116.47	107.90	104.28	102.60	101.79	101.39	101.20	101.10	101.05	101.01	101.00	101.00	CBM
134	1	1	1	100	10000	0.01	10	10000.00	10000.00	151.42	125.47	116.90	113.28	111.60	110.79	110.39	110.20	110.10	110.05	110.01	110.00	110.00	CBM
135	1	1	1	100	10000	0.01	100	10000.00	10000.00	241.42	215.47	206.90	203.28	201.60	200.79	200.39	200.20	200.10	200.05	200.01	200.00	200.00	CBM
136	1	1	1	1000	1000	0.01	0.01	1000.00	1000.00	1414.01	1155.01	1069.01	1033.01	1016.01	1008.01	1004.01	1002.01	1001.01	1000.01	1000.01	1000.01	1000.01	CM
137	1	1	1	1000	1000	0.01	0.1	1000.00	1000.00	1414.10	1155.10	1069.10	1033.10	1016.10	1008.10	1004.10	1002.10	1001.10	1000.10	1000.10	1000.10	1000.10	CM
138	1	1	1	1000	1000	0.01	1	1000.00	1000.00	1415.00	1156.00	1070.00	1034.00	1017.00	1009.00	1005.00	1003.00	1002.00	1001.00	1001.00	1001.00	1001.00	CM
139	1	1	1	1000	1000	0.01	10	1000.00	1000.00	1424.00	1165.00	1079.00	1043.00	1026.00	1018.00	1014.00	1012.00	1011.00	1010.00	1010.00	1010.00	1010.00	CM
140	1	1	1	1000	1000	0.01	100	1000.00	1000.00	1514.00	1255.00	1169.00	1133.00	1116.00	1108.00	1104.00	1102.00	1101.00	1100.00	1100.00	1100.00	1100.00	CM
141	1	1	1	1000	10000	0.01	0.01	10000.00	10000.00	1414.01	1155.01	1069.01	1033.01	1016.01	1008.01	1004.01	1002.01	1001.01	1000.01	1000.01	1000.01	1000.01	CBM
142	1	1	1	1000	10000	0.01	0.1	10000.00	10000.00	1414.10	1155.10	1069.10	1033.10	1016.10	1008.10	1004.10	1002.10	1001.10	1000.10	1000.10	1000.10	1000.10	CBM
143	1	1	1	1000	10000	0.01	1	10000.00	10000.00	1415.00	1156.00	1070.00	1034.00	1017.00	1009.00	1005.00	1003.00	1002.00	1001.00	1001.00	1001.00	1001.00	CBM
144	1	1	1	1000	10000	0.01	10	10000.00	10000.00	1424.00	1165.00	1079.00	1043.00	1026.00	1018.00	1014.00	1012.00	1011.00	1010.00	1010.00	1010.00	1010.00	CBM
145	1	1	1	1000	10000	0.01	100	10000.00	10000.00	1514.00	1255.00	1169.00	1133.00	1116.00	1108.00	1104.00	1102.00	1101.00	1100.00	1100.00	1100.00	1100.00	CBM
146	1	1	1	10000	10000	0.01	0.01	10000.00	10000.00	14140.01	11550.01	10690.01	10330.01	10160.01	10080.01	10040.01	10020.01	10010.01	10000.01	10000.01	10000.01	10000.01	CM
147	1	1	1	10000	10000	0.01	0.1	10000.00	10000.00	14140.10	11550.10	10690.10	10330.10	10160.10	10080.10	10040.10	10020.10	10010.10	10000.10	10000.10	10000.10	10000.10	CM
148	1	1	1	10000	10000	0.01	1	10000.00	10000.00	14141.00	11551.00	10691.00	10331.00	10161.00	10081.00	10041.00	10021.00	10011.00	10001.00	10001.00	10001.00	10001.00	CM
149	1	1	1	10000	10000	0.01	10	10000.00	10000.00	14150.00	11560.00	10700.00	10340.00	10170.00	10090.00	10050.00	10030.00	10020.00	10010.00	10010.00	10010.00	10010.00	CM
150	1	1	1	10000	10000	0.01	100	10000.00	10000.00	14240.00	11650.00	10790.00	10430.00	10260.00	10180.00	10140.00	10120.00	10110.00	10100.00	10100.00	10100.00	10100.00	CM

TABLE B – II
RESULTS: BETA EQUALS 1.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Ciccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
151	1.5	1	1	1	1	0.01	0.01	1.11	1.12	1.58	1.29	1.19	1.15	1.14	1.13	1.12	1.12	1.19	1.12	1.12	1.12	1.12	CM
152	1.5	1	1	1	1	0.01	0.1	1.11	1.12	1.67	1.38	1.28	1.24	1.23	1.22	1.21	1.21	1.28	1.21	1.21	1.21	1.21	CM
153	1.5	1	1	1	1	0.01	1	1.11	1.12	2.57	2.28	2.18	2.14	2.13	2.12	2.11	2.11	2.18	2.11	2.11	2.11	2.11	CM
154	1.5	1	1	1	1	0.01	10	1.11	1.12	11.57	11.28	11.18	11.14	11.13	11.12	11.11	11.11	11.18	11.11	11.11	11.11	11.11	CM
155	1.5	1	1	1	1	0.01	100	1.11	1.12	101.57	101.28	101.18	101.14	101.13	101.12	101.11	101.11	101.18	101.11	101.11	101.11	101.11	CM
156	1.5	1	1	1	10	0.01	0.01	11.08	8.30	1.58	1.29	1.19	1.15	1.14	1.13	1.12	1.12	1.19	1.12	1.12	1.12	1.12	CBM
157	1.5	1	1	1	10	0.01	0.1	11.08	8.30	1.67	1.38	1.28	1.24	1.23	1.22	1.21	1.21	1.28	1.21	1.21	1.21	1.21	CBM
158	1.5	1	1	1	10	0.01	1	11.08	8.30	2.57	2.28	2.18	2.14	2.13	2.12	2.11	2.11	2.18	2.11	2.11	2.11	2.11	CBM
159	1.5	1	1	1	10	0.01	10	11.08	8.30	11.57	11.28	11.18	11.14	11.13	11.12	11.11	11.11	11.18	11.11	11.11	11.11	11.11	Cabm
160	1.5	1	1	1	10	0.01	100	11.08	8.30	101.57	101.28	101.18	101.14	101.13	101.12	101.11	101.11	101.18	101.11	101.11	101.11	101.11	Cabm
161	1.5	1	1	1	100	0.01	0.01	110.77	40.50	1.58	1.29	1.19	1.15	1.14	1.13	1.12	1.12	1.19	1.12	1.12	1.12	1.12	CBM
162	1.5	1	1	1	100	0.01	0.1	110.77	40.50	1.67	1.38	1.28	1.24	1.23	1.22	1.21	1.21	1.28	1.21	1.21	1.21	1.21	CBM
163	1.5	1	1	1	100	0.01	1	110.77	40.50	2.57	2.28	2.18	2.14	2.13	2.12	2.11	2.11	2.18	2.11	2.11	2.11	2.11	CBM
164	1.5	1	1	1	100	0.01	10	110.77	40.50	11.57	11.28	11.18	11.14	11.13	11.12	11.11	11.11	11.18	11.11	11.11	11.11	11.11	CBM
165	1.5	1	1	1	100	0.01	100	110.77	40.50	101.57	101.28	101.18	101.14	101.13	101.12	101.11	101.11	101.18	101.11	101.11	101.11	101.11	Cabm
166	1.5	1	1	1	1000	0.01	0.01	1108.00	188.89	1.58	1.29	1.19	1.15	1.14	1.13	1.12	1.12	1.19	1.12	1.12	1.12	1.12	CBM
167	1.5	1	1	1	1000	0.01	0.1	1108.00	188.89	1.67	1.38	1.28	1.24	1.23	1.22	1.21	1.21	1.28	1.21	1.21	1.21	1.21	CBM
168	1.5	1	1	1	1000	0.01	1	1108.00	188.89	2.57	2.28	2.18	2.14	2.13	2.12	2.11	2.11	2.18	2.11	2.11	2.11	2.11	CBM
169	1.5	1	1	1	1000	0.01	10	1108.00	188.89	11.57	11.28	11.18	11.14	11.13	11.12	11.11	11.11	11.18	11.11	11.11	11.11	11.11	CBM
170	1.5	1	1	1	1000	0.01	100	1108.00	188.89	101.57	101.28	101.18	101.14	101.13	101.12	101.11	101.11	101.18	101.11	101.11	101.11	101.11	CBM
171	1.5	1	1	1	10000	0.01	0.01	11080.00	877.16	1.58	1.29	1.19	1.15	1.14	1.13	1.12	1.12	1.19	1.12	1.12	1.12	1.12	CBM
172	1.5	1	1	1	10000	0.01	0.1	11080.00	877.16	1.67	1.38	1.28	1.24	1.23	1.22	1.21	1.21	1.28	1.21	1.21	1.21	1.21	CBM
173	1.5	1	1	1	10000	0.01	1	11080.00	877.16	2.57	2.28	2.18	2.14	2.13	2.12	2.11	2.11	2.18	2.11	2.11	2.11	2.11	CBM
174	1.5	1	1	1	10000	0.01	10	11080.00	877.16	11.57	11.28	11.18	11.14	11.13	11.12	11.11	11.11	11.18	11.11	11.11	11.11	11.11	CBM
175	1.5	1	1	1	10000	0.01	100	11080.00	877.16	101.57	101.28	101.18	101.14	101.13	101.12	101.11	101.11	101.18	101.11	101.11	101.11	101.11	CBM
176	1.5	1	1	10	10	0.01	0.01	11.08	8.30	15.68	12.80	11.85	11.45	11.27	11.18	11.13	11.11	11.85	11.09	11.09	11.09	11.09	Cabm
177	1.5	1	1	10	10	0.01	0.1	11.08	8.30	15.77	12.89	11.94	11.54	11.36	11.27	11.22	11.20	11.94	11.18	11.18	11.18	11.18	Cabm
178	1.5	1	1	10	10	0.01	1	11.08	8.30	16.67	13.79	12.84	12.44	12.26	12.17	12.12	12.10	12.84	12.08	12.08	12.08	12.08	Cabm
179	1.5	1	1	10	10	0.01	10	11.08	8.30	25.67	22.79	21.84	21.44	21.26	21.17	21.12	21.10	21.84	21.08	21.08	21.08	21.08	Cabm
180	1.5	1	1	10	10	0.01	100	11.08	8.30	115.67	112.79	111.84	111.44	111.26	111.17	111.12	111.10	111.84	111.08	111.08	111.08	111.08	Cabm
181	1.5	1	1	10	100	0.01	0.01	110.77	40.50	15.68	12.80	11.85	11.45	11.27	11.18	11.13	11.11	11.85	11.09	11.09	11.09	11.09	CBM
182	1.5	1	1	10	100	0.01	0.1	110.77	40.50	15.77	12.89	11.94	11.54	11.36	11.27	11.22	11.20	11.94	11.18	11.18	11.18	11.18	CBM
183	1.5	1	1	10	100	0.01	1	110.77	40.50	16.67	13.79	12.84	12.44	12.26	12.17	12.12	12.10	12.84	12.08	12.08	12.08	12.08	CBM
184	1.5	1	1	10	100	0.01	10	110.77	40.50	25.67	22.79	21.84	21.44	21.26	21.17	21.12	21.10	21.84	21.08	21.08	21.08	21.08	CBM
185	1.5	1	1	10	100	0.01	100	110.77	40.50	115.67	112.79	111.84	111.44	111.26	111.17	111.12	111.10	111.84	111.08	111.08	111.08	111.08	Cabm

TABLE B – II continued

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
186	1.5	1	1	10	1000	0.01	0.01	1108.00	188.89	15.68	12.80	11.86	11.45	11.27	11.18	11.13	11.11	11.85	11.09	11.09	11.09	11.09	CBM
187	1.5	1	1	10	1000	0.01	0.1	1108.00	188.89	15.77	12.89	11.94	11.54	11.36	11.27	11.22	11.20	11.94	11.18	11.18	11.18	11.18	CBM
188	1.5	1	1	10	1000	0.01	1	1108.00	188.89	16.67	13.79	12.84	12.44	12.26	12.17	12.12	12.10	12.84	12.08	12.08	12.08	12.08	CBM
189	1.5	1	1	10	1000	0.01	10	1108.00	188.89	25.67	22.79	21.84	21.44	21.26	21.17	21.12	21.10	21.84	21.08	21.08	21.08	21.08	CBM
190	1.5	1	1	10	1000	0.01	100	1108.00	188.89	115.67	112.79	111.84	111.44	111.26	111.17	111.12	111.10	111.84	111.08	111.08	111.08	111.08	CBM
191	1.5	1	1	10	10000	0.01	0.01	11080.00	877.16	15.68	12.80	11.86	11.45	11.27	11.18	11.13	11.11	11.85	11.09	11.09	11.09	11.09	CBM
192	1.5	1	1	10	10000	0.01	0.1	11080.00	877.16	15.77	12.89	11.94	11.54	11.36	11.27	11.22	11.20	11.94	11.18	11.18	11.18	11.18	CBM
193	1.5	1	1	10	10000	0.01	1	11080.00	877.16	16.67	13.79	12.84	12.44	12.26	12.17	12.12	12.10	12.84	12.08	12.08	12.08	12.08	CBM
194	1.5	1	1	10	10000	0.01	10	11080.00	877.16	25.67	22.79	21.84	21.44	21.26	21.17	21.12	21.10	21.84	21.08	21.08	21.08	21.08	CBM
195	1.5	1	1	10	10000	0.01	100	11080.00	877.16	115.67	112.79	111.84	111.44	111.26	111.17	111.12	111.10	111.84	111.08	111.08	111.08	111.08	CBM
196	1.5	1	1	100	100	0.01	0.01	110.77	40.50	156.67	127.92	118.43	114.42	112.56	111.66	111.22	111.00	110.89	110.84	110.79	110.78	110.78	Cabm
197	1.5	1	1	100	100	0.01	0.1	110.77	40.50	156.76	128.01	118.52	114.51	112.65	111.75	111.31	111.09	110.98	110.93	110.88	110.87	110.87	Cabm
198	1.5	1	1	100	100	0.01	1	110.77	40.50	157.66	128.91	119.42	115.41	113.55	112.65	112.21	111.99	111.88	111.83	111.78	111.77	111.77	Cabm
199	1.5	1	1	100	100	0.01	10	110.77	40.50	166.66	137.91	128.42	124.41	122.55	121.65	121.21	120.99	120.88	120.83	120.78	120.77	120.77	Cabm
200	1.5	1	1	100	100	0.01	100	110.77	40.50	256.66	227.91	218.42	214.41	212.55	211.65	211.21	210.99	210.88	210.83	210.78	210.77	210.77	Cabm
201	1.5	1	1	100	1000	0.01	0.01	1108.00	188.89	156.67	127.92	118.43	114.42	112.56	111.66	111.22	111.00	110.89	110.84	110.79	110.78	110.78	CBM
202	1.5	1	1	100	1000	0.01	0.1	1108.00	188.89	156.76	128.01	118.52	114.51	112.65	111.75	111.31	111.09	110.98	110.93	110.88	110.87	110.87	CBM
203	1.5	1	1	100	1000	0.01	1	1108.00	188.89	157.66	128.91	119.42	115.41	113.55	112.65	112.21	111.99	111.88	111.83	111.78	111.77	111.77	CBM
204	1.5	1	1	100	1000	0.01	10	1108.00	188.89	166.66	137.91	128.42	124.41	122.55	121.65	121.21	120.99	120.88	120.83	120.78	120.77	120.77	CBM
205	1.5	1	1	100	1000	0.01	100	1108.00	188.89	256.66	227.91	218.42	214.41	212.55	211.65	211.21	210.99	210.88	210.83	210.78	210.77	210.77	Cabm
206	1.5	1	1	100	10000	0.01	0.01	11080.00	877.16	156.67	127.92	118.43	114.42	112.56	111.66	111.22	111.00	110.89	110.84	110.79	110.78	110.78	CBM
207	1.5	1	1	100	10000	0.01	0.1	11080.00	877.16	156.76	128.01	118.52	114.51	112.65	111.75	111.31	111.09	110.98	110.93	110.88	110.87	110.87	CBM
208	1.5	1	1	100	10000	0.01	1	11080.00	877.16	157.66	128.91	119.42	115.41	113.55	112.65	112.21	111.99	111.88	111.83	111.78	111.77	111.77	CBM
209	1.5	1	1	100	10000	0.01	10	11080.00	877.16	166.66	137.91	128.42	124.41	122.55	121.65	121.21	120.99	120.88	120.83	120.78	120.77	120.77	CBM
210	1.5	1	1	100	10000	0.01	100	11080.00	877.16	256.66	227.91	218.42	214.41	212.55	211.65	211.21	210.99	210.88	210.83	210.78	210.77	210.77	CBM
211	1.5	1	1	1000	1000	0.01	0.01	1108.00	188.89	1567.01	1279.01	1184.01	1144.01	1125.01	1116.01	1112.01	1110.01	1109.01	1108.01	1108.01	1108.01	1108.01	Cabm
212	1.5	1	1	1000	1000	0.01	0.1	1108.00	188.89	1567.10	1279.10	1184.10	1144.10	1125.10	1116.10	1112.10	1110.10	1109.10	1108.10	1108.10	1108.10	1108.10	Cabm
213	1.5	1	1	1000	1000	0.01	1	1108.00	188.89	1568.00	1280.00	1185.00	1145.00	1126.00	1117.00	1113.00	1111.00	1110.00	1109.00	1109.00	1109.00	1109.00	Cabm
214	1.5	1	1	1000	1000	0.01	10	1108.00	188.89	1577.00	1289.00	1194.00	1154.00	1135.00	1126.00	1122.00	1120.00	1119.00	1118.00	1118.00	1118.00	1118.00	Cabm
215	1.5	1	1	1000	1000	0.01	100	1108.00	188.89	1667.00	1379.00	1284.00	1244.00	1225.00	1216.00	1212.00	1210.00	1209.00	1208.00	1208.00	1208.00	1208.00	Cabm
216	1.5	1	1	1000	10000	0.01	0.01	11080.00	877.16	1567.01	1279.01	1184.01	1144.01	1125.01	1116.01	1112.01	1110.01	1109.01	1108.01	1108.01	1108.01	1108.01	Cabm
217	1.5	1	1	1000	10000	0.01	0.1	11080.00	877.16	1567.10	1279.10	1184.10	1144.10	1125.10	1116.10	1112.10	1110.10	1109.10	1108.10	1108.10	1108.10	1108.10	Cabm
218	1.5	1	1	1000	10000	0.01	1	11080.00	877.16	1568.00	1280.00	1185.00	1145.00	1126.00	1117.00	1113.00	1111.00	1110.00	1109.00	1109.00	1109.00	1109.00	Cabm
219	1.5	1	1	1000	10000	0.01	10	11080.00	877.16	1577.00	1289.00	1194.00	1154.00	1135.00	1126.00	1122.00	1120.00	1119.00	1118.00	1118.00	1118.00	1118.00	Cabm
220	1.5	1	1	1000	10000	0.01	100	11080.00	877.16	1667.00	1379.00	1284.00	1244.00	1225.00	1216.00	1212.00	1210.00	1209.00	1208.00	1208.00	1208.00	1208.00	Cabm
221	1.5	1	1	10000	10000	0.01	0.01	11080.00	877.16	15670.01	12790.01	11840.01	11440.01	11250.01	11160.01	11120.01	11100.01	11090.01	11080.01	11080.01	11080.01	11080.01	Cabm
222	1.5	1	1	10000	10000	0.01	0.1	11080.00	877.16	15670.10	12790.10	11840.10	11440.10	11250.10	11160.10	11120.10	11100.10	11090.10	11080.10	11080.10	11080.10	11080.10	Cabm
223	1.5	1	1	10000	10000	0.01	1	11080.00	877.16	15671.00	12791.00	11841.00	11441.00	11251.00	11161.00	11121.00	11101.00	11091.00	11081.00	11081.00	11081.00	11081.00	Cabm
224	1.5	1	1	10000	10000	0.01	10	11080.00	877.16	15680.00	12800.00	11850.00	11450.00	11260.00	11170.00	11130.00	11110.00	11100.00	11090.00	11090.00	11090.00	11090.00	Cabm
225	1.5	1	1	10000	10000	0.01	100	11080.00	877.16	15770.00	12890.00	11940.00	11540.00	11350.00	11260.00	11220.00	11200.00	11190.00	11180.00	11180.00	11180.00	11180.00	Cabm

TABLE B – III
RESULTS: BETA EQUALS 2.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Clccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
226	2.5	1	1	1	1	0.01	0.01	1.13	1.14	1.60	1.31	1.22	1.17	1.16	1.15	1.14	1.14	1.22	1.14	1.14	1.14	1.14	CM
227	2.5	1	1	1	1	0.01	0.1	1.13	1.14	1.69	1.40	1.31	1.26	1.25	1.24	1.23	1.23	1.31	1.23	1.23	1.23	1.23	CM
228	2.5	1	1	1	1	0.01	1	1.13	1.14	2.59	2.30	2.21	2.16	2.15	2.14	2.13	2.13	2.21	2.13	2.13	2.13	2.13	CM
229	2.5	1	1	1	1	0.01	10	1.13	1.14	11.59	11.30	11.21	11.16	11.15	11.14	11.13	11.13	11.21	11.13	11.13	11.13	11.13	CM
230	2.5	1	1	1	1	0.01	100	1.13	1.14	101.59	101.30	101.21	101.16	101.15	101.14	101.13	101.13	101.21	101.13	101.13	101.13	101.13	CM
231	2.5	1	1	1	10	0.01	0.01	11.27	4.75	1.60	1.31	1.22	1.17	1.16	1.15	1.14	1.14	1.22	1.14	1.14	1.14	1.14	CBM
232	2.5	1	1	1	10	0.01	0.1	11.27	4.75	1.69	1.40	1.31	1.26	1.25	1.24	1.23	1.23	1.31	1.23	1.23	1.23	1.23	CBM
233	2.5	1	1	1	10	0.01	1	11.27	4.75	2.59	2.30	2.21	2.16	2.15	2.14	2.13	2.13	2.21	2.13	2.13	2.13	2.13	CBM
234	2.5	1	1	1	10	0.01	10	11.27	4.75	11.59	11.30	11.21	11.16	11.15	11.14	11.13	11.13	11.21	11.13	11.13	11.13	11.13	Cabm
235	2.5	1	1	1	10	0.01	100	11.27	4.75	101.59	101.30	101.21	101.16	101.15	101.14	101.13	101.13	101.21	101.13	101.13	101.13	101.13	Cabm
236	2.5	1	1	1	100	0.01	0.01	112.71	12.33	1.60	1.31	1.22	1.17	1.16	1.15	1.14	1.14	1.22	1.14	1.14	1.14	1.14	CBM
237	2.5	1	1	1	100	0.01	0.1	112.71	12.33	1.69	1.40	1.31	1.26	1.25	1.24	1.23	1.23	1.31	1.23	1.23	1.23	1.23	CBM
238	2.5	1	1	1	100	0.01	1	112.71	12.33	2.59	2.30	2.21	2.16	2.15	2.14	2.13	2.13	2.21	2.13	2.13	2.13	2.13	CBM
239	2.5	1	1	1	100	0.01	10	112.71	12.33	11.59	11.30	11.21	11.16	11.15	11.14	11.13	11.13	11.21	11.13	11.13	11.13	11.13	CBM
240	2.5	1	1	1	100	0.01	100	112.71	12.33	101.59	101.30	101.21	101.16	101.15	101.14	101.13	101.13	101.21	101.13	101.13	101.13	101.13	Cabm
241	2.5	1	1	1	1000	0.01	0.01	1127.00	31.06	1.60	1.31	1.22	1.17	1.16	1.15	1.14	1.14	1.22	1.14	1.14	1.14	1.14	CBM
242	2.5	1	1	1	1000	0.01	0.1	1127.00	31.06	1.69	1.40	1.31	1.26	1.25	1.24	1.23	1.23	1.31	1.23	1.23	1.23	1.23	CBM
243	2.5	1	1	1	1000	0.01	1	1127.00	31.06	2.59	2.30	2.21	2.16	2.15	2.14	2.13	2.13	2.21	2.13	2.13	2.13	2.13	CBM
244	2.5	1	1	1	1000	0.01	10	1127.00	31.06	11.59	11.30	11.21	11.16	11.15	11.14	11.13	11.13	11.21	11.13	11.13	11.13	11.13	CBM
245	2.5	1	1	1	1000	0.01	100	1127.00	31.06	101.59	101.30	101.21	101.16	101.15	101.14	101.13	101.13	101.21	101.13	101.13	101.13	101.13	Cabm
246	2.5	1	1	1	10000	0.01	0.01	11270.00	78.03	1.60	1.31	1.22	1.17	1.16	1.15	1.14	1.14	1.22	1.14	1.14	1.14	1.14	CBM
247	2.5	1	1	1	10000	0.01	0.1	11270.00	78.03	1.69	1.40	1.31	1.26	1.25	1.24	1.23	1.23	1.31	1.23	1.23	1.23	1.23	CBM
248	2.5	1	1	1	10000	0.01	1	11270.00	78.03	2.59	2.30	2.21	2.16	2.15	2.14	2.13	2.13	2.21	2.13	2.13	2.13	2.13	CBM
249	2.5	1	1	1	10000	0.01	10	11270.00	78.03	11.59	11.30	11.21	11.16	11.15	11.14	11.13	11.13	11.21	11.13	11.13	11.13	11.13	CBM
250	2.5	1	1	1	10000	0.01	100	11270.00	78.03	101.59	101.30	101.21	101.16	101.15	101.14	101.13	101.13	101.21	101.13	101.13	101.13	101.13	Cabm
251	2.5	1	1	10	10	0.01	0.01	11.27	4.75	15.95	13.02	12.06	11.65	11.46	11.37	11.33	11.30	12.06	11.29	11.28	11.28	11.28	Cabm
252	2.5	1	1	10	10	0.01	0.1	11.27	4.75	16.04	13.11	12.15	11.74	11.55	11.46	11.42	11.39	12.15	11.38	11.37	11.37	11.37	Cabm
253	2.5	1	1	10	10	0.01	1	11.27	4.75	16.94	14.01	13.05	12.64	12.45	12.36	12.32	12.29	13.05	12.28	12.27	12.27	12.27	Cabm
254	2.5	1	1	10	10	0.01	10	11.27	4.75	25.94	23.01	22.05	21.64	21.45	21.36	21.32	21.29	22.05	21.28	21.27	21.27	21.27	Cabm
255	2.5	1	1	10	10	0.01	100	11.27	4.75	115.94	113.01	112.05	111.64	111.45	111.36	111.32	111.29	112.05	111.28	111.27	111.27	111.27	Cabm
256	2.5	1	1	10	100	0.01	0.01	112.71	12.33	15.95	13.02	12.06	11.65	11.46	11.37	11.33	11.30	12.06	11.29	11.28	11.28	11.28	CBM
257	2.5	1	1	10	100	0.01	0.1	112.71	12.33	16.04	13.11	12.15	11.74	11.55	11.46	11.42	11.39	12.15	11.38	11.37	11.37	11.37	CBM
258	2.5	1	1	10	100	0.01	1	112.71	12.33	16.94	14.01	13.05	12.64	12.45	12.36	12.32	12.29	13.05	12.28	12.27	12.27	12.27	CBM
259	2.5	1	1	10	100	0.01	10	112.71	12.33	25.94	23.01	22.05	21.64	21.45	21.36	21.32	21.29	22.05	21.28	21.27	21.27	21.27	Cabm
260	2.5	1	1	10	100	0.01	100	112.71	12.33	115.94	113.01	112.05	111.64	111.45	111.36	111.32	111.29	112.05	111.28	111.27	111.27	111.27	Cabm

TABLE B – III continued

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
261	2.5	1	1	10	1000	0.01	0.01	1127.00	31.06	15.95	13.02	12.06	11.65	11.46	11.37	11.33	11.30	12.06	11.29	11.28	11.28	11.28	CBM
262	2.5	1	1	10	1000	0.01	0.1	1127.00	31.06	16.04	13.11	12.15	11.74	11.55	11.46	11.42	11.39	12.15	11.38	11.37	11.37	11.37	CBM
263	2.5	1	1	10	1000	0.01	1	1127.00	31.06	16.94	14.01	13.05	12.64	12.45	12.36	12.32	12.29	13.05	12.28	12.27	12.27	12.27	CBM
264	2.5	1	1	10	1000	0.01	10	1127.00	31.06	25.94	23.01	22.05	21.64	21.45	21.36	21.32	21.29	22.05	21.28	21.27	21.27	21.27	CBM
265	2.5	1	1	10	1000	0.01	100	1127.00	31.06	115.94	113.01	112.05	111.64	111.45	111.36	111.32	111.29	112.05	111.28	111.27	111.27	111.27	Cabm
266	2.5	1	1	10	10000	0.01	0.01	11270.00	78.03	15.95	13.02	12.06	11.65	11.46	11.37	11.33	11.30	12.06	11.29	11.28	11.28	11.28	CBM
267	2.5	1	1	10	10000	0.01	0.1	11270.00	78.03	16.04	13.11	12.15	11.74	11.55	11.46	11.42	11.39	12.15	11.38	11.37	11.37	11.37	CBM
268	2.5	1	1	10	10000	0.01	1	11270.00	78.03	16.94	14.01	13.05	12.64	12.45	12.36	12.32	12.29	13.05	12.28	12.27	12.27	12.27	CBM
269	2.5	1	1	10	10000	0.01	10	11270.00	78.03	25.94	23.01	22.05	21.64	21.45	21.36	21.32	21.29	22.05	21.28	21.27	21.27	21.27	CBM
270	2.5	1	1	10	10000	0.01	100	11270.00	78.03	115.94	113.01	112.05	111.64	111.45	111.36	111.32	111.29	112.05	111.28	111.27	111.27	111.27	Cabm
271	2.5	1	1	100	100	0.01	0.01	112.71	12.33	159.40	130.15	120.50	116.41	114.52	113.61	113.16	112.94	112.83	112.77	112.72	112.72	112.72	Cabm
272	2.5	1	1	100	100	0.01	0.1	112.71	12.33	159.49	130.24	120.59	116.50	114.61	113.70	113.25	113.03	112.92	112.86	112.81	112.81	112.81	Cabm
273	2.5	1	1	100	100	0.01	1	112.71	12.33	160.39	131.14	121.49	117.40	115.51	114.60	114.15	113.93	113.82	113.76	113.71	113.71	113.71	Cabm
274	2.5	1	1	100	100	0.01	10	112.71	12.33	169.39	140.14	130.49	126.40	124.51	123.60	123.15	122.93	122.82	122.76	122.71	122.71	122.71	Cabm
275	2.5	1	1	100	100	0.01	100	112.71	12.33	259.39	230.14	220.49	216.40	214.51	213.60	213.15	212.93	212.82	212.76	212.71	212.71	212.71	Cabm
276	2.5	1	1	100	1000	0.01	0.01	1127.00	31.06	159.40	130.15	120.50	116.41	114.52	113.61	113.16	112.94	112.83	112.77	112.72	112.72	112.72	Cabm
277	2.5	1	1	100	1000	0.01	0.1	1127.00	31.06	159.49	130.24	120.59	116.50	114.61	113.70	113.25	113.03	112.92	112.86	112.81	112.81	112.81	Cabm
278	2.5	1	1	100	1000	0.01	1	1127.00	31.06	160.39	131.14	121.49	117.40	115.51	114.60	114.15	113.93	113.82	113.76	113.71	113.71	113.71	Cabm
279	2.5	1	1	100	1000	0.01	10	1127.00	31.06	169.39	140.14	130.49	126.40	124.51	123.60	123.15	122.93	122.82	122.76	122.71	122.71	122.71	Cabm
280	2.5	1	1	100	1000	0.01	100	1127.00	31.06	259.39	230.14	220.49	216.40	214.51	213.60	213.15	212.93	212.82	212.76	212.71	212.71	212.71	Cabm
281	2.5	1	1	100	10000	0.01	0.01	11270.00	78.03	159.40	130.15	120.50	116.41	114.52	113.61	113.16	112.94	112.83	112.77	112.72	112.72	112.72	Cabm
282	2.5	1	1	100	10000	0.01	0.1	11270.00	78.03	159.49	130.24	120.59	116.50	114.61	113.70	113.25	113.03	112.92	112.86	112.81	112.81	112.81	Cabm
283	2.5	1	1	100	10000	0.01	1	11270.00	78.03	160.39	131.14	121.49	117.40	115.51	114.60	114.15	113.93	113.82	113.76	113.71	113.71	113.71	Cabm
284	2.5	1	1	100	10000	0.01	10	11270.00	78.03	169.39	140.14	130.49	126.40	124.51	123.60	123.15	122.93	122.82	122.76	122.71	122.71	122.71	Cabm
285	2.5	1	1	100	10000	0.01	100	11270.00	78.03	259.39	230.14	220.49	216.40	214.51	213.60	213.15	212.93	212.82	212.76	212.71	212.71	212.71	Cabm
286	2.5	1	1	1000	1000	0.01	0.01	1127.00	31.06	1594.01	1301.01	1205.01	1164.01	1145.01	1136.01	1131.01	1129.01	1128.01	1128.01	1127.01	1127.01	1127.01	Cabm
287	2.5	1	1	1000	1000	0.01	0.1	1127.00	31.06	1594.10	1301.10	1205.10	1164.10	1145.10	1136.10	1131.10	1129.10	1128.10	1128.10	1127.10	1127.10	1127.10	Cabm
288	2.5	1	1	1000	1000	0.01	1	1127.00	31.06	1595.00	1302.00	1206.00	1165.00	1146.00	1137.00	1132.00	1130.00	1129.00	1129.00	1128.00	1128.00	1128.00	Cabm
289	2.5	1	1	1000	1000	0.01	10	1127.00	31.06	1604.00	1311.00	1215.00	1174.00	1155.00	1146.00	1141.00	1139.00	1138.00	1138.00	1137.00	1137.00	1137.00	Cabm
290	2.5	1	1	1000	1000	0.01	100	1127.00	31.06	1694.00	1401.00	1305.00	1264.00	1245.00	1236.00	1231.00	1229.00	1228.00	1228.00	1227.00	1227.00	1227.00	Cabm
291	2.5	1	1	1000	10000	0.01	0.01	11270.00	78.03	1594.01	1301.01	1205.01	1164.01	1145.01	1136.01	1131.01	1129.01	1128.01	1128.01	1127.01	1127.01	1127.01	Cabm
292	2.5	1	1	1000	10000	0.01	0.1	11270.00	78.03	1594.10	1301.10	1205.10	1164.10	1145.10	1136.10	1131.10	1129.10	1128.10	1128.10	1127.10	1127.10	1127.10	Cabm
293	2.5	1	1	1000	10000	0.01	1	11270.00	78.03	1595.00	1302.00	1206.00	1165.00	1146.00	1137.00	1132.00	1130.00	1129.00	1129.00	1128.00	1128.00	1128.00	Cabm
294	2.5	1	1	1000	10000	0.01	10	11270.00	78.03	1604.00	1311.00	1215.00	1174.00	1155.00	1146.00	1141.00	1139.00	1138.00	1138.00	1137.00	1137.00	1137.00	Cabm
295	2.5	1	1	1000	10000	0.01	100	11270.00	78.03	1694.00	1401.00	1305.00	1264.00	1245.00	1236.00	1231.00	1229.00	1228.00	1228.00	1227.00	1227.00	1227.00	Cabm
296	2.5	1	1	10000	10000	0.01	0.01	11270.00	78.03	15940.01	13010.01	12050.01	11640.01	11450.01	11360.01	11310.01	11290.01	11280.01	11280.01	11270.01	11270.01	11270.01	Cabm
297	2.5	1	1	10000	10000	0.01	0.1	11270.00	78.03	15940.10	13010.10	12050.10	11640.10	11450.10	11360.10	11310.10	11290.10	11280.10	11280.10	11270.10	11270.10	11270.10	Cabm
298	2.5	1	1	10000	10000	0.01	1	11270.00	78.03	15941.00	13011.00	12051.00	11641.00	11451.00	11361.00	11311.00	11291.00	11281.00	11281.00	11271.00	11271.00	11271.00	Cabm
299	2.5	1	1	10000	10000	0.01	10	11270.00	78.03	15950.00	13020.00	12060.00	11650.00	11460.00	11370.00	11320.00	11300.00	11290.00	11290.00	11280.00	11280.00	11280.00	Cabm
300	2.5	1	1	10000	10000	0.01	100	11270.00	78.03	16040.00	13110.00	12150.00	11740.00	11550.00	11460.00	11410.00	11390.00	11380.00	11380.00	11370.00	11370.00	11370.00	Cabm

TABLE B – IV

RESULTS: BETA EQUALS 3.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
301	3.5	1	1	1	1	0.01	0.01	1.11	1.12	1.58	1.29	1.20	1.16	1.14	1.13	1.13	1.12	1.20	1.12	1.12	1.12	1.12	CM
302	3.5	1	1	1	1	0.01	0.1	1.11	1.12	1.67	1.38	1.29	1.25	1.23	1.22	1.22	1.21	1.29	1.21	1.21	1.21	1.21	CM
303	3.5	1	1	1	1	0.01	1	1.11	1.12	2.57	2.28	2.19	2.15	2.13	2.12	2.12	2.11	2.19	2.11	2.11	2.11	2.11	CM
304	3.5	1	1	1	1	0.01	10	1.11	1.12	11.57	11.28	11.19	11.15	11.13	11.12	11.12	11.11	11.19	11.11	11.11	11.11	11.11	CM
305	3.5	1	1	1	1	0.01	100	1.11	1.12	101.57	101.28	101.19	101.15	101.13	101.12	101.12	101.11	101.19	101.11	101.11	101.11	101.11	CM
306	3.5	1	1	1	10	0.01	0.01	11.11	3.42	1.58	1.29	1.20	1.16	1.14	1.13	1.13	1.12	1.20	1.12	1.12	1.12	1.12	CBM
307	3.5	1	1	1	10	0.01	0.1	11.11	3.42	1.67	1.38	1.29	1.25	1.23	1.22	1.22	1.21	1.29	1.21	1.21	1.21	1.21	CBM
308	3.5	1	1	1	10	0.01	1	11.11	3.42	2.57	2.28	2.19	2.15	2.13	2.12	2.12	2.11	2.19	2.11	2.11	2.11	2.11	CBM
309	3.5	1	1	1	10	0.01	10	11.11	3.42	11.57	11.28	11.19	11.15	11.13	11.12	11.12	11.11	11.19	11.11	11.11	11.11	11.11	Cabm
310	3.5	1	1	1	10	0.01	100	11.11	3.42	101.57	101.28	101.19	101.15	101.13	101.12	101.12	101.11	101.19	101.11	101.11	101.11	101.11	Cabm
311	3.5	1	1	1	100	0.01	0.01	111.14	6.76	1.58	1.29	1.20	1.16	1.14	1.13	1.13	1.12	1.20	1.12	1.12	1.12	1.12	CBM
312	3.5	1	1	1	100	0.01	0.1	111.14	6.76	1.67	1.38	1.29	1.25	1.23	1.22	1.22	1.21	1.29	1.21	1.21	1.21	1.21	CBM
313	3.5	1	1	1	100	0.01	1	111.14	6.76	2.57	2.28	2.19	2.15	2.13	2.12	2.12	2.11	2.19	2.11	2.11	2.11	2.11	CBM
314	3.5	1	1	1	100	0.01	10	111.14	6.76	11.57	11.28	11.19	11.15	11.13	11.12	11.12	11.11	11.19	11.11	11.11	11.11	11.11	Cabm
315	3.5	1	1	1	100	0.01	100	111.14	6.76	101.57	101.28	101.19	101.15	101.13	101.12	101.12	101.11	101.19	101.11	101.11	101.11	101.11	Cabm
316	3.5	1	1	1	1000	0.01	0.01	1111.00	13.09	1.58	1.29	1.20	1.16	1.14	1.13	1.13	1.12	1.20	1.12	1.12	1.12	1.12	CBM
317	3.5	1	1	1	1000	0.01	0.1	1111.00	13.09	1.67	1.38	1.29	1.25	1.23	1.22	1.22	1.21	1.29	1.21	1.21	1.21	1.21	CBM
318	3.5	1	1	1	1000	0.01	1	1111.00	13.09	2.57	2.28	2.19	2.15	2.13	2.12	2.12	2.11	2.19	2.11	2.11	2.11	2.11	CBM
319	3.5	1	1	1	1000	0.01	10	1111.00	13.09	11.57	11.28	11.19	11.15	11.13	11.12	11.12	11.11	11.19	11.11	11.11	11.11	11.11	CBM
320	3.5	1	1	1	1000	0.01	100	1111.00	13.09	101.57	101.28	101.19	101.15	101.13	101.12	101.12	101.11	101.19	101.11	101.11	101.11	101.11	Cabm
321	3.5	1	1	1	10000	0.01	0.01	11110.00	25.27	1.58	1.29	1.20	1.16	1.14	1.13	1.13	1.12	1.20	1.12	1.12	1.12	1.12	CBM
322	3.5	1	1	1	10000	0.01	0.1	11110.00	25.27	1.67	1.38	1.29	1.25	1.23	1.22	1.22	1.21	1.29	1.21	1.21	1.21	1.21	CBM
323	3.5	1	1	1	10000	0.01	1	11110.00	25.27	2.57	2.28	2.19	2.15	2.13	2.12	2.12	2.11	2.19	2.11	2.11	2.11	2.11	CBM
324	3.5	1	1	1	10000	0.01	10	11110.00	25.27	11.57	11.28	11.19	11.15	11.13	11.12	11.12	11.11	11.19	11.11	11.11	11.11	11.11	CBM
325	3.5	1	1	1	10000	0.01	100	11110.00	25.27	101.57	101.28	101.19	101.15	101.13	101.12	101.12	101.11	101.19	101.11	101.11	101.11	101.11	Cabm
326	3.5	1	1	10	10	0.01	0.01	11.11	3.42	15.73	12.84	11.89	11.49	11.30	11.21	11.17	11.15	11.89	11.13	11.13	11.12	11.12	Cabm
327	3.5	1	1	10	10	0.01	0.1	11.11	3.42	15.82	12.93	11.98	11.58	11.39	11.30	11.26	11.24	11.98	11.22	11.22	11.21	11.21	Cabm
328	3.5	1	1	10	10	0.01	1	11.11	3.42	16.72	13.83	12.88	12.48	12.29	12.20	12.16	12.14	12.88	12.12	12.12	12.11	12.11	Cabm
329	3.5	1	1	10	10	0.01	10	11.11	3.42	25.72	22.83	21.88	21.48	21.29	21.20	21.16	21.14	21.88	21.12	21.12	21.11	21.11	Cabm
330	3.5	1	1	10	10	0.01	100	11.11	3.42	115.72	112.83	111.88	111.48	111.29	111.20	111.16	111.14	111.88	111.12	111.12	111.11	111.11	Cabm
331	3.5	1	1	10	100	0.01	0.01	111.14	6.76	15.73	12.84	11.89	11.49	11.30	11.21	11.17	11.15	11.89	11.13	11.13	11.12	11.12	Cabm
332	3.5	1	1	10	100	0.01	0.1	111.14	6.76	15.82	12.93	11.98	11.58	11.39	11.30	11.26	11.24	11.98	11.22	11.22	11.21	11.21	Cabm
333	3.5	1	1	10	100	0.01	1	111.14	6.76	16.72	13.83	12.88	12.48	12.29	12.20	12.16	12.14	12.88	12.12	12.12	12.11	12.11	Cabm
334	3.5	1	1	10	100	0.01	10	111.14	6.76	25.72	22.83	21.88	21.48	21.29	21.20	21.16	21.14	21.88	21.12	21.12	21.11	21.11	Cabm
335	3.5	1	1	10	100	0.01	100	111.14	6.76	115.72	112.83	111.88	111.48	111.29	111.20	111.16	111.14	111.88	111.12	111.12	111.11	111.11	Cabm

TABLE B – IV continued

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM	ABM	Condition-Based Maintenance													Economically Preferred Strategy
								CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	
336	3.5	1	1	10	1000	0.01	0.01	1111.00	13.09	15.73	12.84	11.89	11.49	11.30	11.21	11.17	11.15	11.89	11.13	11.13	11.12	11.12	CBM
337	3.5	1	1	10	1000	0.01	0.1	1111.00	13.09	15.82	12.93	11.98	11.58	11.39	11.30	11.26	11.24	11.98	11.22	11.22	11.21	11.21	CBM
338	3.5	1	1	10	1000	0.01	1	1111.00	13.09	16.72	13.83	12.88	12.48	12.29	12.20	12.16	12.14	12.88	12.12	12.12	12.11	12.11	CBM
339	3.5	1	1	10	1000	0.01	10	1111.00	13.09	25.72	22.83	21.88	21.48	21.29	21.20	21.16	21.14	21.88	21.12	21.12	21.11	21.11	Cabm
340	3.5	1	1	10	1000	0.01	100	1111.00	13.09	115.72	112.83	111.88	111.48	111.29	111.20	111.16	111.14	111.88	111.12	111.12	111.11	111.11	Cabm
341	3.5	1	1	10	10000	0.01	0.01	11110.00	25.27	15.73	12.84	11.89	11.49	11.30	11.21	11.17	11.15	11.89	11.13	11.13	11.12	11.12	CBM
342	3.5	1	1	10	10000	0.01	0.1	11110.00	25.27	15.82	12.93	11.98	11.58	11.39	11.30	11.26	11.24	11.98	11.22	11.22	11.21	11.21	CBM
343	3.5	1	1	10	10000	0.01	1	11110.00	25.27	16.72	13.83	12.88	12.48	12.29	12.20	12.16	12.14	12.88	12.12	12.12	12.11	12.11	CBM
344	3.5	1	1	10	10000	0.01	10	11110.00	25.27	25.72	22.83	21.88	21.48	21.29	21.20	21.16	21.14	21.88	21.12	21.12	21.11	21.11	CBM
345	3.5	1	1	10	10000	0.01	100	11110.00	25.27	115.72	112.83	111.88	111.48	111.29	111.20	111.16	111.14	111.88	111.12	111.12	111.11	111.11	Cabm
346	3.5	1	1	100	100	0.01	0.01	111.14	6.76	157.19	128.35	118.83	114.80	112.93	112.03	111.59	111.37	111.26	111.21	111.16	111.15	111.15	Cabm
347	3.5	1	1	100	100	0.01	0.1	111.14	6.76	157.28	128.44	118.92	114.89	113.02	112.12	111.68	111.46	111.35	111.30	111.25	111.24	111.24	Cabm
348	3.5	1	1	100	100	0.01	1	111.14	6.76	158.18	129.34	119.82	115.79	113.92	113.02	112.58	112.36	112.25	112.20	112.15	112.14	112.14	Cabm
349	3.5	1	1	100	100	0.01	10	111.14	6.76	167.18	138.34	128.82	124.79	122.92	122.02	121.58	121.36	121.25	121.20	121.15	121.14	121.14	Cabm
350	3.5	1	1	100	100	0.01	100	111.14	6.76	257.18	228.34	218.82	214.79	212.92	212.02	211.58	211.36	211.25	211.20	211.15	211.14	211.14	Cabm
351	3.5	1	1	100	1000	0.01	0.01	1111.00	13.09	157.19	128.35	118.83	114.80	112.93	112.03	111.59	111.37	111.26	111.21	111.16	111.15	111.15	Cabm
352	3.5	1	1	100	1000	0.01	0.1	1111.00	13.09	157.28	128.44	118.92	114.89	113.02	112.12	111.68	111.46	111.35	111.30	111.25	111.24	111.24	Cabm
353	3.5	1	1	100	1000	0.01	1	1111.00	13.09	158.18	129.34	119.82	115.79	113.92	113.02	112.58	112.36	112.25	112.20	112.15	112.14	112.14	Cabm
354	3.5	1	1	100	1000	0.01	10	1111.00	13.09	167.18	138.34	128.82	124.79	122.92	122.02	121.58	121.36	121.25	121.20	121.15	121.14	121.14	Cabm
355	3.5	1	1	100	1000	0.01	100	1111.00	13.09	257.18	228.34	218.82	214.79	212.92	212.02	211.58	211.36	211.25	211.20	211.15	211.14	211.14	Cabm
356	3.5	1	1	100	10000	0.01	0.01	11110.00	25.27	157.19	128.35	118.83	114.80	112.93	112.03	111.59	111.37	111.26	111.21	111.16	111.15	111.15	Cabm
357	3.5	1	1	100	10000	0.01	0.1	11110.00	25.27	157.28	128.44	118.92	114.89	113.02	112.12	111.68	111.46	111.35	111.30	111.25	111.24	111.24	Cabm
358	3.5	1	1	100	10000	0.01	1	11110.00	25.27	158.18	129.34	119.82	115.79	113.92	113.02	112.58	112.36	112.25	112.20	112.15	112.14	112.14	Cabm
359	3.5	1	1	100	10000	0.01	10	11110.00	25.27	167.18	138.34	128.82	124.79	122.92	122.02	121.58	121.36	121.25	121.20	121.15	121.14	121.14	Cabm
360	3.5	1	1	100	10000	0.01	100	11110.00	25.27	257.18	228.34	218.82	214.79	212.92	212.02	211.58	211.36	211.25	211.20	211.15	211.14	211.14	Cabm
361	3.5	1	1	1000	1000	0.01	0.01	1111.00	13.09	1572.01	1283.01	1188.01	1148.01	1129.01	1120.01	1116.01	1114.01	1113.01	1112.01	1111.01	1111.01	1111.01	Cabm
362	3.5	1	1	1000	1000	0.01	0.1	1111.00	13.09	1572.10	1283.10	1188.10	1148.10	1129.10	1120.10	1116.10	1114.10	1113.10	1112.10	1111.10	1111.10	1111.10	Cabm
363	3.5	1	1	1000	1000	0.01	1	1111.00	13.09	1573.00	1284.00	1189.00	1149.00	1130.00	1121.00	1117.00	1115.00	1114.00	1113.00	1112.00	1112.00	1112.00	Cabm
364	3.5	1	1	1000	1000	0.01	10	1111.00	13.09	1582.00	1293.00	1198.00	1158.00	1139.00	1130.00	1126.00	1124.00	1123.00	1122.00	1121.00	1121.00	1121.00	Cabm
365	3.5	1	1	1000	1000	0.01	100	1111.00	13.09	1672.00	1383.00	1288.00	1248.00	1229.00	1220.00	1216.00	1214.00	1213.00	1212.00	1211.00	1211.00	1211.00	Cabm
366	3.5	1	1	1000	10000	0.01	0.01	11110.00	25.27	1572.01	1283.01	1188.01	1148.01	1129.01	1120.01	1116.01	1114.01	1113.01	1112.01	1111.01	1111.01	1111.01	Cabm
367	3.5	1	1	1000	10000	0.01	0.1	11110.00	25.27	1572.10	1283.10	1188.10	1148.10	1129.10	1120.10	1116.10	1114.10	1113.10	1112.10	1111.10	1111.10	1111.10	Cabm
368	3.5	1	1	1000	10000	0.01	1	11110.00	25.27	1573.00	1284.00	1189.00	1149.00	1130.00	1121.00	1117.00	1115.00	1114.00	1113.00	1112.00	1112.00	1112.00	Cabm
369	3.5	1	1	1000	10000	0.01	10	11110.00	25.27	1582.00	1293.00	1198.00	1158.00	1139.00	1130.00	1126.00	1124.00	1123.00	1122.00	1121.00	1121.00	1121.00	Cabm
370	3.5	1	1	1000	10000	0.01	100	11110.00	25.27	1672.00	1383.00	1288.00	1248.00	1229.00	1220.00	1216.00	1214.00	1213.00	1212.00	1211.00	1211.00	1211.00	Cabm
371	3.5	1	1	10000	10000	0.01	0.01	11110.00	25.27	15720.01	12830.01	11880.01	11480.01	11290.01	11200.01	11160.01	11140.01	11130.01	11120.01	11110.01	11110.01	11110.01	Cabm
372	3.5	1	1	10000	10000	0.01	0.1	11110.00	25.27	15720.10	12830.10	11880.10	11480.10	11290.10	11200.10	11160.10	11140.10	11130.10	11120.10	11110.10	11110.10	11110.10	Cabm
373	3.5	1	1	10000	10000	0.01	1	11110.00	25.27	15721.00	12831.00	11881.00	11481.00	11291.00	11201.00	11161.00	11141.00	11131.00	11121.00	11111.00	11111.00	11111.00	Cabm
374	3.5	1	1	10000	10000	0.01	10	11110.00	25.27	15730.00	12840.00	11890.00	11490.00	11300.00	11210.00	11170.00	11150.00	11140.00	11130.00	11120.00	11120.00	11120.00	Cabm
375	3.5	1	1	10000	10000	0.01	100	11110.00	25.27	15820.00	12930.00	11980.00	11580.00	11390.00	11300.00	11260.00	11240.00	11230.00	11220.00	11210.00	11210.00	11210.00	Cabm

TABLE B – V
RESULTS: BETA EQUALS 4.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
376	4.5	1	1	1	1	0.01	0.01	1.10	1.11	1.56	1.28	1.18	1.14	1.12	1.11	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CM
377	4.5	1	1	1	1	0.01	0.1	1.10	1.11	1.65	1.37	1.27	1.23	1.21	1.20	1.20	1.20	1.27	1.20	1.20	1.20	1.20	CM
378	4.5	1	1	1	1	0.01	1	1.10	1.11	2.55	2.27	2.17	2.13	2.11	2.10	2.10	2.10	2.17	2.10	2.10	2.10	2.10	CM
379	4.5	1	1	1	1	0.01	10	1.10	1.11	11.55	11.27	11.17	11.13	11.11	11.10	11.10	11.10	11.17	11.10	11.10	11.10	11.10	CM
380	4.5	1	1	1	1	0.01	100	1.10	1.11	101.55	101.27	101.17	101.13	101.11	101.10	101.10	101.10	101.17	101.10	101.10	101.10	101.10	CM
381	4.5	1	1	1	10	0.01	0.01	10.96	2.77	1.56	1.28	1.18	1.14	1.12	1.11	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
382	4.5	1	1	1	10	0.01	0.1	10.96	2.77	1.65	1.37	1.27	1.23	1.21	1.20	1.20	1.20	1.27	1.20	1.20	1.20	1.20	CBM
383	4.5	1	1	1	10	0.01	1	10.96	2.77	2.55	2.27	2.17	2.13	2.11	2.10	2.10	2.10	2.17	2.10	2.10	2.10	2.10	CBM
384	4.5	1	1	1	10	0.01	10	10.96	2.77	11.55	11.27	11.17	11.13	11.11	11.10	11.10	11.10	11.17	11.10	11.10	11.10	11.10	Cabm
385	4.5	1	1	1	10	0.01	100	10.96	2.77	101.55	101.27	101.17	101.13	101.11	101.10	101.10	101.10	101.17	101.10	101.10	101.10	101.10	Cabm
386	4.5	1	1	1	100	0.01	0.01	109.58	4.72	1.56	1.28	1.18	1.14	1.12	1.11	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
387	4.5	1	1	1	100	0.01	0.1	109.58	4.72	1.65	1.37	1.27	1.23	1.21	1.20	1.20	1.20	1.27	1.20	1.20	1.20	1.20	CBM
388	4.5	1	1	1	100	0.01	1	109.58	4.72	2.55	2.27	2.17	2.13	2.11	2.10	2.10	2.10	2.17	2.10	2.10	2.10	2.10	CBM
389	4.5	1	1	1	100	0.01	10	109.58	4.72	11.55	11.27	11.17	11.13	11.11	11.10	11.10	11.10	11.17	11.10	11.10	11.10	11.10	Cabm
390	4.5	1	1	1	100	0.01	100	109.58	4.72	101.55	101.27	101.17	101.13	101.11	101.10	101.10	101.10	101.17	101.10	101.10	101.10	101.10	Cabm
391	4.5	1	1	1	1000	0.01	0.01	1096.00	7.88	1.56	1.28	1.18	1.14	1.12	1.11	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
392	4.5	1	1	1	1000	0.01	0.1	1096.00	7.88	1.65	1.37	1.27	1.23	1.21	1.20	1.20	1.20	1.27	1.20	1.20	1.20	1.20	CBM
393	4.5	1	1	1	1000	0.01	1	1096.00	7.88	2.55	2.27	2.17	2.13	2.11	2.10	2.10	2.10	2.17	2.10	2.10	2.10	2.10	CBM
394	4.5	1	1	1	1000	0.01	10	1096.00	7.88	11.55	11.27	11.17	11.13	11.11	11.10	11.10	11.10	11.17	11.10	11.10	11.10	11.10	Cabm
395	4.5	1	1	1	1000	0.01	100	1096.00	7.88	101.55	101.27	101.17	101.13	101.11	101.10	101.10	101.10	101.17	101.10	101.10	101.10	101.10	Cabm
396	4.5	1	1	1	10000	0.01	0.01	10960.00	13.15	1.56	1.28	1.18	1.14	1.12	1.11	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
397	4.5	1	1	1	10000	0.01	0.1	10960.00	13.15	1.65	1.37	1.27	1.23	1.21	1.20	1.20	1.20	1.27	1.20	1.20	1.20	1.20	CBM
398	4.5	1	1	1	10000	0.01	1	10960.00	13.15	2.55	2.27	2.17	2.13	2.11	2.10	2.10	2.10	2.17	2.10	2.10	2.10	2.10	CBM
399	4.5	1	1	1	10000	0.01	10	10960.00	13.15	11.55	11.27	11.17	11.13	11.11	11.10	11.10	11.10	11.17	11.10	11.10	11.10	11.10	CBM
400	4.5	1	1	1	10000	0.01	100	10960.00	13.15	101.55	101.27	101.17	101.13	101.11	101.10	101.10	101.10	101.17	101.10	101.10	101.10	101.10	Cabm
401	4.5	1	1	10	10	0.01	0.01	10.96	2.77	15.51	12.66	11.73	11.33	11.14	11.06	11.01	10.99	11.73	10.97	10.97	10.97	10.97	Cabm
402	4.5	1	1	10	10	0.01	0.1	10.96	2.77	15.60	12.75	11.82	11.42	11.23	11.15	11.10	11.08	11.82	11.06	11.06	11.06	11.06	Cabm
403	4.5	1	1	10	10	0.01	1	10.96	2.77	16.50	13.65	12.72	12.32	12.13	12.05	12.00	11.98	12.72	11.96	11.96	11.96	11.96	Cabm
404	4.5	1	1	10	10	0.01	10	10.96	2.77	25.50	22.65	21.72	21.32	21.13	21.05	21.00	20.98	21.72	20.96	20.96	20.96	20.96	Cabm
405	4.5	1	1	10	10	0.01	100	10.96	2.77	115.50	112.65	111.72	111.32	111.13	111.05	111.00	110.98	111.72	110.96	110.96	110.96	110.96	Cabm
406	4.5	1	1	10	100	0.01	0.01	109.58	4.72	15.51	12.66	11.73	11.33	11.14	11.06	11.01	10.99	11.73	10.97	10.97	10.97	10.97	Cabm
407	4.5	1	1	10	100	0.01	0.1	109.58	4.72	15.60	12.76	11.82	11.42	11.23	11.16	11.10	11.08	11.82	11.06	11.06	11.06	11.06	Cabm
408	4.5	1	1	10	100	0.01	1	109.58	4.72	16.50	13.65	12.72	12.32	12.13	12.05	12.00	11.98	12.72	11.96	11.96	11.96	11.96	Cabm
409	4.5	1	1	10	100	0.01	10	109.58	4.72	25.50	22.65	21.72	21.32	21.13	21.05	21.00	20.98	21.72	20.96	20.96	20.96	20.96	Cabm
410	4.5	1	1	10	100	0.01	100	109.58	4.72	115.50	112.65	111.72	111.32	111.13	111.05	111.00	110.98	111.72	110.96	110.96	110.96	110.96	Cabm

TABLE B – V continued

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
411	4.5	1	1	10	1000	0.01	0.01	1096.00	7.88	15.51	12.66	11.73	11.33	11.14	11.06	11.01	10.99	11.73	10.97	10.97	10.97	10.97	Cabm
412	4.5	1	1	10	1000	0.01	0.1	1096.00	7.88	15.60	12.75	11.82	11.42	11.23	11.15	11.10	11.08	11.82	11.06	11.06	11.06	11.06	Cabm
413	4.5	1	1	10	1000	0.01	1	1096.00	7.88	16.50	13.65	12.72	12.32	12.13	12.05	12.00	11.98	12.72	11.96	11.96	11.96	11.96	Cabm
414	4.5	1	1	10	1000	0.01	10	1096.00	7.88	25.50	22.65	21.72	21.32	21.13	21.05	21.00	20.98	21.72	20.96	20.96	20.96	20.96	Cabm
415	4.5	1	1	10	1000	0.01	100	1096.00	7.88	115.50	112.65	111.72	111.32	111.13	111.05	111.00	110.98	111.72	110.96	110.96	110.96	110.96	Cabm
416	4.5	1	1	10	10000	0.01	0.01	10960.00	13.15	15.51	12.66	11.73	11.33	11.14	11.06	11.01	10.99	11.73	10.97	10.97	10.97	10.97	CBM
417	4.5	1	1	10	10000	0.01	0.1	10960.00	13.15	15.60	12.75	11.82	11.42	11.23	11.15	11.10	11.08	11.82	11.06	11.06	11.06	11.06	CBM
418	4.5	1	1	10	10000	0.01	1	10960.00	13.15	16.50	13.65	12.72	12.32	12.13	12.05	12.00	11.98	12.72	11.96	11.96	11.96	11.96	CBM
419	4.5	1	1	10	10000	0.01	10	10960.00	13.15	25.50	22.65	21.72	21.32	21.13	21.05	21.00	20.98	21.72	20.96	20.96	20.96	20.96	Cabm
420	4.5	1	1	10	10000	0.01	100	10960.00	13.15	115.50	112.65	111.72	111.32	111.13	111.05	111.00	110.98	111.72	110.96	110.96	110.96	110.96	Cabm
421	4.5	1	1	100	100	0.01	0.01	109.58	4.72	154.98	126.54	117.16	113.18	111.34	110.46	110.02	109.81	109.70	109.64	109.60	109.59	109.59	Cabm
422	4.5	1	1	100	100	0.01	0.1	109.58	4.72	155.07	126.63	117.25	113.27	111.43	110.55	110.11	109.90	109.79	109.73	109.69	109.68	109.68	Cabm
423	4.5	1	1	100	100	0.01	1	109.58	4.72	155.97	127.53	118.15	114.17	112.33	111.45	111.01	110.80	110.69	110.63	110.59	110.58	110.58	Cabm
424	4.5	1	1	100	100	0.01	10	109.58	4.72	164.97	136.53	127.15	123.17	121.33	120.45	120.01	119.80	119.69	119.63	119.59	119.58	119.58	Cabm
425	4.5	1	1	100	100	0.01	100	109.58	4.72	254.97	226.53	217.15	213.17	211.33	210.45	210.01	209.80	209.69	209.63	209.59	209.58	209.58	Cabm
426	4.5	1	1	100	1000	0.01	0.01	1096.00	7.88	154.98	126.54	117.16	113.18	111.34	110.46	110.02	109.81	109.70	109.64	109.60	109.59	109.59	Cabm
427	4.5	1	1	100	1000	0.01	0.1	1096.00	7.88	155.07	126.63	117.25	113.27	111.43	110.55	110.11	109.90	109.79	109.73	109.69	109.68	109.68	Cabm
428	4.5	1	1	100	1000	0.01	1	1096.00	7.88	155.97	127.53	118.15	114.17	112.33	111.45	111.01	110.80	110.69	110.63	110.59	110.58	110.58	Cabm
429	4.5	1	1	100	1000	0.01	10	1096.00	7.88	164.97	136.53	127.15	123.17	121.33	120.45	120.01	119.80	119.69	119.63	119.59	119.58	119.58	Cabm
430	4.5	1	1	100	1000	0.01	100	1096.00	7.88	254.97	226.53	217.15	213.17	211.33	210.45	210.01	209.80	209.69	209.63	209.59	209.58	209.58	Cabm
431	4.5	1	1	100	10000	0.01	0.01	10960.00	13.15	154.98	126.54	117.16	113.18	111.34	110.46	110.02	109.81	109.70	109.64	109.60	109.59	109.59	Cabm
432	4.5	1	1	100	10000	0.01	0.1	10960.00	13.15	155.07	126.63	117.25	113.27	111.43	110.55	110.11	109.90	109.79	109.73	109.69	109.68	109.68	Cabm
433	4.5	1	1	100	10000	0.01	1	10960.00	13.15	155.97	127.53	118.15	114.17	112.33	111.45	111.01	110.80	110.69	110.63	110.59	110.58	110.58	Cabm
434	4.5	1	1	100	10000	0.01	10	10960.00	13.15	164.97	136.53	127.15	123.17	121.33	120.45	120.01	119.80	119.69	119.63	119.59	119.58	119.58	Cabm
435	4.5	1	1	100	10000	0.01	100	10960.00	13.15	254.97	226.53	217.15	213.17	211.33	210.45	210.01	209.80	209.69	209.63	209.59	209.58	209.58	Cabm
436	4.5	1	1	1000	1000	0.01	0.01	1096.00	7.88	1550.01	1265.01	1171.01	1132.01	1113.01	1104.01	1100.01	1098.01	1097.01	1096.01	1096.01	1096.01	1096.01	Cabm
437	4.5	1	1	1000	1000	0.01	0.1	1096.00	7.88	1550.10	1265.10	1171.10	1132.10	1113.10	1104.10	1100.10	1098.10	1097.10	1096.10	1096.10	1096.10	1096.10	Cabm
438	4.5	1	1	1000	1000	0.01	1	1096.00	7.88	1551.00	1266.00	1172.00	1133.00	1114.00	1105.00	1101.00	1099.00	1098.00	1097.00	1097.00	1097.00	1097.00	Cabm
439	4.5	1	1	1000	1000	0.01	10	1096.00	7.88	1560.00	1275.00	1181.00	1142.00	1123.00	1114.00	1110.00	1108.00	1107.00	1106.00	1106.00	1106.00	1106.00	Cabm
440	4.5	1	1	1000	1000	0.01	100	1096.00	7.88	1650.00	1365.00	1271.00	1232.00	1213.00	1204.00	1200.00	1198.00	1197.00	1196.00	1196.00	1196.00	1196.00	Cabm
441	4.5	1	1	1000	10000	0.01	0.01	10960.00	13.15	1550.01	1265.01	1171.01	1132.01	1113.01	1104.01	1100.01	1098.01	1097.01	1096.01	1096.01	1096.01	1096.01	Cabm
442	4.5	1	1	1000	10000	0.01	0.1	10960.00	13.15	1550.10	1265.10	1171.10	1132.10	1113.10	1104.10	1100.10	1098.10	1097.10	1096.10	1096.10	1096.10	1096.10	Cabm
443	4.5	1	1	1000	10000	0.01	1	10960.00	13.15	1551.00	1266.00	1172.00	1133.00	1114.00	1105.00	1101.00	1099.00	1098.00	1097.00	1097.00	1097.00	1097.00	Cabm
444	4.5	1	1	1000	10000	0.01	10	10960.00	13.15	1560.00	1275.00	1181.00	1142.00	1123.00	1114.00	1110.00	1108.00	1107.00	1106.00	1106.00	1106.00	1106.00	Cabm
445	4.5	1	1	1000	10000	0.01	100	10960.00	13.15	1650.00	1365.00	1271.00	1232.00	1213.00	1204.00	1200.00	1198.00	1197.00	1196.00	1196.00	1196.00	1196.00	Cabm
446	4.5	1	1	10000	10000	0.01	0.01	10960.00	13.15	15500.01	12650.01	11710.01	11320.01	11130.01	11040.01	11000.01	10980.01	10970.01	10960.01	10960.01	10960.01	10960.01	Cabm
447	4.5	1	1	10000	10000	0.01	0.1	10960.00	13.15	15500.10	12650.10	11710.10	11320.10	11130.10	11040.10	11000.10	10980.10	10970.10	10960.10	10960.10	10960.10	10960.10	Cabm
448	4.5	1	1	10000	10000	0.01	1	10960.00	13.15	15501.00	12651.00	11711.00	11321.00	11131.00	11041.00	11001.00	10981.00	10971.00	10961.00	10961.00	10961.00	10961.00	Cabm
449	4.5	1	1	10000	10000	0.01	10	10960.00	13.15	15510.00	12660.00	11720.00	11330.00	11140.00	11050.00	11010.00	10990.00	10980.00	10970.00	10970.00	10970.00	10970.00	Cabm
450	4.5	1	1	10000	10000	0.01	100	10960.00	13.15	15600.00	12750.00	11810.00	11420.00	11230.00	11140.00	11100.00	11080.00	11070.00	11060.00	11060.00	11060.00	11060.00	Cabm

TABLE B – VI

RESULTS: BETA EQUALS 5.5

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM	ABM	Condition-Based Maintenance													Economically Preferred Strategy
								CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	
451	5.6	1	1	1	1	0.01	0.01	1.08	1.09	1.54	1.26	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.09	1.09	1.09	1.09	CM
452	5.5	1	1	1	1	0.01	0.1	1.08	1.09	1.63	1.35	1.26	1.22	1.20	1.19	1.19	1.19	1.26	1.18	1.18	1.18	1.18	CM
453	5.5	1	1	1	1	0.01	1	1.08	1.09	2.53	2.25	2.16	2.12	2.10	2.09	2.09	2.09	2.16	2.08	2.08	2.08	2.08	CM
454	5.5	1	1	1	1	0.01	10	1.08	1.09	11.53	11.25	11.16	11.12	11.10	11.09	11.09	11.09	11.16	11.08	11.08	11.08	11.08	CM
455	5.5	1	1	1	1	0.01	100	1.08	1.09	101.53	101.25	101.16	101.12	101.10	101.09	101.09	101.09	101.16	101.08	101.08	101.08	101.08	CM
456	5.5	1	1	1	10	0.01	0.01	10.83	2.40	1.54	1.26	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.09	1.09	1.09	1.09	CBM
457	5.5	1	1	1	10	0.01	0.1	10.83	2.40	1.63	1.35	1.26	1.22	1.20	1.19	1.19	1.19	1.26	1.18	1.18	1.18	1.18	CBM
458	5.5	1	1	1	10	0.01	1	10.83	2.40	2.53	2.25	2.16	2.12	2.10	2.09	2.09	2.09	2.16	2.08	2.08	2.08	2.08	CBM
459	5.5	1	1	1	10	0.01	10	10.83	2.40	11.53	11.25	11.16	11.12	11.10	11.09	11.09	11.09	11.16	11.08	11.08	11.08	11.08	Cabm
460	5.5	1	1	1	10	0.01	100	10.83	2.40	101.53	101.25	101.16	101.12	101.10	101.09	101.09	101.09	101.16	101.08	101.08	101.08	101.08	Cabm
461	5.5	1	1	1	100	0.01	0.01	108.32	3.71	1.54	1.26	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.09	1.09	1.09	1.09	CBM
462	5.5	1	1	1	100	0.01	0.1	108.32	3.71	1.63	1.35	1.26	1.22	1.20	1.19	1.19	1.19	1.26	1.18	1.18	1.18	1.18	CBM
463	5.5	1	1	1	100	0.01	1	108.32	3.71	2.53	2.25	2.16	2.12	2.10	2.09	2.09	2.09	2.16	2.08	2.08	2.08	2.08	CBM
464	5.5	1	1	1	100	0.01	10	108.32	3.71	11.53	11.25	11.16	11.12	11.10	11.09	11.09	11.09	11.16	11.08	11.08	11.08	11.08	Cabm
465	5.5	1	1	1	100	0.01	100	108.32	3.71	101.53	101.25	101.16	101.12	101.10	101.09	101.09	101.09	101.16	101.08	101.08	101.08	101.08	Cabm
466	5.5	1	1	1	1000	0.01	0.01	1083.00	5.64	1.54	1.26	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.09	1.09	1.09	1.09	CBM
467	5.5	1	1	1	1000	0.01	0.1	1083.00	5.64	1.63	1.35	1.26	1.22	1.20	1.19	1.19	1.19	1.26	1.18	1.18	1.18	1.18	CBM
468	5.5	1	1	1	1000	0.01	1	1083.00	5.64	2.53	2.25	2.16	2.12	2.10	2.09	2.09	2.09	2.16	2.08	2.08	2.08	2.08	CBM
469	5.5	1	1	1	1000	0.01	10	1083.00	5.64	11.53	11.25	11.16	11.12	11.10	11.09	11.09	11.09	11.16	11.08	11.08	11.08	11.08	Cabm
470	5.5	1	1	1	1000	0.01	100	1083.00	5.64	101.53	101.25	101.16	101.12	101.10	101.09	101.09	101.09	101.16	101.08	101.08	101.08	101.08	Cabm
471	5.5	1	1	1	10000	0.01	0.01	10830.00	8.57	1.54	1.26	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.09	1.09	1.09	1.09	CBM
472	5.5	1	1	1	10000	0.01	0.1	10830.00	8.57	1.63	1.35	1.26	1.22	1.20	1.19	1.19	1.19	1.26	1.18	1.18	1.18	1.18	CBM
473	5.5	1	1	1	10000	0.01	1	10830.00	8.57	2.53	2.25	2.16	2.12	2.10	2.09	2.09	2.09	2.16	2.08	2.08	2.08	2.08	CBM
474	5.5	1	1	1	10000	0.01	10	10830.00	8.57	11.53	11.25	11.16	11.12	11.10	11.09	11.09	11.09	11.16	11.08	11.08	11.08	11.08	Cabm
475	5.5	1	1	1	10000	0.01	100	10830.00	8.57	101.53	101.25	101.16	101.12	101.10	101.09	101.09	101.09	101.16	101.08	101.08	101.08	101.08	Cabm
476	5.5	1	1	10	10	0.01	0.01	10.83	2.40	15.33	12.52	11.59	11.20	11.02	10.93	10.88	10.86	11.59	10.85	10.84	10.84	10.84	Cabm
477	5.5	1	1	10	10	0.01	0.1	10.83	2.40	15.42	12.61	11.68	11.29	11.11	11.02	10.97	10.95	11.68	10.94	10.93	10.93	10.93	Cabm
478	5.5	1	1	10	10	0.01	1	10.83	2.40	16.32	13.51	12.58	12.19	12.01	11.92	11.87	11.85	12.58	11.84	11.83	11.83	11.83	Cabm
479	5.5	1	1	10	10	0.01	10	10.83	2.40	25.32	22.51	21.58	21.19	21.01	20.92	20.87	20.85	21.58	20.84	20.83	20.83	20.83	Cabm
480	5.5	1	1	10	10	0.01	100	10.83	2.40	115.32	112.51	111.58	111.19	111.01	110.92	110.87	110.85	111.58	110.84	110.83	110.83	110.83	Cabm
481	5.5	1	1	10	100	0.01	0.01	108.32	3.71	15.33	12.52	11.59	11.20	11.02	10.93	10.88	10.86	11.59	10.85	10.84	10.84	10.84	Cabm
482	5.5	1	1	10	100	0.01	0.1	108.32	3.71	15.42	12.61	11.68	11.29	11.11	11.02	10.97	10.95	11.68	10.94	10.93	10.93	10.93	Cabm
483	5.5	1	1	10	100	0.01	1	108.32	3.71	16.32	13.51	12.58	12.19	12.01	11.92	11.87	11.85	12.58	11.84	11.83	11.83	11.83	Cabm
484	5.5	1	1	10	100	0.01	10	108.32	3.71	25.32	22.51	21.58	21.19	21.01	20.92	20.87	20.85	21.58	20.84	20.83	20.83	20.83	Cabm
485	5.5	1	1	10	100	0.01	100	108.32	3.71	115.32	112.51	111.58	111.19	111.01	110.92	110.87	110.85	111.58	110.84	110.83	110.83	110.83	Cabm

TABLE B – VI continued

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Clccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
486	5.5	1	1	10	1000	0.01	0.01	1083.00	5.64	15.33	12.52	11.59	11.20	11.02	10.93	10.88	10.86	11.59	10.85	10.84	10.84	10.84	Cabm
487	5.5	1	1	10	1000	0.01	0.1	1083.00	5.64	15.42	12.61	11.68	11.29	11.11	11.02	10.97	10.95	11.68	10.94	10.93	10.93	10.93	Cabm
488	5.5	1	1	10	1000	0.01	1	1083.00	5.64	16.32	13.51	12.58	12.19	12.01	11.92	11.87	11.85	12.58	11.84	11.83	11.83	11.83	Cabm
489	5.5	1	1	10	1000	0.01	10	1083.00	5.64	25.32	22.51	21.58	21.19	21.01	20.92	20.87	20.85	21.58	20.84	20.83	20.83	20.83	Cabm
490	5.5	1	1	10	1000	0.01	100	1083.00	5.64	115.32	112.51	111.58	111.19	111.01	110.92	110.87	110.85	111.58	110.84	110.83	110.83	110.83	Cabm
491	5.5	1	1	10	10000	0.01	0.01	10830.00	8.57	15.33	12.52	11.59	11.20	11.02	10.93	10.88	10.86	11.59	10.85	10.84	10.84	10.84	Cabm
492	5.5	1	1	10	10000	0.01	0.1	10830.00	8.57	15.42	12.61	11.68	11.29	11.11	11.02	10.97	10.95	11.68	10.94	10.93	10.93	10.93	Cabm
493	5.5	1	1	10	10000	0.01	1	10830.00	8.57	16.32	13.51	12.58	12.19	12.01	11.92	11.87	11.85	12.58	11.84	11.83	11.83	11.83	Cabm
494	5.5	1	1	10	10000	0.01	10	10830.00	8.57	25.32	22.51	21.58	21.19	21.01	20.92	20.87	20.85	21.58	20.84	20.83	20.83	20.83	Cabm
495	5.5	1	1	10	10000	0.01	100	10830.00	8.57	115.32	112.51	111.58	111.19	111.01	110.92	110.87	110.85	111.58	110.84	110.83	110.83	110.83	Cabm
496	5.5	1	1	100	100	0.01	0.01	108.32	3.71	153.20	125.09	115.81	111.88	110.06	109.19	108.75	108.54	108.44	108.38	108.33	108.33	108.33	Cabm
497	5.5	1	1	100	100	0.01	0.1	108.32	3.71	153.29	125.18	115.90	111.97	110.15	109.28	108.84	108.63	108.53	108.47	108.42	108.42	108.42	Cabm
498	5.5	1	1	100	100	0.01	1	108.32	3.71	154.19	126.08	116.80	112.87	111.05	110.18	109.74	109.53	109.43	109.37	109.32	109.32	109.32	Cabm
499	5.5	1	1	100	100	0.01	10	108.32	3.71	163.19	135.08	125.80	121.87	120.05	119.18	118.74	118.53	118.43	118.37	118.32	118.32	118.32	Cabm
500	5.5	1	1	100	100	0.01	100	108.32	3.71	253.19	225.08	215.80	211.87	210.05	209.18	208.74	208.53	208.43	208.37	208.32	208.32	208.32	Cabm
501	5.5	1	1	100	1000	0.01	0.01	1083.00	5.64	153.20	125.09	115.81	111.88	110.06	109.19	108.75	108.54	108.44	108.38	108.33	108.33	108.33	Cabm
502	5.5	1	1	100	1000	0.01	0.1	1083.00	5.64	153.29	125.18	115.90	111.97	110.15	109.28	108.84	108.63	108.53	108.47	108.42	108.42	108.42	Cabm
503	5.5	1	1	100	1000	0.01	1	1083.00	5.64	154.19	126.08	116.80	112.87	111.05	110.18	109.74	109.53	109.43	109.37	109.32	109.32	109.32	Cabm
504	5.5	1	1	100	1000	0.01	10	1083.00	5.64	163.19	135.08	125.80	121.87	120.05	119.18	118.74	118.53	118.43	118.37	118.32	118.32	118.32	Cabm
505	5.5	1	1	100	1000	0.01	100	1083.00	5.64	253.19	225.08	215.80	211.87	210.05	209.18	208.74	208.53	208.43	208.37	208.32	208.32	208.32	Cabm
506	5.5	1	1	100	10000	0.01	0.01	10830.00	8.57	153.20	125.09	115.81	111.88	110.06	109.19	108.75	108.54	108.44	108.38	108.33	108.33	108.33	Cabm
507	5.5	1	1	100	10000	0.01	0.1	10830.00	8.57	153.29	125.18	115.90	111.97	110.15	109.28	108.84	108.63	108.53	108.47	108.42	108.42	108.42	Cabm
508	5.5	1	1	100	10000	0.01	1	10830.00	8.57	154.19	126.08	116.80	112.87	111.05	110.18	109.74	109.53	109.43	109.37	109.32	109.32	109.32	Cabm
509	5.5	1	1	100	10000	0.01	10	10830.00	8.57	163.19	135.08	125.80	121.87	120.05	119.18	118.74	118.53	118.43	118.37	118.32	118.32	118.32	Cabm
510	5.5	1	1	100	10000	0.01	100	10830.00	8.57	253.19	225.08	215.80	211.87	210.05	209.18	208.74	208.53	208.43	208.37	208.32	208.32	208.32	Cabm
511	5.5	1	1	1000	1000	0.01	0.01	1083.00	5.64	1632.01	1251.01	1168.01	1119.01	1101.01	1092.01	1087.01	1085.01	1084.01	1084.01	1083.01	1083.01	1083.01	Cabm
512	5.5	1	1	1000	1000	0.01	0.1	1083.00	5.64	1532.10	1251.10	1158.10	1119.10	1101.10	1092.10	1087.10	1085.10	1084.10	1084.10	1083.10	1083.10	1083.10	Cabm
513	5.5	1	1	1000	1000	0.01	1	1083.00	5.64	1533.00	1252.00	1159.00	1120.00	1102.00	1093.00	1088.00	1086.00	1085.00	1085.00	1084.00	1084.00	1084.00	Cabm
514	5.5	1	1	1000	1000	0.01	10	1083.00	5.64	1542.00	1261.00	1168.00	1129.00	1111.00	1102.00	1097.00	1095.00	1094.00	1094.00	1093.00	1093.00	1093.00	Cabm
515	5.5	1	1	1000	1000	0.01	100	1083.00	5.64	1632.00	1351.00	1258.00	1219.00	1201.00	1192.00	1187.00	1185.00	1184.00	1184.00	1183.00	1183.00	1183.00	Cabm
516	6.5	1	1	1000	10000	0.01	0.01	10830.00	8.57	1532.01	1251.01	1158.01	1119.01	1101.01	1092.01	1087.01	1085.01	1084.01	1084.01	1083.01	1083.01	1083.01	Cabm
517	5.5	1	1	1000	10000	0.01	0.1	10830.00	8.57	1532.10	1251.10	1158.10	1119.10	1101.10	1092.10	1087.10	1085.10	1084.10	1084.10	1083.10	1083.10	1083.10	Cabm
518	5.5	1	1	1000	10000	0.01	1	10830.00	8.57	1533.00	1252.00	1159.00	1120.00	1102.00	1093.00	1088.00	1086.00	1085.00	1085.00	1084.00	1084.00	1084.00	Cabm
519	5.5	1	1	1000	10000	0.01	10	10830.00	8.57	1542.00	1261.00	1168.00	1129.00	1111.00	1102.00	1097.00	1095.00	1094.00	1094.00	1093.00	1093.00	1093.00	Cabm
520	5.5	1	1	1000	10000	0.01	100	10830.00	8.57	1632.00	1351.00	1258.00	1219.00	1201.00	1192.00	1187.00	1185.00	1184.00	1184.00	1183.00	1183.00	1183.00	Cabm
521	5.5	1	1	10000	10000	0.01	0.01	10830.00	8.57	15320.01	12510.01	11580.01	11190.01	11010.01	10920.01	10870.01	10850.01	10840.01	10840.01	10830.01	10830.01	10830.01	Cabm
522	5.5	1	1	10000	10000	0.01	0.1	10830.00	8.57	15320.10	12510.10	11580.10	11190.10	11010.10	10920.10	10870.10	10850.10	10840.10	10840.10	10830.10	10830.10	10830.10	Cabm
523	5.5	1	1	10000	10000	0.01	1	10830.00	8.57	15321.00	12511.00	11581.00	11191.00	11011.00	10921.00	10871.00	10851.00	10841.00	10841.00	10831.00	10831.00	10831.00	Cabm
524	5.5	1	1	10000	10000	0.01	10	10830.00	8.57	15330.00	12520.00	11590.00	11200.00	11020.00	10930.00	10880.00	10860.00	10850.00	10850.00	10840.00	10840.00	10840.00	Cabm
525	5.5	1	1	10000	10000	0.01	100	10830.00	8.57	15420.00	12610.00	11680.00	11290.00	11110.00	11020.00	10970.00	10950.00	10940.00	10940.00	10930.00	10930.00	10930.00	Cabm

TABLE B – VII

RESULTS: BETA EQUALS 1.0

Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Clccbm	CM CM	ABM Cabm	Condition-Based Maintenance DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
16	1	1	1	1	1	1	1	1.00	1.00	1.41	1.16	1.07	1.03	1.02	1.01	1.00	1.00	1.07	1.00	1.00	1.00	1.00	CM
17	1	1	1	1	10	1	1	10.00	10.00	1.41	1.16	1.07	1.03	1.02	1.01	1.00	1.00	1.07	1.00	1.00	1.00	1.00	CBM
18	1	1	1	1	100	1	1	100.00	100.00	1.41	1.16	1.07	1.03	1.02	1.01	1.00	1.00	1.07	1.00	1.00	1.00	1.00	CBM
19	1	1	1	1	1000	1	1	1000.00	1000.00	1.41	1.16	1.07	1.03	1.02	1.01	1.00	1.00	1.07	1.00	1.00	1.00	1.00	CBM
20	1	1	1	1	10000	1	1	10000.00	10000.00	1.41	1.16	1.07	1.03	1.02	1.01	1.00	1.00	1.07	1.00	1.00	1.00	1.00	CBM
21	1	1	1	10	10	1	1	10.00	10.00	14.14	11.55	10.69	10.33	10.16	10.08	10.04	10.02	10.69	10.01	10.00	10.00	10.00	CM
22	1	1	1	10	100	1	1	100.00	100.00	14.14	11.55	10.69	10.33	10.16	10.08	10.04	10.02	10.69	10.01	10.00	10.00	10.00	CBM
23	1	1	1	10	1000	1	1	1000.00	1000.00	14.14	11.55	10.69	10.33	10.16	10.08	10.04	10.02	10.69	10.01	10.00	10.00	10.00	CBM
24	1	1	1	10	10000	1	1	10000.00	10000.00	14.14	11.55	10.69	10.33	10.16	10.08	10.04	10.02	10.69	10.01	10.00	10.00	10.00	CBM
25	1	1	1	100	100	1	1	100.00	100.00	141.42	115.47	106.90	103.28	101.60	100.79	100.39	100.20	100.10	100.05	100.01	100.00	100.00	CM
26	1	1	1	100	1000	1	1	1000.00	1000.00	141.42	115.47	106.90	103.28	101.60	100.79	100.39	100.20	100.10	100.05	100.01	100.00	100.00	CBM
27	1	1	1	100	10000	1	1	10000.00	10000.00	141.42	115.47	106.90	103.28	101.60	100.79	100.39	100.20	100.10	100.05	100.01	100.00	100.00	CBM
28	1	1	1	1000	1000	1	1	1000.00	1000.00	1414.00	1155.00	1069.00	1033.00	1016.00	1008.00	1004.00	1002.00	1001.00	1000.00	1000.00	1000.00	1000.00	CM
29	1	1	1	1000	10000	1	1	10000.00	10000.00	1414.00	1155.00	1069.00	1033.00	1016.00	1008.00	1004.00	1002.00	1001.00	1000.00	1000.00	1000.00	1000.00	CBM
30	1	1	1	10000	10000	1	1	10000.00	10000.00	14140.00	11550.00	10690.00	10330.00	10160.00	10080.00	10040.00	10020.00	10010.00	10000.00	10000.00	10000.00	10000.00	CM

Trial	Beta	Theta	Cp	Ccbm	Cu	C Icp	Clccbm	CM CM	ABM Cabm	Condition-Based Maintenance DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
16	1	1	1	1	1	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CM
17	1	1	1	1	10	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
18	1	1	1	1	100	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
19	1	1	1	1	1000	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
20	1	1	1	1	10000	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
21	1	1	1	10	10	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CM
22	1	1	1	10	100	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
23	1	1	1	10	1000	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
24	1	1	1	10	10000	1	1	1.00	26.10	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
25	1	1	1	100	100	1	1	1.00	20.53	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CM
26	1	1	1	100	1000	1	1	1.00	20.53	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
27	1	1	1	100	10000	1	1	1.00	20.53	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
28	1	1	1	1000	1000	1	1	1.00	20.53	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CM
29	1	1	1	1000	10000	1	1	1.00	20.53	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CBM
30	1	1	1	10000	10000	1	1	1.00	20.53	0.71	0.87	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	CM

TABLE B – VIII

RESULTS: BETA EQUALS 1.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
31	1.5	1	1	1	1	1	1	1.11	1.11	1.57	1.28	1.18	1.14	1.13	1.12	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CM
32	1.5	1	1	1	10	1	1	11.08	8.30	1.57	1.28	1.18	1.14	1.13	1.12	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
33	1.5	1	1	1	100	1	1	110.77	40.50	1.57	1.28	1.18	1.14	1.13	1.12	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
34	1.5	1	1	1	1000	1	1	1108.00	188.89	1.57	1.28	1.18	1.14	1.13	1.12	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
35	1.5	1	1	1	10000	1	1	11080.00	877.16	1.57	1.28	1.18	1.14	1.13	1.12	1.11	1.11	1.18	1.11	1.11	1.11	1.11	CBM
36	1.5	1	1	10	10	1	1	11.08	8.30	15.67	12.79	11.84	11.44	11.26	11.17	11.12	11.10	11.84	11.08	11.08	11.08	11.08	Cabm
37	1.5	1	1	10	100	1	1	110.77	40.50	15.67	12.79	11.84	11.44	11.26	11.17	11.12	11.10	11.84	11.08	11.08	11.08	11.08	CBM
38	1.5	1	1	10	1000	1	1	1108.00	188.89	15.67	12.79	11.84	11.44	11.26	11.17	11.12	11.10	11.84	11.08	11.08	11.08	11.08	CBM
39	1.5	1	1	10	10000	1	1	11080.00	877.16	15.67	12.79	11.84	11.44	11.26	11.17	11.12	11.10	11.84	11.08	11.08	11.08	11.08	CBM
40	1.5	1	1	100	100	1	1	110.773	40.50	156.66	127.91	118.42	114.41	112.55	111.65	111.21	110.99	110.88	110.83	110.78	110.77	110.77	Cabm
41	1.5	1	1	100	1000	1	1	1.11E+03	188.89	156.66	127.91	118.42	114.41	112.55	111.65	111.21	110.99	110.88	110.83	110.78	110.77	110.77	CBM
42	1.5	1	1	100	10000	1	1	1.11E+04	877.16	156.66	127.91	118.42	114.41	112.55	111.65	111.21	110.99	110.88	110.83	110.78	110.77	110.77	CBM
43	1.5	1	1	1000	1000	1	1	1.11E+03	188.89	1567.00	1279.00	1184.00	1144.00	1125.00	1116.00	1112.00	1110.00	1109.00	1108.00	1108.00	1108.00	1108.00	Cabm
44	1.5	1	1	1000	10000	1	1	1.11E+04	877.16	1567.00	1279.00	1184.00	1144.00	1125.00	1116.00	1112.00	1110.00	1109.00	1108.00	1108.00	1108.00	1108.00	Cabm
45	1.5	1	1	10000	10000	1	1	1.11E+04	877.16	15670.00	12790.00	11840.00	11440.00	11250.00	11160.00	11120.00	11100.00	11090.00	11080.00	11080.00	11080.00	11080.00	Cabm

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
31	1.5	1	1	1	1	1	1	0.90	6.90	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CM
32	1.5	1	1	1	10	1	1	0.90	0.38	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
33	1.5	1	1	1	100	1	1	0.90	0.07	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
34	1.5	1	1	1	1000	1	1	0.90	0.02	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
35	1.5	1	1	1	10000	1	1	0.90	0.00	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
36	1.5	1	1	10	10	1	1	0.90	0.38	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
37	1.5	1	1	10	100	1	1	0.90	0.07	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
38	1.5	1	1	10	1000	1	1	0.90	0.02	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
39	1.5	1	1	10	10000	1	1	0.90	0.00	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
40	1.5	1	1	100	100	1	1	0.90	0.07	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
41	1.5	1	1	100	1000	1	1	0.90	0.02	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
42	1.5	1	1	100	10000	1	1	0.90	0.00	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
43	1.5	1	1	1000	1000	1	1	0.90	0.02	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
44	1.5	1	1	1000	10000	1	1	0.90	0.00	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
45	1.5	1	1	10000	10000	1	1	0.90	0.00	0.64	0.78	0.84	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm

TABLE B – IX

RESULTS: BETA EQUALS 2.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
46	2.5	1	1	1	1	1	1	1.13	1.13	1.59	1.30	1.21	1.16	1.15	1.14	1.13	1.13	1.21	1.13	1.13	1.13	1.13	CM
47	2.5	1	1	1	10	1	1	11.27	4.75	1.59	1.30	1.21	1.16	1.15	1.14	1.13	1.13	1.21	1.13	1.13	1.13	1.13	CBM
48	2.5	1	1	1	100	1	1	112.71	12.33	1.59	1.30	1.21	1.16	1.15	1.14	1.13	1.13	1.21	1.13	1.13	1.13	1.13	CBM
49	2.5	1	1	1	1000	1	1	1127.00	31.06	1.59	1.30	1.21	1.16	1.15	1.14	1.13	1.13	1.21	1.13	1.13	1.13	1.13	CBM
50	2.5	1	1	1	10000	1	1	11270.00	78.03	1.59	1.30	1.21	1.16	1.15	1.14	1.13	1.13	1.21	1.13	1.13	1.13	1.13	CBM
51	2.5	1	1	10	10	1	1	11.27	4.75	15.94	13.01	12.05	11.64	11.45	11.36	11.32	11.29	12.05	11.28	11.27	11.27	11.27	Cabm
52	2.5	1	1	10	100	1	1	112.71	12.33	15.94	13.01	12.05	11.64	11.45	11.36	11.32	11.29	12.05	11.28	11.27	11.27	11.27	CBM
53	2.5	1	1	10	1000	1	1	1127.00	31.06	15.94	13.01	12.05	11.64	11.45	11.36	11.32	11.29	12.05	11.28	11.27	11.27	11.27	CBM
54	2.5	1	1	10	10000	1	1	11270.00	78.03	15.94	13.01	12.05	11.64	11.45	11.36	11.32	11.29	12.05	11.28	11.27	11.27	11.27	CBM
55	2.5	1	1	100	100	1	1	112.71	12.33	159.39	130.14	120.49	116.40	114.51	113.60	113.15	112.93	112.82	112.76	112.71	112.71	112.71	Cabm
56	2.5	1	1	100	1000	1	1	1127.00	31.06	159.39	130.14	120.49	116.40	114.51	113.60	113.15	112.93	112.82	112.76	112.71	112.71	112.71	Cabm
57	2.5	1	1	100	10000	1	1	11270.00	78.03	159.39	130.14	120.49	116.40	114.51	113.60	113.15	112.93	112.82	112.76	112.71	112.71	112.71	Cabm
58	2.5	1	1	1000	1000	1	1	1127.00	31.06	1594.00	1301.00	1205.00	1164.00	1145.00	1136.00	1131.00	1129.00	1128.00	1128.00	1127.00	1127.00	1127.00	Cabm
59	2.5	1	1	1000	10000	1	1	11270.00	78.03	1594.00	1301.00	1205.00	1164.00	1145.00	1136.00	1131.00	1129.00	1128.00	1128.00	1127.00	1127.00	1127.00	Cabm
60	2.5	1	1	10000	10000	1	1	11270.00	78.03	15940.00	13010.00	12050.00	11640.00	11450.00	11360.00	11310.00	11290.00	11280.00	11280.00	11270.00	11270.00	11270.00	Cabm

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
46	2.5	1	1	1	1	1	1	0.89	3.70	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CM
47	2.5	1	1	1	10	1	1	0.89	0.36	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
48	2.5	1	1	1	100	1	1	0.89	0.14	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
49	2.5	1	1	1	1000	1	1	0.89	0.05	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
50	2.5	1	1	1	10000	1	1	0.89	0.02	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
51	2.5	1	1	10	10	1	1	0.89	0.36	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm
52	2.5	1	1	10	100	1	1	0.89	0.14	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
53	2.5	1	1	10	1000	1	1	0.89	0.05	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
54	2.5	1	1	10	10000	1	1	0.89	0.02	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	CBM
55	2.5	1	1	100	100	1	1	0.89	0.14	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm
56	2.5	1	1	100	1000	1	1	0.89	0.05	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm
57	2.5	1	1	100	10000	1	1	0.89	0.02	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm
58	2.5	1	1	1000	1000	1	1	0.89	0.05	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm
59	2.5	1	1	1000	10000	1	1	0.89	0.02	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm
60	2.5	1	1	10000	10000	1	1	0.89	0.02	0.63	0.77	0.83	0.86	0.87	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	Cabm

TABLE B – X

RESULTS: BETA EQUALS 3.5

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
61	3.5	1	1	1	1	1	1	1.11	1.11	1.57	1.28	1.19	1.15	1.13	1.12	1.12	1.11	1.19	1.11	1.11	1.11	1.11	CM
62	3.5	1	1	1	10	1	1	11.11	3.42	1.57	1.28	1.19	1.15	1.13	1.12	1.12	1.11	1.19	1.11	1.11	1.11	1.11	CBM
63	3.5	1	1	1	100	1	1	111.14	6.76	1.57	1.28	1.19	1.15	1.13	1.12	1.12	1.11	1.19	1.11	1.11	1.11	1.11	CBM
64	3.5	1	1	1	1000	1	1	1111.00	13.09	1.57	1.28	1.19	1.15	1.13	1.12	1.12	1.11	1.19	1.11	1.11	1.11	1.11	CBM
65	3.5	1	1	1	10000	1	1	11110.00	25.27	1.57	1.28	1.19	1.15	1.13	1.12	1.12	1.11	1.19	1.11	1.11	1.11	1.11	CBM
66	3.5	1	1	10	10	1	1	11.11	3.42	15.72	12.83	11.88	11.48	11.29	11.20	11.16	11.14	11.88	11.12	11.12	11.11	11.11	Cabm
67	3.5	1	1	10	100	1	1	111.14	6.76	15.72	12.83	11.88	11.48	11.29	11.20	11.16	11.14	11.88	11.12	11.12	11.11	11.11	Cabm
68	3.5	1	1	10	1000	1	1	1111.00	13.09	15.72	12.83	11.88	11.48	11.29	11.20	11.16	11.14	11.88	11.12	11.12	11.11	11.11	CBM
69	3.5	1	1	10	10000	1	1	11110.00	25.27	15.72	12.83	11.88	11.48	11.29	11.20	11.16	11.14	11.88	11.12	11.12	11.11	11.11	CBM
70	3.5	1	1	100	100	1	1	111.14	6.76	157.18	128.34	118.82	114.79	112.92	112.02	111.58	111.36	111.25	111.20	111.15	111.14	111.14	Cabm
71	3.5	1	1	100	1000	1	1	1111.00	13.09	157.18	128.34	118.82	114.79	112.92	112.02	111.58	111.36	111.25	111.20	111.15	111.14	111.14	Cabm
72	3.5	1	1	100	10000	1	1	11110.00	25.27	157.18	128.34	118.82	114.79	112.92	112.02	111.58	111.36	111.25	111.20	111.15	111.14	111.14	Cabm
73	3.5	1	1	1000	1000	1	1	1111.00	13.09	1572.00	1283.00	1188.00	1148.00	1129.00	1120.00	1116.00	1114.00	1113.00	1112.00	1111.00	1111.00	1111.00	Cabm
74	3.5	1	1	1000	10000	1	1	11110.00	25.27	1572.00	1283.00	1188.00	1148.00	1129.00	1120.00	1116.00	1114.00	1113.00	1112.00	1111.00	1111.00	1111.00	Cabm
75	3.5	1	1	10000	10000	1	1	11110.00	25.27	15720.00	12830.00	11880.00	11480.00	11290.00	11200.00	11160.00	11140.00	11130.00	11120.00	11110.00	11110.00	11110.00	Cabm

								CM	ABM	Condition-Based Maintenance													
Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM	Cabm	DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
61	3.5	1	1	1	1	1	1	0.90	3.33	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CM
62	3.5	1	1	1	10	1	1	0.90	0.41	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
63	3.5	1	1	1	100	1	1	0.90	0.21	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
64	3.5	1	1	1	1000	1	1	0.90	0.11	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
65	3.5	1	1	1	10000	1	1	0.90	0.06	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
66	3.5	1	1	10	10	1	1	0.90	0.41	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
67	3.5	1	1	10	100	1	1	0.90	0.21	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
68	3.5	1	1	10	1000	1	1	0.90	0.11	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
69	3.5	1	1	10	10000	1	1	0.90	0.06	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	CBM
70	3.5	1	1	100	100	1	1	0.90	0.21	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
71	3.5	1	1	100	1000	1	1	0.90	0.11	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
72	3.5	1	1	100	10000	1	1	0.90	0.06	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
73	3.5	1	1	1000	1000	1	1	0.90	0.11	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
74	3.5	1	1	1000	10000	1	1	0.90	0.06	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm
75	3.5	1	1	10000	10000	1	1	0.90	0.06	0.64	0.78	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	Cabm

TABLE B – XI
RESULTS: BETA EQUALS 4.5

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM (CM)	Cabm (ABM)	DL50 (Condition-Based Maintenance)	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
76	4.5	1	1	1	1	1	1	1.10	1.10	1.55	1.27	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.10	1.10	1.10	1.096	CM
77	4.5	1	1	1	10	1	1	10.96	2.77	1.55	1.27	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.10	1.10	1.10	1.096	CBM
78	4.5	1	1	1	100	1	1	109.58	4.72	1.55	1.27	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.10	1.10	1.10	1.096	CBM
79	4.5	1	1	1	1000	1	1	1096.00	7.88	1.55	1.27	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.10	1.10	1.10	1.096	CBM
80	4.5	1	1	1	10000	1	1	10960.00	13.15	1.55	1.27	1.17	1.13	1.11	1.10	1.10	1.10	1.17	1.10	1.10	1.10	1.096	CBM
81	4.5	1	1	10	10	1	1	10.96	2.77	15.50	12.65	11.72	11.32	11.13	11.05	11.00	10.98	11.72	10.96	10.96	10.96	10.958	Cabm
82	4.5	1	1	10	100	1	1	109.58	4.72	15.50	12.65	11.72	11.32	11.13	11.05	11.00	10.98	11.72	10.96	10.96	10.96	10.958	Cabm
83	4.5	1	1	10	1000	1	1	1096.00	7.88	15.50	12.65	11.72	11.32	11.13	11.05	11.00	10.98	11.72	10.96	10.96	10.96	10.958	Cabm
84	4.5	1	1	10	10000	1	1	10960.00	13.15	15.50	12.65	11.72	11.32	11.13	11.05	11.00	10.98	11.72	10.96	10.96	10.96	10.958	CBM
85	4.5	1	1	100	100	1	1	109.58	4.72	154.97	126.53	117.15	113.17	111.33	110.45	110.01	109.80	109.69	109.63	109.59	109.58	109.58	Cabm
86	4.5	1	1	100	1000	1	1	1096.00	7.88	154.97	126.53	117.15	113.17	111.33	110.45	110.01	109.80	109.69	109.63	109.59	109.58	109.58	Cabm
87	4.5	1	1	100	10000	1	1	10960.00	13.15	154.97	126.53	117.15	113.17	111.33	110.45	110.01	109.80	109.69	109.63	109.59	109.58	109.58	Cabm
88	4.5	1	1	1000	1000	1	1	1096.00	7.88	1550.00	1265.00	1171.00	1132.00	1113.00	1104.00	1100.00	1098.00	1097.00	1096.00	1096.00	1096.00	1096.00	Cabm
89	4.5	1	1	1000	10000	1	1	10960.00	13.15	1550.00	1265.00	1171.00	1132.00	1113.00	1104.00	1100.00	1098.00	1097.00	1096.00	1096.00	1096.00	1096.00	Cabm
90	4.5	1	1	10000	10000	1	1	10960.00	13.15	15500.00	12650.00	11710.00	11320.00	11130.00	11040.00	11000.00	10980.00	10970.00	10960.00	10960.00	10960.00	10960.00	Cabm

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Cicbm	CM (CM)	Cabm (ABM)	DL50 (Condition-Based Maintenance)	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
76	4.5	1	1	1	1	1	1	0.91	2.10	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	CM
77	4.5	1	1	1	10	1	1	0.91	0.47	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	CBM
78	4.5	1	1	1	100	1	1	0.91	0.27	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	CBM
79	4.5	1	1	1	1000	1	1	0.91	0.16	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	CBM
80	4.5	1	1	1	10000	1	1	0.91	0.10	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	CBM
81	4.5	1	1	10	10	1	1	0.91	0.47	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
82	4.5	1	1	10	100	1	1	0.91	0.27	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
83	4.5	1	1	10	1000	1	1	0.91	0.16	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
84	4.5	1	1	10	10000	1	1	0.91	0.10	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	CBM
85	4.5	1	1	100	100	1	1	0.91	0.27	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
86	4.5	1	1	100	1000	1	1	0.91	0.16	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
87	4.5	1	1	100	10000	1	1	0.91	0.10	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
88	4.5	1	1	1000	1000	1	1	0.91	0.16	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
89	4.5	1	1	1000	10000	1	1	0.91	0.10	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm
90	4.5	1	1	10000	10000	1	1	0.91	0.10	0.65	0.79	0.85	0.88	0.90	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	Cabm

TABLE B – XII

RESULTS: BETA EQUALS 5.5

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM: CM	ABM: Cabm	Condition-Based Maintenance: DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
91	5.5	1	1	1	1	1	1	1.08	1.08	1.53	1.25	1.16	1.12	1.10	1.09	1.09	1.09	1.16	1.08	1.08	1.08	1.08	CM
92	5.5	1	1	1	10	1	1	10.83	2.40	1.53	1.25	1.16	1.12	1.10	1.09	1.09	1.09	1.16	1.08	1.08	1.08	1.08	CBM
93	5.5	1	1	1	100	1	1	108.32	3.71	1.53	1.25	1.16	1.12	1.10	1.09	1.09	1.09	1.16	1.08	1.08	1.08	1.08	CBM
94	5.5	1	1	1	1000	1	1	1083.00	5.64	1.53	1.25	1.16	1.12	1.10	1.09	1.09	1.09	1.16	1.08	1.08	1.08	1.08	CBM
95	5.5	1	1	1	10000	1	1	10830.00	8.57	1.53	1.25	1.16	1.12	1.10	1.09	1.09	1.09	1.16	1.08	1.08	1.08	1.08	CBM
96	5.5	1	1	10	10	1	1	10.83	2.40	15.32	12.51	11.58	11.19	11.01	10.92	10.87	10.85	11.58	10.84	10.83	10.83	10.83	Cabm
97	5.5	1	1	10	100	1	1	108.32	3.71	15.32	12.51	11.58	11.19	11.01	10.92	10.87	10.85	11.58	10.84	10.83	10.83	10.83	Cabm
98	5.5	1	1	10	1000	1	1	1083.00	5.64	15.32	12.51	11.58	11.19	11.01	10.92	10.87	10.85	11.58	10.84	10.83	10.83	10.83	Cabm
99	5.5	1	1	10	10000	1	1	10830.00	8.57	15.32	12.51	11.58	11.19	11.01	10.92	10.87	10.85	11.58	10.84	10.83	10.83	10.83	Cabm
100	5.5	1	1	100	100	1	1	108.32	3.71	153.19	125.08	115.80	111.87	110.05	109.18	108.74	108.53	108.43	108.37	108.32	108.32	108.32	Cabm
101	5.5	1	1	100	1000	1	1	1083.00	5.64	153.19	125.08	115.80	111.87	110.05	109.18	108.74	108.53	108.43	108.37	108.32	108.32	108.32	Cabm
102	5.5	1	1	100	10000	1	1	10830.00	8.57	153.19	125.08	115.80	111.87	110.05	109.18	108.74	108.53	108.43	108.37	108.32	108.32	108.32	Cabm
103	5.5	1	1	1000	1000	1	1	1083.00	5.64	1532.00	1251.00	1158.00	1119.00	1101.00	1092.00	1087.00	1085.00	1084.00	1084.00	1083.00	1083.00	1083.00	Cabm
104	5.5	1	1	1000	10000	1	1	10830.00	8.57	1532.00	1251.00	1158.00	1119.00	1101.00	1092.00	1087.00	1085.00	1084.00	1084.00	1083.00	1083.00	1083.00	Cabm
105	5.5	1	1	10000	10000	1	1	10830.00	8.57	15320.00	12510.00	11580.00	11190.00	11010.00	10920.00	10870.00	10850.00	10840.00	10840.00	10830.00	10830.00	10830.00	Cabm

Trial	Beta	Theta	Cp	Ccbm	Cu	C icp	Ciccbm	CM: CM	ABM: Cabm	Condition-Based Maintenance: DL50	DL25	DL12.5	DL6.25	DL03125	DL015625	DL_7812	DL_3906	DL_1953	DL_097565	DL_0097565	DL_00097565	DL_000097565	Economically Preferred Strategy
91	5.5	1	1	1	1	1	1	0.92	2.10	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	CM
92	5.5	1	1	1	10	1	1	0.92	0.51	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	CBM
93	5.5	1	1	1	100	1	1	0.92	0.33	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	CBM
94	5.5	1	1	1	1000	1	1	0.92	0.22	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	CBM
95	5.5	1	1	1	10000	1	1	0.92	0.14	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	CBM
96	5.5	1	1	10	10	1	1	0.92	0.51	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
97	5.5	1	1	10	100	1	1	0.92	0.33	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
98	5.5	1	1	10	1000	1	1	0.92	0.22	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
99	5.5	1	1	10	10000	1	1	0.92	0.14	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
100	5.5	1	1	100	100	1	1	0.92	0.33	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
101	5.5	1	1	100	1000	1	1	0.92	0.22	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
102	5.5	1	1	100	10000	1	1	0.92	0.14	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
103	5.5	1	1	1000	1000	1	1	0.92	0.22	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
104	5.5	1	1	1000	10000	1	1	0.92	0.14	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm
105	5.5	1	1	10000	10000	1	1	0.92	0.14	0.65	0.80	0.86	0.89	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	Cabm

APPENDIX C - REGRESSION ANALYSIS OF ORIGINAL 90 POINTS

```
dm 'log;clear;output;clear;';
options ps=50 ls=70 pageno=1;
goptions reset=global border ftext=swiss gunit=cm htext=0.4 htitle=0.5;
goptions display noprompt;

**********************************************************************;
**                                                                  **;
** AUTHOR: Ed Mccombs (orig by Chris Bilder                         **;
**                                                                  **;
**                                                                  **;
** DATE: 3-10-02                                                    **;
** UPDATE:                                                          **;
** PURPOSE: Read in the Maintenance data from an excel file and     **;
**          perform a multivariate regression analysis              **;
**                                                                  **;
** NOTES:                                                           **;
**                                                                  **;
**********************************************************************;
*Read in Excel file containing the cereal data';
*  Note: The variable names are beta Ccbm Cu CC CCB LL LB LC LLCCB;
proc import out=set1
            datafile= "a:\SASreg1.xls"
            dbms=excel2000 replace;
     getnames=yes;
run;
title2 'Maintenance data set';
proc print data=set1;
run;
PROC REG;
MODEL Type = beta Ccbm Cu/SELECTION=backward SLS=.05;
 RUN;
```

Figure C - 1. SAS Code for Multivariate Linear Regression Analysis on the decision variables beta, C_{CBM} and C_u

Obs	Trial	beta	Ccbm	Cu	Type
1	32	1.5	1	10	-1
2	33	1.5	1	100	-1
3	34	1.5	1	1000	-1
4	35	1.5	1	10000	-1
5	37	1.5	10	100	-1
6	38	1.5	10	1000	-1
7	39	1.5	10	10000	-1
8	41	1.5	100	1000	-1
9	42	1.5	100	10000	-1
10	47	2.5	1	10	-1
11	48	2.5	1	100	-1
12	49	2.5	1	1000	-1
13	50	2.5	1	10000	-1
14	52	2.5	10	100	-1
15	53	2.5	10	1000	-1
16	54	2.5	10	10000	-1
17	62	3.5	1	10	-1
18	63	3.5	1	100	-1
19	64	3.5	1	1000	-1
20	65	3.5	1	10000	-1
21	68	3.5	10	1000	-1
22	69	3.5	10	10000	-1
23	77	4.5	1	10	-1
24	78	4.5	1	100	-1
25	79	4.5	1	1000	-1
26	80	4.5	1	10000	-1
27	84	4.5	10	10000	-1
28	92	5.5	1	10	-1
29	93	5.5	1	100	-1
30	94	5.5	1	1000	-1
31	95	5.5	1	10000	-1
32	36	1.5	10	10	1
33	40	1.5	100	100	1
34	43	1.5	1000	1000	1
35	44	1.5	1000	10000	1
36	45	1.5	10000	10000	1
37	51	2.5	10	10	1
38	55	2.5	100	100	1
39	56	2.5	100	1000	1
40	57	2.5	100	10000	1
41	58	2.5	1000	1000	1
42	59	2.5	1000	10000	1
43	60	2.5	10000	10000	1
44	66	3.5	10	10	1

Figure C - 2. SAS output for Multivariate Linear Regression Analysis on the decision variables beta, C_{CBM} and C_u

Obs	Trial	beta	Ccbm	Cu	Type
45	67	3.5	10	100	1
46	70	3.5	100	100	1
47	71	3.5	100	1000	1
48	72	3.5	100	10000	1
49	73	3.5	1000	1000	1
50	74	3.5	1000	10000	1
51	75	3.5	10000	10000	1
52	81	4.5	10	10	1
53	82	4.5	10	100	1
54	83	4.5	10	1000	1
55	85	4.5	100	100	1
56	86	4.5	100	1000	1
57	87	4.5	100	10000	1
58	88	4.5	1000	1000	1
59	89	4.5	1000	10000	1
60	90	4.5	10000	10000	1
61	96	5.5	10	10	1
62	97	5.5	10	100	1
63	98	5.5	10	1000	1
64	99	5.5	10	10000	1
65	100	5.5	100	100	1
66	101	5.5	100	1000	1
67	102	5.5	100	10000	1
68	103	5.5	1000	1000	1
69	104	5.5	1000	10000	1
70	105	5.5	10000	10000	1
71	31	1.5	1	1	0
72	46	2.5	1	1	0
73	61	3.5	1	1	0
74	76	4.5	1	1	0
75	91	5.5	1	1	0

Figure C – 2. Continued

Maintenance data set

The REG Procedure
Model: MODEL1
Dependent Variable: Type Type
Backward Elimination: Step 0

All Variables Entered: R-Square = 0.1523 and C(p) = 4.0000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	10.53273	3.51091	4.25	0.0080
Error	71	58.61394	0.82555		
Corrected Total	74	69.14667			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.51134	0.29236	2.52540	3.06	0.0846
beta	0.16000	0.07419	3.84000	4.65	0.0344
Ccbm	0.00012834	0.00004630	6.34458	7.69	0.0071
Cu	-0.00001315	0.00002531	0.22276	0.27	0.6051

Bounds on condition number: 1.1926, 10.156

Backward Elimination: Step 1

Variable Cu Removed: R-Square = 0.1491 and C(p) = 2.2698

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10.30997	5.15498	6.31	0.0030
Error	72	58.83670	0.81718		
Corrected Total	74	69.14667			

The REG Procedure
Model: MODEL1
Dependent Variable: Type Type

Figure C – 2. Continued

Backward Elimination: Step 1

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.55101	0.28078	3.14704	3.85	0.0536
beta	0.16000	0.07381	3.84000	4.70	0.0335
Ccbm	0.00011868	0.00004218	6.46997	7.92	0.0063

Bounds on condition number: 1, 4

All variables left in the model are significant at the 0.0500 level.

Summary of Backward Elimination

Step	Variable Removed	Label	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value
1	Cu	Cu	2	0.0032	0.1491	2.2698	0.27

Summary of Backward Elimination

Step	Pr > F
1	0.6051

Figure C – 2. Continued

Obs	Trial	beta	Ccbm	Cu	Type
1	32	1.5	0	1	-1
2	33	1.5	0	2	-1
3	34	1.5	0	3	-1
4	35	1.5	0	4	-1
5	37	1.5	1	2	-1
6	38	1.5	1	3	-1
7	39	1.5	1	4	-1
8	41	1.5	2	3	-1
9	42	1.5	2	4	-1
10	47	2.5	0	1	-1
11	48	2.5	0	2	-1
12	49	2.5	0	3	-1
13	50	2.5	0	4	-1
14	52	2.5	1	2	-1
15	53	2.5	1	3	-1
16	54	2.5	1	4	-1
17	62	3.5	0	1	-1
18	63	3.5	0	2	-1
19	64	3.5	0	3	-1
20	65	3.5	0	4	-1
21	68	3.5	1	3	-1
22	69	3.5	1	4	-1
23	77	4.5	0	1	-1
24	78	4.5	0	2	-1
25	79	4.5	0	3	-1
26	80	4.5	0	4	-1
27	84	4.5	1	4	-1
28	92	5.5	0	1	-1
29	93	5.5	0	2	-1
30	94	5.5	0	3	-1
31	95	5.5	0	4	-1
32	36	1.5	1	1	1
33	40	1.5	2	2	1
34	43	1.5	3	3	1
35	44	1.5	3	4	1
36	45	1.5	4	4	1
37	51	2.5	1	1	1
38	55	2.5	2	2	1
39	56	2.5	2	3	1
40	57	2.5	2	4	1
41	58	2.5	3	3	1
42	59	2.5	3	4	1
43	60	2.5	4	4	1
44	66	3.5	1	1	1

Figure C - 3. SAS output for Multivariate Linear Regression Analysis on the decision variables beta, log(C_{CBM}) and log(C_u.)

Obs	Trial	beta	Ccbm	Cu	Type
45	67	3.5	1	2	1
46	70	3.5	2	2	1
47	71	3.5	2	3	1
48	72	3.5	2	4	1
49	73	3.5	3	3	1
50	74	3.5	3	4	1
51	75	3.5	4	4	1
52	81	4.5	1	1	1
53	82	4.5	1	2	1
54	83	4.5	1	3	1
55	85	4.5	2	2	1
56	86	4.5	2	3	1
57	87	4.5	2	4	1
58	88	4.5	3	3	1
59	89	4.5	3	4	1
60	90	4.5	4	4	1
61	96	5.5	1	1	1
62	97	5.5	1	2	1
63	98	5.5	1	3	1
64	99	5.5	1	4	1
65	100	5.5	2	2	1
66	101	5.5	2	3	1
67	102	5.5	2	4	1
68	103	5.5	3	3	1
69	104	5.5	3	4	1
70	105	5.5	4	4	1
71	31	1.5	0	0	0
72	46	2.5	0	0	0
73	61	3.5	0	0	0
74	76	4.5	0	0	0
75	91	5.5	0	0	0

Figure C – 3. Continued

The REG Procedure
Model: MODEL1
Dependent Variable: Type Type

Backward Elimination: Step 0

All Variables Entered: R-Square = 0.6561 and C(p) = 4.0000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	45.36381	15.12127	45.14	<.0001
Error	71	23.78286	0.33497		
Corrected Total	74	69.14667			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.60571	0.22856	2.35258	7.02	0.0099
beta	0.16000	0.04726	3.84000	11.46	0.0012
Ccbm	0.68571	0.06187	41.14286	122.83	<.0001
Cu	-0.28571	0.06187	7.14286	21.32	<.0001

Bounds on condition number: 1.3333, 11

All variables left in the model are significant at the 0.0500 level.

Figure C – 3. Continued

APPENDIX D: EVOLUTIONARY PROCESS OF THE DECISION MODEL

The evolutionary process used to develop the decision variables in this research relied on regression analysis and principal component analysis. The decision variables D_L and $C_{IC\text{-}x}$ are not discussed. These variables were explored in Phase Two of this research's experimental methodology.

Initially, a backward elimination regression analysis (Reg1) was performed (Figure D – 1) on the decision variables, beta, C_{CBM}, and C_u, discussed in Chapter III. Note that the dependent variables of the data set are classification variables. Therefore, before the regression analysis was performed these variables were transformed to numerical values (i.e., -1.0 equals CBM, 0.0 equals CM and 1.0 equals ABM). The results (Table D – I) were that only 19 out the 75 trials were predicted correctly. The decision criteria used to make the predictions were as follows.

- Choose CBM if the regression model result was less than –0.33.
- Choose ABM if the regression model result was greater than 0.33.
- Otherwise, choose CM.

The bounds were set arbitrarily based on having three equal decision intervals over the range of –1.0 to 1.0. A plot of the results (Figure D – 2) showed that these bounds will likely perform as well as any other simple set.

The REG Procedure
Model: MODEL1
Dependent Variable: Type Type
Backward Elimination: Step 0
All Variables Entered: R-Square = 0.1523 and C(p) = 4.0000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	10.53273	3.51091	4.25	0.0080
Error	71	58.61394	0.82555		
Corrected Total	74	69.14667			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.51134	0.29236	2.52540	3.06	0.0846
Beta	0.16000	0.07419	3.84000	4.65	0.0344
Ccbm	0.00012834	0.00004630	6.34458	7.69	0.0071
Cu	-0.00001315	0.00002531	0.22276	0.27	0.6051

Bounds on condition number: 1.1926, 10.156

Backward Elimination: Step 1
Variable Cu Removed: R-Square = 0.1491 and C(p) = 2.2698

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10.30997	5.15498	6.31	0.0030
Error	72	58.83670	0.81718		
Corrected Total	74	69.14667			

Backward Elimination: Step 1

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.55101	0.28078	3.14704	3.85	0.0536
Beta	0.16000	0.07381	3.84000	4.70	0.0335
Ccbm	0.00011868	0.00004218	6.46997	7.92	0.0063

Bounds on condition number: 1, 4

All variables left in the model are significant at the 0.0500 level.

Summary of Backward Elimination

Step	Variable Removed	Label	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value
1	Cu	Cu	2	0.0032	0.1491	2.2698	0.27

Summary of Backward Elimination

Step	Pr > F
1	0.6051

Figure D – 1. Results of backward the elimination regression analysis (Reg1) on the decision variables beta, C_{CBM}, and C_u

TABLE D – I

RESULTS OF REGRESSION ANALYSIS (Reg1)

Trial	Beta	Ccbm	Cu	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
31	1.5	1	1	0	-0.31	Yes
32	1.5	1	10	-1	-0.31	No
33	1.5	1	100	-1	-0.31	No
34	1.5	1	1000	-1	-0.31	No
35	1.5	1	10000	-1	-0.31	No
36	1.5	10	10	1	-0.31	No
37	1.5	10	100	-1	-0.31	No
38	1.5	10	1000	-1	-0.31	No
39	1.5	10	10000	-1	-0.31	No
40	1.5	100	100	1	-0.30	No
41	1.5	100	1000	-1	-0.30	No
42	1.5	100	10000	-1	-0.30	No
43	1.5	1000	1000	1	-0.19	No
44	1.5	1000	10000	1	-0.19	No
45	1.5	10000	10000	1	0.88	Yes
46	2.5	1	1	0	-0.15	Yes
47	2.5	1	10	-1	-0.15	No
48	2.5	1	100	-1	-0.15	No
49	2.5	1	1000	-1	-0.15	No
50	2.5	1	10000	-1	-0.15	No
51	2.5	10	10	1	-0.15	No
52	2.5	10	100	-1	-0.15	No
53	2.5	10	1000	-1	-0.15	No
54	2.5	10	10000	-1	-0.15	No
55	2.5	100	100	1	-0.14	No
56	2.5	100	1000	1	-0.14	No
57	2.5	100	10000	1	-0.14	No
58	2.5	1000	1000	1	-0.03	No
59	2.5	1000	10000	1	-0.03	No
60	2.5	10000	10000	1	1.04	Yes
61	3.5	1	1	0	0.01	Yes
62	3.5	1	10	-1	0.01	No
63	3.5	1	100	-1	0.01	No
64	3.5	1	1000	-1	0.01	No
65	3.5	1	10000	-1	0.01	No
66	3.5	10	10	1	0.01	No
67	3.5	10	100	1	0.01	No
68	3.5	10	1000	-1	0.01	No
69	3.5	10	10000	-1	0.01	No
70	3.5	100	100	1	0.02	No
71	3.5	100	1000	1	0.02	No

TABLE D – I continued

Trial	Beta	Ccbm	Cu	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
72	3.5	100	10000	1	0.02	No
73	3.5	1000	1000	1	0.13	No
74	3.5	1000	10000	1	0.13	No
75	3.5	10000	10000	1	1.20	Yes
76	4.5	1	1	0	0.17	Yes
77	4.5	1	10	-1	0.17	No
78	4.5	1	100	-1	0.17	No
79	4.5	1	1000	-1	0.17	No
80	4.5	1	10000	-1	0.17	No
81	4.5	10	10	1	0.17	No
82	4.5	10	100	1	0.17	No
83	4.5	10	1000	1	0.17	No
84	4.5	10	10000	-1	0.17	No
85	4.5	100	100	1	0.18	No
86	4.5	100	1000	1	0.18	No
87	4.5	100	10000	1	0.18	No
88	4.5	1000	1000	1	0.29	No
89	4.5	1000	10000	1	0.29	No
90	4.5	10000	10000	1	1.36	Yes
91	5.5	1	1	0	0.33	Yes
92	5.5	1	10	-1	0.33	No
93	5.5	1	100	-1	0.33	No
94	5.5	1	1000	-1	0.33	No
95	5.5	1	10000	-1	0.33	No
96	5.5	10	10	1	0.33	Yes
97	5.5	10	100	1	0.33	Yes
98	5.5	10	1000	1	0.33	Yes
99	5.5	10	10000	1	0.33	Yes
100	5.5	100	100	1	0.34	Yes
101	5.5	100	1000	1	0.34	Yes
102	5.5	100	10000	1	0.34	Yes
103	5.5	1000	1000	1	0.45	Yes
104	5.5	1000	10000	1	0.45	Yes
105	5.5	10000	10000	1	1.52	Yes

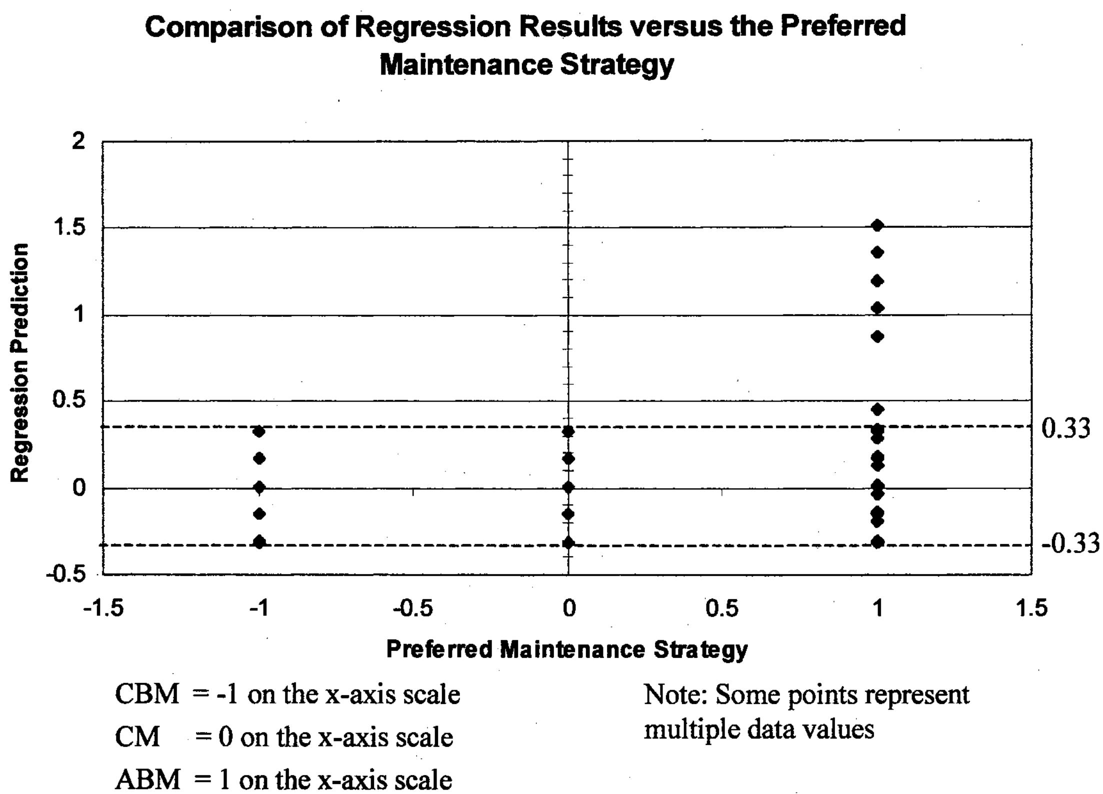

Figure D – 2. Plot of preferred maintenance strategy versus the regression model's (Reg1) predicted maintenance strategy

The next step taken was to perform a backward elimination regression analysis (Reg2) on the variables beta, log(C_{CBM}) and log(C_u) (Figure D – 3). The logarithmic values of C_{CBM} and C_u were chosen to explore whether the large differences in the magnitudes of these variables versus the magnitude of beta was having a detrimental effect on the predictive ability of the regression model. The results (Table D – II and Figure D – 4) showed that the revised regression model predicted more trials correctly (56 out of 75) than the initial regression model (again using the same decision bounds as stated above).

```
                              The REG Procedure
                                Model: MODEL1
                       Dependent Variable: Type Type
                        Backward Elimination: Step 0

     All Variables Entered: R-Square = 0.6561 and C(p) = 4.0000

                            Analysis of Variance
                                    Sum of           Mean
Source                    DF       Squares         Square   F Value   Pr > F

Model                      3      45.36381       15.12127     45.14   <.0001
Error                     71      23.78286        0.33497
Corrected Total           74      69.14667


              Parameter      Standard
 Variable      Estimate         Error   Type II SS  F Value  Pr > F
 Intercept     -0.60571       0.22856      2.35258     7.02  0.0099
 Beta           0.16000       0.04726      3.84000    11.46  0.0012
 Log Ccbm       0.68571       0.06187     41.14286   122.83  <.0001
 Log Cu        -0.28571       0.06187      7.14286    21.32  <.0001

               Bounds on condition number: 1.3333, 11
--------------------------------------------------------------------
All variables left in the model are significant at the 0.0500 level.
```

Figure D – 3. Results of backward elimination regression analysis (Reg2) on the decision variables beta, $\log(C_{CBM})$, and $\log(C_u)$

TABLE D – II

RESULTS OF REGRESSION ANALYSIS (Reg2)

Trial	Beta	log Ccbm	log Cu	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
31	1.5	0	0	0	-0.37	No
32	1.5	0	1	-1	-0.65	Yes
33	1.5	0	2	-1	-0.94	Yes
34	1.5	0	3	-1	-1.22	Yes
35	1.5	0	4	-1	-1.51	Yes
36	1.5	1	1	1	0.03	No
37	1.5	1	2	-1	-0.25	No

TABLE D – II continued

Trial	Beta	log Ccbm	log Cu	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
38	1.5	1	3	-1	-0.54	Yes
39	1.5	1	4	-1	-0.82	Yes
40	1.5	2	2	1	0.43	Yes
41	1.5	2	3	-1	0.15	No
42	1.5	2	4	-1	-0.14	No
43	1.5	3	3	1	0.83	Yes
44	1.5	3	4	1	0.55	Yes
45	1.5	4	4	1	1.23	Yes
46	2.5	0	0	0	-0.21	Yes
47	2.5	0	1	-1	-0.49	Yes
48	2.5	0	2	-1	-0.78	Yes
49	2.5	0	3	-1	-1.06	Yes
50	2.5	0	4	-1	-1.35	Yes
51	2.5	1	1	1	0.19	No
52	2.5	1	2	-1	-0.09	No
53	2.5	1	3	-1	-0.38	Yes
54	2.5	1	4	-1	-0.66	Yes
55	2.5	2	2	1	0.59	Yes
56	2.5	2	3	1	0.31	No
57	2.5	2	4	1	0.02	No
58	2.5	3	3	1	0.99	Yes
59	2.5	3	4	1	0.71	Yes
60	2.5	4	4	1	1.39	Yes
61	3.5	0	0	0	-0.05	Yes
62	3.5	0	1	-1	-0.33	Yes
63	3.5	0	2	-1	-0.62	Yes
64	3.5	0	3	-1	-0.90	Yes
65	3.5	0	4	-1	-1.19	Yes
66	3.5	1	1	1	0.35	Yes
67	3.5	1	2	1	0.07	No
68	3.5	1	3	-1	-0.22	No
69	3.5	1	4	-1	-0.50	Yes
70	3.5	2	2	1	0.75	Yes
71	3.5	2	3	1	0.47	Yes
72	3.5	2	4	1	0.18	No
73	3.5	3	3	1	1.15	Yes
74	3.5	3	4	1	0.87	Yes
75	3.5	4	4	1	1.55	Yes
76	4.5	0	0	0	0.11	Yes
77	4.5	0	1	-1	-0.17	No
78	4.5	0	2	-1	-0.46	Yes
79	4.5	0	3	-1	-0.74	Yes

TABLE D – II continued

Trial	Beta	log Ccbm	log Cu	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
80	4.5	0	4	-1	-1.03	Yes
81	4.5	1	1	1	0.51	Yes
82	4.5	1	2	1	0.23	No
83	4.5	1	3	1	-0.06	No
84	4.5	1	4	-1	-0.34	Yes
85	4.5	2	2	1	0.91	Yes
86	4.5	2	3	1	0.63	Yes
87	4.5	2	4	1	0.34	Yes
88	4.5	3	3	1	1.31	Yes
89	4.5	3	4	1	1.03	Yes
90	4.5	4	4	1	1.71	Yes
91	5.5	0	0	0	0.27	Yes
92	5.5	0	1	-1	-0.01	No
93	5.5	0	2	-1	-0.30	No
94	5.5	0	3	-1	-0.58	Yes
95	5.5	0	4	-1	-0.87	Yes
96	5.5	1	1	1	0.67	Yes
97	5.5	1	2	1	0.39	Yes
98	5.5	1	3	1	0.10	No
99	5.5	1	4	1	-0.18	No
100	5.5	2	2	1	1.07	Yes
101	5.5	2	3	1	0.79	Yes
102	5.5	2	4	1	0.50	Yes
103	5.5	3	3	1	1.47	Yes
104	5.5	3	4	1	1.19	Yes
105	5.5	4	4	1	1.87	Yes

Next, a backward elimination regression analysis (Reg3) was performed using beta, C_{CBM}, C_u, $\log(C_{CBM})$, $\log(C_u)$ and C_u/C_{CBM} (Figure D – 5). The ratio C_u/C_{CBM} was included to provide the linear regression model a variable reflecting the relationship between the cost of failure and the cost of performing CBM. The results (Table D – III) showed that 32 out of the 75 trials were predicted correctly. Even though the ratio

C_u/C_{CBM} was not significant at the 0.05 level it was significant at the 0.1278 level and was included in succeeding analyses.

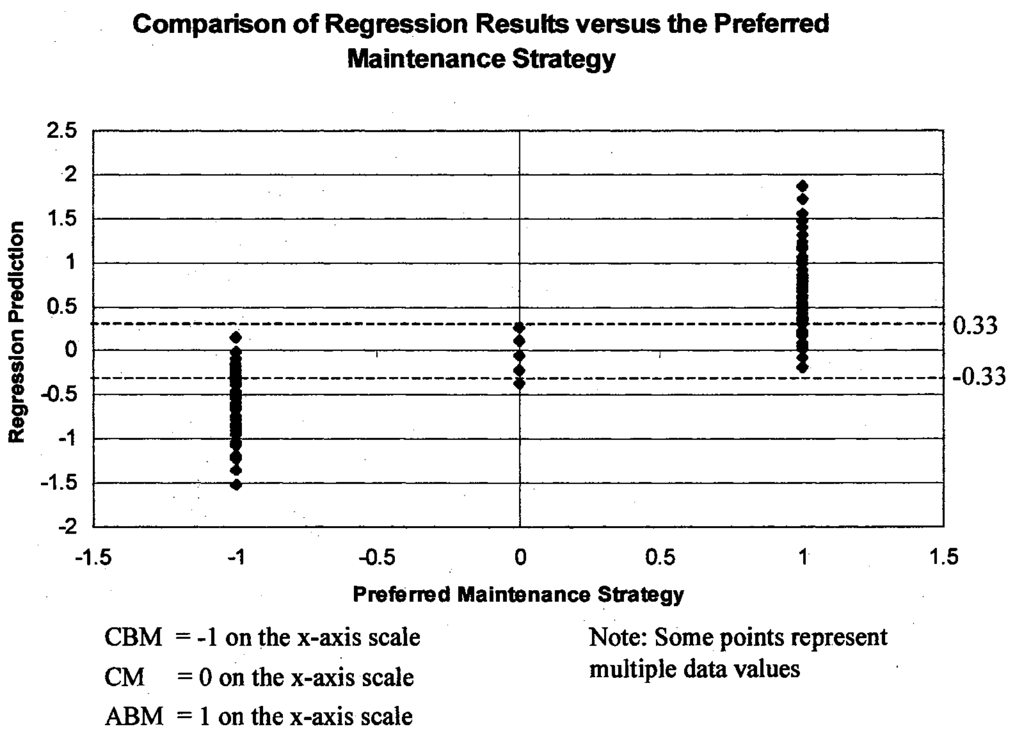

Figure D – 4. Plot of preferred maintenance strategy versus the regression model's (Reg2) predicted maintenance strategy

The REG Procedure
Model: MODEL1
Dependent Variable: Type Type
Backward Elimination: Step 0
All Variables Entered: R-Square = 0.7110 and C(p) = 7.0000
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	49.16347	8.19391	27.88	<.0001
Error	68	19.98319	0.29387		
Corrected Total	74	69.14667			

Figure D – 5. Results of backward elimination regression analysis (Reg3) on the decision variables beta, C_u, C_{CBM}, C_u/C_{CBM}, log(C_{CBM}), and log(C_u)

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.57897	0.23425	1.79522	6.11	0.0160
Beta	0.16000	0.04426	3.84000	13.07	0.0006
Ccbm	-0.00012206	0.00003523	3.52808	12.01	0.0009
Cu	0.00002374	0.00002521	0.26059	0.89	0.3497
LCcbm	0.39061	0.03857	30.14014	102.56	<.0001
LCu	-0.17827	0.04115	5.51559	18.77	<.0001
CuCcbm	0.00004316	0.00003523	0.44105	1.50	0.2248

Bounds on condition number: 3.5641, 89.392

Backward Elimination: Step 1

Variable Cu Removed: R-Square = 0.7072 and C(p) = 5.8867

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	48.90289	9.78058	33.34	<.0001
Error	69	20.24378	0.29339		
Corrected Total	74	69.14667			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.66055	0.21746	2.70717	9.23	0.0034
Beta	0.16000	0.04423	3.84000	13.09	0.0006
Ccbm	-0.00011302	0.00003387	3.26749	11.14	0.0014
LCcbm	0.39061	0.03854	30.14014	102.73	<.0001
LCu	-0.15341	0.03153	6.94366	23.67	<.0001
CuCcbm	0.00005220	0.00003387	0.69692	2.38	0.1278

Bounds on condition number: 3.1313, 49.096

Backward Elimination: Step 2

Variable CuCcbm Removed: R-Square = 0.6972 and C(p) = 6.2583

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	48.20596	12.05149	40.29	<.0001
Error	70	20.94071	0.29915		
Corrected Total	74	69.14667			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.69923	0.21811	3.07441	10.28	0.0020
Beta	0.16000	0.04466	3.84000	12.84	0.0006
Ccbm	-0.00010372	0.00003365	2.84215	9.50	0.0029
LCcbm	0.35607	0.03166	37.84580	126.51	<.0001
LCu	-0.12408	0.02539	7.14286	23.88	<.0001

Figure D – 5. Continued

```
            Bounds on condition number: 2.0722, 24.577

All variables left in the model are significant at the 0.0500 level.

                 Summary of Backward Elimination

      Variable             Number  Partial   Model
Step  Removed    Label     Vars In R-Square  R-Square   C(p)    F Value
  1   Cu         Cu              5   0.0038   0.7072   5.8867     0.89
  2   CuCcbm                     4   0.0101   0.6972   6.2583     2.38

                 Summary of Backward Elimination
                         Step Pr > F
                           1.  0.3497
                           2.  0.1278
```

Figure D – 5. Continued

TABLE D – III

RESULTS OF REGRESSION ANALYSIS (Reg3)

Trial	Beta	Ccbm	Cu	Log Ccbm	Log Cu	CuCcbm	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
31	1.5	1	1	0	0	1	0	-0.46	No
32	1.5	1	10	0	1	10	-1	-0.58	Yes
33	1.5	1	100	0	2	100	-1	-0.71	Yes
34	1.5	1	1000	0	3	1000	-1	-0.83	Yes
35	1.5	1	10000	0	4	10000	-1	-0.96	Yes
36	1.5	10	10	1	1	1	1	-0.23	No
37	1.5	10	100	1	2	10	-1	-0.35	Yes
38	1.5	10	1000	1	3	100	-1	-0.48	Yes
39	1.5	10	10000	1	4	1000	-1	-0.60	Yes
40	1.5	100	100	2	2	1	1	-0.01	No
41	1.5	100	1000	2	3	10	-1	-0.13	No
42	1.5	100	10000	2	4	100	-1	-0.25	No
43	1.5	1000	1000	3	3	1	1	0.13	No
44	1.5	1000	10000	3	4	10	1	0.01	No
45	1.5	10000	10000	4	4	1	1	-0.57	No
46	2.5	1	1	0	0	1	0	-0.30	Yes
47	2.5	1	10	0	1	10	-1	-0.42	Yes
48	2.5	1	100	0	2	100	-1	-0.55	Yes
49	2.5	1	1000	0	3	1000	-1	-0.67	Yes

TABLE D – III continued

Trial	Beta	Ccbm	Cu	Log Ccbm	Log Cu	CuCcbm	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
50	2.5	1	10000	0	4	10000	-1	-0.80	Yes
51	2.5	10	10	1	1	1	1	-0.07	No
52	2.5	10	100	1	2	10	-1	-0.19	No
53	2.5	10	1000	1	3	100	-1	-0.32	No
54	2.5	10	10000	1	4	1000	-1	-0.44	Yes
55	2.5	100	100	2	2	1	1	0.15	No
56	2.5	100	1000	2	3	10	1	0.03	No
57	2.5	100	10000	2	4	100	1	-0.09	No
58	2.5	1000	1000	3	3	1	1	0.29	No
59	2.5	1000	10000	3	4	10	1	0.17	No
60	2.5	10000	10000	4	4	1	1	-0.41	No
61	3.5	1	1	0	0	1	0	-0.14	Yes
62	3.5	1	10	0	1	10	-1	-0.26	No
63	3.5	1	100	0	2	100	-1	-0.39	Yes
64	3.5	1	1000	0	3	1000	-1	-0.51	Yes
65	3.5	1	10000	0	4	10000	-1	-0.64	Yes
66	3.5	10	10	1	1	1	1	0.09	No
67	3.5	10	100	1	2	10	1	-0.03	No
68	3.5	10	1000	1	3	100	-1	-0.16	No
69	3.5	10	10000	1	4	1000	-1	-0.28	No
70	3.5	100	100	2	2	1	1	0.31	No
71	3.5	100	1000	2	3	10	1	0.19	No
72	3.5	100	10000	2	4	100	1	0.07	No
73	3.5	1000	1000	3	3	1	1	0.45	Yes
74	3.5	1000	10000	3	4	10	1	0.33	No
75	3.5	10000	10000	4	4	1	1	-0.25	No
76	4.5	1	1	0	0	1	0	0.02	Yes
77	4.5	1	10	0	1	10	-1	-0.10	No
78	4.5	1	100	0	2	100	-1	-0.23	No
79	4.5	1	1000	0	3	1000	-1	-0.35	Yes
80	4.5	1	10000	0	4	10000	-1	-0.48	Yes
81	4.5	10	10	1	1	1	1	0.25	No
82	4.5	10	100	1	2	10	1	0.13	No
83	4.5	10	1000	1	3	100	1	0.00	No
84	4.5	10	10000	1	4	1000	-1	-0.12	No
85	4.5	100	100	2	2	1	1	0.47	Yes
86	4.5	100	1000	2	3	10	1	0.35	Yes
87	4.5	100	10000	2	4	100	1	0.23	No
88	4.5	1000	1000	3	3	1	1	0.61	Yes
89	4.5	1000	10000	3	4	10	1	0.49	Yes
90	4.5	10000	10000	4	4	1	1	-0.09	No
91	5.5	1	1	0	0	1	0	0.18	Yes

TABLE D – III continued

Trial	Beta	Ccbm	Cu	Log Ccbm	Log Cu	CuCcbm	Preferred Maintenance Strategy	Predicted	Correct? Yes/No
92	5.5	1	10	0	1	10	-1	0.06	No
93	5.5	1	100	0	2	100	-1	-0.07	No
94	5.5	1	1000	0	3	1000	-1	-0.19	No
95	5.5	1	10000	0	4	10000	-1	-0.32	No
96	5.5	10	10	1	1	1	1	0.41	Yes
97	5.5	10	100	1	2	10	1	0.29	No
98	5.5	10	1000	1	3	100	1	0.16	No
99	5.5	10	10000	1	4	1000	1	0.04	No
100	5.5	100	100	2	2	1	1	0.63	Yes
101	5.5	100	1000	2	3	10	1	0.51	Yes
102	5.5	100	10000	2	4	100	1	0.39	Yes
103	5.5	1000	1000	3	3	1	1	0.77	Yes
104	5.5	1000	10000	3	4	10	1	0.65	Yes
105	5.5	10000	10000	4	4	1	1	0.07	No

The above regression analyses indicated that beta, C_{CBM}, C_u, $\log(C_{CBM})$, $\log(C_u)$ and potentially the ratio C_u/C_{CBM} were possible decision variables with regard to predicting the economically preferred maintenance strategy. However, while regression analysis is useful for eliminating variables and developing prediction equations given a set of decision variables, regression analysis does not offer insight with regard to discovering additional predictive decision variables. Therefore, the next step in this search for decision variables used principal component analysis. A principal component analysis was chosen because it can offer insight into the relationships between decision variables.

A principal component analysis was performed using the variables beta, C_{CBM}, C_u, $\log(C_{CBM})$, $\log(C_u)$ and the ratio C_u/C_{CBM}. The results are shown in Figure D – 6.

```
                      The PRINCOMP Procedure
                     Observations          75
                     Variables              6

                        Simple Statistics
                      Beta                 Ccbm                  Cu
Mean           3.500000000           823.000000         3621.400000
StD            1.423736994          2491.478314         4556.789793

                        Simple Statistics
                     LCcbm                  LCu              CuCcbm
Mean           3.070113457          6.140226915          823.000000
StD            2.891167303          2.891167303         2491.478314

                        Correlation Matrix
                    Beta      Ccbm        Cu     LCcbm       LCu    CuCcbm
Beta       Beta   1.0000    0.0000    0.0000    0.0000    0.0000    0.0000
Ccbm       Ccbm   0.0000    1.0000    0.4019    0.6518    0.3259    -.1100
Cu         Cu     0.0000    0.4019    1.0000    0.4001    0.8002    0.4019
LCcbm             0.0000    0.6518    0.4001    1.0000    0.5000    -.3259
LCu               0.0000    0.3259    0.8002    0.5000    1.0000    0.3259
CuCcbm            0.0000    -.1100    0.4019    -.3259    0.3259    1.0000

                  Eigenvalues of the Correlation Matrix
            Eigenvalue    Difference    Proportion    Cumulative
       1    2.56608073    1.04336349        0.4277        0.4277
       2    1.52271724    0.52271724        0.2538        0.6815
       3    1.00000000    0.47361973        0.1667        0.8481
       4    0.52638027    0.29053529        0.0877        0.9359
       5    0.23584498    0.08686820        0.0393        0.9752
       6    0.14897678                      0.0248        1.0000
```

Figure D – 6. Results of a principal component analysis on the decision variables beta, C_{CBM}, C_u, $\log(C_{CBM})$, $\log(C_u)$ and the ratio C_u/C_{CBM}

The first three eigenvalues explained 84.81% of the variance in the data. If the fourth eigenvalue was included, the total variance explained by the data increased to 93.59%. The fourth eigenvalue was less than one and therefore explained less variation than one of the original variables. However, given the nearly 10% increase in explained variation, the indication was that there were four fundamental decision variables.

Consider the composition of the first four principal components (Prin1 – Prin4, Figure D – 7). The first principal component Prin1 (corresponding to the largest eigenvector) approximately represented the relationship between the cost of failure, the logarithm of the cost of failure, the cost of performing CBM and the logarithm of the cost of performing CBM. Prin2 (the second largest eigenvector) was dominated by the ratio C_u/C_{CBM}. Princ3 was completely defined by beta. The fourth principal component represented the relationships between the cost of CBM, the logarithm of the cost of failure and the ratio C_u/C_{CBM}.

The PRINCOMP Procedure

Eigenvectors

	Prin1	Prin2	Prin3
Beta	0.000000	0.000000	1.00000
Ccbm	0.435013	-.357856	0.00000
Cu	0.537427	0.287221	0.00000
LCcbm	0.464948	-.457371	0.00000
LCu	0.539147	0.231572	0.00000
CuCcbm	0.122798	0.725693	0.00000

Eigenvectors

	Prin4	Prin5	Prin6
Beta	0.000000	0.000000	0.000000
Ccbm	0.756771	-.133928	-.303420
Cu	-.103137	-.639750	0.456901
LCcbm	-.193982	0.556785	0.476442
LCu	-.438855	0.154268	-.662799
CuCcbm	0.431784	0.488851	0.181322

Figure D – 7. Eigenvector results of a principal component analysis on the decision variables beta, C_{CBM}, C_u, $\log(C_{CBM})$, $\log(C_u)$ and the ratio C_u/C_{CBM}

Given that the second largest eigenvector was dominated by the ratio C_u/C_{CBM}, there was cause to believe that this term was important even though it was not shown to be significant in the regression analysis. Also, there was an indication that the cost of failure, the logarithm of the cost of failure, the cost of performing CBM and the logarithm of the cost of performing CBM could be combined into a functional form and serve as a decision variable.

Recall that the initial three decision variables (beta, C_{CBM}, and C_u) performed poorly with regard to their ability to predict the economically preferred maintenance strategy. The purpose of most of the above analysis was to gain insight into variables that could potentially enhance the predictive ability of a decision model. The above analyses indicated that the set of predictive decision variables could include the following variables.

1. beta
2. C_u
3. C_{CBM}
4. $\log(C_{CBM})$
5. $\log(C_u)$
6. C_u/C_{CBM}

However, a simple regression analysis using these decision variables (see the third regression analysis presented previously) did not produce a satisfactory model. Therefore, the question becomes, "Are there functional relationships between these six variables that might better predict the economically preferred maintenance strategy?" This research assumed that the answer to this question was, "Yes, there are more predictive decision variables."

The approach taken in this research was to sum the variables beta, $\log(C_{CBM})$, and $\log(C_u)$, and sum the variables $\log(C_{CBM})$, $\log(C_u)$, and $\log(C_u/C_{CBM})$ to form two new decision variables. The logarithm of C_u, C_{CBM}, and Cu/C_{CBM} was used in the sums so that values of approximately equal magnitude were added together. Recall that beta was defined as greater than or equal to one and less than or equal to 5.5. The magnitudes of C_u, C_{CBM}, and Cu/C_{CBM} ranged from one to 10,000 but not all three ranges were of the same order of magnitude under the same conditions.

A principal component analysis was again performed to include these new decision variables. The following SAS code (Figure D – 8) shows the calculation for the derived decision variables.

```
data set2;
set set1;
CuCcbm=Cu/Ccbm;
LCC=log(CuCcbm);
LCcbm=Log(Ccbm);
LCu=Log(Cu);
LB=LCcbm+LCu+beta;
LC=LCu+LCcbm+LCC;
run;
proc princomp data=set2;
  var Beta LCcbm LCu CuCcbm LB LC LCC;
run;
```

Figure D – 8. SAS code for defining the new decision variables and performing a principal component analysis

In this analysis (Figure D – 9), the first four eigenvalues explained 100% of the variation within the data. Therefore, only the first four principal components were explored.

The PRINCOMP Procedure

Observations 75

Variables 7

Simple Statistics

	Beta	LCcbm	LCu	CuCcbm
Mean	3.500000000	3.070113457	6.140226915	823.000000
StD	1.423736994	2.891167303	2.891167303	2491.478314

Simple Statistics

	LB	LC	LCC
Mean	12.71034037	12.28045383	3.070113457
StD	5.20610912	5.78233461	2.891167303

Correlation Matrix

		Beta	LCcbm	LCu	CuCcbm	LB	LC	LCC
Beta	Beta	1.0000	0.0000	0.0000	0.0000	0.2735	0.0000	0.0000
LCcbm		0.0000	1.0000	0.5000	-.3259	0.8330	0.5000	-.5000
LCu		0.0000	0.5000	1.0000	0.3259	0.8330	1.0000	0.5000
CuCcbm		0.0000	-.3259	0.3259	1.0000	0.0000	0.3259	0.6518
LB		0.2735	0.8330	0.8330	0.0000	1.0000	0.8330	0.0000
LC		0.0000	0.5000	1.0000	0.3259	0.8330	1.0000	0.5000
LCC		0.0000	-.5000	0.5000	0.6518	0.0000	0.5000	1.0000

Eigenvalues of the Correlation Matrix

	Eigenvalue	Difference	Proportion	Cumulative
1	3.37395984	1.21766586	0.4820	0.4820
2	2.15629398	1.11573269	0.3080	0.7900
3	1.04056128	0.61137638	0.1487	0.9387
4	0.42918490	0.42918490	0.0613	1.0000
5	0.00000000	0.00000000	0.0000	1.0000
6	0.00000000	0.00000000	0.0000	1.0000
7	0.00000000	0.00000000	0.0000	1.0000

Figure D – 9. Results of a principal component analysis on the decision variables beta, LCcbm, LCu, CuCcbm, LB, LC, and LCC

Eigenvectors

	Prin1	Prin2	Prin3	Prin4
Beta	0.057596	-.058839	0.970951	-.028856
LCcbm	0.337933	-.511992	-.125895	0.277132
LCu	0.534007	0.092990	-.092926	-.154466
CuCcbm	0.154071	0.537785	0.048042	0.827491
LB	0.499975	-.248780	0.144010	0.060230
LC	0.534007	0.092990	-.092926	-.154466
LCC	0.196073	0.604982	0.032968	-.431598

Figure D – 10. Eigenvector results of a principal component analysis on the decision variables beta, LCcbm, LCu, CuCcbm, LB, LC, and LCC

	Prin5	Prin6	Prin7
Beta	-.073690	0.210266	0.000000
LCcbm	0.123954	0.426984	0.577350
LCu	-.820789	0.000000	0.000000
CuCcbm	0.000000	0.000000	0.000000
LB	0.269460	-.768868	0.000000
LC	0.397550	0.426984	-.577350
LCC	0.273596	0.000000	0.577350

Eigenvectors

Figure D – 10. Continued

The first principal component (Figure D – 10) approximately represented the relationship between the variables LB, LC, and LCu. The first two variables were the summation of beta, log(C_{CBM}), and log(C_u), and the summation of log(C_{CBM}), log(C_u), and log(C_u/C_{CBM}), respectively. The third variable, LCu, was the logarithm of C_u, which was an element of the first two variables. The second principal component represented the relationship between log(C_{CBM}), C_u/C_{CBM}, and log(C_u/C_{CBM}). The third principal component was dominated by beta. The fourth principal component was dominated by the ratio C_u/C_{CBM}.

The above principal component analysis indicated that one decision variable was a functional relationship between the summation of beta, log(C_{CBM}), and log(C_u), and the summation log(C_{CBM}), log(C_u), and log(C_u/C_{CBM}). Simplistically, the available options for this functional relationship were addition, subtraction, multiplication and division. Subtraction, would result in the function ± [beta – log(C_u/C_{CBM})]. However, beta was not a major component of the first principal component. A similar argument held for the addition and multiplication options. Therefore, this research selected division as the functional relationship. Specifically, the new possible decision variable was [beta + $\log(C_{CBM})$ + $\log(C_u)$] / [$\log(C_{CBM})$ + $\log(C_u)$ + $\log(C_u/C_{CBM})$].

Once again a principal component analysis was performed to include the new decision variable (Figure D – 11).

```
data set2;
set set1;
CuCcbm=Cu/Ccbm;
LCC=log(CuCcbm);
LCcbm=Log(Ccbm);
LCu=Log(Cu);
LB=LCcbm+LCu+beta;
LC=LCu+LCcbm+LCC;
LL=LB/LC;
run;
proc princomp data=set2;
  var Beta CuCcbm LB LC LCC LL;
run;
```

Figure D – 11. SAS code for defining the new decision variables and performing a principal component analysis

Again focusing only on the first four principal components (Figure D – 12), the results show that Prin1 again represented the relationship between the defined variables

$$\text{beta} + \log(C_u) + \log(C_{CBM}) \text{ and } \log\left(\frac{C_u}{C_{CBM}}\right) + \log(C_u) + \log(C_{CBM}),$$

with the division of these two defined variables being the largest (albeit only slightly).

The PRINCOMP Procedure

Observations 70

Variables 6

Simple Statistics

	Beta	CuCcbm	LB
Mean	3.500000000	881.714286	13.36822183
StD	1.424424623	2569.984532	4.72614671

Figure D – 12. Results of a principal component analysis on the decision variables beta, CuCcbm, LB, LC, LCC, and LL

Simple Statistics

	LC	LCC	LL
Mean	13.15762910	3.289407276	1.080244762
StD	4.91420720	2.869278836	0.315619327

Correlation Matrix

	Beta	CuCcbm	LB	LC	LCC	LL
Beta	1.0000	0.0000	0.3014	0.0000	0.0000	0.4258
CuCcbm	0.0000	1.0000	-.0484	0.3367	0.6563	-.4057
LB	0.3014	-.0484	1.0000	0.7798	-.1619	0.0141
LC	0.0000	0.3367	0.7798	1.0000	0.4282	-.5529
LCC	0.0000	0.6563	-.1619	0.4282	1.0000	-.7588
LL	0.4258	-.4057	0.0141	-.5529	-.7588	1.0000

Eigenvalues of the Correlation Matrix

	Eigenvalue	Difference	Proportion	Cumulative
1	2.64755928	0.92450154	0.4413	0.4413
2	1.72305774	0.64859390	0.2872	0.7284
3	1.07446384	0.59955659	0.1791	0.9075
4	0.47490725	0.39489535	0.0792	0.9867
5	0.08001190	0.08001190	0.0133	1.0000
6	0.00000000	0.00000000	0.0000	1.0000

Eigenvectors

		Prin1	Prin2	Prin3
Beta	Beta	-.114221	0.413728	0.744058
CuCcbm		0.433301	-.124843	0.438804
LB		0.131027	0.724992	-.192902
LC		0.467015	0.459082	-.218696
LCC		0.527329	-.202514	0.312560
LL		-.534655	0.189373	0.266639

Eigenvectors

	Prin4	Prin5	Prin6
Beta	-.381786	-.283983	-.189089
CuCcbm	0.747825	-.211831	0.000000
LB	0.131129	-.095927	0.627384
LC	0.022700	0.311832	-.652348
LCC	-.366646	0.551101	0.380889
LL	0.377965	0.681416	0.000000

Figure D – 12. Continued

The second principal component was dominated by $\text{beta} + \log(C_u) + \log(C_{CBM})$. The third and fourth principal components were interesting in that they appeared to have interchanged the most dominant and the second dominant components (beta and the ratio

C_u/C_{CBM}). This appeared to indicate that there was a decision variable that represented a functional relationship between beta and the ratio C_u/C_{CBM}.

In summary, the possible decision variables thus far are shown in Figure D – 13.

$$\text{Beta}$$
$$C_{CBM}$$
$$C_u$$
$$\log\left(\frac{C_u}{C_{CBM}}\right)$$
$$\log(C_u)$$
$$\log(C_{CBM})$$
$$\text{beta} + \log(C_u) + \log(C_{CBM})$$
$$\log\left(\frac{C_u}{C_{CBM}}\right) + \log(C_u) + \log(C_{CBM})$$
$$\left(\frac{\log(C_{CBM}) + \log(C_u) + \text{beta}}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}\right)$$
$$\frac{C_u}{C_{CBM}}$$

Figure D – 13. Results of a principal component analysis on the decision variables beta, C_{CBM}, C_u, $\log(C_{CBM})$, $\log(C_u)$ and the ratio C_u/C_{CBM}

The next step in the this evolutionary approach to developing a decision model was to attempt to use the decision variables defined in Figure D – 13 to predict the economically preferred maintenance strategy for the initial 90 trials. This was accomplished using a spreadsheet. Table D – IV shows the values of the original decision variables and the newly defined decision variables, along with the economically preferred maintenance strategy.

TABLE D – IV

ORIGINAL AND DEFINED DECISION VARIABLE VALUES

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
16	1.0	1	1	0	0	0	1	#DIV/0!	1.00	0.00	CM
17	1.0	1	10	1	1	0	10	1.000	2.00	2.00	CBM
18	1.0	1	100	2	2	0	100	0.750	3.00	4.00	CBM
19	1.0	1	1000	3	3	0	1000	0.667	4.00	6.00	CBM
20	1.0	1	10000	4	4	0	10000	0.625	5.00	8.00	CBM
21	1.0	10	10	0	1	1	1	1.500	3.00	2.00	CM
22	1.0	10	100	1	2	1	10	1.000	4.00	4.00	CBM
23	1.0	10	1000	2	3	1	100	0.833	5.00	6.00	CBM
24	1.0	10	10000	3	4	1	1000	0.750	6.00	8.00	CBM
25	1.0	100	100	0	2	2	1	1.250	5.00	4.00	CM
26	1.0	100	1000	1	3	2	10	1.000	6.00	6.00	CBM
27	1.0	100	10000	2	4	2	100	0.875	7.00	8.00	CBM
28	1.0	1000	1000	0	3	3	1	1.167	7.00	6.00	CM
29	1.0	1000	10000	1	4	3	10	1.000	8.00	8.00	CBM
30	1.0	10000	10000	0	4	4	1	1.125	9.00	8.00	CM
31	1.5	1	1	0	0	0	1	#DIV/0!	1.50	0.00	CM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM
33	1.5	1	100	2	2	0	100	0.875	3.50	4.00	CBM
34	1.5	1	1000	3	3	0	1000	0.750	4.50	6.00	CBM
35	1.5	1	10000	4	4	0	10000	0.688	5.50	8.00	CBM
36	1.5	10	10	0	1	1	1	1.750	3.50	2.00	ABM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
38	1.5	10	1000	2	3	1	100	0.917	5.50	6.00	CBM
39	1.5	10	10000	3	4	1	1000	0.813	6.50	8.00	CBM
40	1.5	100	100	0	2	2	1	1.375	5.50	4.00	ABM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
42	1.5	100	10000	2	4	2	100	0.938	7.50	8.00	CBM
43	1.5	1000	1000	0	3	3	1	1.250	7.50	6.00	ABM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
45	1.5	10000	10000	0	4	4	1	1.188	9.50	8.00	ABM
46	2.5	1	1	0	0	0	1	#DIV/0!	2.50	0.00	CM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
49	2.5	1	1000	3	3	0	1000	0.917	5.50	6.00	CBM
50	2.5	1	10000	4	4	0	10000	0.813	6.50	8.00	CBM
51	2.5	10	10	0	1	1	1	2.250	4.50	2.00	ABM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM

TABLE D – IV continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM
54	2.5	10	10000	3	4	1	1000	0.938	7.50	8.00	CBM
55	2.5	100	100	0	2	2	1	1.625	6.50	4.00	ABM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
58	2.5	1000	1000	0	3	3	1	1.417	8.50	6.00	ABM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
60	2.5	10000	10000	0	4	4	1	1.313	10.50	8.00	ABM
61	3.5	1	1	0	0	0	1	#DIV/0!	3.50	0.00	CM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.50	6.00	CBM
65	3.5	1	10000	4	4	0	10000	0.938	7.50	8.00	CBM
66	3.5	10	10	0	1	1	1	2.750	5.50	2.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
69	3.5	10	10000	3	4	1	1000	1.063	8.50	8.00	CBM
70	3.5	100	100	0	2	2	1	1.875	7.50	4.00	ABM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
73	3.5	1000	1000	0	3	3	1	1.583	9.50	6.00	ABM
74	3.5	1000	10000	1	4	3	10	1.313	10.50	8.00	ABM
75	3.5	10000	10000	0	4	4	1	1.438	11.50	8.00	ABM
76	4.5	1	1	0	0	0	1	#DIV/0!	4.50	0.00	CM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.50	6.00	CBM
80	4.5	1	10000	4	4	0	10000	1.063	8.50	8.00	CBM
81	4.5	10	10	0	1	1	1	3.250	6.50	2.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
84	4.5	10	10000	3	4	1	1000	1.188	9.50	8.00	CBM
85	4.5	100	100	0	2	2	1	2.125	8.50	4.00	ABM
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
87	4.5	100	10000	2	4	2	100	1.313	10.50	8.00	ABM
88	4.5	1000	1000	0	3	3	1	1.750	10.50	6.00	ABM
89	4.5	1000	10000	1	4	3	10	1.438	11.50	8.00	ABM
90	4.5	10000	10000	0	4	4	1	1.563	12.50	8.00	ABM

TABLE D – IV continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
91	5.5	1	1	0	0	0	1	#DIV/0!	5.50	0.00	CM
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
94	5.5	1	1000	3	3	0	1000	1.417	8.50	6.00	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.50	8.00	CBM
96	5.5	10	10	0	1	1	1	3.750	7.50	2.00	ABM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
99	5.5	10	10000	3	4	1	1000	1.313	10.50	8.00	ABM
100	5.5	100	100	0	2	2	1	2.375	9.50	4.00	ABM
101	5.5	100	1000	1	3	2	10	1.750	10.50	6.00	ABM
102	5.5	100	10000	2	4	2	100	1.438	11.50	8.00	ABM
103	5.5	1000	1000	0	3	3	1	1.917	11.50	6.00	ABM
104	5.5	1000	10000	1	4	3	10	1.563	12.50	8.00	ABM
105	5.5	10000	10000	0	4	4	1	1.688	13.50	8.00	ABM

The method used to determine if any of the decision variables could predict the economically preferred maintenance strategy was to sort the spreadsheet on selected columns and then visually search for relationships. When a relationship was discovered, a decision rule was developed for the relationship. The first sort (SortA) used the beta column as the sort column. Table D – V shows the results of this sort.

The notable relationship shown with this sort was between the decision variables beta and the ratio C_u/C_{CBM}, and a CM strategy. Specifically, when beta was equal to one and the ratio C_u/C_{CBM} was equal to one, the economically preferred maintenance strategy was CM.

TABLE D – V

DATA SORTED ON BETA COLUMN (SortA)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
16	1.0	1	1	0	0	0	1	#DIV/0!	1.00	0.00	CM
21	1.0	10	10	0	1	1	1	1.500	3.00	2.00	CM
25	1.0	100	100	0	2	2	1	1.250	5.00	4.00	CM
28	1.0	1000	1000	0	3	3	1	1.167	7.00	6.00	CM
30	1.0	10000	10000	0	4	4	1	1.125	9.00	8.00	CM
17	1.0	1	10	1	1	0	10	1.000	2.00	2.00	CBM
18	1.0	1	100	2	2	0	100	0.750	3.00	4.00	CBM
19	1.0	1	1000	3	3	0	1000	0.667	4.00	6.00	CBM
20	1.0	1	10000	4	4	0	10000	0.625	5.00	8.00	CBM
22	1.0	10	100	1	2	1	10	1.000	4.00	4.00	CBM
23	1.0	10	1000	2	3	1	100	0.833	5.00	6.00	CBM
24	1.0	10	10000	3	4	1	1000	0.750	6.00	8.00	CBM
26	1.0	100	1000	1	3	2	10	1.000	6.00	6.00	CBM
27	1.0	100	10000	2	4	2	100	0.875	7.00	8.00	CBM
29	1.0	1000	10000	1	4	3	10	1.000	8.00	8.00	CBM
31	1.5	1	1	0	0	0	1	#DIV/0!	1.50	0.00	CM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM
33	1.5	1	100	2	2	0	100	0.875	3.50	4.00	CBM
34	1.5	1	1000	3	3	0	1000	0.750	4.50	6.00	CBM
35	1.5	1	10000	4	4	0	10000	0.688	5.50	8.00	CBM
36	1.5	10	10	0	1	1	1	1.750	3.50	2.00	ABM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
38	1.5	10	1000	2	3	1	100	0.917	5.50	6.00	CBM
39	1.5	10	10000	3	4	1	1000	0.813	6.50	8.00	CBM
40	1.5	100	100	0	2	2	1	1.375	5.50	4.00	ABM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
42	1.5	100	10000	2	4	2	100	0.938	7.50	8.00	CBM
43	1.5	1000	1000	0	3	3	1	1.250	7.50	6.00	ABM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
45	1.5	10000	10000	0	4	4	1	1.188	9.50	8.00	ABM
46	2.5	1	1	0	0	0	1	#DIV/0!	2.50	0.00	CM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
49	2.5	1	1000	3	3	0	1000	0.917	5.50	6.00	CBM
50	2.5	1	10000	4	4	0	10000	0.813	6.50	8.00	CBM
51	2.5	10	10	0	1	1	1	2.250	4.50	2.00	ABM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM

TABLE D – V continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
54	2.5	10	10000	3	4	1	1000	0.938	7.50	8.00	CBM
55	2.5	100	100	0	2	2	1	1.625	6.50	4.00	ABM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
58	2.5	1000	1000	0	3	3	1	1.417	8.50	6.00	ABM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
60	2.5	10000	10000	0	4	4	1	1.313	10.50	8.00	ABM
61	3.5	1	1	0	0	0	1	#DIV/0!	3.50	0.00	CM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.50	6.00	CBM
65	3.5	1	10000	4	4	0	10000	0.938	7.50	8.00	CBM
66	3.5	10	10	0	1	1	1	2.750	5.50	2.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
69	3.5	10	10000	3	4	1	1000	1.063	8.50	8.00	CBM
70	3.5	100	100	0	2	2	1	1.875	7.50	4.00	ABM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
73	3.5	1000	1000	0	3	3	1	1.583	9.50	6.00	ABM
74	3.5	1000	10000	1	4	3	10	1.313	10.50	8.00	ABM
75	3.5	10000	10000	0	4	4	1	1.438	11.50	8.00	ABM
76	4.5	1	1	0	0	0	1	#DIV/0!	4.50	0.00	CM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.50	6.00	CBM
80	4.5	1	10000	4	4	0	10000	1.063	8.50	8.00	CBM
81	4.5	10	10	0	1	1	1	3.250	6.50	2.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
84	4.5	10	10000	3	4	1	1000	1.188	9.50	8.00	CBM
85	4.5	100	100	0	2	2	1	2.125	8.50	4.00	ABM
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
87	4.5	100	10000	2	4	2	100	1.313	10.50	8.00	ABM
88	4.5	1000	1000	0	3	3	1	1.750	10.50	6.00	ABM
89	4.5	1000	10000	1	4	3	10	1.438	11.50	8.00	ABM
90	4.5	10000	10000	0	4	4	1	1.563	12.50	8.00	ABM
91	5.5	1	1	0	0	0	1	#DIV/0!	5.50	0.00	CM

TABLE D – V continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
94	5.5	1	1000	3	3	0	1000	1.417	8.50	6.00	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.50	8.00	CBM
96	5.5	10	10	0	1	1	1	3.750	7.50	2.00	ABM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
99	5.5	10	10000	3	4	1	1000	1.313	10.50	8.00	ABM
100	5.5	100	100	0	2	2	1	2.375	9.50	4.00	ABM
101	5.5	100	1000	1	3	2	10	1.750	10.50	6.00	ABM
102	5.5	100	10000	2	4	2	100	1.438	11.50	8.00	ABM
103	5.5	1000	1000	0	3	3	1	1.917	11.50	6.00	ABM
104	5.5	1000	10000	1	4	3	10	1.563	12.50	8.00	ABM
105	5.5	10000	10000	0	4	4	1	1.688	13.50	8.00	ABM

The second sort (SortB) was performed on the Ccbm column (Table D – VI). Note that trials 16, 21, 25, 28, and 30 were removed from consideration as a results of SortA.

TABLE D – VI

DATA SORTED ON CCBM COLUMN (SortB)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
45	1.5	10000	10000	0	4	4	1	1.188	9.50	8.00	ABM
60	2.5	10000	10000	0	4	4	1	1.313	10.50	8.00	ABM
75	3.5	10000	10000	0	4	4	1	1.438	11.50	8.00	ABM
90	4.5	10000	10000	0	4	4	1	1.563	12.50	8.00	ABM
105	5.5	10000	10000	0	4	4	1	1.688	13.50	8.00	ABM

TABLE D – VI continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
29	1.0	1000	10000	1	4	3	10	1.000	8.00	8.00	CBM
43	1.5	1000	1000	0	3	3	1	1.250	7.50	6.00	ABM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
58	2.5	1000	1000	0	3	3	1	1.417	8.50	6.00	ABM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
73	3.5	1000	1000	0	3	3	1	1.583	9.50	6.00	ABM
74	3.5	1000	10000	1	4	3	10	1.313	10.50	8.00	ABM
88	4.5	1000	1000	0	3	3	1	1.750	10.50	6.00	ABM
89	4.5	1000	10000	1	4	3	10	1.438	11.50	8.00	ABM
103	5.5	1000	1000	0	3	3	1	1.917	11.50	6.00	ABM
104	5.5	1000	10000	1	4	3	10	1.563	12.50	8.00	ABM
26	1.0	100	1000	1	3	2	10	1.000	6.00	6.00	CBM
27	1.0	100	10000	2	4	2	100	0.875	7.00	8.00	CBM
40	1.5	100	100	0	2	2	1	1.375	5.50	4.00	ABM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
42	1.5	100	10000	2	4	2	100	0.938	7.50	8.00	CBM
55	2.5	100	100	0	2	2	1	1.625	6.50	4.00	ABM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
70	3.5	100	100	0	2	2	1	1.875	7.50	4.00	ABM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
85	4.5	100	100	0	2	2	1	2.125	8.50	4.00	ABM
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
87	4.5	100	10000	2	4	2	100	1.313	10.50	8.00	ABM
100	5.5	100	100	0	2	2	1	2.375	9.50	4.00	ABM
101	5.5	100	1000	1	3	2	10	1.750	10.50	6.00	ABM
102	5.5	100	10000	2	4	2	100	1.438	11.50	8.00	ABM
22	1.0	10	100	1	2	1	10	1.000	4.00	4.00	CBM
23	1.0	10	1000	2	3	1	100	0.833	5.00	6.00	CBM
24	1.0	10	10000	3	4	1	1000	0.750	6.00	8.00	CBM
36	1.5	10	10	0	1	1	1	1.750	3.50	2.00	ABM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
38	1.5	10	1000	2	3	1	100	0.917	5.50	6.00	CBM

TABLE D – VI continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
39	1.5	10	10000	3	4	1	1000	0.813	6.50	8.00	CBM
51	2.5	10	10	0	1	1	1	2.250	4.50	2.00	ABM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM
54	2.5	10	10000	3	4	1	1000	0.938	7.50	8.00	CBM
66	3.5	10	10	0	1	1	1	2.750	5.50	2.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
69	3.5	10	10000	3	4	1	1000	1.063	8.50	8.00	CBM
81	4.5	10	10	0	1	1	1	3.250	6.50	2.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
84	4.5	10	10000	3	4	1	1000	1.188	9.50	8.00	CBM
96	5.5	10	10	0	1	1	1	3.750	7.50	2.00	ABM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
99	5.5	10	10000	3	4	1	1000	1.313	10.50	8.00	ABM
17	1.0	1	10	1	1	0	10	1.000	2.00	2.00	CBM
18	1.0	1	100	2	2	0	100	0.750	3.00	4.00	CBM
19	1.0	1	1000	3	3	0	1000	0.667	4.00	6.00	CBM
20	1.0	1	10000	4	4	0	10000	0.625	5.00	8.00	CBM
31	1.5	1	1	0	0	0	1	#DIV/0!	1.50	0.00	CM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM
33	1.5	1	100	2	2	0	100	0.875	3.50	4.00	CBM
34	1.5	1	1000	3	3	0	1000	0.750	4.50	6.00	CBM
35	1.5	1	10000	4	4	0	10000	0.688	5.50	8.00	CBM
46	2.5	1	1	0	0	0	1	#DIV/0!	2.50	0.00	CM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
49	2.5	1	1000	3	3	0	1000	0.917	5.50	6.00	CBM
50	2.5	1	10000	4	4	0	10000	0.813	6.50	8.00	CBM
61	3.5	1	1	0	0	0	1	#DIV/0!	3.50	0.00	CM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.50	6.00	CBM
65	3.5	1	10000	4	4	0	10000	0.938	7.50	8.00	CBM

TABLE D – VI continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
76	4.5	1	1	0	0	0	1	#DIV/0!	4.50	0.00	CM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.50	6.00	CBM
80	4.5	1	10000	4	4	0	10000	1.063	8.50	8.00	CBM
91	5.5	1	1	0	0	0	1	#DIV/0!	5.50	0.00	CM
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
94	5.5	1	1000	3	3	0	1000	1.417	8.50	6.00	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.50	8.00	CBM

The decision rule resulting from this sort was that if Ccbm was equal to one and Cu was equal to one, then the economically preferred maintenance strategy was CM (trials 31, 46, 61, 76, and 91). The first two decision rules classified all the trials where CM was preferred.

The remainder of this discussion will only show the sorts that resulted in the development of a decision rule. However, for all of the remaining decision rules, several preliminary sorts were performed before the final relationship was discovered.

SortC was performed on the LL column. Table D – VII shows the results of this sort.

TABLE D – VII

DATA SORTED ON LL COLUMN (SortC)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
20	1.0	1	10000	4	4	0	10000	0.625	5.00	8.00	CBM
19	1.0	1	1000	3	3	0	1000	0.667	4.00	6.00	CBM
35	1.5	1	10000	4	4	0	10000	0.688	5.50	8.00	CBM
24	1.0	10	10000	3	4	1	1000	0.750	6.00	8.00	CBM
18	1.0	1	100	2	2	0	100	0.750	3.00	4.00	CBM
34	1.5	1	1000	3	3	0	1000	0.750	4.50	6.00	CBM
39	1.5	10	10000	3	4	1	1000	0.813	6.50	8.00	CBM
50	2.5	1	10000	4	4	0	10000	0.813	6.50	8.00	CBM
23	1.0	10	1000	2	3	1	100	0.833	5.00	6.00	CBM
27	1.0	100	10000	2	4	2	100	0.875	7.00	8.00	CBM
33	1.5	1	100	2	2	0	100	0.875	3.50	4.00	CBM
38	1.5	10	1000	2	3	1	100	0.917	5.50	6.00	CBM
49	2.5	1	1000	3	3	0	1000	0.917	5.50	6.00	CBM
42	1.5	100	10000	2	4	2	100	0.938	7.50	8.00	CBM
54	2.5	10	10000	3	4	1	1000	0.938	7.50	8.00	CBM
65	3.5	1	10000	4	4	0	10000	0.938	7.50	8.00	CBM
29	1.0	1000	10000	1	4	3	10	1.000	8.00	8.00	CBM
26	1.0	100	1000	1	3	2	10	1.000	6.00	6.00	CBM
22	1.0	10	100	1	2	1	10	1.000	4.00	4.00	CBM
17	1.0	1	10	1	1	0	10	1.000	2.00	2.00	CBM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
69	3.5	10	10000	3	4	1	1000	1.063	8.50	8.00	CBM
80	4.5	1	10000	4	4	0	10000	1.063	8.50	8.00	CBM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.50	6.00	CBM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
45	1.5	10000	10000	0	4	4	1	1.188	9.50	8.00	ABM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
84	4.5	10	10000	3	4	1	1000	1.188	9.50	8.00	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.50	8.00	CBM
43	1.5	1000	1000	0	3	3	1	1.250	7.50	6.00	ABM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.50	6.00	CBM
60	2.5	10000	10000	0	4	4	1	1.313	10.50	8.00	ABM
74	3.5	1000	10000	1	4	3	10	1.313	10.50	8.00	ABM

TABLE D – VII continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
87	4.5	100	10000	2	4	2	100	1.313	10.50	8.00	ABM
99	5.5	10	10000	3	4	1	1000	1.313	10.50	8.00	ABM
40	1.5	100	100	0	2	2	1	1.375	5.50	4.00	ABM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
58	2.5	1000	1000	0	3	3	1	1.417	8.50	6.00	ABM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
94	5.5	1	1000	3	3	0	1000	1.417	8.50	6.00	CBM
75	3.5	10000	10000	0	4	4	1	1.438	11.50	8.00	ABM
89	4.5	1000	10000	1	4	3	10	1.438	11.50	8.00	ABM
102	5.5	100	10000	2	4	2	100	1.438	11.50	8.00	ABM
90	4.5	10000	10000	0	4	4	1	1.563	12.50	8.00	ABM
104	5.5	1000	10000	1	4	3	10	1.563	12.50	8.00	ABM
73	3.5	1000	1000	0	3	3	1	1.583	9.50	6.00	ABM
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
55	2.5	100	100	0	2	2	1	1.625	6.50	4.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
105	5.5	10000	10000	0	4	4	1	1.688	13.50	8.00	ABM
36	1.5	10	10	0	1	1	1	1.750	3.50	2.00	ABM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
88	4.5	1000	1000	0	3	3	1	1.750	10.50	6.00	ABM
101	5.5	100	1000	1	3	2	10	1.750	10.50	6.00	ABM
70	3.5	100	100	0	2	2	1	1.875	7.50	4.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
103	5.5	1000	1000	0	3	3	1	1.917	11.50	6.00	ABM
85	4.5	100	100	0	2	2	1	2.125	8.50	4.00	ABM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
51	2.5	10	10	0	1	1	1	2.250	4.50	2.00	ABM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
100	5.5	100	100	0	2	2	1	2.375	9.50	4.00	ABM
66	3.5	10	10	0	1	1	1	2.750	5.50	2.00	ABM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
81	4.5	10	10	0	1	1	1	3.250	6.50	2.00	ABM
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM
96	5.5	10	10	0	1	1	1	3.750	7.50	2.00	ABM

The decision rule developed from this sort was that CBM was the preferred strategy if beta was equal to one or if LL was less than 1.06 (trials 17 – 20, 22 – 24, 26, 27, 29, 33 – 35, 38, 39, 42, 49, 50, 54, 65).

SortD was performed on column CuCcbm (Table D – VIII). The decision rule developed from this sort was that if the decision variable CuCcbm was equal to one then the preferred maintenance strategy was ABM.

TABLE D – VIII

DATA SORTED ON CUCCBM COLUMN (SortD)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
45	1.5	10000	10000	0	4	4	1	1.188	9.50	8.00	ABM
43	1.5	1000	1000	0	3	3	1	1.250	7.50	6.00	ABM
60	2.5	10000	10000	0	4	4	1	1.313	10.50	8.00	ABM
40	1.5	100	100	0	2	2	1	1.375	5.50	4.00	ABM
58	2.5	1000	1000	0	3	3	1	1.417	8.50	6.00	ABM
75	3.5	10000	10000	0	4	4	1	1.438	11.50	8.00	ABM
90	4.5	10000	10000	0	4	4	1	1.563	12.50	8.00	ABM
73	3.5	1000	1000	0	3	3	1	1.583	9.50	6.00	ABM
55	2.5	100	100	0	2	2	1	1.625	6.50	4.00	ABM
105	5.5	10000	10000	0	4	4	1	1.688	13.50	8.00	ABM
36	1.5	10	10	0	1	1	1	1.750	3.50	2.00	ABM
88	4.5	1000	1000	0	3	3	1	1.750	10.50	6.00	ABM
70	3.5	100	100	0	2	2	1	1.875	7.50	4.00	ABM
103	5.5	1000	1000	0	3	3	1	1.917	11.50	6.00	ABM
85	4.5	100	100	0	2	2	1	2.125	8.50	4.00	ABM
51	2.5	10	10	0	1	1	1	2.250	4.50	2.00	ABM
100	5.5	100	100	0	2	2	1	2.375	9.50	4.00	ABM
66	3.5	10	10	0	1	1	1	2.750	5.50	2.00	ABM
81	4.5	10	10	0	1	1	1	3.250	6.50	2.00	ABM
96	5.5	10	10	0	1	1	1	3.750	7.50	2.00	ABM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
69	3.5	10	10000	3	4	1	1000	1.063	8.50	8.00	CBM

TABLE D – VIII continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
80	4.5	1	10000	4	4	0	10000	1.063	8.50	8.00	CBM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.50	6.00	CBM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
84	4.5	10	10000	3	4	1	1000	1.188	9.50	8.00	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.50	8.00	CBM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.50	6.00	CBM
74	3.5	1000	10000	1	4	3	10	1.313	10.50	8.00	ABM
87	4.5	100	10000	2	4	2	100	1.313	10.50	8.00	ABM
99	5.5	10	10000	3	4	1	1000	1.313	10.50	8.00	ABM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
94	5.5	1	1000	3	3	0	1000	1.417	8.50	6.00	CBM
89	4.5	1000	10000	1	4	3	10	1.438	11.50	8.00	ABM
102	5.5	100	10000	2	4	2	100	1.438	11.50	8.00	ABM
104	5.5	1000	10000	1	4	3	10	1.563	12.50	8.00	ABM
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
101	5.5	100	1000	1	3	2	10	1.750	10.50	6.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM

SortE was performed on column LB (Table D – IX). The decision rule developed from this sort was that if LB was greater than 8.5 then the preferred maintenance strategy was ABM (later experiments refined this rule to LB > 9.6).

Table D – IX

DATA SORTED ON LB COLUMN (SortE)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
74	3.5	1000	10000	1	4	3	10	1.313	10.50	8.00	ABM
87	4.5	100	10000	2	4	2	100	1.313	10.50	8.00	ABM
99	5.5	10	10000	3	4	1	1000	1.313	10.50	8.00	ABM
89	4.5	1000	10000	1	4	3	10	1.438	11.50	8.00	ABM
102	5.5	100	10000	2	4	2	100	1.438	11.50	8.00	ABM
104	5.5	1000	10000	1	4	3	10	1.563	12.50	8.00	ABM
101	5.5	100	1000	1	3	2	10	1.750	10.50	6.00	ABM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
69	3.5	10	10000	3	4	1	1000	1.063	8.50	8.00	CBM
80	4.5	1	10000	4	4	0	10000	1.063	8.50	8.00	CBM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.50	6.00	CBM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
84	4.5	10	10000	3	4	1	1000	1.188	9.50	8.00	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.50	8.00	CBM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.50	6.00	CBM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
94	5.5	1	1000	3	3	0	1000	1.417	8.50	6.00	CBM

TABLE D – IX continued

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM

SortF was performed on column CCb (Table D – X). The column CCb represented the decision variable (C_u/C_{CBM})/ beta and was added after several preliminary explorations. The principal component analysis indicated that a predictive decision variable might exist that represented a functional relationship between the ratio C_u/C_{CBM} and beta. The decision rule that resulted was to choose CBM as the preferred maintenance strategy if the decision variable, (C_u/C_{CBM})/ beta, was greater than 40. Later work refined this decision rule. The final decision rule was to choose CBM if the sum of the decision variables CCb and LB was greater then 75.

TABLE D – X

DATA SORTED ON CCb COLUMN (SortF)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	CCb	CCb + LB	Economically Preferred Maintenance Strategy
80	4.5	1	10000	4	4	0	10000	1.063	8.5	8	2222	2231	CBM
95	5.5	1	10000	4	4	0	10000	1.188	9.5	8	1818	1828	CBM
69	3.5	10	10000	3	4	1	1000	1.063	8.5	8	286	294	CBM
64	3.5	1	1000	3	3	0	1000	1.083	6.5	6	286	292	CBM
84	4.5	10	10000	3	4	1	1000	1.188	9.5	8	222	232	CBM
79	4.5	1	1000	3	3	0	1000	1.250	7.5	6	222	230	CBM
94	5.5	1	1000	3	3	0	1000	1.417	8.5	6	182	190	CBM
57	2.5	100	10000	2	4	2	100	1.063	8.5	8	40	49	ABM
53	2.5	10	1000	2	3	1	100	1.083	6.5	6	40	47	CBM
48	2.5	1	100	2	2	0	100	1.125	4.5	4	40	45	CBM
72	3.5	100	10000	2	4	2	100	1.188	9.5	8	29	38	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.5	6	29	36	CBM
63	3.5	1	100	2	2	0	100	1.375	5.5	4	29	34	CBM
83	4.5	10	1000	2	3	1	100	1.417	8.5	6	22	31	ABM
78	4.5	1	100	2	2	0	100	1.625	6.5	4	22	29	CBM
98	5.5	10	1000	2	3	1	100	1.583	9.5	6	18	28	ABM
93	5.5	1	100	2	2	0	100	1.875	7.5	4	18	26	CBM
44	1.5	1000	10000	1	4	3	10	1.063	8.5	8	7	15	ABM
59	2.5	1000	10000	1	4	3	10	1.188	9.5	8	4	14	ABM
41	1.5	100	1000	1	3	2	10	1.083	6.5	6	7	13	CBM
86	4.5	100	1000	1	3	2	10	1.583	9.5	6	2	12	ABM
56	2.5	100	1000	1	3	2	10	1.250	7.5	6	4	12	ABM
71	3.5	100	1000	1	3	2	10	1.417	8.5	6	3	11	ABM
37	1.5	10	100	1	2	1	10	1.125	4.5	4	7	11	CBM
97	5.5	10	100	1	2	1	10	2.125	8.5	4	2	10	ABM
82	4.5	10	100	1	2	1	10	1.875	7.5	4	2	10	ABM
52	2.5	10	100	1	2	1	10	1.375	5.5	4	4	10	CBM
67	3.5	10	100	1	2	1	10	1.625	6.5	4	3	9	ABM
32	1.5	1	10	1	1	0	10	1.250	2.5	2	7	9	CBM
92	5.5	1	10	1	1	0	10	3.250	6.5	2	2	8	CBM
77	4.5	1	10	1	1	0	10	2.750	5.5	2	2	8	CBM
47	2.5	1	10	1	1	0	10	1.750	3.5	2	4	8	CBM
62	3.5	1	10	1	1	0	10	2.250	4.5	2	3	7	CBM

SortG was performed on column LB (Table D – XI). The decision rule developed was that a practitioner should choose ABM if the decision variable LB was greater than 7.5. This decision rule was later modified so that ABM was chosen if LB was greater than 7.9.

TABLE D – XI

DATA SORTED ON LB COLUMN (SortG)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
72	3.5	100	10000	2	4	2	100	1.188	9.50	8.00	ABM
98	5.5	10	1000	2	3	1	100	1.583	9.50	6.00	ABM
59	2.5	1000	10000	1	4	3	10	1.188	9.50	8.00	ABM
86	4.5	100	1000	1	3	2	10	1.583	9.50	6.00	ABM
57	2.5	100	10000	2	4	2	100	1.063	8.50	8.00	ABM
83	4.5	10	1000	2	3	1	100	1.417	8.50	6.00	ABM
44	1.5	1000	10000	1	4	3	10	1.063	8.50	8.00	ABM
71	3.5	100	1000	1	3	2	10	1.417	8.50	6.00	ABM
97	5.5	10	100	1	2	1	10	2.125	8.50	4.00	ABM
68	3.5	10	1000	2	3	1	100	1.250	7.50	6.00	CBM
93	5.5	1	100	2	2	0	100	1.875	7.50	4.00	CBM
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM
53	2.5	10	1000	2	3	1	100	1.083	6.50	6.00	CBM
78	4.5	1	100	2	2	0	100	1.625	6.50	4.00	CBM
41	1.5	100	1000	1	3	2	10	1.083	6.50	6.00	CBM
92	5.5	1	10	1	1	0	10	3.250	6.50	2.00	CBM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
63	3.5	1	100	2	2	0	100	1.375	5.50	4.00	CBM
52	2.5	10	100	1	2	1	10	1.375	5.50	4.00	CBM
77	4.5	1	10	1	1	0	10	2.750	5.50	2.00	CBM
48	2.5	1	100	2	2	0	100	1.125	4.50	4.00	CBM
37	1.5	10	100	1	2	1	10	1.125	4.50	4.00	CBM
62	3.5	1	10	1	1	0	10	2.250	4.50	2.00	CBM
47	2.5	1	10	1	1	0	10	1.750	3.50	2.00	CBM
32	1.5	1	10	1	1	0	10	1.250	2.50	2.00	CBM

SortH was performed on column CCb * LL (Table D - XII). The decision rule developed from this sort was that CBM was the preferred strategy if the variable CCb + LL was greater than 5.5. The inspiration for the decision variable CCb + LL was taken from the fourth principal component shown in Figure D – 12 previously.

TABLE D – XII

DATA SORTED ON CCB * LL COLUMN (SortH)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	CCb	CCb*LL	Economically Preferred Maintenance Strategy
48	2.5	1	100	2	2	0	100	1.125	4.5	4	40	45	CBM
53	2.5	10	1000	2	3	1	100	1.083	6.5	6	40	43	CBM
63	3.5	1	100	2	2	0	100	1.375	5.5	4	29	39	CBM
78	4.5	1	100	2	2	0	100	1.625	6.5	4	22	36	CBM
68	3.5	10	1000	2	3	1	100	1.250	7.5	6	29	36	CBM
93	5.5	1	100	2	2	0	100	1.875	7.5	4	18	34	CBM
32	1.5	1	10	1	1	0	10	1.250	2.5	2	7	8	CBM
37	1.5	10	100	1	2	1	10	1.125	4.5	4	7	8	CBM
41	1.5	100	1000	1	3	2	10	1.083	6.5	6	7	7	CBM
47	2.5	1	10	1	1	0	10	1.750	3.5	2	4	7	CBM
62	3.5	1	10	1	1	0	10	2.250	4.5	2	3	6	CBM
77	4.5	1	10	1	1	0	10	2.750	5.5	2	2	6	CBM
92	5.5	1	10	1	1	0	10	3.250	6.5	2	2	6	CBM
52	2.5	10	100	1	2	1	10	1.375	5.5	4	4	6	CBM
56	2.5	100	1000	1	3	2	10	1.250	7.5	6	4	5	ABM
67	3.5	10	100	1	2	1	10	1.625	6.5	4	3	5	ABM
82	4.5	10	100	1	2	1	10	1.875	7.5	4	2	4	ABM

The final sort (SortI) was performed on column LB (Table D – XIII). The decision rule that resulted from this sort was to choose ABM if the decision variable LB was greater than 6.5. This decision rule was later revised so that ABM was chosen if LB was greater than 6.42.

This concluded the development of the decision rules necessary to predict all of the trials in the initial data set (nine decision rules). Through further testing with six validation sets (Appendix E), seven additional decision rules were added using the same sort/re-sort approach, as described above.

TABLE D – XIII

DATA SORTED ON LB COLUMN (SortI)

Trial	Beta	Ccbm	Cu	LCC	LCu	LCcbm	CuCcbm	LL	LB	LC	Economically Preferred Maintenance Strategy
56	2.5	100	1000	1	3	2	10	1.250	7.50	6.00	ABM
67	3.5	10	100	1	2	1	10	1.625	6.50	4.00	ABM
82	4.5	10	100	1	2	1	10	1.875	7.50	4.00	ABM

APPENDIX E – VALIDATION SETS

Validation Set #1

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy	Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	4.51	4	8052	CBM	26	5.10	214	3794	ABM
2	2.12	3	7712	CBM	27	4.75	721	4722	ABM
3	3.63	2	6585	CBM	28	3.55	828	1643	ABM
4	3.95	4	4539	CBM	29	3.24	824	2611	ABM
5	3.27	1	7205	CBM	30	2.83	110	4354	ABM
6	4.27	8	8205	CBM	31	5.03	1578	8748	ABM
7	4.69	3	7553	CBM	32	2.34	6085	9797	ABM
8	2.45	4	4813	CBM	33	1.30	4774	6579	ABM
9	1.99	5	7816	CBM	34	1.99	483	1877	ABM
10	5.06	2	6914	CBM	35	1.75	2574	3654	ABM
11	2.88	3	8783	CBM	36	1.64	3152	5372	ABM
12	4.30	26	2257	ABM	37	5.89	6237	9532	ABM
13	1.34	71	3517	CBM	38	3.52	8983	9187	ABM
14	5.99	77	5194	ABM	39	3.69	331	8146	ABM
15	5.66	38	1174	ABM	40	3.84	1928	6501	ABM
16	2.69	68	4973	ABM	41	4.62	2	6	CBM
17	3.14	66	3991	ABM	42	3.38	2	9	CBM
18	2.42	54	4614	CBM	43	2.97	5	7	ABM
19	3.33	15	1666	CBM	44	2.07	4	5	ABM
20	3.09	87	8404	ABM	45	5.85	3	8	ABM
21	1.21	313	5744	CBM	46	4.74	4	5	ABM
22	3.05	382	4252	ABM	47	4.40	5	7	ABM
23	5.76	337	9835	ABM	48	5.57	1	1	CM
24	1.63	867	7754	ABM	49	1.48	7	7	ABM
25	3.25	964	4037	ABM	50	1.43	10	10	ABM

Validation Set #2

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	4.21	4	3558	CBM
2	4.63	6	9214	CBM
3	2.74	2	8401	CBM
4	2.91	1	1726	CBM
5	3.70	7	9590	CBM
6	3.1500	4	5841	CBM
7	2.90	7	1445	CBM
8	4.01	6	4246	CBM
9	1.47	9	8314	CBM
10	2.09	6	1227	CBM
11	2.14	4	6599	CBM
12	4.64	72	4233	ABM
13	1.50	100	5515	CBM
14	4.12	75	2543	ABM
15	3.63	24	1954	ABM
16	5.87	45	5200	ABM
17	2.41	24	6089	CBM
18	2.24	94	9854	CBM
19	3.02	66	1178	ABM
20	1.97	96	8540	CBM
21	2.04	185	2019	ABM
22	4.14	631	7663	ABM
23	1.10	655	3459	CBM
24	5.65	984	5483	ABM
25	4.74	332	6511	ABM
26	4.30	823	2798	ABM
27	4.20	73	8942	ABM
28	3.45	771	6481	ABM
29	1.57	125	6210	CBM
30	3.96	924	3791	ABM
31	1.64	7402	8516	ABM
32	2.67	8249	8355	ABM
33	5.93	3135	3591	ABM
34	4.09	8914	9809	ABM
35	3.94	9068	9383	ABM
36	1.39	9960	9972	ABM
37	3.48	3364	8323	ABM
38	3.87	2299	6323	ABM
39	4.47	8159	9974	ABM
40	5.47	1369	6734	ABM
41	1.16	9	10	CBM
42	3.30	4	7	ABM
43	1.47	2	8	CBM
44	1.42	3	3	ABM
45	4.96	2	5	CBM
46	4.81	5	5	ABM
47	3.16	4	9	ABM
48	3.78	5	6	ABM
49	2.89	4	8	ABM
50	2.60	6	8	ABM

Validation Set #3

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	1.06	8	7166	CBM
2	1.12	4	7293	CBM
3	1.37	10	3103	CBM
4	1.34	5	1662	CBM
5	1.05	4	3416	CBM
6	1.37	3	1436	CBM
7	1.11	4	920	CBM
8	1.03	9	9897	CBM
9	1.11	5	8554	CBM
10	1.13	8	798	CBM
11	1.04	78	2355	CBM
12	1.36	6	4683	CBM
13	1.22	77	1744	CBM
14	1.30	99	9445	CBM
15	1.01	79	9168	CBM
16	1.04	42	8611	CBM
17	1.36	12	9721	CBM
18	1.00	18	4998	CBM
19	1.29	6	1274	CBM
20	1.27	19	6550	CBM
21	1.05	851	2228	CBM
22	1.46	179	8308	CBM
23	1.44	316	5963	CBM
24	1.47	444	3283	ABM
25	1.25	342	1136	CBM
26	1.15	74	6818	CBM
27	1.32	72	7312	CBM
28	1.08	475	7072	CBM
29	1.48	838	3624	ABM
30	1.03	53	2044	CBM
31	1.10	269	7088	CBM
32	1.22	140	4570	CBM
33	1.29	8888	9621	ABM
34	1.47	3275	9485	ABM
35	1.08	476	8891	CBM
36	1.26	1564	3730	ABM
37	1.27	5380	9308	ABM
38	1.22	7109	8266	ABM
39	1.49	2516	8884	ABM
40	1.10	2875	3257	ABM
41	1.38	2	6	CBM
42	1.31	8	9	ABM
43	1.02	5	6	CBM
44	1.43	5	10	CBM
45	1.02	7	7	CM
46	1.15	7	9	CBM
47	1.30	9	9	ABM
48	1.36	7	8	ABM
49	1.28	10	10	ABM
50	1.41	8	8	ABM

Validation Set #4

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy	Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	1.95	5	14	CBM	26	1.02	661	1302	CBM
2	1.79	8	15	ABM	27	1.09	107	376	CBM
3	1.09	6	7	CBM	28	1.71	134	460	ABM
4	1.90	8	19	CBM	29	1.59	293	910	ABM
5	1.04	9	23	CBM	30	1.73	251	672	ABM
6	1.07	2	6	CBM	31	1.38	2576	5976	ABM
7	1.03	2	4	CBM	32	1.26	7982	28439	ABM
8	1.40	9	19	CBM	33	1.57	1182	1202	ABM
9	1.18	7	19	CBM	34	1.62	874	1796	ABM
10	1.11	1	4	CBM	35	1.62	5562	11640	ABM
11	1.91	41	148	ABM	36	1.36	3603	10503	ABM
12	1.41	50	175	CBM	37	1.84	2150	5535	ABM
13	1.16	4	6	CBM	38	1.70	9813	21437	ABM
14	1.62	79	143	ABM	39	1.82	78	224	ABM
15	1.94	18	63	ABM	40	1.58	9032	25648	ABM
16	1.72	58	99	ABM	41	1.79	8	10	ABM
17	1.38	11	28	CBM	42	1.09	8	14	CBM
18	1.67	12	41	CBM	43	1.38	7	10	CBM
19	1.26	92	357	CBM	44	1.83	10	23	ABM
20	1.14	75	198	CBM	45	1.44	5	12	CBM
21	1.84	446	537	ABM	46	1.62	6	13	CBM
22	1.45	986	3576	ABM	47	1.84	9	31	CBM
23	1.97	945	2026	ABM	48	1.12	6	11	CBM
24	1.82	847	2829	ABM	49	1.79	3	11	CBM
25	1.30	755	1801	ABM	50	1.54	5	20	CBM

Validation Set #5

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy	Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	2.22	7	2560	CBM	26	4.88	794	2554	ABM
2	4.40	5	317	CBM	27	4.69	755	6574	ABM
3	4.27	9	7908	CBM	28	4.04	338	7776	ABM
4	3.68	4	6294	CBM	29	5.97	444	6440	ABM
5	1.88	6	7636	CBM	30	5.45	794	4149	ABM
6	1.71	4	6108	CBM	31	1.44	2842	9377	ABM
7	1.17	4	9496	CBM	32	5.95	9008	9798	ABM
8	2.56	6	7472	CBM	33	2.44	3450	8543	ABM
9	3.77	6	2642	CBM	34	2.71	1172	4214	ABM
10	5.90	1	1037	CBM	35	3.12	8312	9257	ABM
11	4.77	25	9573	ABM	36	1.71	4158	5866	ABM
12	4.46	41	2216	ABM	37	3.00	8100	9835	ABM
13	1.18	67	4690	CBM	38	4.78	5344	7632	ABM
14	2.24	15	7759	CBM	39	3.23	1025	7005	ABM
15	5.86	71	6268	ABM	40	4.34	6156	8996	ABM
16	1.92	56	4001	CBM	41	3.59	3	9	ABM
17	5.34	82	8378	ABM	42	4.38	3	8	ABM
18	2.13	33	5905	CBM	43	1.56	8	10	ABM
19	3.07	62	1256	ABM	44	5.79	3	8	ABM
20	2.74	43	262	ABM	45	2.08	4	7	CBM
21	3.44	798	1157	ABM	46	1.87	6	9	ABM
22	2.83	816	8217	ABM	47	5.64	5	7	ABM
23	2.69	556	4221	ABM	48	5.33	4	6	ABM
24	5.63	398	9549	ABM	49	2.27	5	8	ABM
25	3.13	459	2762	ABM	50	5.71	4	7	ABM

Validation Set #6

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	5.32	5	15	ABM
2	4.66	7	21	ABM
3	4.87	9	27	ABM
4	5.01	7	21	ABM
5	1.72	2	6	CBM
6	1.14	5	15	CBM
7	4.29	4	12	ABM
8	3.58	4	12	ABM
9	4.75	4	12	ABM
10	2.15	7	21	CBM
11	1.05	65	195	CBM
12	4.30	58	174	ABM
13	3.03	13	39	ABM
14	5.64	50	150	ABM
15	2.41	33	99	ABM
16	3.30	55	165	ABM
17	3.32	93	279	ABM
18	5.20	47	141	ABM
19	3.95	19	57	ABM
20	1.81	18	54	ABM
21	2.43	870	2610	ABM
22	2.97	974	2922	ABM
23	1.52	490	1470	ABM
24	2.82	68	204	ABM
25	3.64	103	306	ABM
26	3.19	140	420	ABM
27	2.35	985	2955	ABM
28	3.93	981	2943	ABM
29	5.71	207	621	ABM
30	4.75	165	495	ABM
31	4.83	9807	29421	ABM
32	5.06	423	1269	ABM
33	3.66	4166	12498	ABM
34	2.65	1547	4641	ABM
35	4.73	8306	24918	ABM
36	1.39	5797	17391	ABM
37	2.73	9829	29487	ABM
38	2.07	1668	5004	ABM
39	5.95	5413	16239	ABM
40	4.39	195	585	ABM
41	3.27	10	30	ABM
42	5.74	3	9	ABM
43	1.19	2	6	CBM
44	5.81	10	30	ABM
45	1.92	5	15	CBM
46	1.05	9	27	CBM
47	4.62	4	12	ABM
48	4.65	4	12	ABM
49	4.38	3	9	ABM
50	5.34	2	6	CBM

Validation Set #6a

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	1.83	7	74	CBM
2	1.51	1	10	CBM
3	2.35	4	38	CBM
4	2.09	5	52	CBM
5	1.60	9	85	CBM
6	1.92	7	66	CBM
7	2.41	2	21	CBM
8	2.41	9	89	CBM
9	2.24	6	60	CBM
10	1.69	2	21	CBM
11	2.05	71	746	ABM
12	2.31	30	324	ABM
13	2.12	98	1000	ABM
14	2.27	19	194	ABM
15	2.22	92	978	ABM
16	2.01	46	432	ABM
17	2.41	40	434	ABM
18	2.18	100	921	ABM
19	1.92	50	455	ABM
20	2.20	43	418	ABM
21	2.09	313	2991	ABM
22	1.80	896	8379	ABM
23	1.78	957	9784	ABM
24	1.89	138	1272	ABM
25	1.68	281	2813	ABM
26	1.87	472	5107	ABM
27	2.07	596	6543	ABM
28	1.69	72	694	CBM
29	1.86	208	2103	ABM
30	2.19	701	6632	ABM
31	2.43	1792	19470	ABM
32	1.50	9241	94284	ABM
33	1.73	7558	70142	ABM
34	1.53	6093	58784	ABM
35	1.81	3119	29226	ABM
36	1.77	9727	96817	ABM
37	1.66	749	7195	ABM
38	2.29	4430	47644	ABM
39	1.56	3450	37795	ABM
40	1.89	5563	51742	ABM
41	1.66	7	70	CBM
42	2.45	4	37	CBM
43	2.39	9	94	CBM
44	1.59	5	46	CBM
45	2.41	6	65	CBM
46	2.46	5	46	CBM
47	1.58	6	62	CBM
48	2.42	5	48	CBM
49	2.44	9	84	CBM
50	2.27	5	54	CBM

Validation Set #7

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy	Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	6.98	2	8792	CBM	26	1.15	684	1463	CBM
2	5.52	9	5492	ABM	27	6.36	135	6580	ABM
3	5.56	2	5916	CBM	28	4.88	32	6679	ABM
4	6.34	7	4583	ABM	29	3.96	954	6197	ABM
5	2.18	3	9190	CBM	30	5.33	38	6826	ABM
6	1.44	7	2796	CBM	31	5.93	3888	9104	ABM
7	1.03	8	5922	CBM	32	3.55	3507	3545	ABM
8	5.25	1	3199	CBM	33	5.74	8198	9341	ABM
9	6.68	7	155	ABM	34	5.23	6757	7685	ABM
10	3.15	2	9775	CBM	35	4.79	2911	7059	ABM
11	4.36	32	9443	ABM	36	1.20	4081	5150	ABM
12	1.43	25	1988	CBM	37	5.43	3344	8412	ABM
13	4.88	52	9328	ABM	38	4.03	7722	9683	ABM
14	3.60	12	3618	CBM	39	6.75	5978	7350	ABM
15	4.54	39	9092	ABM	40	1.08	5464	8159	ABM
16	2.72	71	7006	ABM	41	3.22	3	6	ABM
17	3.74	36	1977	ABM	42	1.91	6	8	ABM
18	2.86	90	5756	ABM	43	2.97	6	6	ABM
19	2.49	5	5531	CBM	44	4.10	1	6	CBM
20	5.03	94	1928	ABM	45	1.04	4	7	CBM
21	6.91	716	9094	ABM	46	1.81	7	10	ABM
22	6.60	455	1664	ABM	47	6.18	5	7	ABM
23	3.60	195	1098	ABM	48	1.81	10	10	ABM
24	6.54	228	3781	ABM	49	4.34	3	5	ABM
25	6.33	657	9707	ABM	50	6.38	7	9	ABM

Validation Set #8

Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy	Trial	Beta	Ccbm	Cu	Economically Preferred Maintenance Strategy
1	5.96	8	7397	Cabm	26	2.66	379	6928	ABM
2	5.89	4	9794	CBM	27	1.28	208	1759	CBM
3	3.96	9	8804	CBM	28	1.75	455	5619	ABM
4	1.06	4	3783	CBM	29	5.80	481	2080	ABM
5	2.55	6	5768	CBM	30	2.25	260	2631	ABM
6	4.67	2	7468	CBM	31	4.37	7929	8338	ABM
7	4.64	4	9791	CBM	32	1.99	360	8696	ABM
8	4.44	5	8174	CBM	33	3.95	4151	7582	ABM
9	3.05	2	488	CBM	34	1.05	6051	6570	ABM
10	2.69	2	9588	CBM	35	1.82	6252	9916	ABM
11	3.91	64	3528	ABM	36	2.19	6269	8393	ABM
12	4.26	4	7929	CBM	37	5.11	5305	7468	ABM
13	1.69	12	3327	CBM	38	4.99	1483	6064	ABM
14	5.74	78	6010	ABM	39	5.26	9866	9904	ABM
15	3.57	39	8960	ABM	40	4.65	2101	2480	ABM
16	2.43	50	462	ABM	41	1.22	10	10	ABM
17	4.03	95	9903	ABM	42	2.90	4	7	ABM
18	1.32	59	3798	CBM	43	5.65	4	7	ABM
19	4.19	18	822	ABM	44	4.98	9	10	ABM
20	2.04	73	3846	CBM	45	3.18	9	9	ABM
21	4.87	158	4495	ABM	46	5.42	3	3	ABM
22	2.52	541	6498	ABM	47	5.65	4	8	ABM
23	1.11	342	2332	CBM	48	3.24	8	10	ABM
24	5.43	607	6345	ABM	49	2.73	7	8	ABM
25	2.23	604	1325	ABM	50	3.22	3	4	ABM

APPENDIX F – MVLR ANALYSIS ON ORIGINAL AND VS1 – VS6A

```
                          The REG Procedure
                            Model: MODEL1
                   Dependent Variable: Type Type

                    Backward Elimination: Step 0

        All Variables Entered: R-Square = 0.6242 and C(p) = 10.0000
The model is not of full rank. A subset of the model which is of full
                           rank is chosen.


                        Analysis of Variance

                                 Sum of          Mean
 Source                DF       Squares        Square   F Value   Pr > F

 Model                  9     261.18746      29.02083     77.15   <.0001
 Error                418     157.24245       0.37618
 Corrected Total      427     418.42991


              Parameter     Standard
  Variable     Estimate        Error   Type II SS   F Value   Pr > F

  Intercept    -1.15931      0.20956     11.51278     30.60   <.0001
  beta         -0.72642      0.06877     41.96876    111.57   <.0001
  Ccbm      -0.00010816   0.00002129      9.70502     25.80   <.0001
  Cu         0.00001002   0.00000442      1.93620      5.15   0.0238
  CuCcbm    -0.00030546   0.00026292      0.50776      1.35   0.2460
  CCb          -0.00121      0.00111      0.44702      1.19   0.2763
  LL            0.18788      0.10022      1.32210      3.51   0.0615
  LB            0.94572      0.07477     60.17927    159.98   <.0001
  LCC          -0.68461      0.07571     30.75547     81.76   <.0001
  LLCCB         0.00270      0.00219      0.57083      1.52   0.2187

              Bounds on condition number: 1331.2, 19965
----------------------------------------------------------------------
                    Backward Elimination: Step 1

     Variable CCb Removed: R-Square = 0.6231 and C(p) = 9.188
```

Figure F – 1. MVLR analysis on original and VS1 – VS6a data sets

The REG Procedure

Model: MODEL1

Dependent Variable: Type Type

Backward Elimination: Step 1

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	260.74044	32.59255	86.60	<.0001
Error	419	157.68947	0.37635		
Corrected Total	427	418.42991			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.20906	0.20458	13.14525	34.93	<.0001
beta	-0.68117	0.05485	58.05226	154.25	<.0001
Ccbm	-0.00010271	0.00002070	9.26204	24.61	<.0001
Cu	0.00000923	0.00000436	1.68794	4.49	0.0348
CuCcbm	-0.00002719	0.00006296	0.07017	0.19	0.6661
LL	0.21447	0.09722	1.83142	4.87	0.0279
LB	0.88880	0.05353	103.76215	275.71	<.0001
LCC	-0.62670	0.05396	50.76207	134.88	<.0001
LLCCB	0.00031702	0.00016438	1.39982	3.72	0.0545

Bounds on condition number: 22.18, 581.65

Backward Elimination: Step 2

Variable CCBLB Entered: R-Square = 0.6242 and C(p) = 10.0000
NOTE: The variable which previously had small tolerance is now allowed to enter after removal of some variables from the model.

Backward Elimination: Step 2

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	261.18746	29.02083	77.15	<.0001
Error	418	157.24245	0.37618		
Corrected Total	427	418.42991			

Figure F – 1. Continued

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.15931	0.20956	11.51278	30.60	<.0001
beta	-0.72642	0.06877	41.96876	111.57	<.0001
Ccbm	-0.00010816	0.00002129	9.70502	25.80	<.0001
Cu	0.00001002	0.00000442	1.93620	5.15	0.0238
CuCcbm	-0.00030546	0.00026292	0.50776	1.35	0.2460
LL	0.18788	0.10022	1.32210	3.51	0.0615
LB	0.94693	0.07555	59.09743	157.10	<.0001
LCC	-0.68461	0.07571	30.75547	81.76	<.0001
CCBLB	-0.00121	0.00111	0.44702	1.19	0.2763
LLCCB	0.00270	0.00219	0.57083	1.52	0.2187

Bounds on condition number: 1331.2, 19970

Backward Elimination: Step 3

Variable CCBLB Removed: R-Square = 0.6231 and C(p) = 9.1883

Backward Elimination: Step 3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	260.74044	32.59255	86.60	<.0001
Error	419	157.68947	0.37635		
Corrected Total	427	418.42991			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.20906	0.20458	13.14525	34.93	<.0001
beta	-0.68117	0.05485	58.05226	154.25	<.0001
Ccbm	-0.00010271	0.00002070	9.26204	24.61	<.0001
Cu	0.00000923	0.00000436	1.68794	4.49	0.0348
CuCcbm	-0.00002719	0.00006296	0.07017	0.19	0.6661
LL	0.21447	0.09722	1.83142	4.87	0.0279
LB	0.88880	0.05353	103.76215	275.71	<.0001
LCC	-0.62670	0.05396	50.76207	134.88	<.0001
LLCCB	0.00031702	0.00016438	1.39982	3.72	0.0545

Bounds on condition number: 22.18, 581.65

Backward Elimination: Step 4

Variable CuCcbm Removed: R-Square = 0.6230 and C(p) = 7.3749

Backward Elimination: Step 4

Figure F – 1. Continued

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	260.67026	37.23861	99.14	<.0001
Error	420	157.75965	0.37562		
Corrected Total	427	418.42991			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.21062	0.20435	13.18329	35.10	<.0001
beta	-0.68772	0.05265	64.08435	170.61	<.0001
Ccbm	-0.00010327	0.00002065	9.39797	25.02	<.0001
Cu	0.00000917	0.00000435	1.66709	4.44	0.0357
LL	0.21860	0.09666	1.92113	5.11	0.0242
LB	0.89234	0.05284	107.10347	285.14	<.0001
LCC	-0.62891	0.05367	51.58716	137.34	<.0001
LLCCB	0.00025409	0.00007599	4.19953	11.18	0.0009

Bounds on condition number: 21.659, 404.64

All variables left in the model are significant at the 0.0500 level.

Figure F – 1. Continued

APPENDIX G – VS6A MVLR ANALYSIS

The REG Procedure
Model: MODEL1
Dependent Variable: Type Type

Backward Elimination: Step 0

All Variables Entered: R-Square = 0.7883 and C(p) = 10.0000
The model is not of full rank. A subset of the model which is of full rank is chosen.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	38.40755	4.26751	16.55	<.0001
Error	40	10.31245	0.25781		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.74897	74.76321	0.00014109	0.00	0.9815
beta	12.88129	131.51799	0.00247	0.01	0.9225
Ccbm	0.00000785	0.00075139	0.00002817	0.00	0.9917
Cu	-0.00001181	0.00007603	0.00621	0.02	0.8774
CuCcbm	-0.52291	5.73585	0.00214	0.01	0.9278
CCb	-0.75897	1.52064	0.06422	0.25	0.6204
LL	-6.67320	6.04358	0.31433	1.22	0.2761
LB	-11.90711	131.44285	0.00212	0.01	0.9283
LCC	12.23127	131.45693	0.00223	0.01	0.9263
LLCCB	0.57711	1.54978	0.03575	0.14	0.7116

Bounds on condition number: 17893801, 313470734

Backward Elimination: Step 1

Variable Ccbm Removed: R-Square = 0.7883 and C(p) = 8.0001

Figure G – 1. SAS results for regression analysis of VS6a

Backward Elimination: Step 1

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	38.40753	4.80094	19.09	<.0001
Error	41	10.31247	0.25152		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.75219	73.84531	0.00014161	0.00	0.9812
beta	12.93307	129.81218	0.00250	0.01	0.9211
Cu	-0.00001101	0.00000650	0.72262	2.87	0.0977
CuCcbm	-0.52479	5.66268	0.00216	0.01	0.9266
CCb	-0.76573	1.35970	0.07977	0.32	0.5764
LL	-6.67832	5.94977	0.31689	1.26	0.2682
LB	-11.96882	129.69917	0.00214	0.01	0.9269
LCC	12.29329	129.71178	0.00226	0.01	0.9250
LLCCB	0.58024	1.50202	0.03754	0.15	0.7013

Bounds on condition number: 17857357, 278066823

Backward Elimination: Step 2
Variable LB Removed: R-Square = 0.7883 and C(p) = 6.0084

Backward Elimination: Step 2

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	38.40538	5.48648	22.34	<.0001
Error	42	10.31462	0.24559		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	5.04494	5.21347	0.22997	0.94	0.3387
beta	0.95650	2.70867	0.03062	0.12	0.7258
Cu	-0.00001094	0.00000637	0.72398	2.95	0.0934
CuCcbm	-0.00481	0.55570	0.00001841	0.00	0.9931
CCb	-0.76913	1.34307	0.08054	0.33	0.5699
LL	-6.68867	5.87808	0.31799	1.29	0.2616
LCC	0.32331	0.14649	1.19635	4.87	0.0328
LLCCB	0.58256	1.48397	0.03785	0.15	0.6966

Figure G – 1. Continued

Bounds on condition number: 248.37, 5445.6

Backward Elimination: Step 3

Variable LBLC Entered: R-Square = 0.7883 and C(p) = 8.0001
NOTE: The variable which previously had small tolerance is now allowed to enter after removal of some variables from the model.

Backward Elimination: Step 3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	38.40753	4.80094	19.09	<.0001
Error	41	10.31247	0.25152		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.75219	73.84530	0.00014161	0.00	0.9812
beta	12.93307	129.81217	0.00250	0.01	0.9211
Cu	-0.00001101	0.00000650	0.72262	2.87	0.0977
CuCcbm	-0.52479	5.66268	0.00216	0.01	0.9266
CCb	-0.76573	1.35970	0.07977	0.32	0.5764
LL	-6.67832	5.94977	0.31689	1.26	0.2682
LCC	0.32447	0.14877	1.19638	4.76	0.0350
LBLC	-11.96881	129.69916	0.00214	0.01	0.9269
LLCCB	0.58024	1.50202	0.03754	0.15	0.7013

Bounds on condition number: 319937, 5093659

Backward Elimination: Step 4
Variable LBLC Removed: R-Square = 0.7883 and C(p) = 6.0084

Backward Elimination: Step 4

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	38.40538	5.48648	22.34	<.0001
Error	42	10.31462	0.24559		
Corrected Total	49	48.72000			

Figure G – 1. Continued

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	5.04494	5.21347	0.22997	0.94	0.3387
beta	0.95650	2.70867	0.03062	0.12	0.7258
Cu	-0.00001094	0.00000637	0.72398	2.95	0.0934
CuCcbm	-0.00481	0.55570	0.00001841	0.00	0.9931
CCb	-0.76913	1.34307	0.08054	0.33	0.5699
LL	-6.68867	5.87808	0.31799	1.29	0.2616
LCC	0.32331	0.14649	1.19635	4.87	0.0328
LLCCB	0.58256	1.48397	0.03785	0.15	0.6966

Bounds on condition number: 248.37, 5445.6

Backward Elimination: Step 5

Variable CCBLB Entered: R-Square = 0.7883 and C(p) = 8.0001
NOTE: The variable which previously had small tolerance is now allowed to enter after removal of some variables from the model.

Backward Elimination: Step 5

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	38.40753	4.80094	19.09	<.0001
Error	41	10.31247	0.25152		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-1.75219	73.84530	0.00014161	0.00	0.9812
beta	12.93307	129.81217	0.00250	0.01	0.9211
Cu	-0.00001101	0.00000650	0.72262	2.87	0.0977
CuCcbm	-0.52479	5.66268	0.00216	0.01	0.9266
CCb	11.20309	129.74312	0.00188	0.01	0.9316
LL	-6.67832	5.94977	0.31689	1.26	0.2682
LCC	12.29328	129.71177	0.00226	0.01	0.9250
CCBLB	-11.96882	129.69916	0.00214	0.01	0.9269
LLCCB	0.58024	1.50202	0.03754	0.15	0.7013

Bounds on condition number: 21038890, 331854545

Backward Elimination: Step 6

Variable CCb Removed: R-Square = 0.7883 and C(p) = 6.0074

Figure G – 1. Continued

Backward Elimination: Step 6

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	38.40565	5.48652	22.34	<.0001
Error	42	10.31435	0.24558		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	4.61152	4.60341	0.24645	1.00	0.3222
beta	1.72705	2.98092	0.08243	0.34	0.5654
Cu	-0.00001095	0.00000637	0.72438	2.95	0.0933
CuCcbm	-0.03832	0.56489	0.00113	0.00	0.9462
LL	-6.69148	5.87712	0.31835	1.30	0.2613
LCC	1.09360	1.43345	0.14294	0.58	0.4498
CCBLB	-0.77014	1.34259	0.08081	0.33	0.5693
LLCCB	0.58352	1.48369	0.03799	0.15	0.6961

Bounds on condition number: 2309, 35557

Backward Elimination: Step 7
Variable CuCcbm Removed: R-Square = 0.7883 and C(p) = 4.0118

Backward Elimination: Step 7

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	38.40452	6.40075	26.68	<.0001
Error	43	10.31548	0.23989		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	4.57789	4.52337	0.24571	1.02	0.3172
beta	1.53606	0.96875	0.60314	2.51	0.1202
Cu	-0.00001082	0.00000604	0.77031	3.21	0.0802
LL	-6.38064	3.63775	0.73805	3.08	0.0866
LCC	1.07119	1.37862	0.14483	0.60	0.4414
CCBLB	-0.75118	1.29791	0.08036	0.33	0.5658
LLCCB	0.51152	1.02469	0.05978	0.25	0.6202

Bounds on condition number: 2209, 27010

Figure G – 1. Continued

Backward Elimination: Step 8

Variable LLCCB Removed: R-Square = 0.7870 and C(p) = 2.2436

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	38.34474	7.66895	32.52	<.0001
Error	44	10.37526	0.23580		
Corrected Total	49	48.72000			

The REG Procedure

Model: MODEL1

Dependent Variable: Type Type

Backward Elimination: Step 8

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	3.03620	3.27666	0.20246	0.86	0.3592
beta	1.16795	0.62287	0.82910	3.52	0.0674
Cu	-0.00001025	0.00000588	0.71702	3.04	0.0882
LL	-4.94111	2.19853	1.19105	5.05	0.0297
LCC	0.39435	0.24724	0.59989	2.54	0.1179
CCBLB	-0.11441	0.23755	0.05470	0.23	0.6325

Bounds on condition number: 75.28, 856.96

Backward Elimination: Step 9

Variable CCBLB Removed: R-Square = 0.7859 and C(p) = 0.4558

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	38.29004	9.57251	41.30	<.0001
Error	45	10.42996	0.23178		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	1.89322	2.24001	0.16557	0.71	0.4025
beta	1.31115	0.54264	1.35315	5.84	0.0198
Cu	-0.00001074	0.00000574	0.81054	3.50	0.0680
LL	-4.84056	2.16984	1.15347	4.98	0.0307
LCC	0.28713	0.10665	1.67987	7.25	0.0099

Backward Elimination: Step 9

Figure G – 1. Continued

Bounds on condition number: 14.785, 151.86

Backward Elimination: Step 10

Variable Cu Removed: R-Square = 0.7693 and C(p) = 1.5998

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	37.47950	12.49317	51.13	<.0001
Error	46	11.24050	0.24436		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	4.55652	1.77528	1.60975	6.59	0.0136
beta	1.95716	0.42969	5.06964	20.75	<.0001
LL	-7.43801	1.71166	4.61428	18.88	<.0001
LCC	0.12512	0.06387	0.93768	3.84	0.0562

Bounds on condition number: 8.7264, 50.375

Backward Elimination: Step 11
Variable LCC Removed: R-Square = 0.7500 and C(p) = 3.2369
The REG Procedure
Model: MODEL1
Dependent Variable: Type Type

Backward Elimination: Step 11

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	36.54181	18.27091	70.51	<.0001
Error	47	12.17819	0.25911		
Corrected Total	49	48.72000			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	7.73989	0.73594	28.65977	110.61	<.0001
beta	2.48305	0.34548	13.38486	51.66	<.0001
LL	-10.33777	0.88494	35.36004	136.47	<.0001

Bounds on condition number: 2.1997, 8.7989

All variables left in the model are significant at the 0.0500 level.

Figure G – 1. Continued

Summary of Backward Elimination

Step	Variable Entered	Variable Removed	Label	Number Vars In	Partial R-Square	Model R-Square	C(p)
1		Ccbm	Ccbm	8	0.0000	0.7883	8.0001
2		LB	LB	7	0.0000	0.7883	6.0084
3	LBLC		LBLC	8	0.0000	0.7883	8.0001
4		LBLC	LBLC	7	0.0000	0.7883	6.0084
5	CCBLB		CCBLB	8	0.0000	0.7883	8.0001
6		CCb	CCb	7	0.0000	0.7883	6.0074
7		CuCcbm	CuCcbm	6	0.0000	0.7883	4.0118
8		LLCCB	LLCCB	5	0.0012	0.7870	2.2436
9		CCBLB	CCBLB	4	0.0011	0.7859	0.4558
10		Cu	Cu	3	0.0166	0.7693	1.5998
11		LCC	LCC	2	0.0192	0.7500	3.2369

Summary of Backward Elimination

Step	F Value	Pr > F
1	0.00	0.9917
2	0.01	0.9269
3	0.01	0.9269
4	0.01	0.9269
5	0.01	0.9269
6	0.01	0.9316
7	0.00	0.9462
8	0.25	0.6202
9	0.23	0.6325
10	3.50	0.0680
11	3.84	0.0562

Summary of Backward Elimination

Step	Variable Entered	Variable Removed	Label	Number Vars In	Partial R-Square	Model R-Square	C(p)
1		CCb	CCb	8	0.0011	0.6231	9.1883
2	CCBLB		CCBLB	9	0.0011	0.6242	10.0000
3		CCBLB	CCBLB	8	0.0011	0.6231	9.1883
4		CuCcbm	CuCcbm	7	0.0002	0.6230	7.3749

Summary of Backward Elimination

Step	F Value	Pr > F
1	1.19	0.2763
2	1.19	0.2763
3	1.19	0.2763
4	0.19	0.6661

Figure G – 1. Continued

APPENDIX H – SENSITIVITY RESULTS FOR THETA

TABLE H – I

SENSITIVITY RESULTS FOR THETA EQUALS TWO

Trial	Beta	Ccbm	Cu	Theta = 1.0	Theta = 2.0
16	1	1	1	CM	CM
17	1	1	10	CBM	CBM
18	1	1	100	CBM	CBM
19	1	1	1000	CBM	CBM
20	1	1	10000	CBM	CBM
21	1	10	10	CM	CM
22	1	10	100	CBM	CBM
23	1	10	1000	CBM	CBM
24	1	10	10000	CBM	CBM
25	1	100	100	CM	CM
26	1	100	1000	CBM	CBM
27	1	100	10000	CBM	CBM
28	1	1000	1000	CM	CM
29	1	1000	10000	CBM	CBM
30	1	10000	10000	CM	CM
31	1.5	1	1	CM	CM
32	1.5	1	10	CBM	CBM
33	1.5	1	100	CBM	CBM
34	1.5	1	1000	CBM	CBM
35	1.5	1	10000	CBM	CBM
36	1.5	10	10	ABM	ABM
37	1.5	10	100	CBM	CBM
38	1.5	10	1000	CBM	CBM
39	1.5	10	10000	CBM	CBM
40	1.5	100	100	ABM	ABM
41	1.5	100	1000	CBM	CBM
42	1.5	100	10000	CBM	CBM
43	1.5	1000	1000	ABM	ABM
44	1.5	1000	10000	ABM	ABM
45	1.5	10000	10000	ABM	ABM
46	2.5	1	1	CM	CM
47	2.5	1	10	CBM	CBM
48	2.5	1	100	CBM	CBM
49	2.5	1	1000	CBM	CBM
50	2.5	1	10000	CBM	CBM
51	2.5	10	10	ABM	ABM
52	2.5	10	100	CBM	CBM
53	2.5	10	1000	CBM	CBM
54	2.5	10	10000	CBM	CBM
55	2.5	100	100	ABM	ABM
56	2.5	100	1000	ABM	ABM
57	2.5	100	10000	ABM	ABM
58	2.5	1000	1000	ABM	ABM
59	2.5	1000	10000	ABM	ABM
60	2.5	10000	10000	ABM	ABM
61	3.5	1	1	CM	CM
62	3.5	1	10	CBM	CBM
63	3.5	1	100	CBM	CBM
64	3.5	1	1000	CBM	CBM
65	3.5	1	10000	CBM	CBM
66	3.5	10	10	ABM	ABM
67	3.5	10	100	ABM	ABM
68	3.5	10	1000	CBM	CBM
69	3.5	10	10000	CBM	CBM
70	3.5	100	100	ABM	ABM
71	3.5	100	1000	ABM	ABM
72	3.5	100	10000	ABM	ABM
73	3.5	1000	1000	ABM	ABM
74	3.5	1000	10000	ABM	ABM
75	3.5	10000	10000	ABM	ABM
76	4.5	1	1	CM	CM
77	4.5	1	10	CBM	CBM
78	4.5	1	100	CBM	CBM
79	4.5	1	1000	CBM	CBM
80	4.5	1	10000	CBM	CBM
81	4.5	10	10	ABM	ABM
82	4.5	10	100	ABM	ABM
83	4.5	10	1000	ABM	ABM
84	4.5	10	10000	CBM	CBM
85	4.5	100	100	ABM	ABM
86	4.5	100	1000	ABM	ABM
87	4.5	100	10000	ABM	ABM
88	4.5	1000	1000	ABM	ABM
89	4.5	1000	10000	ABM	ABM
90	4.5	10000	10000	ABM	ABM
91	5.5	1	1	CM	CM
92	5.5	1	10	CBM	CBM
93	5.5	1	100	CBM	CBM
94	5.5	1	1000	CBM	CBM
95	5.5	1	10000	CBM	CBM
96	5.5	10	10	ABM	ABM
97	5.5	10	100	ABM	ABM
98	5.5	10	1000	ABM	ABM
99	5.5	10	10000	ABM	ABM
100	5.5	100	100	ABM	ABM
101	5.5	100	1000	ABM	ABM
102	5.5	100	10000	ABM	ABM
103	5.5	1000	1000	ABM	ABM
104	5.5	1000	10000	ABM	ABM
105	5.5	10000	10000	ABM	ABM

APPENDIX I – PRINCIPAL COMPONENT ANALYSES ON CBM SPECIFIED TRIALS AND ABM TRIALS

```
proc princomp data=set1 out=scores;
  var beta Ccbm Cu CuCcbm CCb LL LB LCC LBLC CCBLB LLCCB;
run;

dm 'log;clear;output;clear;';
options ps=50 ls=70 pageno=1;
goptions reset=global border ftext=swiss gunit=cm htext=0.4 htitle=0.5;
goptions display noprompt;

**********************************************************************;
**                                                                  **;
** AUTHOR: Ed Mccombs (orig by Chris Bilder)                        **;
**                                                                  **;
** DATE: 3-10-02                                                    **;
** UPDATE:                                                          **;
** PURPOSE: Read in the Maintenance data from an excel file and     **;
**          perform a principal component analysis                  **;
**                                                                  **;
** NOTES:                                                           **;
**                                                                  **;
**********************************************************************;
title1 'Ed Mccombs;

*Read in Excel file containing the cereal data';
*  Note: The variable names are beta Ccbm Cu CC CCB LL LB LC LLCCB;
proc import out=set1
            datafile= "a:\SASregCBM.xls"
            dbms=excel2000 replace;
     getnames=yes;
run;
title2 'Maintenance data set';
proc print data=set1;
run;
```

Figure I – 1. SAS Code for principal component analysis

The PRINCOMP Procedure

Observations 182
Variables 11

Simple Statistics

	beta	Ccbm	Cu	CuCcbm
Mean	2.140092334	47.1648352	3238.780220	769.178526
StD	1.231219038	134.2845798	3731.478707	1922.813481

Simple Statistics

	CCb	LL	LB	LCC
Mean	349.111840	1.217125162	5.742183179	5.363676672
StD	1017.422869	0.513512376	1.871969061	2.361678921

Simple Statistics

	LBLC	CCBLB	LLCCB
Mean	0.378506506	354.854023	292.1416415
StD	1.334139035	1017.652002	727.6878247

Correlation Matrix

		beta	Ccbm	Cu	CuCcbm	CCb
beta	beta	1.0000	-.2493	0.0835	0.2690	0.0177
Ccbm	Ccbm	-.2493	1.0000	0.1710	-.1287	-.1072
Cu	Cu	0.0835	0.1710	1.0000	0.5147	0.4476
CuCcbm	CuCcbm	0.2690	-.1287	0.5147	1.0000	0.8311
CCb	CCb	0.0177	-.1072	0.4476	0.8311	1.0000
LL	LL	0.4504	-.1228	-.4631	-.2243	-.2555
LB	LB	0.5350	0.2602	0.6821	0.2952	0.1215
LCC	LCC	0.0781	0.2411	0.8448	0.3952	0.3394
LBLC	LBLC	0.6125	-.0617	-.5384	-.2853	-.4303
CCBLB	CCBLB	0.0187	-.1067	0.4488	0.8315	1.0000
LLCCB	LLCCB	0.1018	-.1242	0.5054	0.9180	0.9824

The PRINCOMP Procedure

Correlation Matrix

	LL	LB	LCC	LBLC	CCBLB	LLCCB
beta	0.4504	0.5350	0.0781	0.6125	0.0187	0.1018
Ccbm	-.1228	0.2602	0.2411	-.0617	-.1067	-.1242
Cu	-.4631	0.6821	0.8448	-.5384	0.4488	0.5054
CuCcbm	-.2243	0.2952	0.3952	-.2853	0.8315	0.9180
CCb	-.2555	0.1215	0.3394	-.4303	1.0000	0.9824
LL	1.0000	-.2218	-.6518	0.8425	-.2559	-.2691
LB	-.2218	1.0000	0.8258	-.0587	0.1233	0.1950
LCC	-.6518	0.8258	1.0000	-.6115	0.3408	0.3907
LBLC	0.8425	-.0587	-.6115	1.0000	-.4303	-.4181
CCBLB	-.2559	0.1233	0.3408	-.4303	1.0000	0.9825
LLCCB	-.2691	0.1950	0.3907	-.4181	0.9825	1.0000

Figure I – 2. SAS output for principal component analysis for the CBM trials

Eigenvalues of the Correlation Matrix

	Eigenvalue	Difference	Proportion	Cumulative
1	5.11407452	2.79315585	0.4649	0.4649
2	2.32091867	0.27288139	0.2110	0.6759
3	2.04803728	1.16041809	0.1862	0.8621
4	0.88761920	0.58249865	0.0807	0.9428
5	0.30512054	0.11327901	0.0277	0.9705
6	0.19184154	0.11093617	0.0174	0.9880
7	0.08090537	0.02977890	0.0074	0.9953
8	0.05112647	0.05077006	0.0046	1.0000
9	0.00035641	0.00035641	0.0000	1.0000
10	0.00000000	0.00000000	0.0000	1.0000
11	0.00000000		0.0000	1.0000

The PRINCOMP Procedure

Eigenvectors

		Prin1	Prin2	Prin3	Prin4	Prin5
beta	beta	0.004988	0.376064	0.541506	-.170744	-.256209
Ccbm	Ccbm	0.016300	-.329535	0.136406	0.885844	-.159112
Cu	Cu	0.347574	-.182686	0.245016	-.051765	0.677805
CuCcbm	CuCcbm	0.364680	0.288631	0.008765	0.051218	-.224533
CCb	CCb	0.376789	0.264308	-.180167	0.152713	0.020637
LL	LL	-.255931	0.420262	0.164953	0.262489	0.609693
LB	LB	0.211475	-.132662	0.585950	-.022970	-.104450
LCC	LCC	0.333712	-.308603	0.292040	-.127190	-.016536
LBLC	LBLC	-.294006	0.360144	0.305197	0.192920	-.117285
CCBLB	CCBLB	0.377094	0.264005	-.179049	0.152636	0.020440
LLCCB	LLCCB	0.392065	0.273101	-.120652	0.106687	-.041200

Eigenvectors

	Prin6	Prin7	Prin8	Prin9	Prin10	Prin11
beta	0.005696	-.202676	-.653878	0.043118	0.000000	0.000000
Ccbm	-.083015	-.050425	-.230344	0.002384	0.000000	0.000000
Cu	-.342879	-.453685	-.013230	0.010715	0.000000	0.000000
CuCcbm	-.709999	0.365145	0.148850	0.266459	0.000000	0.000000
CCb	0.342528	-.154265	0.028317	0.300252	0.000522	0.707027
LL	0.119546	0.517277	-.089542	0.012624	0.000000	0.000000
LB	0.257426	0.171523	0.404989	-.023955	-.568000	0.001301
LCC	0.231089	0.353054	-.000126	0.010480	0.716591	0.000000
LBLC	-.047869	-.384304	0.568475	-.052162	0.404811	0.000000
CCBLB	0.342925	-.153915	0.029055	0.300141	-.000523	-.707186
LLCCB	0.015335	0.019984	-.014483	-.862102	0.000000	-.000000

Figure I – 2. Continued

The PRINCOMP Procedure

Observations	247
Variables	11

Simple Statistics

	beta	Ccbm	Cu	CuCcbm
Mean	3.215375668	1685.655870	6112.06883	16.86534534
StD	1.485901274	2863.750000	12098.35079	71.00771712

Simple Statistics

	CCb	LL	LB	LCC
Mean	4.40925792	1.641137608	8.482417998	5.905009606
StD	13.64280986	0.690522513	2.480464558	2.371963428

Simple Statistics

	LBLC	CCBLB	LLCCB
Mean	2.577408392	12.89167592	5.81392341
StD	1.461111691	14.14817969	17.66867860

Correlation Matrix

		beta	Ccbm	Cu	CuCcbm	CCb
beta	beta	1.0000	-.1331	-.1561	0.1896	0.1331
Ccbm	Ccbm	-.1331	1.0000	0.5861	-.1102	-.1190
Cu	Cu	-.1561	0.5861	1.0000	0.0369	0.0742
CuCcbm	CuCcbm	0.1896	-.1102	0.0369	1.0000	0.9848
CCb	CCb	0.1331	-.1190	0.0742	0.9848	1.0000
LL	LL	0.5127	-.2752	-.2924	-.0968	-.1516
LB	LB	0.4691	0.5132	0.3885	0.1255	0.1166
LCC	LCC	-.0795	0.5505	0.5422	0.1466	0.1889
LBLC	LBLC	0.9254	-.0224	-.2207	-.0249	-.1088
CCBLB	CCBLB	0.2106	-.0248	0.1397	0.9717	0.9847
LLCCB	LLCCB	0.1629	-.1293	0.0565	0.9924	0.9978

Figure I – 3. SAS output for principal component analysis for the ABM trials

The PRINCOMP Procedure

Correlation Matrix

	LL	LB	LCC	LBLC	CCBLB	LLCCB
beta	0.5127	0.4691	-.0795	0.9254	0.2106	0.1629
Ccbm	-.2752	0.5132	0.5505	-.0224	-.0248	-.1293
Cu	-.2924	0.3885	0.5422	-.2207	0.1397	0.0565
CuCcbm	-.0968	0.1255	0.1466	-.0249	0.9717	0.9924
CCb	-.1516	0.1166	0.1889	-.1088	0.9847	0.9978
LL	1.0000	-.3289	-.7408	0.6443	-.2038	-.1269
LB	-.3289	1.0000	0.8196	0.3672	0.2878	0.1150
LCC	-.7408	0.8196	1.0000	-.2320	0.3259	0.1677
LBLC	0.6443	0.3672	-.2320	1.0000	-.0405	-.0771
CCBLB	-.2038	0.2878	0.3259	-.0405	1.0000	0.9823
LLCCB	-.1269	0.1150	0.1677	-.0771	0.9823	1.0000

Eigenvalues of the Correlation Matrix

	Eigenvalue	Difference	Proportion	Cumulative
1	4.23776904	1.17805588	0.3853	0.3853
2	3.05971316	0.70985442	0.2782	0.6634
3	2.34985875	1.53197887	0.2136	0.8770
4	0.81787988	0.42219221	0.0744	0.9514
5	0.39568767	0.29315251	0.0360	0.9874
6	0.10253515	0.07573660	0.0093	0.9967
7	0.02679855	0.01725120	0.0024	0.9991
8	0.00954735	0.00933690	0.0009	1.0000
9	0.00021045	0.00021045	0.0000	1.0000
10	0.00000000	0.00000000	0.0000	1.0000
11	0.00000000		0.0000	1.0000

The PRINCOMP Procedure

Eigenvectors

		Prin1	Prin2	Prin3	Prin4	Prin5
beta	beta	0.069506	0.312137	0.520753	-.117070	-.196282
Ccbm	Ccbm	0.056363	-.388816	0.256179	0.441505	0.724464
Cu	Cu	0.135274	-.362991	0.128951	0.622203	-.635558
CuCcbm	CuCcbm	0.448423	0.189956	-.085150	0.081758	0.109767
CCb	CCb	0.456009	0.160279	-.119135	0.070027	0.030964
LL	LL	-.175470	0.425644	0.181126	0.474364	0.005969
LB	LB	0.200619	-.233153	0.501749	-.278121	-.032402
LCC	LCC	0.243599	-.431021	0.192262	-.291597	-.089933
LBLC	LBLC	-.054875	0.303905	0.539680	0.001224	0.090989
CCBLB	CCBLB	0.474894	0.113678	-.026912	0.018765	0.024177
LLCCB	LLCCB	0.453599	0.176818	-.107774	0.069910	0.040583

Figure I – 3. Continued

	Prin6	Prin7	Prin8	Prin9	Prin10	Prin11
beta	-.241467	-.634904	0.313745	-.120327	0.000000	0.000000
Ccbm	-.119857	-.208320	0.047087	-.016196	0.000000	0.000000
Cu	-.186624	0.083195	-.021384	0.005749	0.000000	0.000000
CuCcbm	-.091884	0.442685	0.650561	-.330467	-.000000	0.000000
CCb	0.033216	-.158125	-.414012	-.266870	0.691070	0.000000
LL	0.725732	0.002906	0.058914	-.002677	0.000000	0.000000
LB	0.246359	0.243549	-.061709	0.065628	0.070085	-.664983
LCC	0.444501	-.049871	0.132448	0.001583	0.053131	0.635895
LBLC	-.303369	0.494423	-.319777	0.108843	0.032728	0.391707
CCBLB	0.075221	-.109777	-.410042	-.245832	-.716670	0.000000
LLCCB	-.017392	-.085372	0.095085	0.853347	0.000000	-.000000

Eigenvectors

Figure I – 3. Continued

TABLE I – I

VARIABLE DEFINITIONS

Variable Name	Variable Definition
beta	The beta parameter of the Weibull distribution
Ccbm	The cost of performing CBM
Cu	The cost of failure
CuCcbm	$\frac{C_u}{C_{CBM}}$
CCb	$\frac{C_u / C_{CBM}}{beta}$
LL	$\frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$
LB	$\log(C_{CBM}) + \log(C_u) + beta$
LLC	$\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)$
LBLC	$\log(C_{CBM}) + \log(C_u) + beta - (\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right))$

TABLE I – I continued

VARIABLE DEFINITIONS

Variable Name	Variable Definition
CCBLB	$\frac{C_u / C_{CBM}}{beta} + \log(C_{CBM}) + \log(C_u) + beta$
LLCCB	$\frac{C_u / C_{CBM}}{beta} * \frac{\log(C_{CBM}) + \log(C_u) + beta}{\log(C_{CBM}) + \log(C_u) + \log\left(\frac{C_u}{C_{CBM}}\right)}$

APPENDIX J – DATA FOR RESEARCH QUESTION #4: STUDYING CBM IMPLEMENTATION AND CONTINUATION COSTS

TABLE J – I

THE COST OF ABM MINUS THE COST OF CBM

	Trial	Beta	Ccbm	Cu	LBLC	Economically Preferred Maintenance Strategy	Cost of ABM -Cost of CBM
vs6	50	5.34	2	6	4.86	CBM	0.01
vs2	45	4.96	2	5	4.56	CBM	0.00
vs1	41	4.62	2	6	4.14	CBM	0.06
vs5	10	5.90	1	1037	2.89	CBM	3.59
vs1	42	3.38	2	9	2.73	CBM	0.26
vs5	2	4.40	5	317	2.60	CBM	0.46
vs5	45	2.08	4	7	1.84	CBM	0.13
vs6	10	2.15	7	21	1.67	CBM	0.04
vs1	10	5.06	2	6914	1.53	CBM	6.36
vs4	4	1.90	8	19	1.52	CBM	0.03
vs4	1	1.95	5	14	1.50	CBM	0.99
vs2	2	4.63	6	9214	1.45	CBM	2.82
vs6	45	1.92	5	15	1.44	CBM	1.44
vs5	3	4.27	9	7908	1.32	CBM	0.11
vs4	47	1.84	9	31	1.30	CBM	0.99
vs1	7	4.69	3	7553	1.29	CBM	6.63
vs1	19	3.33	15	1666	1.28	CBM	0.11
vs4	46	1.62	6	13	1.28	CBM	1.37
vs2	1	4.21	4	3558	1.26	CBM	5.84
vs1	6	4.27	8	8205	1.26	CBM	1.79

TABLE J – I continued

	Trial	Beta	Ccbm	Cu	LBLC	Economically Preferred Maintenance Strategy	Cost of ABM -Cost of CBM
vs6	5	1.72	2	6	1.25	CBM	1.97
vs4	43	1.38	7	10	1.23	CBM	0.16
vs4	49	1.79	3	11	1.23	CBM	2.49
vs1	1	4.51	4	8052	1.21	CBM	6.27
vs2	8	4.01	6	4246	1.16	CBM	4.72
vs4	18	1.67	12	41	1.14	CBM	2.40
vs3	44	1.43	5	10	1.13	CBM	0.93
vs5	9	3.77	6	2642	1.12	CBM	5.02
vs2	41	1.16	9	10	1.11	CBM	0.04
vs4	8	1.40	9	19	1.07	CBM	0.49
vs4	45	1.44	5	12	1.06	CBM	2.12
vs3	46	1.15	7	9	1.04	CBM	0.75
vs4	3	1.09	6	7	1.03	CBM	0.07
vs4	13	1.16	4	6	0.99	CBM	0.31
vs4	17	1.38	11	28	0.97	CBM	2.71
vs3	43	1.02	5	6	0.94	CBM	0.23
vs4	50	1.54	5	20	0.94	CBM	5.17
vs3	41	1.38	2	6	0.91	CBM	2.88
vs1	4	3.95	4	4539	0.90	CBM	8.60
vs2	43	1.47	2	8	0.87	CBM	4.05
vs4	12	1.41	50	175	0.87	CBM	7.58
vs4	48	1.12	6	11	0.85	CBM	2.40
vs4	42	1.09	8	14	0.85	CBM	2.57
vs4	9	1.18	7	19	0.74	CBM	7.48
vs3	25	1.25	342	1136	0.73	CBM	34.55
vs4	7	1.03	2	4	0.73	CBM	1.19
vs4	26	1.02	661	1302	0.73	CBM	302.54
vs4	20	1.14	75	198	0.72	CBM	38.43
vs6	43	1.19	2	6	0.71	CBM	3.27
vs4	19	1.26	92	357	0.67	CBM	36.36
vs6	6	1.14	5	15	0.66	CBM	7.52

TABLE J – I continued

	Trial	Beta	Ccbm	Cu	LBLC	Economically Preferred Maintenance Strategy	Cost of ABM -Cost of CBM
vs3	21	1.05	851	2228	0.64	CBM	642.00
vs4	5	1.04	9	23	0.63	CBM	10.36
vs4	6	1.07	2	6	0.59	CBM	3.26
vs2	7	2.90	7	1445	0.59	CBM	12.30
vs6	46	1.05	9	27	0.57	CBM	14.26
vs6	11	1.05	65	195	0.57	CBM	89.31
vs2	5	3.70	7	9590	0.56	CBM	10.39
vs4	27	1.09	107	376	0.55	CBM	149.52
vs4	10	1.11	1	4	0.51	CBM	2.69
vs1	18	2.42	54	4614	0.49	CBM	1.44
vs5	4	3.68	4	6294	0.48	CBM	13.07
vs2	23	1.10	655	3459	0.37	CBM	1276.01
vs2	18	2.24	94	9854	0.22	CBM	7.15
vs3	23	1.44	316	5963	0.17	CBM	282.28
vs1	3	3.63	2	6585	0.11	CBM	17.00
vs5	16	1.92	56	4001	0.07	CBM	60.95
vs2	20	1.97	96	8540	0.02	CBM	44.83
vs2	17	2.41	24	6089	0.00	CBM	35.01
vs2	6	3.15	4	5841	-0.01	CBM	23.00
vs1	21	1.21	313	5744	-0.05	CBM	1556.43
vs3	28	1.08	475	7072	-0.09	CBM	4084.12
vs2	29	1.57	125	6210	-0.12	CBM	304.93
vs5	18	2.13	33	5905	-0.13	CBM	64.99
vs3	13	1.22	77	1744	-0.14	CBM	611.18
vs3	35	1.08	476	8891	-0.19	CBM	5209.67
vs3	22	1.46	179	8308	-0.21	CBM	622.47
vs2	10	2.09	6	1227	-0.22	CBM	50.46
vs2	13	1.50	100	5515	-0.24	CBM	433.21
vs3	32	1.22	140	4570	-0.29	CBM	1391.64
vs3	31	1.10	269	7088	-0.32	CBM	3898.74
vs2	4	2.91	1	1726	-0.33	CBM	23.06
vs5	1	2.22	7	2560	-0.34	CBM	23.43

TABLE J – I continued

	Trial	Beta	Ccbm	Cu	LBLC	Economically Preferred Maintenance Strategy	Cost of ABM -Cost of CBM
vs1	13	1.34	71	3517	-0.36	CBM	671.03
vs3	11	1.04	78	2355	-0.44	CBM	1943.94
vs5	14	2.24	15	7759	-0.47	CBM	84.45
vs5	8	2.56	6	7472	-0.54	CBM	54.06
vs3	30	1.03	53	2044	-0.56	CBM	1791.14
vs1	11	2.88	3	8783	-0.58	CBM	39.88
vs1	5	3.27	1	7205	-0.58	CBM	26.42
vs1	8	2.45	4	4813	-0.63	CBM	56.23
vs5	13	1.18	67	4690	-0.66	CBM	1879.72
vs3	14	1.30	99	9445	-0.68	CBM	1809.41
vs3	27	1.32	72	7312	-0.69	CBM	1361.42
vs3	26	1.15	74	6818	-0.81	CBM	3065.04
vs3	10	1.13	8	798	-0.87	CBM	516.36
vs2	3	2.74	2	8401	-0.88	CBM	48.97
vs3	19	1.29	6	1274	-1.04	CBM	425.69
vs3	15	1.01	79	9168	-1.06	CBM	8741.81
vs2	11	2.14	4	6599	-1.08	CBM	115.20
vs3	3	1.37	10	3103	-1.12	CBM	618.41
vs3	4	1.34	5	1662	-1.18	CBM	438.25
vs1	9	1.99	5	7816	-1.21	CBM	172.85
vs5	5	1.88	6	7636	-1.23	CBM	222.43
vs3	7	1.11	4	920	-1.25	CBM	639.89
vs3	20	1.27	19	6550	-1.27	CBM	1668.05
vs3	16	1.04	42	8611	-1.27	CBM	7092.66
vs1	2	2.12	3	7712	-1.29	CBM	131.32
vs3	6	1.37	3	1436	-1.31	CBM	356.48
vs3	18	1.00	18	4998	-1.44	CBM	4972.54
vs5	6	1.71	4	6108	-1.47	CBM	316.28
vs2	9	1.47	9	8314	-1.49	CBM	854.23
vs3	12	1.36	6	4683	-1.53	CBM	881.68
vs3	17	1.36	12	9721	-1.55	CBM	1505.47
vs3	5	1.05	4	3416	-1.88	CBM	2801.23

TABLE J – I continued

	Trial	Beta	Ccbm	Cu	LBLC	Economically Preferred Maintenance Strategy	Cost of ABM -Cost of CBM
vs3	1	1.06	8	7166	-1.89	CBM	5377.42
vs3	8	1.03	9	9897	-2.01	CBM	8623.12
vs3	9	1.11	5	8554	-2.12	CBM	4809.65
vs3	2	1.12	4	7293	-2.14	CBM	3946.10
vs5	7	1.17	4	9496	-2.21	CBM	3792.03

VITA 2

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Candidate for the Degree of

Doctor of Philosophy

Dissertation: A METHODOLOGY FOR COMPARING AGE-BASED MAINTENANCE AND CONDITION-BASED MAINTENANCE USING ECONOMIC MEASURES OF PERFORMANCE

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