Major Equipment Life-cycle Cost Analysis

Minnesota
Department of
Transportation

RESEARCH
SERVICES
&
LIBRARY

Office of
Transportation
System
Management

Douglas D. Gransberg, Principal Investigator
Institute for Transportation
Iowa State University

April 2015

Research Project
Final Report 2015-16

LRRB
LOCAL
ROAD RESEARCH
BOARD

Technical Report Documentation Page

1. Report No. MN/RC 2015-16	2.	3. Recipients Accession No.
4. Title and Subtitle Major Equipment Life-cycle Cost Analysis		5. Report Date April 2015
		6.
7. Author(s) Douglas D. Gransberg and Edward Patrick O' Connor		8. Performing Organization Report No.
9. Performing Organization Name and Address Iowa State University Institute for Transportation 2711 South Loop Drive, Suite 4700 Ames, Iowa 50010-8664		10. Project/Task/Work Unit No.
		11. Contract (C) or Grant (G) No. (c) 99004 (wo) 8
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/201516.pdf

16. Abstract (Limit: 250 words)

Equipment life-cycle cost analysis (LCCA) is typically used as one component of the equipment fleet management process and allows the fleet manager to make equipment repair, replacement, and retention decisions on the basis of a given piece of equipment's economic life. The objective of this research is to develop a robust method that permits equipment fleet managers to maximize the cost effectiveness of the fleet by optimizing the overall life-cycle value of each piece in the fleet. Minneapolis Public Works Fleet Services Division (MPWFSD) equipment fleet data was utilized in developing the proposed stochastic LCCA model for public agency's fleet. The research compared output using actual data from current software to the output from the new stochastic LCCA method using equipment deterioration curves and probabilistic input variables for capital costs, fuel, and other operating costs to demonstrate enhanced ability to optimize fleet management decisions. The interest rate was found to have a greater impact on economic life output than fuel prices for a dump truck. The fuel volatility did impact the life-cycle costs when applying the stochastic confidence levels. Based on Monte Carlo simulation sensitivity analysis results, the time factor and engine factor were found to be the most sensitive input variables to the LCCA model. This leads to the conclusion that when deciding to replace a piece of equipment, engine efficiency should be a high priority due to the costs associated with the time factor, engine factor, and its subsequent annual usage.

17. Document Analysis/Descriptors Equipment life-cycle cost analysis, Equipment maintenance, Fleet management, Benefit cost analysis		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 107	22. Price

Major Equipment Life-cycle Cost Analysis

Final Report

Prepared by:

Douglas D. Gransberg
Edward Patrick O'Connor
Institute for Transportation
Iowa State University

April 2015

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, MN 55155

ACKNOWLEDGEMENTS

The authors of the report would like to acknowledge the support provided for this project by the Minnesota Local Roads Research Board, with special thanks to John Scharfbillig and the members of the research oversight panel.

TABLE OF CONTENTS

Appendix A

Appendix B

Appendix C

Appendix D

List of Tables

List of Figures

Executive Summary

Equipment life-cycle cost analysis (LCCA) is typically used as one component of the equipment fleet management process and allows the fleet manager to make equipment repair, replacement, and retention decisions on the basis of a given piece of equipment's economic life. The decision to repair, overhaul, or replace a piece of equipment in a public agency's fleet is a function of ownership and operating costs. Before 2000, most fleet management decisions in Minnesota were delivered by analyzing a piece of equipment's remaining service life, which can be mathematically defined in three different ways: physical life, profit life and economic life (Mitchell 1998). Since public agencies have no profit motive, profit life is not applicable to this research. Physical and economic life both must be defined and calculated when considering equipment life because they provide two important means to approach replacement analysis and to ultimately make an equipment replacement decision (Douglas 1975). The concepts of depreciation, inflation, investment, maintenance and repairs, downtime, and obsolescence are all integral to replacement analysis (Gransberg et al. 2006).

Equipment replacement decisions are critical to the success of public agency fleet management. If a piece of equipment is not replaced at the end of its economic service life, maintenance, repair, and fuel consumption costs will outweigh the value of its purpose (Jensen and Bard 2002), eating more than its fair share of the agency's limited operations budget. Earlier methods used for determining a replacement age are based on deterministic approaches that don't account for uncertainty with inputs that affect equipment LCCA (West et al. 2013). To take into account uncertainty, a stochastic approach has to be employed to define a viable economic life of equipment within a public agency. The overall goal of the model should be to optimize the life-cycle costs and the economic life of equipment for a pubic agency's fleet. To accomplish this, fuel volatility, interest rate fluctuation, and changing market values are used as stochastic inputs for the model. Monte Carlo simulations are commonly used to produce probability distributions, which allow the development of probabilistic output.

The objective of this research is to develop a robust method that permits equipment fleet managers to maximize the cost effectiveness of the fleet by optimizing the overall life-cycle value of each piece in the fleet. Minneapolis Public Works Fleet Services Division (MPWFSD) equipment fleet data was utilized in developing the proposed stochastic LCCA model. The research has three main areas of focus:

- Impact of fuel volatility on equipment economic life
- Determination of the most sensitive inputs to a LCCA model for equipment
- Stochastic equipment LCCA model to calculate the economic life that varies from deterministic methods

The research compared output using actual data from current software to the output from the new stochastic LCCA method using equipment deterioration curves and probabilistic input variables for capital costs, fuel, and other operating costs to demonstrate enhanced ability to optimize fleet management decisions. It also contains a second component where non-financial parameters such as sustainability, safety, etc. can be evaluated and combined with the stochastic financial

analysis to assist managers in considering cost-technical trade-offs for new equipment. The final deliverable is a robust, spreadsheet-based decision tool.
Deterministic and stochastic models were developed for public agencies to calculate equipment fleet life-cycle costs and optimal economic life. This was achieved by modifying the Peurifoy and Schexnayder method (PSM) to fit the public agency equipment fleet environment and applying basic engineering economics principles to find optimal life-cycle cost solutions. When the stochastic model was applied to a piece of equipment using fluctuating interest rates and fuel prices, the sensitivity of the model's input variables were determined. The interest rate was found to have a greater impact on economic life output than fuel prices for a dump truck illustrated in Chapter 4. The fuel volatility did impact the life-cycle costs when applying the stochastic confidence levels.

With the increasing cost of diesel fuel, the issue of upgrading to a more fuel-efficient model of equipment using the latest technology has become an increasingly important element of the replace/repair decision. Therefore, employing the stochastic inputs allows the analyst to determine the impact of the most sensitive component of the equipment LCCA model. Based on Monte Carlo simulation sensitivity analysis results, the time factor and engine factor were found to be the most sensitive input variables to the LCCA model. This leads to the conclusion that when deciding to replace a piece of equipment, engine efficiency should be a high priority due to the costs associated with the time factor, engine factor, and its subsequent annual usage.

Applying that conclusion to the public sector, one must realize that once a given piece of equipment is added to public agency's equipment fleet, the equipment fleet manager can no longer influence many of the model's variables. These include the equipment's idle time, its working conditions, and its engine efficiency. Thus, while accounting for uncertainty, it was shown to add value to the overall decision, making all the input variables stochastic introducing a level of complication that is not necessary. Therefore, it is concluded that employing deterministic inputs for these values is the most practical. Such inputs as the repair and maintenance uncertainty are more critical to equipment decisions because the fleet manager can control those inputs more closely. Consequently, Chapter 5 discusses and demonstrates which variables are to be included in the equipment LCCA model as deterministic values and those better portrayed as stochastic variables to aid public agency equipment fleet managers.

Lastly a stochastic equipment LCCA model for a public agency's fleet was developed. The stochastic model accounted for uncertainty within input parameters, unlike deterministic methods that only use discrete input value assumptions. A range for the optimal replacement age was formulated within a 70% to 90% confidence level. Since public agencies must make equipment replacement decisions years in advance, the economic life range allows fleet managers to plan the replacement with certain levels of confidence. The use of Monte Carlo simulations provided for a sensitivity analysis in conjunction with the stochastic economic life determination. The outcomes displayed a change in the sensitivity from year to year in the change in market value and repair and maintenance costs. The variation between the two input variables occurred within the economic life range developed by the confidence levels. Therefore, the confidence levels along with the sensitivity analysis provide a trigger point that signals when the equipment manager should consider replacing a piece of equipment as it nears the end of its optimum economic life. Chapter 8 contains recommendations for further future research.

Chapter 1
Introduction

The objective of this research is to develop a stochastic equipment LCCA model to determine the economic life of equipment for a public agency's fleet. Minneapolis Public Works Fleet Services Division (MPWFSD) equipment fleet data was utilized in the LCCA. The thesis has three main areas of focus:

- Impact of Fuel Volatility on Equipment Economic Life
- Determination of the Most Sensitive Inputs to a LCCA Model for Equipment
- Stochastic Equipment LCCA Model to Calculate the Economic Life that Varies from Deterministic Methods

1.1 Background

In order to develop an effective and reliable equipment LCCA model the stages of equipment life had to be established. Also, the equipment LCCA methods had to be examined to discover the most applicable LCCA determination. Therefore, this section presents the fundamental formation from the literature upon which the analyses performed in the thesis were based. The content within this chapter is used to complement and support the information found in Chapters 4, 5, and 6.

1.1.1 Equipment Life

Before 2000, most of the roadway construction projects in Minnesota were delivered through traditional low Equipment life can be mathematically defined in three different ways: physical life, profit life and economic life (Mitchell 1998). Physical and economic life both must be defined and calculated when considering equipment life because they provide two important means to approach replacement analysis and to ultimately make an equipment replacement decision (Douglas 1975). The concepts of depreciation, inflation, investment, maintenance and repairs, downtime, and obsolescence are all integral to replacement analysis (Gransberg et al. 2006). Combining these concepts and processes allows the equipment manager to properly perform replacement analysis and make reasonable equipment replacement decisions.

Figure 1.1 shows the relationship between the three stages of each life-cycle (Douglas 1978). One can see in the graph that over the physical life of the machine, it takes some time for the new machine to earn enough to cover the capital cost of its procurement. It then moves into a phase where it earns more than it costs to own, operate and maintain. A machine finishes its life in a stage where the costs of keeping it going and the productive time lost to repairs it is greater than what it earns during the periods when it is operational. Thus, an equipment fleet manager needs the tools to identify the point in time where retaining a given piece of equipment is no longer profitable so that the machine can be replaced by either purchasing a new piece or by leasing an equivalent piece.

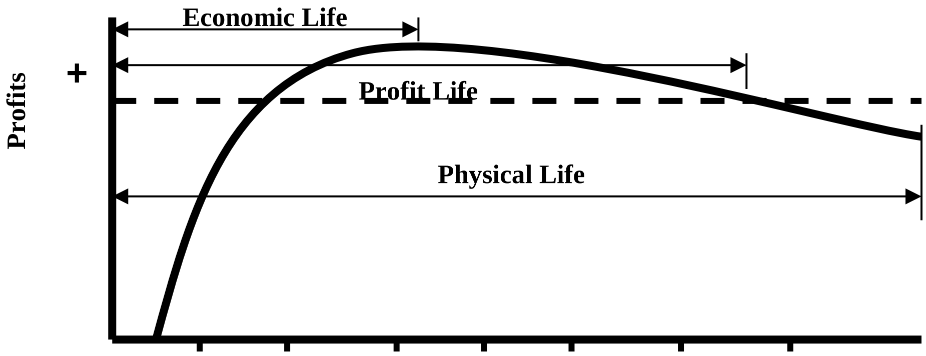


Figure 1.1 Equipment Life (Douglas 1978)

Figure 1.1 also graphically illustrates three different definitions for the useful life of a given machine: economic life, profit life, and physical life. These are explained in the following sections.

1.1.2 Physical life

For this research, the physical life of equipment will be identified as the service life. This time period ends when equipment can no longer be operated. This stage is greatly impacted by the repair and maintenance attention that the machine has been provided over its lifespan (Gransberg et al. 2006). A piece of equipment that has not been given adequate maintenance throughout its lifespan will deteriorate at a faster rate than a machine that was been given substantial preventative maintenance. Thus, the service lives will vary depending on the piece of equipment and the amount of upkeep it has been provided.

1.1.3 Profit life

Profit life is the time period where equipment is generating a profit (Gransberg et al. 2006). This is the most desired stage of the equipment life because after this point in time the equipment will operate with a loss (Douglas 1978). "Increasingly costly repairs exacerbate this as major components wear out and need to be replaced" (Gransberg et al. 2006). Thus, this is a critical stage in the equipment life to maximize on profitability and efficiencies. Also, the equipment fleet manager must be able to determine this time period to implement a replacement plan for a new machine while the components are useful (Gransberg et al. 2006).

1.1.4 Economic life

Economic life is based on decreasing ownership costs with the increase in operating costs (Mitchell 1998). The time period that these costs are equivalent is called the economic life. When the operating costs exceed the ownership costs a piece of equipment is costing more to operate rather than own. Thus, to maximize profits the replacement of a piece of equipment should occur before the economic life is reached. "The proper timing of equipment replacement prevents an erosion of profitability by the increased cost of maintenance and operation as the equipment ages beyond its economic life" (Gransberg et al. 2006).

The economic life will be the primary tool applied in the research to determine the replacement time period. The usage of engineering economic will be utilized to calculate the optimal economic life based on principles laid down by Park (2011) and, Peurifoy, and Schexnayder (2002). Of the equipment life-cycle cost models proposed Peuifoy, and Schexnayder (2002) will be extended by incorporating stochastic inputs to the economic life determination calculation.

1.1.5 Life-cycle Cost Analysis

Equipment LCCA comprises life-cycle costs, equipment decision procedures, replacement analysis, and replacement models. The decision to repair, overhaul, or replace a piece of equipment in a public agency's fleet is a function of ownership and operating costs. The research explores the impact of commodity price volatility as well as normal variation in the costs of tires and repair parts. The accuracy of the life-cycle costs can be improved by implementing stochastic functions. Thus, this research employed a stochastic model to better depict life-cycle costs and compute optimal economic life to improve equipment fleet decisions.

Life-cycle costs for equipment have two components, ownership and operating costs. Ownership costs would include initial costs, depreciation, insurance, taxes, storage, and investment costs (Peurifoy, and Schexnayder 2002). Operating costs would include repair and maintenance, tire, tire repair, fuel, operator, and any other consumable equipment cost (Gransberg et al. 2006). MPWFSD provided equipment fleet data which is used in the research to evaluate equipment life and answer the research questions in a quantitative manner.

1.1.6 Stochastic Modeling

"A quantitative description of a natural phenomenon is called a mathematical model of that phenomenon" (Pinsky and Karlin 2011). A deterministic phenomenon or model predicts a single result from a set of conditions (Pinsky and Karlin 2011). A stochastic phenomenon does not always lead to the same outcome but to different results regulated by statistical regularity (Haldorsen and Damselth 1990). The prediction of a stochastic model is built by articulating the likelihood or probability of a given result (Pinsky and Karlin 2011).

Pinsky and Karlin (2011) hold that stochastic modeling has three components:

1. A phenomenon under study,
2. A logical system for deducing implications about the phenomenon, and
3. A connection or equation which links the elements of the system under study together

In order to create stochastic phenomenon, considerations must be selected within a given model because phenomenon are not naturally stochastic (Pinsky and Karlin 2011). This allows the versatility of stochastic models for an abundant of applications.

A critical part of stochastic models are the probability functions used to determine the outcome of a phenomenon. The equally likely approach, originated in 1812, "was made to define the probability of an event A as the ratio of the total number of ways that A could occur to the total number of possible outcome of the experiment" (Pinsky and Karlin 2011). This approach is the basis for the utilization of probabilities distributions in stochastic models.

The stochastic process utilizes random variables within a model to determine the most likely outcome. The random variables are generated using Monte Carlo simulations. Monte Carlo simulations perform iterations, using random variables, on the output of a stochastic model. The results are then obtained from the simulation based on statistical data. The equipment LCCA model proposed in the thesis is a stochastic process applied to determine the economic life of equipment and calculate life-cycle costs.

1.1.7 Peurifoy and Schexnayder Equipment LCCA Model

The Peurifoy and Schexnayder method (PSM) to calculate life-cycle costs for equipment was employed for this research. R.L. Peurifoy is considered by many to be the father of modern construction engineering (Gransberg 2006). Thus, the model was selected for the equipment LCCA and the following details the parameters of the model.

The PSM equipment LCCA model utilizes cost factors that are separated into ownership and operating costs. The initial cost is defined as the purchase amount of a piece of equipment minus the tire cost (Peurifoy and Schexnayder 2002). Taxes, insurance, and storage costs are calculated as single percentage of initial costs. Ownership costs are determined by computing the equivalent uniform annual cost (EUAC) of the initial costs and the estimated salvage value.

The PSM operating costs include the fuel costs, repair and maintenance costs, filter, oil, and grease (FOG) costs, tire cost, and tire repair costs. Fuel costs include a function "of how a machine is used in the field and the local cost of fuel" (Peurifoy and Schexnayder 2002). To calculate the fuel costs, a consumption rate found in their book is multiplied by the fuel price, engine horsepower, and time and engine factor. The time factor is based on the production rate in an hour, and engine factor is based on the percentage of horsepower utilized.

The repair and maintenance costs are calculated taking into account a percentage of the annual depreciation. This method uses the straight-line method for depreciation. The percentage for the repair and maintenance cost is a function of the machine type and work application. Also, the tire repair cost is a percentage of the tire cost.

1.1.8 Public Agency Financial Constraints

The PSM was selected because it is a well-accepted approach to the development of an equipment ownership cost model and contained all the elements necessary to allow it to be transformed into a stochastic LCCA model for use in the research. However, the PSM was originally developed for use in private industry by construction contractors (Peurifoy and Schexnayder 2002), and as a result must be adapted for application to public agency equipment fleet management decisions. For example, since public agencies don't pay sales or property taxes, the tax component was dropped from the PSM to adapt it to the final deterministic model for the public sector. The subsequent paragraphs in this section will discuss the other adjustments made to make the PSM fully applicable to the typical public agency financial environment.

Private contractors operate with the access to requisite funding when it comes time to repair or replace a specific piece of equipment. This is not the case in the public sector. The major source of funding for public equipment fleet expenses come from tax revenues that feed capital budgets (Antich 2010). Public purchases of capital equipment must often gain approval from an appropriate authority and be paid for from tax revenues that were collected for this purpose. This creates a constraint on expenditures that is often referred to as the "color of money," where it is possible to have surplus funds that were designated for one purpose in the public coffers while at the same time have insufficient funds to make purchases for another specific purpose (Lang 2008). The most common situation is a strict separation of capital expenditures for the purchase of new pieces of equipment from operations and maintenance expenses, which are designated to pay for routine expenses such as fuel and repair parts (Lang 2008). Often major capital expenses must pass through an appropriations process where the governing authority reviews and approves a specific sum of money to purchase a specific item. This process may require the agency to identify the need to replace a given piece of equipment a year or more in advance of the need, making the results of this research both timely and valuable for implementation.

The City of Minneapolis, whose equipment fleet records are used in the subsequent analysis, provides an excellent example of the constraints faced by public agency equipment fleet managers. Its operating budget is established to "ensure maintenance of capital assets and infrastructure in the most cost-efficient manner" (COM 2014). Within that budget, the equipment fleet will be repaired and replaced from current revenues "where possible" (COM 2014). Minneapolis maintains a five-year capital improvement program (CIP) that provides funding for capital projects (COM 2014). Equipment fleet is not "the [appropriate] asset nature to fund through the City's CIP process" (COM 2014). Thus, Minneapolis maintains a separate five-year funding plan to address major equipment purchases (COM 2014). Theoretically, to get the purchase of a piece of equipment into this budget requires the equipment fleet manager to make replacement decisions at least five years in advance of the need to provide the time for the city to appropriate the necessary funding. While private contractors often have long-term equipment replacement plans of their own, they are not constrained to executing deviations from that plan because they are in full control of what and when available financial resources are expended. Minneapolis' five-year plan for equipment forces its equipment fleet manager to make decisions in conditions of greater uncertainty than that faced by its private sector counterpart. Thus, using a stochastic LCCA model to inform these decisions is more appropriate for the public sector because of the length of the decisions' time horizon.

Some public agencies avail themselves of other funding mechanisms to partially support their fleet operations. Examples are grant acquisitions, purchasing of used parts, and leasing agreements (Antich 2010). Private contractors normally have an immediately available line of credit upon which they can draw to finance large purchases whether planned or unexpected (The Bond Exchange 2010). A public agency does not have the same financial flexibility and consequently, the constraints on the use of available funding can affect the replacement and repair cycles for equipment fleet. For example, the City of Macomb, Michigan deferred all vehicle and equipment purchases for one year in 2010 due to budget deficits. As a result, in 2011 they were faced with substantially higher maintenance and repair costs (Antich 2010). While choosing the null option of not spending money on the equipment fleet may have been an unavoidable fiscal reality, the consequence was that the decision effectively extended the service life of the equipment scheduled to be replaced in 2010 beyond its economic life. The result conceivably could be equipment that is unable to be productively employed because of unacceptably high repair costs and end up being disposed of at a salvage value far below the unit's possible market value if it had been repaired the previous year (Antich 2010).

The other issue is purely mechanical as experience has shown that idle equipment deteriorates if it is not operated as designed. Things like gaskets and seals dry out causing fluid to leak or the gasket to blow when the machine is operated for the first time after a long period of being idle (Moss 2014). Thus, the public sectors financial constraints have the potential to put an agency's fleet into a virtual demise if needed repairs cannot be made and old equipment cannot be replaced when it reaches the end of its economic life. One can infer from this discussion that from the public perspective, there is a strong tendency to keep a piece of equipment for as long as possible before replacing it because of the administrative burden required to get purchase authority. Therefore, it is critical that the fleet manager have a tool that will provide the most accurate information to assist in making major repair and replacement decisions. Developing that tool is the objective of this research.

1.2 Research Objectives

Managing an agency's major equipment fleet is rife with conflicting priorities. One of the most important is the economic trade-off between capital cost of replacing a piece of equipment and the ownership costs of operating and maintaining it the machine in question is retained for another year. Fleet management software based on basic engineering economic theory oversimplify this complex relationship by failing to account for non-financial input parameters, such as the agency's sustainability goals, volatility of fuel prices, actual annual usage rates for seasonal equipment, etc. Thus, the research objective is to develop a robust method permit equipment fleet managers to maximize the cost effectiveness of the fleet by optimizing the overall life-cycle value of each piece in the fleet. A recent project completed for the Oklahoma DOT developed a new stochastic life-cycle cost analysis (LCCA) tool for pavement maintenance that included inputs for sustainability, price volatility, and actual rates of pavement deterioration which can be easily adapted to apply to machinery. The project will compare output using actual data from current software to the output from the new stochastic LCCA method using equipment deterioration curves and probabilistic input variables for capital costs, fuel, and other operating costs to demonstrate enhanced ability to optimize fleet management decisions. It will also contain a second component where non-financial parameters, such as sustainability, safety, etc. can be evaluated and combined with the stochastic financial analysis to assist managers in considering cost-technical trade-offs for new equipment. The final deliverable will be a robust, spreadsheet-based decision tool.

1.3 Problem Framework and Methodology

The research will be conducted in three phases:

- *Phase 1 (Tasks 1 and 2)***:** Consisted of a comprehensive literature review, a short on-line survey of DOTs and other agencies to identify who are currently using LCCA and fleet management software. The survey will also seek to identify nonfinancial parameters that are used by agencies outside Minnesota. Available fleet management software and LCCA software will be reviewed to create a benchmark against which the final project deliverable can be measured. This phase will also identify at least two case study agencies that are willing to provide data to be analyzed in Phase 2.
- *Phase 2 (Tasks 3 and 4)*: This phase will focus on data collection from the case study agencies using the rigorous methodology proposed by Yin (2008). The primary

instrument for data collection will be structured interviews with agency fleet managers and procurement personnel at each case study agency. The interviews will be developed using the GAO (1991) methodology, an approach the research team as successfully used on over a dozen TRB projects. Additionally, each agency will be asked to furnish past equipment data including life, hours, mileage, etc. for a select group of vehicles/equipment that represents cross-section of the agency's equipment management needs. The Phase 2 product will be a report discussing the case studies and an analysis that boils the life-cycle equipment management approaches currently in use into a generic LCCA model that contains the essential financial, informational, technical, and sustainability requirements to permit it to function as a robust decision-making tool.

- *Phase 3 (Tasks 5, 6, and 7)*: This phase will flesh out the stochastic LCCA model in a manner that is both consistent to the constraints imposed on a typical agency's procurement regulations and performs in a manner that satisfies the research sponsor. The model will be based on the "Cumulative Cost Model" methodology (Mitchell 1998) shown in Figure 1. The full analysis of each case study agency's fleet will be conducted to demonstrate the utility of the new LCCA algorithm and to validate the model's content and process. A user's guide will be developed and an agency outreach session with the LRRB community will be held to present the guide, collect issues and concerns, and to identify possible solutions to these issues that will make the implementation as smooth as possible. After the outreach meeting, the researchers will meet with the LRRB staff and agree on any necessary adjustments to the LCCA guidebook. A final draft guide with the spreadsheet template will be produced and submitted to LRRB. Additionally a final research report will also be developed that documents the project and captures the details of the data used to develop the guide.

1.3.1 Task Description

- *Phase 1:*

  - *Task 1**:** Benchmark the state-of-the-practice in major equipment LCCA:* A literature review will be conducted and from its results, a short on-line survey will be issued to transportation agencies to benchmark the use of LCCA and other parameters in agency fleet management programs and to solicit case study projects. LCCA and fleet management software will be obtained and evaluated. National-level benchmarks will be sought and evaluated for potential use.
    - *Deliverable:* Case study agency list and literature review
    - *Submission Date:* December 31, 2013

  - *Task 2: Evaluate current LCCA and fleet management software:* Based on the result of Task 2, a comparative analysis of current LCCA software output will be conducted using a standard data set and an in-depth sensitivity analysis will be conducted to understand the both the impact of each input parameter and LCCA assumption. The results will be used to address critical sensitivities in the generic framework to be developed in Task 5.
    - *Deliverable:* Summary of software analysis and Task 5 input
    - *Submission Date:* December 31, 2013

- *Phase 2:*

  - *Task 3: Case study, pricing, and sustainability data collection and reduction:* Case study agency data collection will be conducted through structured interviews of the stakeholders in each case study agency. Particular attention will be paid to capturing lessons learned and successful practices that can be adopted for use in the framework. The equipment usage performance data for each agency will be reduced and categorized in accordance with needs of each agency. The data will be used to develop equipment depreciation curves like the one shown in Figure 2 for each major piece of equipment in the study. Simultaneously, historical price data over the same period as the case study data will be collected for equipment operating cost items such as diesel, gasoline, tires, etc. to be used as input for the stochastic analysis of price volatility. Figure 3 shows the price volatility curve for diesel fuel. Finally, appropriate environmental impact data such as carbon footprint, fuel efficiency, etc. will be collected for the same equipment for use in Task 5 model of nonfinancial decision parameters.
    - *Deliverable:* Case Study Analysis Report
    - *Submission Date:* January 31, 2014

  - *Task 4: Develop generic major equipment stochastic LCCA model:* Based on the result of Task 3, a generic LCCA model will be created. The model will be composed of both deterministic and stochastic modes and be built in standard commercial spreadsheet software. The stochastic model will use a Monte Carlo simulation utility that is compatible with the base spreadsheet. Data from each of the case study agencies will be analyzed using both the new model and at least one current LCCA software program to evaluate the differences and benchmark the improvements. Additionally, a separate spreadsheet-based decision tool will be developed to take the output from the LCCA model and combine it with nonfinancial decision parameters to provide fleet managers the ability to consider the making decisions using a multi-criteria model. It is anticipated that the tool will be based on Cost Index Number Theory (lit cite); a variant of utility theory that essentially measures the "bang for the buck" and has been successful used by the team on previous maintenance research projects.
    - *Deliverable:* Stochastic LCCA Model and Case Study Analysis Report
    - *Submission Date:* May 31, 2014

- *Phase 3:*

  - *Task 5: Major equipment stochastic LCCA guide:* A users' guide for the newly developed model and spreadsheet will be prepared and used as a strawman from which to solicit input from both LRRB and MnDOT sources. This will be used for the LRRB major equipment LCCA outreach session. The purpose of the session will be twofold. First, the guide and model will be presented and demonstrated to fleet managers recruited from LRRB member agencies to validate this form, content, and understandability. Second, issues, problems, and clarifications will be collected from the session to refine and revise both the guide and model as required. The corrected model will and final guide will then be produced and delivered during Task 6.

    - *Deliverable:* Major equipment stochastic LCCA guide and spreadsheet model.
    - *Submission Date:* July 31, 2014

- *Task 6: Compile Report, Technical Advisory Panel Review and Revisions:*A draft report will be prepared, following MnDOT publication guidelines, to document project activities, findings and recommendations. This report will need to be reviewed by the Technical Advisory Panel (TAP), updated by the Principal Investigator and then approved by Technical Liaison before this task is considered complete. Holding a TAP meeting to discuss the draft report and review comments is strongly encouraged. TAP members may be consulted for clarification or discussion of comments.
    - *Deliverables:* Approved Report
    - *Submission Date***:** October 31, 2014

- *Task 7: Final Published Report Completion:*During this task the Approved Report will be processed by MnDOT's Contract Editors. The editors will review the document to ensure the document meets the publication standard. A Final Report will then be prepared by the Principal Investigator and submitted for publication through MnDOT's publishing process.
    - **Deliverables:** Final Published Report
    - **Submission Date:** December 31,2014

1.4 Project Schedule

Table 1.1 contains the project schedule, representing the duration of each task in months with a bar chart and indicating start and end dates for each activity. The beginning and end of the bars represent the first and last day of the month, respectively.

Table 1.1 Project Schedule

Task/Month	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Task 1																
Task 2																
Task 3																
Task 4																
Task 5																
Task 6																
Task 7																

1.5 Content Organization

This report was divided into eight chapters. Basically, this report presents all data, documents, findings and recommendations, used to or resulted from the development of the stochastic equipment LCCA model for public agencies. As can be seen in section 1.3.1 Task Description, Tasks 1, 2, 3, and 4 comprise all data collection and analysis activities, while Task 5, 6, and 7 mainly consist of the elaboration of documents from results obtained from the other four tasks. Thus, the following chapters are principally focused on activities conducted during Tasks 1, 2, 3, and 4, which essentially contain the literature review and research analysis. Below is a brief description of the content of this report by chapter.

- *Chapter 1. Introduction:* This chapter provides an introduction and brief background required to get a better understanding of this report and works as a guide for the rest of the document. Additionally, this chapter present and overview of the research process and the principal research instruments used in this study.
- *Chapter 2. Literature Review:* This chapter contains some relevant information and findings resulted from the comprehensive literature review and a complete content analysis process of several solicitations and contract documents conducted during Task 1.
- *Chapter 3. Research Analysis:* This chapter describes the analysis tools that were utilized to develop the stochastic equipment LCCA model.
- *Chapter 4. Impact of Fuel Volatility on Equipment economic life:* This chapter presents the impact of fuel volatility to the economic life of equipment using the stochastic LCCA model.
- *Chapter 5. Equipment Life-cycle Cost Analysis Input Variable Sensitivity Analysis using a Stochastic Model:* This chapter comprises principal findings and recommendations in regard with numerous input parameters being stochastic within the LCCA equipment model.
- *Chapter 6. Optimizing Public Agency Equipment Economic Life using Stochastic Modeling Techniques:* This chapter comprises principal findings and recommendations in regard with the stochastic LCCA equipment model.
- *Chapter 7. Consolidated Conclusions and Recommendations:* This chapter consolidates the principal conclusions and recommendations resulted from this research project.
- *Chapter 8. Recommendations for Future Research:* This chapter presents some topics that the research team considers should be implemented for future research to complement the research described in this report.

Chapter 2

Literature Review

A comprehensive literature review was conducted to highlight the main concepts of Life-cycle Cost Analysis (LCCA), methods to compute life-cycle cost, equipment decision procedures, replacement analysis, and replacement models.

2.1 Equipment Ownership Costs

Total equipment costs are comprised of two separate components: ownership costs and operating costs. Except for the one-time initial capital cost of purchasing the machine, ownership costs are fixed costs that are incurred each year, regardless of whether the equipment is operated or idle. Operating costs are the costs incurred only when the equipment is used. Ownership costs are fixed costs. Almost all of these costs are annual in nature; and include:
Initial capital cost

On an average, initial cost makes up about twenty five percent of the total cost that will be invested during the equipment's useful life (Douglas 1978). This cost is paid for getting equipment into the contractor's yard, or construction site, and ready for operation. Many kinds of ownership and operating costs are calculated using initial cost as a basis, and normally this cost can be calculated accurately. Initial cost consists of the following items; price at factory, extra equipment, sales tax, shipping, assembling, and erection.

2.1.1 <u>Depreciation</u>

Depreciation represents the decline in market value of a piece of equipment due to age, wear, deterioration, and obsolescence. Depreciation can result from:

- Physical deterioration occurring from wear and tear of the machine;
- Economic decline or obsolescence occurring over the passage of time.

There are many depreciation methods. Among them, the straight-line method, double-declining-balance method, and sum-of-the-years'-digits method are most commonly used in the construction equipment industry. In the appraisal of depreciation some factors are explicit while other factors have to be estimated. Generally, the asset costs are known:

- Initial cost: The amount needed to acquire the equipment.
- Useful life: The number of years it is expected to last.
- Salvage value: The expected amount the asset will be sold at the end of its useful life.

2.1.2 <u>Investment (or interest) cost</u>

Investment (or interest) cost represents the annual cost (converted to an hourly cost) of capital invested in a machine (Nunnally 1987). If borrowed funds are utilized for purchasing a piece of equipment, the equipment cost is simply the interest charged on these funds. However, if the equipment is purchased with company assets, an interest rate that is equal to the rate of return on company investment should be charged. Therefore, investment cost is computed as the product of an interest rate multiplied by the value of the equipment, then converted to cost per hour of operation.

2.1.3 Insurance Costs, Taxes, and Storage Cost

- Insurance cost represents the cost of fire, theft, accident, and liability insurance for the equipment.
- Tax cost represents the cost of property tax and licenses for the equipment.
- Storage cost includes the cost of rent and maintenance for equipment storage yards, the wages of guards and employees involved in moving equipment in and out of storage, and associated direct overhead.

2.2 Equipment Operating Costs

Operating costs of the construction equipment, which represents a significant cost category and should not be overlooked, are those costs associated with the operation of a piece of equipment. They are incurred only when the equipment is actually being used. Operating costs of the equipment is also called “variable” costs because they depend on several factors such as the number of operating hours, the types of equipment used, and the location and working condition of operation.

2.2.1 Maintenance and Repair Cost

The cost of maintenance and repairs usually constitutes the largest amount of operating expense for construction equipment. Construction operations can subject equipment to considerable wear and tear, but the amount of wear varies enormously between the different items of equipment used and between different job conditions. Generally, the maintenance and repair cost gets higher as the equipment gets older. Equipment owners will agree that good maintenance, including periodic wear measurement, timely attention to recommended service and daily cleaning when conditions warrant it, can extend the life of equipment and actually reduce the operating costs by minimizing the effects of adverse conditions.

The annual cost of maintenance and repairs may be expressed as a percentage of the annual cost of depreciation or it may be expressed independently of depreciation. The hourly cost of maintenance and repair can be obtained by dividing the annual cost by its operating hours per year.

2.2.2 Tire Cost

The tire cost represents the cost of tire repair and replacement. Because the life expectancy of rubber tires is generally far less than the life of the equipment they are used on, the depreciation rate of tires will be quite different from the depreciation rate on the rest of the vehicle. The repair and maintenance cost of tires as a percentage of their depreciation will also be different from the percentage associated with the repair and maintenance of the vehicle. The best source of information in estimating tire life is the historical data obtained under similar operating conditions.

2.2.3 Consumable Costs

Consumables are those items that are required for the operation of a piece of equipment that literally get consumed in the course of its operation. These include but are not limited to fuel, lubricants, and other petroleum products. They also include such things as filters, hoses, strainers, and other small parts and items that are used as the equipment is run.

2.2.4 Fuel Cost

Fuel consumption is incurred when the equipment is operated. When operating under standard conditions, a gasoline engine will consume approximately 0.06 gal of fuel per flywheel horsepower hour (fwhp-hr), while a diesel engine will consume approximately 0.04 gal per fwhp-hr. A horsepower hour is a measure of the work performed by an engine. The hourly cost of fuel is estimated by multiplying the hourly fuel consumption by the unit cost of fuel. The amount of fuel consumed by the equipment can be obtained from the historical data.

2.2.5 Lubricating Oil Cost

The quantity of oil required by an engine per change will include the amount added during the change plus the make-up oil between changes. It will vary with the engine size, the capacity of crankcase, the condition of the piston rings, and the number of hours between oil changes. It is a common practice to change oil every 100 to 200 hrs. (Peurifoy and Schexnayder 2002). The consumption data or average cost factors for oil, lubricants, and filters for their equipment under average conditions are available from the equipment manufacturers.

2.2.6 Equipment operator cost

Operator’s wages are usually added as a separate item after other operating costs have been calculated. They should include overtime or premium charges, workmen’s compensation insurance, social security taxes, bonus, and fringe benefits in the hourly wage figure. Care must be taken by companies that operate in more than one state or work for federal as well as state and private owners. The federal government requires that prevailing scale (union scale) wages be paid to workers on its project regardless if the state is a union state or not. This is a requirement of the Davis Bacon Act and most federal contracts will contain a section in the general conditions that details the wage rates that are applicable to each trade on the project (Clough and Sears 1994).

2.2.7 Special Items Cost.

The cost of replacing high wear items such a dozer, grader, and scraper blade cutting and end bits, as well as ripper tips, shanks, and shank protectors, should be calculated as a separate item of operating expense. As usual, unit cost is divided by expected life to yield cost per hour.

2.3 Methods of Calculating Ownership and Operating Cost

The most common methods available are the Caterpillar method, Association of General Contractor method (AGC), the Equipment Guide Book method (EGB), the Dataquest method, the Corps of Engineers method, and the Peurifoy method.

2.3.1 Caterpillar Method

Caterpillar Method is based on the following principles (Caterpillar 1998):

1. No prices for any items are provided. For reliable estimates, these must always be obtained locally.
2. Calculations are based on the complete machine. Separate estimates are not necessary for the basic machine, dozer, control, etc.
3. The multiplier factors provided will work equally well in any currency expressed in decimals.
4. Because of different standards of comparison, what may seem a severe application to one machine owner may appear only average to another. Therefore, in order to better describe machine use, the operating conditions and applications are defined in zones.

- *Ownership Costs:*
  These costs are calculated for depreciation, interest, insurance, and taxes. Usually depreciation is done to zero value with the Straight Line Method, which is not based on tax consideration, but resale or residual value at replacement may be included for depreciation or tax incentive purposes. Service life of several types of equipment is given in the *Caterpillar Performance Handbook* (Caterpillar 1998). Acquisition or delivered costs should include costs due to freight, sales tax, delivery, and installation. On rubber-tired machines, tires are considered a wear item and covered as an operating expense. Tire cost is subtracted from the delivered price. The delivered price less the estimated residual value results in the value to be recovered through work, divided by the total usage hours, giving the hourly cost to project the asset's value. The interest on capital used to purchase a machine must be considered, whether the machine is purchased outright or financed. Insurance cost and property taxes can be calculated in one of two ways.

- *Operating Costs:*
  Operating costs are based on charts and tables in the handbook. They are broken down as follows:
  1. Fuel;
  2. Filter, oil, and grease (FOG) costs;
  3. Tires;
  4. Repairs;
  5. Special items; and
  6. Operator's wages.

  The factors for fuel, FOG, tires and repairs costs can be obtained for each model from tables and charts given in the *Caterpillar Performance Handbook* (Caterpillar 1998). Tire costs can be estimated from previous records or from local prices. Repairs are estimated on the basis of a repair factor that depends on the type, employment and capital cost of the machine. The operator's wages are the local wages plus the fringe benefits.

2.3.2 Corps of Engineers Method

This method is often considered as the most sophisticated method for calculating equipment ownership costs because it not only covers economic items but it also includes geographic conditions. This method generally provides hourly use rates for construction equipment based on a standard 40-hour workweek. The total hourly use rates include all costs of owning and operating equipment except operator wages and overhead expenses. The ownership portion of the rate consists of allowances for depreciation and costs of facilities capital cost of money (FCCM). Operating costs include allowances for fuel, filter, oil, grease, servicing the equipment, repair and maintenance, and tire wear and tire repair (US Army Corps of Engineers 2003).

- *Ownership Costs:*
  1. Depreciation: It is calculated by using the straight-line method. The equipment cost used for depreciation calculation is subtracted by tire cost at the time the equipment was manufactured. Another cost that has to be subtracted is salvage value. It is determined from the "Handbook of New and Used Construction Equipment Values" (Green Guide), and advertisements of used equipment for sale displayed in current engineering and construction magazines (Handler 2004). The expected life span of the equipment is designated from the manufacturers' or equipment associations' recommendations.
  2. Facilities Capital Cost of Money (FCCM), the Department of the Treasury adjust the cost-of-money rate on or about January 1st and July 1st each year. This cost is computed by multiplying the cost-of-money rate, determined by the Secretary of the Treasury, by the average value of equipment and prorating the result over the annual operating hours. It is normally presented in terms of FCCM per hour.

     It should be noted that licenses, taxes, storage and insurance cost are not included in this computation. Instead, they are considered as indirect costs.

- *Operating Cost:*
  1. Fuel costs: Fuel costs are calculated from records of equipment consumption, which is done in cost-per-gallon per hour. Fuel consumption varies depending on the machine's requirements. The fuel can be either gasoline or diesel.
  2. Filter, oil, and grease (FOG): FOG costs are usually computed as percentage of the hourly fuel costs.
  3. Maintenance and repair costs: These are the expenses charged for parts, labor, sale taxes, and so on. Primarily, maintenance and repair cost per hour are computed by multiplying the repair factor to the new equipment cost, which is subtracted by tire cost, and divided by the number of operating hours.
  4. Hourly tire cost: This is the current cost of new tires plus cost of one recapping and then divided by the expected life of new tires plus the life of recapped tires. It has been determined that the recapping cost is approximately 50% of the new tire cost, and that the life of a new tire plus recapping will equal approximately 1.8 times the "useful life" of a new tire.
  5. Tire repair cost: This cost is assumed to be 15% of the hourly tire wear cost.

2.3.3 The Associated General Contractors of America (AGC) Method

This method enables the owner to calculate the owning and operating costs to determine capital recovery. Rather than dealing with the specific makes and models of the machines, the equipment is classified according to capacity or size. For example, this method computes the average annual ownership expense and the average hourly repair and maintenance expense as a percentage of the acquisition costs.

- *Ownership Cost:* The ownership costs considered in this method are the same as described in the Caterpillar Method, however, replacement cost escalation is also considered. Depreciation is calculated by the straight-line method, and includes purchase price, sales tax, freight, and erection cost, with an assumed salvage value of ten percent. Average economic life in hours and average annual operating hours are shown for each size range. Replacement cost escalation of seven percent is designed to augment the capital recovery, and to offset inflation and machine price increase. Interest on the investment is assumed to be seven percent, whereas taxes, insurance, and storage are taken as 4.5 percent.

- *Operating Costs:* Maintenance and repair costs are calculated based on an hourly percentage rate times the acquisition cost. It is a level rate regardless of the age of the machine. This expense includes field and shop repairs, overhaul, and replacement of tires and tracks, etc. The FOG costs and operator's wages are not considered in this method.

2.3.4 Peurifoy/Schexnayder Method

R.L. Peurifoy is considered by many to be the father of modern construction engineering. His seminal work on the subject, now in its sixth edition set the standard for using rigorous engineering principles to develop rational means for developing cost estimates based on equipment fleet production rates (Peurifoy and Schexnayder 2002).

- *Ownership Cost:*
  This method assumes the straight-line method for depreciation. The value of the equipment is depreciated to zero at the end of the useful life of the equipment. The ownership costs are based on an average investment cost that is taken as 60 percent of the initial cost of the equipment. Usually equipment owners charge an annual fixed rate of interest against the full purchase cost of the equipment. This gives an annual interest cost, which is higher than it should be. Since the cost of depreciation has already been claimed, it is more realistic to base the annual cost of investment on the average value of equipment during its useful life. This value can be obtained by taking an average of values at the beginning of each year that the equipment will be used, and this is the major difference between the Peurifoy Method and the other methods. The cost of investment is taken as 15 percent of the average investment.

- *Operating Costs:*
  Since the tire life is different from that of the equipment, its costs are treated differently. The maintenance cost is taken as 50 percent of the annual depreciation, the fuel and the FOG costs are included, whereas the operator wages are not included.

2.4 Equipment Replacement Procedures

Once a piece of equipment is purchased and used, it eventually begins to wear out and suffer mechanical problems. At some point, it reaches the end of its useful life and must be replaced. Thus, a major element of profitable equipment fleet management is the process of making the equipment replacement decision. This decision essentially involves determining when it is longer economically feasible to repair a broken piece of machinery. Thus, the three components of equipment management economic decision-making include:

- Equipment life: Determining the economic useful life for a given piece of equipment.
- Replacement analysis: Analytic tools to compare alternatives to replace a piece of equipment that has reached the end of its useful life.
- Replacement equipment selection: Methods to make a logical decision as to which alternative furnishes the most promising solution to the equipment replacement decision.

The economic life, alternative selection and replacement timing of equipment can be determined using replacement analysis. The methods can be categorized as either theoretical replacement methods or practical replacement methods. The theoretical replacement methods include:

- Intuitive method that can be used by owners of small equipment fleets.
- Minimum cost method that can be used by public agencies with large equipment fleets.
- Maximum profit method that can be used by construction contractors and other that own large equipment fleets.
- Payback period method, which is based in engineering economics and can be generally applied.
- Mathematical modeling method which furnishes a theoretical basis for developing the some of the equipment cost input for computer simulations used to optimize equipment fleet size and composition.

Determining the appropriate timing to replace a piece of equipment requires that its owner include not only ownership costs and operating costs, but also other costs that are associated with owning and operating the given piece of equipment (Nunnally 1987). These include depreciation, inflation, investment, maintenance, repair, downtime, and obsolescence costs.

- *Inflation:* Like all everything, equipment replacement costs are affected by economic and industry inflation. Economic inflation is defined as the loss in buying power of the national currency, and industry inflation is the change in construction costs due to long and short-term fluctuations in commodity pricing. For example, the Consumer Price Index is a widely reported inflation index that seeks to model the purchasing power of the US consumer dollar. It acts as a measure of economic inflation because it measures inflation across the general economy. The unprecedented rise in the price of steel during 2004-2005 would be an example of industry inflation because it is specific to the construction industry. While the inflation should always be considered in equipment replacement decision- making, its effects can be ignored if the equipment manager is using a comparative analytical method because it can be assumed to affect all alternatives equally (Lambie 1980).

- *Downtime:* Downtime is the time that equipment does not work due to repairs or mechanical adjustments (Douglas 1978). Downtime tends to increase as equipment usage increases. Availability, the portion of the time when equipment is in actual production or is available for production, is the opposite of downtime. For example, if the equipment's downtime is 10 percent, its availability is 90 percent. The downtime cost includes the ownership cost, operating cost, operator cost, and productivity loss caused by the loss of equipment availability. Productivity is a measure of the equipment's ability to produce at the original rate. The productivity decrease results in the cost increase of production because operating time of equipment should be extended or more equipment should be deployed to get the same production rate.

- *Obsolescence:* Obsolescence is the reduction in value and marketability due to competition from newer or more productive models (Lambie 1980). Obsolescence can be subdivided into two types: technological and market preference. Technological obsolescence can be measured in terms of productivity. Over the short term, technological obsolescence has typically occurred at a fairly constant rate. Market preference obsolescence occurs as a function of customers' taste. This is much less predictable, although just as real, in terms of lost value.

2.5 Replacement Analysis

Replacement analysis is a tool with which equipment owners time the equipment replacement decision. Through this analysis, the cost of owning the present equipment is compared with the cost of owning potential alternatives for replacing it. The following sections explain both theoretical and practical methods to accomplish this important equipment management task.

2.5.1 Theoretical Methods

Dr. James Douglas, Professor Emeritus at Stanford University, wrote the seminal work on this subject in his 1975 book *Construction Equipment Policy* (Douglas 1978). In that work he posited four different theoretical approaches to establishing an equipment replacement policy based on a rigorous and rational analysis of cost time and production. Douglas' theoretical methods for performing replacement analysis include the intuitive method, the minimum cost method, maximum profit method, and the mathematical modeling method. The value in these different approaches lies in the fact that each method can be applied to a different type of equipment owner. The intuitive method acts as a baseline against which other methods can be compared. It is simply the application of common sense to decision-making. The minimum cost method fits very nicely into a public construction agency's equipment management policy as the focus on replacing equipment at a point in time where the overall cost of operating and maintaining a given piece of equipment is minimized and hence the strain on the taxpayer is also reduced. The maximum profit method furnishes a model for construction contractors and other entities that utilize their equipment in a profit-making enterprise to make the replacement decision with an eye to their bottom-line. Finally, the mathematical modeling method fulfills a need for a rigorous analytical approach to this decision for those who will eventually utilize computer-based simulations to assist in optimizing equipment fleet size and composition for large equipment-intensive projects.

2.5.2 Intuitive Method

Intuitive method is perhaps the most prevalent one for making replacement decisions due to its simplicity and reliance on individual judgment. This method mainly depends on professional judgment or an apparent feeling of correctness to make replacement decisions. Equipment is often replaced when it requires a major overhaul or at times at the beginning of a new equipment-intensive job. In addition to these situations, availability of capital is often a decisive factor because no reserve has been built up in anticipation of replacement. However, none of these judgmental decisions has a sound economic basis to be used as a criterion for an orderly, planned replacement program.

Even though the example can be solved with the intuitive method, there is no rational answer for the economic life of the two types of trucks. That means since superficially that retaining the current trucks seem to make better in sense that they are only one year old and earning revenues at the same rate that the new trucks would earn. And as the potential reduction in maintenance costs does not seem to be particularly dramatic, the owner will probably choose to keep using the current trucks, which cost $5,000 less than proposed trucks. In this case, it is clearly seen that long-term maintenance and operating cost is overlooked by “professional judgment” (Douglas 1978).

2.5.3 Minimum Cost Method

Minimizing equipment costs is always an important goal for equipment owners. However, it is a paramount to public agencies that own large and small fleets of construction equipment, as they have no mechanism to generate revenue to offset their costs. To achieve this goal, the minimum cost method focuses on minimizing equipment costs based on not only cost to operate and maintain (O&M costs) a piece of equipment but also the decline in its book value due to depreciation. This is quite straightforward and furnishes a rational method with which to conduct the objective comparison of alternatives rather than the intuitive method’s professional judgment. In Douglas’ minimum cost method, the decision to replace equipment is made when the estimated annual cost of the current machine for the next year exceeds the minimum average annual cumulative cost of the replacement (1978).

2.5.4 Maximum Profit Method

This method is based on maximizing equipment profit. The method should be used by organizations that are able to generate revenue and hence profits from their equipment. It works very well if the profits associated with a given piece of equipment can be isolated and clearly defined. However, it is not often easy to separate annual equipment profit from entire project or equipment fleet profit. When it proves impossible, the minimize cost method should be used to make the replacement decision.

For the maximum profit method, the economic life of equipment is the year in which the average annual cumulative profit is maximized. This results in higher profits over a long period of time. The next issue in this method is to identify the proper timing of the replacement. This occurs when the next year's estimated annual profits of the current equipment fall below the average annual cumulative profit of the proposed replacement.

2.5.5 Payback Period Method

The payback period is the time required for a piece of equipment to return its original investment by generating profit (Peurifoy and Schexnayder 2002). The capital recovery is calculated using the total of net savings on an after-tax basis and the depreciation tax benefit disregarding financing costs. This method furnishes a metric that is based in time rather than money and allows the comparison of alternatives based on how long it takes for each possible piece of equipment to recover its investment. The payback period method is useful when it is hard to forecast equipment cash flow due to market instability, inherent uncertainty, and technological changes. This method springs from classical engineering economic theory and thus does not seek to identify the economic life of the equipment or economic effects beyond the payback period. Therefore, it is recommended that this method be used in conjunction with other analysis methods to furnish another slant on the view optimizing the equipment replacement decision.

2.5.6 Mathematical Modeling Method

The advent of computer application for construction management problems has furnished a simple and accurate means to solve problems related to complex interrelated systems containing dozens of input parameters. Modeling construction equipment systems is both appropriate and efficient as it allows the estimator or project manager the ability to control the level of complexity of the input and tailor the output to meet the needs of organization. Utilizing a computer model to furnish output to assist in making the all-important equipment replacement timing and selection decision allows for more than technical accuracy to be achieved. It also creates a continuity of institutional equipment management policy that can be carried from one manager to the next without a loss in institutional knowledge. It serves as a means to codify business decision-making based on a rigorous engineering economic analysis.

The model developed at Stanford University's Construction Institute in the 1970's is very simple conceptually and can be best described as a discounted-cash-flow model (Douglas 1978). It models revenues and costs as exponential functions. The latter are subtracted from the former and discounted to their present values to yield the present worth of profits after taxes.

A mathematical model is a function or group of functions comprising a system. Douglas specifies that the model must include the following factors (Douglas 1978).

- "Time value of money
- Technological advances in equipment (obsolescence)
- Effect of taxes (depreciation techniques, etc.)
- Influence of inflation, investment credit, gain on sale
- Increased cost of borrowing money
- Continuing replacements in the future
- Increased cost of future machines
- Effect of periodic overhaul costs and reduced availability"

Other factors important to revenue are increased productivity (productivity obsolescence), availability of machines (maintenance policy), and deterioration of the machine with age.

Additionally, in this model revenues and costs may be classified as follows:

- “Revenues from the service of the machines
- Maintenance and operating costs, including annual fixed costs, penalties, and overhead
- Capital costs, including interest on investment, depreciation charges, and interest on borrowed funds
- Discrete costs such as engine, track, and final drive overhauls
- Income and corporation taxes, considering depreciation method, recapture of income on sale, and investment credit” (Douglas 1978)

2.6 Public Agency Method: Texas Department of Transportation

The Texas Department of Transportation (TxDOT) has equipment replacement criteria that are based on age, usage (miles or hours) and estimated repair costs. TxDOT’s equipment fleet is quite large comprising approximately 17,000 units. This fleet is used to furnish in-house road maintenance and small construction on the state’s 301,081 total miles of roads and highways. With a fleet this large, the annual disposal program involves the replacement of approximately ten percent of the total fleet (TxDOT 2003). There are twenty-five subordinate districts in TxDOT that each manage their own portion of the TxDOT fleet. Evaluation of existing equipment for replacement is done at the district level subjectively using input from equipment, maintenance, and field personnel. This input is then combined with objective equipment performance data that includes age, miles (or hours) of operation, downtime, as well as operating and maintenance costs, to arrive at the final decision on which units to keep and which ones need to be replaced. The replacement decision is made one year before a given piece of equipment hits its target age/usage/repair cost level to allow sufficient time for the procurement of the replacement model.

In 1991, the department fielded the TxDOT Equipment Replacement Model (TERM) to identify fleet candidates for equipment replacement. The model was based on research of other DOT policies and an analysis of actual equipment costs incurred by TxDOT prior to that date. The logic of the model is expressed in the following terms:

> “…each equipment item reaches a point when there are significant increases in repair costs. Replacement should occur prior to this point. Ad hoc reports were developed and are monitored annually to display historical cost information on usage and repairs to identify vehicles for replacement consideration. From this historical information, standards/benchmarks for each criteria [sic] are established for each class of equipment.”(TxDOT 2003)

Input data for the TERM model comes from TxDOT’s Equipment Operations System (EOS), which has historical equipment usage and cost data dating back to 1984. EOS captures an extensive amount of information on all aspects of equipment operation and maintenance. Using the model’s logic is relatively simple. First, the EOS historical cost data is processed against three benchmarks for each identified equipment class on an annual basis. There are three criteria that are checked:

1. Equipment age,
2. Life usage expressed in miles (or hours), and
3. Inflation adjusted life repair costs expressed as a percentage of original purchase cost which has been adjusted to its capital value.

Next, when a given piece of equipment exceeds all three criteria, it is identified as a candidate for replacement. Finally, the owning district makes the subjective evaluation of the given item of equipment including downtime, condition of existing equipment, new equipment needs, identified projects, and other factors. A final decision on whether or not to replace is then made. TERM is not meant to replace the knowledge of the equipment manager. It does furnish a good tool to assist in the decision-making process.

2.7 Peer Reviewed Articles and Reports

Table 2.1 contains the information found from various journal articles and reports. The author, title, and short description are shown in the table for each article and report. The content pertains to the LCCA project and the various subsets within the project.

Table 2.1 Summary of Related Articles and Reports

Author	Title	Description/Significance
Aronson and Aronofsky 1983	Network Generating Models for Equipment Replacement	Utilizing Interactive Financial Planning Systems to generate equipment replacement models
Arditi and Messiha 1999	Life-cycle Cost Analysis in Municipal Organizations	LCCA in municipal organizations, main parameters utilized in LCCA calculations, and efficiency improvements of LCCA
Barringer 2005	How to Justify Equipment Improvements Using Life-cycle Cost and Reliability Principles	Utilizing LCCA, financial details, and alternatives to justify equipment improvements.
Fan et al. 2012	Equipment Replacement Decision Making: Opportunities and Challenges	Dynamic programming based solutions to solve equipment replacement optimization problem
Fan and Jin 2011	A Study on the Factos Affecting the Economical Life of Heavy Construction Equipment	Most important factors for economic life
Flintsch and Chen 2004	Soft Computing-Based Infrastructure Life-Cycle Cost Analysis Tools	LCCA tool to compute pavement maintenance and rehabilitation treatment selection and timing
FDOT 2009	Minimum Equipment Replacement Criteria	Replacement Techniques for varying equipment fleet
Furuta et al. 2003	Life-cycle Cost Analysis for Infrastructure Systems: Life-Cycle Cost vs. Safety Level vs. Service Life	Relationships among the minimization of Life-Cycle Cost (LCC), the optimal extension of structural service life, and the target safety level by using the multi-objective genetic algorithm
Kauffman et al. 2012	Criteria for Fleet Management: Identification of Optimal Disposal Points with the Use of Equivalent Uniform Annual Cost	A decision model developed to identify the optimal asset life for six equipment classes utilizing EUAC
Mitchell 1998	A Statistical Analysis of Construction Equipment Repair Costs Using Field Data & The Cumulative Cost Model	The purpose of this research was to identify a regression model that can adequately represent repair costs in terms of machine age in cumulative hours of use
Sabetghadam et al. 2012	Determining Economic Life of Earth Moving Equipment by Using Life-cycle Cost Analysis: Case Study	Determining the economic life of earth moving equipment using life-cycle cost analysis for operation and maintenance (O&M) costs. Economic engineering techniques were implemented for calculating time value of money, inflation and equivalent annual cost (EAC) of O&M.
Spitzley et al. 2004	Automotive Life-cycle Economics and Replacement Intervals	Two phase study of automobile ownership economics and replacement intervals
Weissmann and Weissmann 2003	A Computerized Equipment Replacement Methodology	The paper includes an economical methodology developed to assist equipment replacement at TxDOT
Wyrick and Erquicia 2008	Fleet Asset Life-cycle Costing with Intelligent Vehicles	A model was built to calculate economic life-cycles for four classes of passenger cars and three classes of motor trucks and truck tractors within Minnesota's Department of Transportation using data from the M4 information system
Zayed et al. 2002	Life-Cycle Cost Analysis using Deterministic and Stochastic Methods	Deterministic and stochastic models were developed for two DOT's, applied to paint deterioration on bridges.

Chapter 3
Research Analysis

Figure 3.1 displays the research steps that were employed for this study. This is the overall approach in the development of the stochastic model and economic life determination used to implement equipment LCCA.

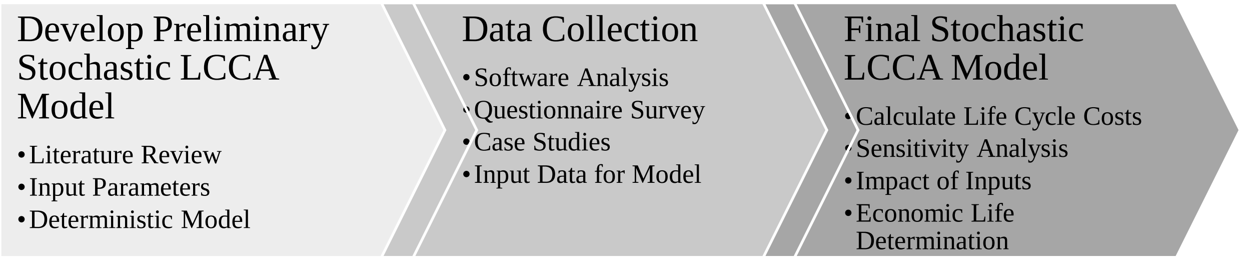


Figure 3.1 Research Steps

This chapter contains the stochastic model that was developed based on the Peurifoy and Schexnayder model (PSM) to calculate equipment life-cycle costs (2002). The usage of engineering economics is detailed to explain the economic life calculation based on the works of Park (2011). Additionally, the statistical F-test is defined because it was applied to determine the historical fuel price range in chapters 5 and 6.

3.1 Software Analysis

Currently available LCCA and fleet management software is extensive and diverse. Each platform has unique abilities for varying applications. Thus, this research conducted an analysis of 28 individual commercial products to differentiate between software packages. The purpose of the research effort was to determine if any existing packages would serve as viable software programs for use by Minnesota Local Road Research Board (LRRB) members. Each piece of software was analyzed on its features, capabilities and functionality. Based on this analysis a determination was made as to the viability of the software and its application to be able to satisfy the needs articulated in the request for proposals for the current project.

The primary research instrument was a formal content analysis of the features, capabilities and functions found in the marketing and specification literature available on the Internet. A content analysis can be used to develop “valid inferences from a message, written or visual, using a set of procedures” (Neuendorf 2002). Based on the equipment LCCA capabilities, the most viable software programs were Fleet Maintenance Pro, Fleet & Equipment Manager, FleetFocus, J. J. Keller's Maintenance Manager™ Software, and collectiveFleet™. The programs were found to have the highest capabilities to apply to LCCA of equipment fleet.

Table 3.1 depicts the results of the examined software programs premised on the life-cycle (LC) capabilities and the functionality for this project. The life-cycle capabilities were broken down into three categories; generates LC, could generate LC based on input data, and no viable inputs to compute LC. Next, the software was categorized into definitely functional, maybe functional, and not functional. The functionality is dependent on how applicable the software is to the project.

Table 3.1 Software Categorization and Utilization

Equipment Fleet Software	**Life-cycle (LC) Capabilities**			**Functionality**		
	Generates LC	**Could Generate LC (ie. Generates Input Data)**	**No Viable Inputs for LC**	**Definitely Functional**	**Maybe Functional**	**Not Functional**
Fleetmatics		x			x	
TMT Fleet Maintenance Software		x			x	
Fleet Maintenance Pro (by IMS)		x		x		
(AgileAssets®) Fleet & Equipment Manager™	x			x		
FleetFocus (by AssetWorks)	x			x		
J. J. Keller's Maintenance Manager™ Software		x		x		
collectiveFleet™	x			x		
MH Fleet by MH Equipment			x			x
Maintenance Connection			x			x
eMaint X_3		x			x	
Maintenance Coordinator		x			x	
Maintenance5000			x			x
Maintenance Pro		x			x	
Accruent 360Facility	x				x	
Infor EAM	x				x	
4Site			x			x
Guide TI			x			x
ManagerPlus			x			x
iMaint (Fleet)			x			x
Maintenance Assistant CMMS			x			x
MSI Service Pro Repair Center and Field Service			x			x
Fleetio			x			x
TATEMS			x			x

FleetCommander			x			x
Arsenault, Dossier Fleet Maintenance	x				x	
RTA Fleet Management		x			x	
FleetWave/RoadBASE			x			x
FleetWise VB			x			x

3.2 Benchmarking Survey

An online survey was distributed to benchmark the usage of LCCA and other parameters in agency fleet management programs. The questionnaire was developed from the literature review and assembled in accordance with the thirteen-point protocol established by Oppenheim (1992). The questionnaire design protocol is summarized as follows:

1. "Deciding the *aims* of the study."
2. General aims must then lead to a statement of specific aims, and these should be turned into *operationalized* aims; that is, a specified set of practical issues or hypotheses to be investigated.
3. [Developing] a statement of the *variables* to be measured, and … a set of questions, scales and indicators will have to be formulated.
4. Reviewing the relevant *literature*.
5. Preliminary *conceptualization* of the study, followed by a series of exploratory in-'depth' interviews; revised conceptualization and research objectives.
6. Deciding the *design* of the study and assessing its feasibility.
7. Deciding which *hypotheses* will be investigated.
8. Making these hypotheses specific to the situation… [i.e.] *operational*.
9. Listing the *variables to be measured*
10. Designing… the necessary *research instruments* and techniques.
11. Doing the necessary *pilot work* to try out the instruments,
12. Designing the *samplers*.
13. Drawing the sample: *selection of the people* to be approached." (Oppenheim 1992).

The survey was distributed by the City of Minneapolis to solicit a substantial amount of respondents. The questionnaire consisted of seven questions pertaining to equipment fleet management. The main objective of the survey was to gather information about input parameters, fleet data, budget information, and the decision-making processes for equipment. The survey results were found to be inconclusive based on the limited number of respondents and varied results.

3.3 Minnesota Case Study Analysis

The case study analysis for this research entailed three agencies: City of Eagan, City of Minneapolis, and Dodge County. The candidates were selected by the research team because they comprise three different levels of equipment fleet sizes and practices. Minneapolis is a large city; Eagan is a small city, and Dodge is a county. The case studies were conducted through structured interviews of the stakeholders in each agency. The objective of the case studies was to capture current practices and obtain data.

City of Eagan: Eagan utilizes a vehicle rating policy to determine repair and replacement decisions. The policy is based on the age of the vehicle and a rating system. Once the piece of equipment reaches a certain criteria, the vehicle is evaluated and reviewed to determine if a replacement is required. The repair decisions for pieces of equipment are related to the rating system as well. Pieces of equipment are repaired and maintained until they reach the minimum criteria for replacement.

City of Minneapolis: Minneapolis utilizes various methods and techniques to make major equipment fleet decisions. The utilization of the M5 software program, minimum cost method, and maximum number of hours are some of the procedures that aid in equipment decisions. The replacement evaluation has three major sets of information that are analyzed, including equipment life-cycle, equipment utilization, and business need of equipment. The repair process is specified by 50% to 60% of the original value of a piece of equipment. If a piece of equipment is above the optimal range of 50% to 60% of the initial value than the equipment is repaired. Although, utilization and agency need are vital in the repair and replacement decision process of equipment.

Dodge County: Dodge County does not utilize any formal decision making techniques to make equipment fleet decisions. The replacement process is based on the needs and allowable budget. Also, repairs for both light and heavy pieces of equipment are performed on an as- needed basis without any analysis of the economics of the repair.

The City of Minneapolis and the City of Eagan have the most dynamic equipment fleet replacement and repair policies. Dodge County's absence of overall structure within the equipment fleet management is mostly due to the lack of data recording and policy implementation. The City of Minneapolis and the City of Eagan are the most significant case studies for this research project. Therefore, the data for this research was chosen to be derived from the City of Minneapolis.

3.4 Equipment Data

Two options were evaluated when deciding on the data to use for the thesis. The first option was to use data gathered from MPWFSD and the second was obtaining data from the literature review. MPWFSD provided historical equipment fleet data dating back to 2009. Some of the data was able to be utilized in the thesis, such as service lives, acquisition costs, and salvage values. Although, not all the data was able to be exploited, such as the repair, maintenance, tire, tire repair, and depreciation cost. Regression analysis was performed to determine if the data could be employed but with the lack of historical data found this option to be inapplicable. The quality of the data from MPWFSD was not consistent and the data for the equipment had to be derived from the literature review.

3.5 Deterministic and Stochastic Equipment LCCA Model

The equipment LCCA model was built on components of the PSM and engineering economics. The model was employed in all the papers found in Chapters 4, 5, and 6. The model uses Equation 1 to determine the life-cycle costs of equipment.

$$LCC = Operating\ Cost + Ownership\ Cost \tag{1}$$

Where:
LCC = Life-cycle cost
Operating Cost = R&MC + FC + + TC + TRC
R&MC = Repair and maintenance cost
FC = Fuel cost
TC = Tire cost
TRC = Tire repair cost

The operating costs are based on Equations 2 through 6 (Peurifoy and Schexnayder 2002, Atcheson 1993). Equation 3 is utilized to calculate the repair and maintenance costs at a constant rate each year, while Equation 4 is used to calculate the repair and maintenance costs in a given year. Equation 4 is used in the economic life determination because it may be applied stochastically and increases as the machine ages.

$$Straight\text{-}line\ depreciation = (IC - SV)/N \tag{2}$$

Where:
IC = Initial Cost
SV = Salvage Value
N = Useful Life

$$R\&MC = (Repair\ factor)\ x\ (straight\text{-}line\ depreciation\ cost) \tag{3}$$

$$Years\ R\&MC = \left(\left(\frac{Year\ Digit}{Sum\ of\ Years\ Digit}\right) x\ Total\ repair\ Cost\right) + R\&MC \tag{4}$$

Where:
Year Digit = Year taken in ascending order
Sum of Years Digit = Sum of years' digit for the depreciation period
Total Repair Cost = Repair Factor x (List Price – Tire Cost)
Repair Factors given by Table 1

Table 3.2 Repair Factors (Atcheson 1993)

Equipment Type	Operating Conditions		
	Favorable	Average	Unfavorable
Scrapers-All Types	42%	50%	62%
Front-End Loaders-Rubber-Tired	45%	55%	62%
Haulers	37%	45%	60%
Bottom Dumps	30%	35%	45%
Crawler Tractors (by Application)			
Industrial	10%	25%	75%
General Contracting	40%	60%	80%
Quarrying	50%	85%	115%
Mining	70%	110%	150%

$$FC = (TF) \times (EF) \times (CF) \times (hp) \times (FP) \qquad (5)$$

Where:
TF = Time factor, based on the minutes of productivity within an hour utilized as a percent
EF = Engine factor, based on the percent of horsepower utilized
CF = Consumption factor, units of gal/fwhp-hr
hp = Engine horsepower
FP = Fuel price, units of $/gal

$$TRC = \%\ of\ TC \qquad (6)$$

The ownership costs for the model utilize Equations 7 and 8 (Peurifoy and Schexnayder 2002, Park 2011).

$$Ownership\ Cost = (IC - SV)A_P \qquad (7)$$

$$A_P = P[(i(1+i)^N)/((1+i)^N-1] \qquad (8)$$

Where:
IC = (list price – tire cost)
SV = % of the initial cost
N = Year of calculation
i = Interest rate
P = Present worth

A_P = *often shown as (A/P, i, N) (Park 2011)*

3.6 Equipment Economic Life Calculation

The economic life calculation was employed in Chapters 4 and 6. The EUAC takes into account the operating and ownership cost differently than the life-cycle cost calculations, shown in

Equations 9 through 12 (Park 2011). The ownership costs utilize the market value of the vehicle in a given year, displayed by Equation 11 (Park 2011). The operating costs must also be calculated, using Equation 10, on an annual basis in a given year to properly calculate the EUAC (Park 2011).

$$EUAC = LCC = Operating\ Cost + Ownership\ Cost \tag{9}$$

$$Operating\ Cost = (\textstyle\sum_{n=1}^{N} OC_n(P_F)(A_P) \tag{10}$$

$$Ownership\ Cost = (IC - S_N)A_P + i(S_N) \tag{11}$$

$$P_F = P[F(1+i)^{-N}] \tag{12}$$

Where:
$IC = (list\ price - tire\ cost)$
S_N = *Market value at the end the ownership period of N years*
N = *Year of calculation*
i = *Interest rate*
P = *Present worth*
F = *Future worth*

P_F = *often shown as (P/F, i, N) (Park 2011)*

3.7 Determining Historical Fuel Cost Sampling Ranges

The statistical F-test was applied to determine the historical fuel cost sampling ranges for Chapters 5 and 6. "The F-test evaluates the ratio of two variances as evidence to test the null hypothesis that two population variances are equal" (LeBlanc 2004). The data used for the F-test must be obtained from "unbiased study design" to create a population variance and a normal distribution (LeBlanc 2004). A major assumption of the test is that both populations under investigation have a normal distribution (LeBlanc 2004). The F-test utilizes Equation 13 to determine the ratio (LeBlanc 2004). This equation is based on the variances, S, within two populations.

$$F_{test} = S^2{}_1/S^2{}_2 \tag{13}$$

The larger of the two variances is placed in the numerator and the smaller in the denominator (LeBlanc 2004). The null hypothesis is true if the ratio is calculated to be 1.0, but the larger the ratio the "stronger the evidence that the two population variances are unequal" (LeBlanc 2004).

The F-test may be employed for a one or two-tailed test, with the p-value determining the significance of the data. The p-value represents the area on the right and left end of a normal distribution for a two-tailed test (LeBlanc 2004). If $p \leq 0.05$, "the probability associated with the random-variation explanation for the observed difference between the two sample variances is sufficiently low to reject this explanation" (LeBlanc 2004). Thus, if the p-value was greater than 0.05 the null hypothesis could be rejected and the two samples do not have significantly similar data. This logic will be employed to determine the appropriate choice, in months, for the historical fuel prices in Chapters 5 and 6.

Chapter 4
Impact of Fuel Volatility on Equipment Economic Life

4.1 Introduction

Equipment replacement decisions are critical to the success of public agency fleet management. If a piece of equipment is not replaced at the end of its economic service life, maintenance, repair, and fuel consumption costs will outweigh the value of its purpose (Jensen and Bard 2002), eating more than its fair share of the agency's limited operations budget. The issue is exacerbated by the fact that in most cases purchases of new equipment are made using the agency's capital budget, which typically requires approval from authorities in the fleet manager's chain of command (Gransberg et al. 2006). Therefore, if a machine is selected for replacement before it literally stops running, the fleet manager must be able to justify the purchase to those individuals. To do so, often requires a means to demonstrate the business case for buying a new machine rather than keeping the old one for another year.

The purpose of this chapter is to demonstrate the usage of a deterministic and stochastic model to quantify equipment life-cycle costs, economic life, and the impact of fuel volatility. The usage of commercial software will be employed to perform Monte Carlo simulations to calculate the stochastic life-cycle costs. Also, a sensitivity analysis will be performed to determine the impact of fuel fluctuation. An example using a dump truck from the MPWFSD equipment fleet will be used to demonstrate the fuel impact and difference between the deterministic and stochastic models.

Past research has provided a number of options to base the replacement decision on accepted financial terms that are easily understood by nontechnical personnel with limited fleet management expertise or experience. According to Fan and Jin (2011), the most widely accepted approach is called the "cost minimization method" and was first proposed by Taylor (1923). Schexnayder (1980) describes it as "the most appropriate analysis method" and proposes that it "yields an optimum replacement timing cycle and a corresponding equivalent annual cost." The method was adapted for public transportation agencies by Gillerspie and Hyde (2004). All three models use life-cycle cost analysis based on engineering economics to identify a point in a given machine's life where the cumulative cost of operating and ownership costs is at its minimum. Figure 4.1 graphically illustrates the basis of this theory. It shows that as a piece of equipment ages its capital value decreases while its operation and maintenance costs increase. The theoretical optimum service life is the point where cumulative costs are at the minimum and defines the economic life (Kauffman 2012).

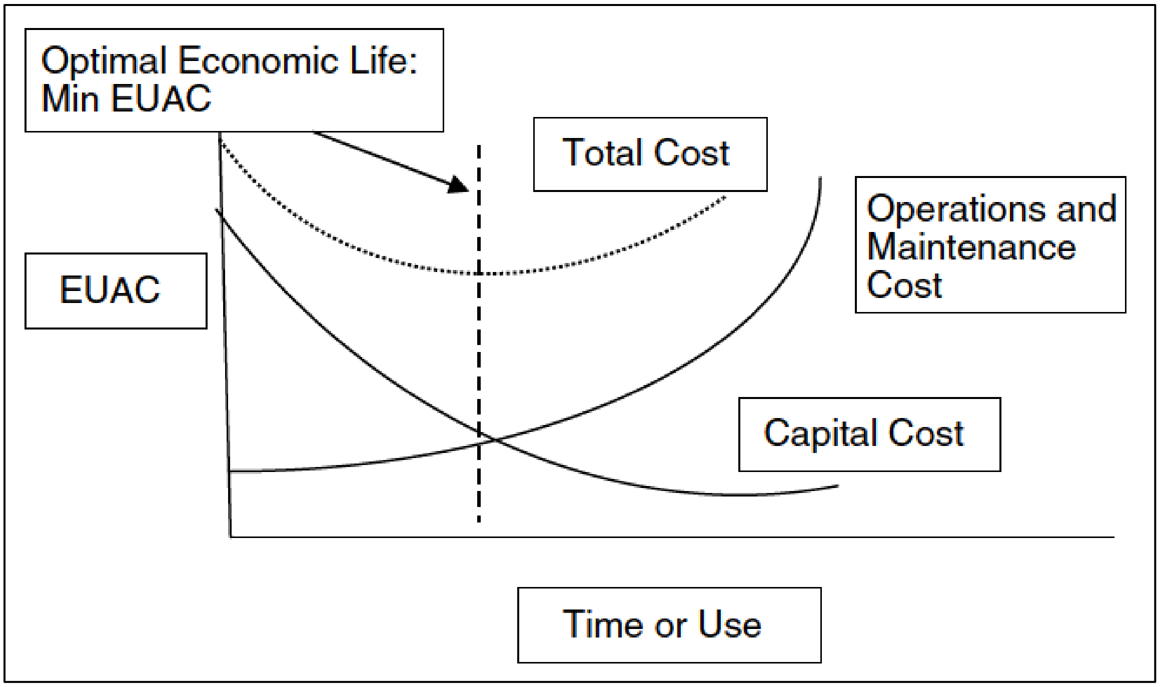


Figure 4.1 Economic Life of Equipment Based on the Cost Minimization Method

Each of the models described above are deterministic models that require the analyst to develop single values for each input variable. Thus, the economic life is really a snapshot based on the values used at the time of the analysis. While all models are merely mathematical analogs for real conditions, assuming a given cost for a significant variable like fuel prices makes the output used by the decision-maker highly dependent on the quality of the assumptions used in the analysis. Two key input variables are the interest rate used in the model and the values used for operating costs that are highly volatile, like fuel prices. According to Schexnayder (1980), "Because the analysis process incorporates [engineering economic] procedures it was necessary to establish the correct interest rate factor." The interest rate assumption issue was validated by several other studies (Pittenger et al. 2012, Gransberg 2009, Gransberg and Kelly 2008, Gransberg and Scheepbouwer 2010) and in each case the value of allowing the interest rate to be modeled as a stochastic value rather than a single assumption was demonstrated.

Diesel fuel prices are also an input variable that fluctuate within a wide range and are "considered as a significant input to the annual operating costs" (Richardson 2007). Therefore, understanding the impact of fuel prices is vital to optimize the life-cycle equipment fleet management decisions. Figure 4.2 depicts the monthly diesel fuel prices from January 2011 to March 2014 (U.S. Department of Energy 2014). The quantities shown in the figure were utilized for the creation of the stochastic model. The fuel prices are shown to fluctuate from three to four dollars with no certain pattern. Thus, this volatility impacts the life-cycle costs and equipment decisions substantially. The fluctuation in the fuel costs directly impacts the life-cycle costs of equipment because life-cycle costs will increase along with the fuel prices, directly impacting the calculated economic life of equipment. By allowing the fuel price input variable to vary over its historic range, a better life-cycle cost may be achieved. Consequently, making fuel costs a stochastic input will allow for a more realistic calculation in the economic life determination.

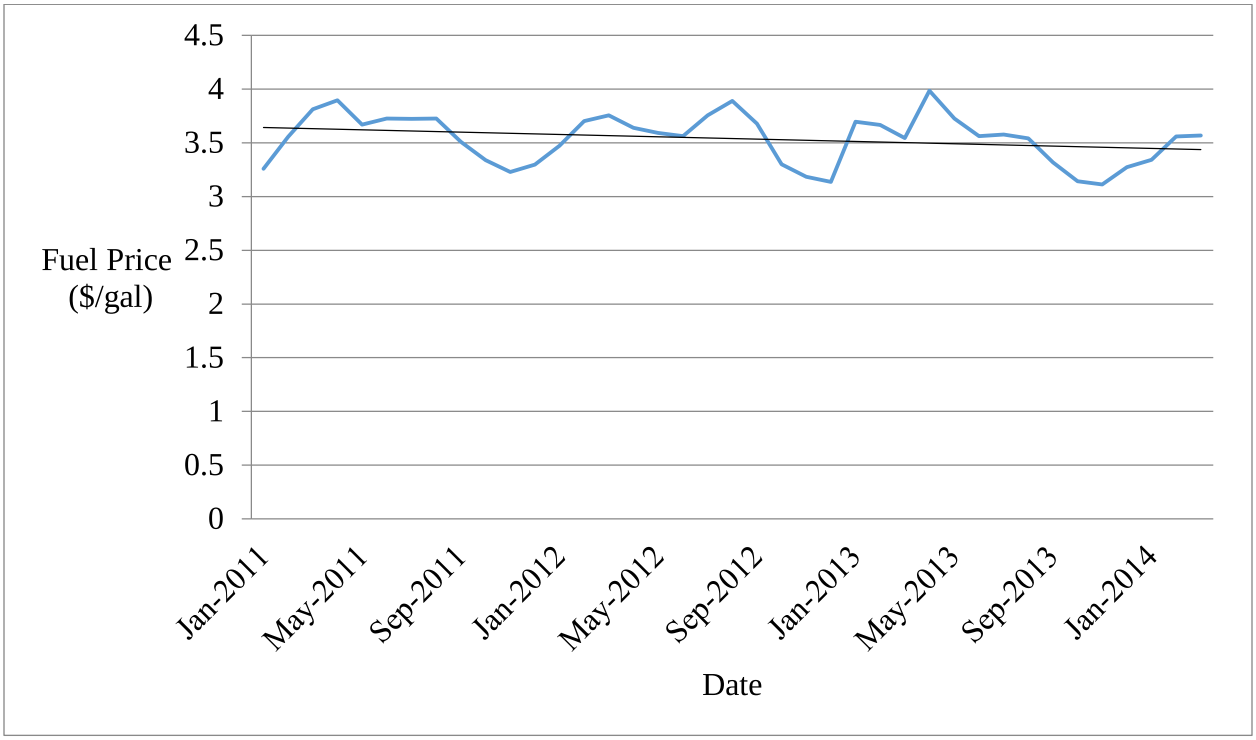


Figure 4.2 Historical Fuel Costs (U.S. Department of Energy 2014)

The Both models were developed using equipment ownership cost inputs prescribed by Peurifoy and Schexnayder (2002) and engineering economic life-cycle cost analysis (LCCA) to determine the economic life of equipment. The overall goal of the model was to optimize the life-cycle costs and the economic life of equipment for a pubic agency's fleet. To accomplish this, fuel volatility, interest rate fluctuation, and changing market values were made stochastic inputs for the model. Monte Carlo simulations were then run to produce probability distributions which allow the development of probability output.

The PSM was determined to be the most thorough and applicable method that could be applied in the development of the model. The method was adapted to apply to a public agency. For example, since public agencies don't pay sales or property taxes, that component was dropped in the formulation of the final deterministic model illustrated in the remainder of this chapter.

The input parameters utilized in the PSM to formulate the deterministic and stochastic models consist of solely cost variables. The costs are analyzed on an annual basis for all the parameters. Therefore, the final output for the life-cycle cost is an annual amount. Since most agency budgets are based on the fiscal year, using EUAC analysis provides output in a form that correlates with the purpose for conducting the analysis: to determine the required equipment replacement capital budget (Pittenger et al. 2012). The model uses Equation 1 to determine the life-cycle cost of equipment.

The operating costs for the deterministic and stochastic models are based on Equations 2 through 6 (Peurifoy and Schexnayder 2002, Park 2011). Equation 4 is used to calculate the repair and maintenance cost in a given year, while Equation 3 is utilized to calculate the repair and maintenance costs at a constant rate each year. The ownership costs for the deterministic and stochastic models utilize Equation 7 (Peurifoy and Schexnayder 2002).

For this study, Equation 5 used a 50 minute productive hour for the time factor, which equates to 0.83. Also, for Equation 5, 0.04 gal/fwhp-hr. was used for the consumption factor and one was used for the engine factor. For Equation 3, 37% was used for the repair and maintenance factor, and 16% was used for the tire repair factor in equation 6 (Peurifoy and Schexnayder 2002).

Figure 4.3 summarizes the stochastic LCCA model based on the adapted public sector version of the PSM. The stochastic inputs are the fuel costs within the operating costs and the interest rate utilized in the ownership costs. The deterministic inputs include the initial cost, salvage value, useful life, depreciation, tire cost, and tire repair costs.

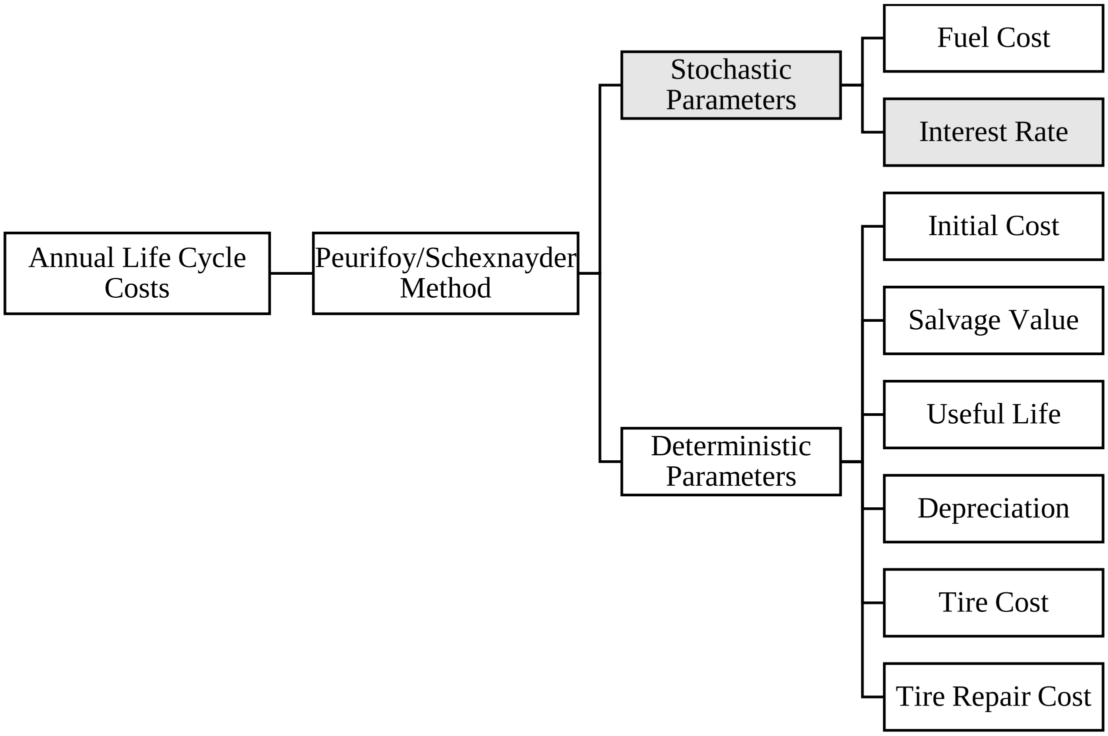


Figure 4.3 Flow Chart of LCCA Method

4.2 Optimal Economic Life-cycle Analysis

The determination of the economic life for equipment fleet is a critical component of the LCCA. The economic life or the optimal time to sell a piece of equipment requires the usage of EUAC calculations. To properly utilize EUAC the ownership costs and operating costs must be calculated on an annual basis in the correct year. The life-cycle costs must also be calculated, using Equation 9, on an annual basis in a given year to properly calculate the EUAC (Park 2011).

Additionally, Equations 10 and 11 are utilized for the operating and ownership costs within the EUAC (Park 2011).

Schexnayder (1980) found that in the private sector that “the proper interest rate is the cost-of-capital rate for the particular firm making the analysis.” Public agencies may or may not be able to determine its own cost-of-capital. However, if the replacement equipment will be funded by the sale of municipal bonds or some other financial instrument, then that rate would be appropriate and the need to evaluate life-cycle cost using a stochastic interest rate is no longer necessary.

The calculation of the EUAC is done over the entire life span for a piece of equipment. The lowest EUAC in a given year will be the optimal economic life. This will be the point in time in which the piece of equipment has the lowest combined operating and ownership costs.

Figure 4.4 summarizes the stochastic inputs that were utilized during the economic life calculations. Since the interest rate is a stochastic input all the calculations for the economic life employ a stochastic function. Additionally, the market value has been applied stochastically within the economic life calculation.

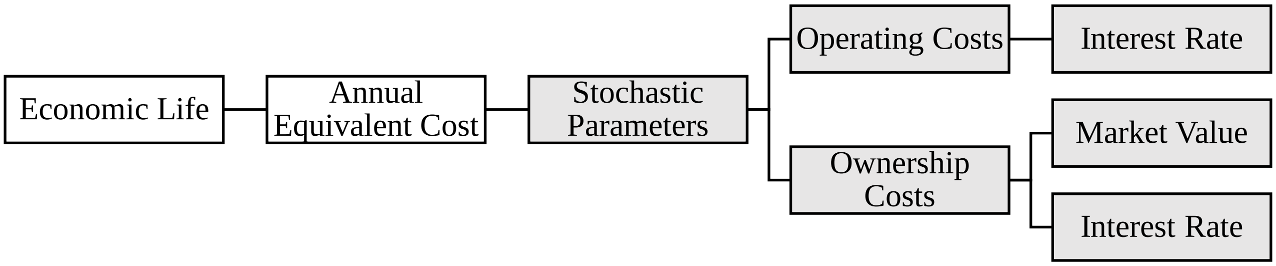


Figure 4.3 Equipment Economic Life Flow Chart

4.3 Results

The results contain the output from the deterministic and stochastic equipment example. A sensitivity analysis quantified the impact of fuel volatility associated with the LCCA. Additionally, the stochastic model is compared with the deterministic model to illustrate the discrepancies.

4.3.1 Deterministic Equipment Example

A 2002 Sterling LT9500 dump truck was employed in an example to demonstrate the deterministic method. The data for the dump truck was derived from the records furnished by MPWFSD. Table 4.1 shows the information that was used during the formation of the model for the dump truck. The dump truck was chosen for this demonstration it is a typical piece of equipment used in public agencies.

Table 4.1 Deterministic LCCA for the 2002 Sterling LT9500 Dump Truck

Parameters	**2002 Sterling LT9500 Dump Truck**
Initial Cost	$96,339
Annual Usage in Hours	1000
Annual Initial Cost (A_{IC})	$11,265
Tire Cost	$3,240
Salvage Value (12%)	$11,561
Annual Salve Value (A_{SV})	$1,456
Useful Life	14
Sum of Years Digit	105
Change in Market Value	10.60%
Interest Rate	7.38%
Depreciation	$6,056
Tire Repair Costs	$518
R&MC	$2,241
Fuel Price	$3.54/gal
Fuel Costs	$50,523
Total Operating Costs	$56,522
Ownership Costs	$9,809
Annual Life-cycle Cost	$66,330

Figure 4.5 depicts the plot of the annual life-cycle costs for the 2002 Sterling LT9500 dump truck versus varying fuel prices. As fuel prices increase the annual life-cycle cost of the dump truck increase. The figure shows the drastic impact of the fuel pricing to the life-cycle costs of a piece of equipment. This figure stresses the importance of accurately calculating the fuel costs to optimize the LCCA of equipment.

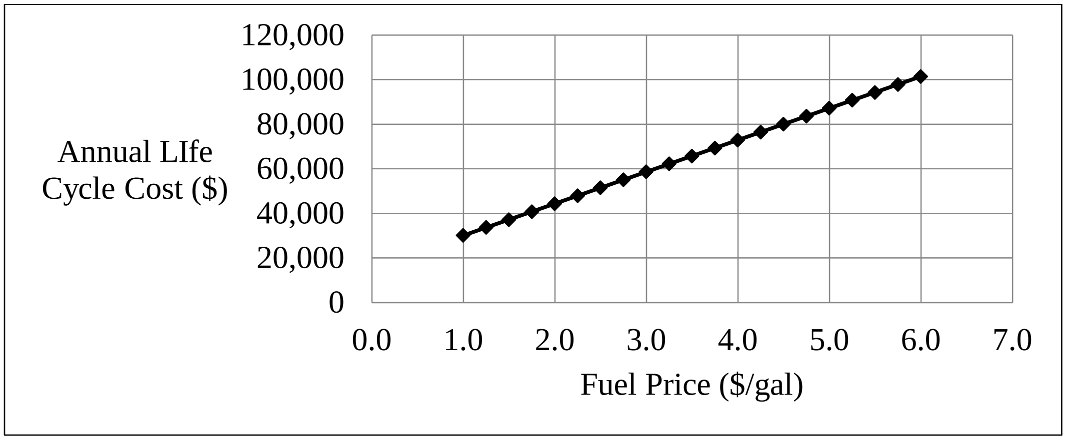


Figure 4.4 Fuel Impact to Equipment Life-cycle Cost

Figure 4.6 shows the optimal economic life of the dump truck. The plot consists of the annual costs vs. replacement age of the dump truck with the associated cost parameters. The economic life of the dump truck is depicted by the dashed line at year 12, this is the optimal point where the M&RC are increasing while the ownership costs are decreasing.

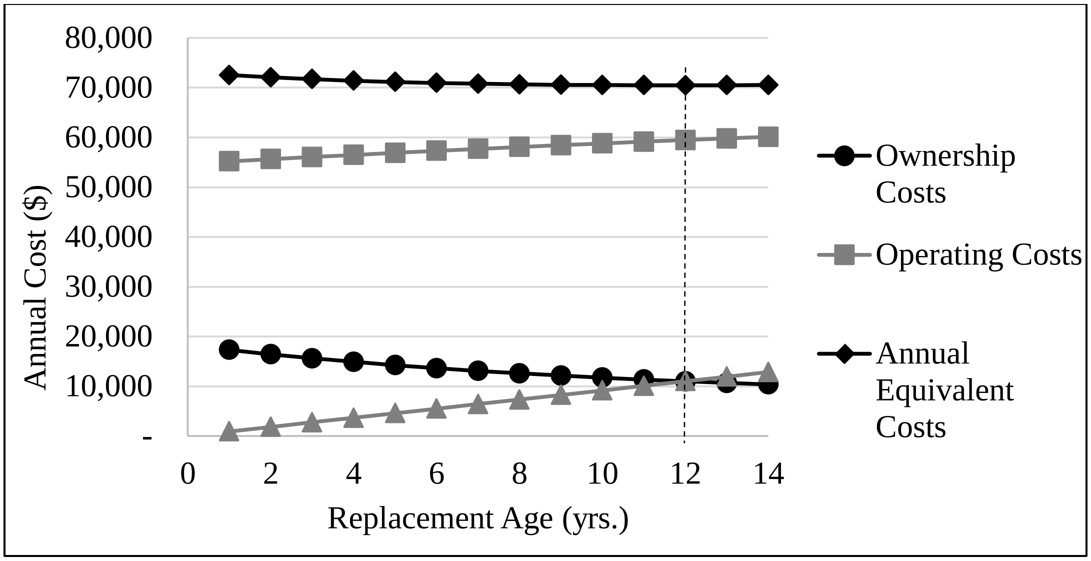


Figure 4.5 Economic Life of the Dump Truck Using Deterministic Model

4.3.2 Stochastic Equipment Example

The After the creation of the deterministic model, input values for the variables of interest are allowed to vary within their historic ranges in the stochastic model. The first priority was to create probability distributions for the stochastic inputs. Utilizing the 2002 Sterling LT9500 Dump Truck, the fuel prices, interest rate, and market value were made stochastic inputs. After creating distributions for the stochastic inputs, the stochastic model was created. The model ran Monte Carlo simulations to calculate the expected life-cycle costs. Table 4.2 summarizes the parameters of the stochastic model and the output. The fuel cost, interest rate, market value, and annual life-cycle costs are shown in Table 4.2 by the output that was calculated in the simulation. The market value was only utilized in the economic life calculations.

Table 4.2 Stochastic LCCA for the 2002 Sterling LT9500 Dump Truck

Parameters	2002 Sterling LT9500 Dump Truck
Initial Cost	$96,339
Annual Usage in Hours	1000
Annual Initial Cost (A_{IC})	$11,049
Tire Cost	$3,240
Salvage Value (12%)	$11,561
Annual Salve Value (A_{SV})	$1,300
Useful Life	14
Sum of Years Digit	105
Change in Market Value	10.78%
Interest Rate	7.05%

Depreciation	$6,056
Tire Repair Costs	$518
R&MC	$2,241
Fuel Costs	$50,813
Total Operating Costs	$56,812
Ownership Costs	$9,749
Annual Life-cycle Costs	$66,560

Figure 4.7 shows the model's sensitivity to both interest rates and fuel prices. This diagram depicts the relationship between the input values and the impact to the annual life-cycle costs. According to this simulation, the interest rate is shown to have a higher financial impact than the fuel prices in the calculation of the life-cycle costs for the dump truck.

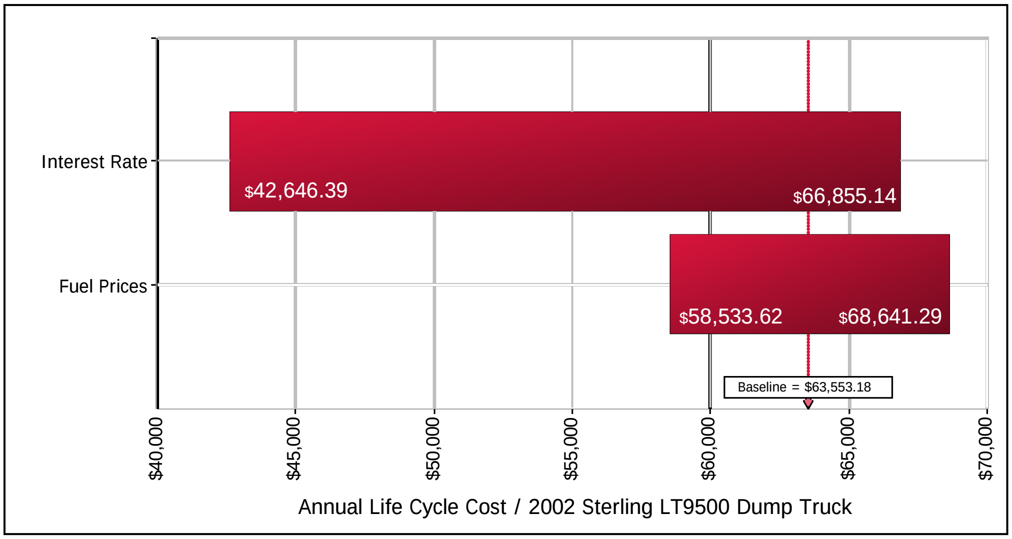


Figure 4.6 Input Sensitivity

Figure 4.8 shows the economic life of the dump truck using the output from the stochastic model. The yellow triangle specifies the optimal economic life (i.e. the replacement age) of the 2002 Sterling LT9500 Dump Truck. The figure shows that as the level of confidence increases both the EUAC and the economic life increase. With a 90% confidence, an economic life of fourteen years was determined, which is equal to the service life of the dump truck.

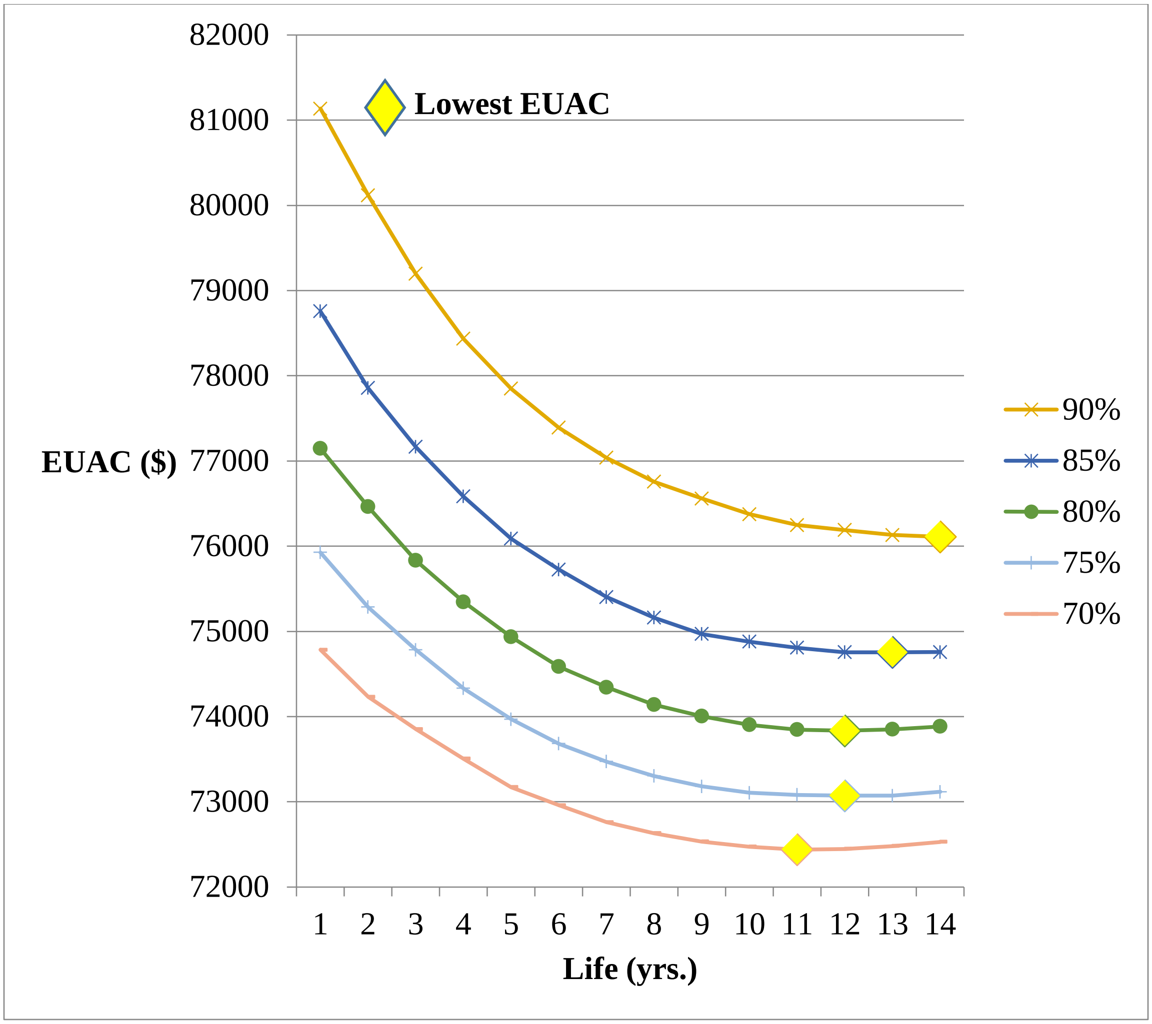


Figure 4.7 Economic Life of the Dump Truck Using Stochastic Model

Figure 4.8 provides the equipment fleet manager with information not available in a deterministic model's output. The range of 70% confidence to 90% confidence translates to an economic life between 11 and 14 years. Thus, if the equipment fleet manager wants to be completely sure that a piece of equipment has achieved its maximum economic life then the truck would be retained in the fleet for 14 years. However, that desire to get the most value out of each capital equipment investment would be offset by the potential loss if the equipment had been replaced with the most current technology at an earlier point in its service life. Therefore, the best way to interpret the output shown in Figure 4.8 is to use it a trigger point to begin a detailed evaluation of costs and benefit of retaining the current piece of equipment for another year or replacing it with a comparable new machine. Taking this approach to decision-making would then trigger the fleet manager to begin an annual retain-replace analysis starting in year 11 and repeat it in years 12 and 13 with a replacement being occurring in year 14 if the analysis did not show it should be replaced in a previous year.

Implementing the proposed model would then allow the fleet manager to be able to forecast several years in advance the need for equipment replacement for the entire fleet and therefore be able to generate a rational annual equipment replacement budget for the agency over a period of 3 to 5 years with relatively increased confidence that the decisions can be justified.

4.3.3 Comparison of the Models

The change from deterministic to stochastic modeling is evident in the fuel costs and life-cycle costs displayed in Table 4.3. The fuel cost for the deterministic model used a unit price of $3.54/gal. While the stochastic model used a statistic distribution of the historical fuel costs. Additionally, the deterministic model utilized a fixed interest rate which the stochastic model did not. Based on the confidence levels the life-cycle costs differ. For example, the stochastic model determined a life-cycle cost of $68,467 with an 80% confidence, and the cost only increases as the confidence increases. Thus, the costs are separated by a larger quantity when the confidence levels are introduced.

Table 4.3 Comparison of Deterministic Model vs. Stochastic Model

Parameters	Deterministic	Stochastic
Deterministic Life-cycle Costs (LCC)	$66,330	-
95% Confidence of the LCC	-	$70,631
90% Confidence of the LCC	-	$69,705
85% Confidence of the LCC	-	$69,040
80% Confidence of the LCC	-	$68,467

The economic life of the dump truck was determined to be 12 years for the deterministic model. Whereas, the stochastic model demonstrated that the truck's economic life could be as much as 14 years. The value added by the stochastic analysis directly relates to public agency funding constraints discussed in Chapter 2 and provides quantified justification for potentially retaining a piece of equipment past the point identified in the deterministic model.

4.4 Conclusions

Deterministic and stochastic models were developed to calculate life-cycle costs and the optimal economic life of equipment. An example was demonstrated, using a dump truck to show the usage of the models and to determine the impact of fuel volatility. This was achieved by applying the PSM and basic engineering economics principals to find the optimal life-cycle cost solutions. The deterministic and stochastic models were than compared to examine the impact of the inputs.

When the stochastic model was applied to a piece of equipment, the sensitivity of the model's input variables were determined. The interest rate was found to have a greater impact on economic life output than fuel prices. Thus, the assumption selecting an arbitrary interest rate with which to evaluate all alternatives is faulty. One author describes the issue in this manner: "engineering economics textbooks have over-simplified the [LCCA] process…" (Gransberg and Scheepbouwer 2010).

The confidence levels associated with the stochastic model demonstrates a difference from the deterministic calculations. The deterministic model determined an economic life of 12 years while the stochastic model determined a range from 11 to 14 years, with 14 years being the most certain time frame. Once again, this proves that allowing fuel prices to range probabilistically in the analysis provides a means to quantify the certainty of the equipment replacement decision.

To put the above analysis in perspective of the public agency fleet manager, the interest rate chosen for the calculation is less important that the impact of fuel prices because the funding for the replacement alternative comes from the capital expense budget and the funding for fuel consumption comes from the agency's operations and maintenance budget. Additionally, many agencies have mandated interest rates that must be used in LCCA (Gransberg and Scheepbouwer 2010), which effectively forces the fleet manager to use a deterministic rate in order to receive approval to purchase the new equipment. Therefore, the results argue that the fuel price is probably the most critical input when determining the economic life of equipment since fuel will be funded from the operations and maintenance budget. The capital budget will either contain funding for a purchase or not, but the operations and maintenance budget must purchase the fuel that the equipment fleet needs for the given fiscal year. Hence, with the increasing cost of diesel fuel, the issue of upgrading to a more fuel-efficient model of equipment using the latest technology has become an increasingly important element of the replace/repair decision. Therefore, employing the stochastic inputs allows the analyst to determine the impact of the most volatile component of the model.

Chapter 5

Equipment Life-cycle Cost Analysis Input Variable Sensitivity Analysis Using a Stochastic Model

5.1 Introduction

Deterministic equipment LCCA models are employed to calculate various costs associated with equipment fleet. The input parameters utilize a fixed quantity to calculate the costs, fluctuation within an input is not taken into account. “In the deterministic model, each variable has a single “best” value that is used” (Gransberg et al. 2006). This may not reflect the actual costs associated with a piece of equipment, especially with volatile inputs. A stochastic model is employed for more accurate analysis. “Stochastic model predicts a set of possible outcomes weighted by their likelihood or probabilities” (Pinsky and Karlin 2011).

This chapter will illustrate the usage of an equipment LCCA model with a large number of the input variables being stochastic. The usage of a sensitivity analysis will identify the most vital input parameters to the model. MPWFSD equipment fleet data was applied to the study to use actual information from a public agency. Therefore, managers will be able to make equipment fleet decisions with the identification of the essential equipment characteristics. These decisions are especially critical to public agencies because they must minimize the costs of owning, operating, and maintaining equipment due to the lack of profit motive within public agencies equipment replacement policies (Gransberg et al. 2006).

Sensitivity analysis will be applied to the stochastic model using the Monte Carlo simulations. The analysis will determine the most sensitive inputs to the model by highlighting “the parameters that have the greatest influence on the results of the model” (McCarthy et al. 1995). Additionally, the analysis will allow for a more accurate depiction of the actual life-cycle costs; “sensitivity analysis can highlight model parameters that ought to be the most accurately measured so as to maximize the precision of the model” (McCarthy et al. 1995).

Most common stochastic models utilize Monte Carlo simulations (Gransberg et al. 2006). Monte Carlo simulations use “random samples from known populations of simulated data to track a statistic’s behavior” (Mooney 1997). The first step in creating a simulation would be to define the analysis data, more importantly the deterministic and stochastic variables (Mooney 1997). The next step is to create probability distributions for the stochastic or random variables. Next, an output variable must be created using a logarithm or mathematical equation utilizing the stochastic functions. Then the output variable is utilized to run the Monte Carlo simulations.

The common assumption is that repair and maintenance costs are the most influential parameter to equipment life-cycle costs (Peurifoy and Schexnayder 2002). This is due to the uncertainty associated with the cost item. Equipment may need routine maintenance, minor repairs, or complete overhauls whose costs are hard to predict for each type of equipment. Additional influential cost parameters to equipment life-cycle costs are depicted in Table 5.1.

Table 5.1 Breakdown of Machine Cost over its Service Life (Peurifoy and Schexnayder 2002)

Cost Parameter	Percentage of Total Cost (%)
Repair	37
Depreciation	25
Operating	23

5.2 Input Data

The following input variables that were portrayed as stochastic in the model: annual usage, engine factor, time factor, fuel price, interest rate, salvage value, tire repair factor, repair and maintenance cost, and tire cost. Each was selected to determine the uncertainty associated with the inputs and to determine the impact of each parameter on the model.

The engine factor is a parameter that affects fuel efficiency and fuel cost. Engine factors "depend on the engine horsepower, engine type, fuel type, and operating conditions" (Atcheson 1994). Atcheson (1994) categorizes operating conditions in three degrees: low, medium, or high. Under standard conditions a gasoline engine will operate with a 0.06 gal/fwhp-h, and a diesel engine will operate with a 0.04 gal/fwhp-h (Peurifoy and Schexnayder 2002). These are deterministic factors utilized in the model, but an engine factor was made stochastic to take into account the variations in operating conditions and equipment type.

MPWFSD portrays salvage values as a percentage of capital cost and the analysis uses this value to maintain consistency with the other data provided by the MPWFSD. MPWFSD maintains equipment fleet data on a variety of both construction equipment and administrative vehicles. Administrative vehicles and construction equipment use percentages for salvage values shown in Table 5.2. The percentages for the construction equipment only reflect values from loaders, dump trucks, and bobcats. The administrative vehicles' salvage values are from sedans and pick-ups from the fleet data.

Table 5.2 Salvage Values used for the Stochastic Model

Equipment Type	Salvage Values Utilized
Administrative Vehicles	10%, 12&, 15%, 20%, 25%
Construction Equipment	5%, 10%, 12%, 15%, 30%

The tire repair factor is associated with the tire repair cost. Tire costs include the replacement of the tires, while tire repair cost takes into account the repairs on the tires (Gransberg et al. 2006). The tire costs were obtained from dealers within Minnesota to provide an accurate depiction of the costs associated with MPWFSD's equipment fleet. The tire repair factors and annual usage for the stochastic model were identified in the literature review ranging from 12% to 16% (Gransberg et al. 2006, Atcheson 1993, Peurifoy and Schexnayder 2002). Additionally, the annual usage for the equipment was determined from the literature review, ranging from 1,560 hours to 2,600 hours (Atcheson 1993, Peurifoy and Schexnayder 2002).

The interest rate was characterized by a range of values found in the literature plus Minnesota municipal bond rates to establish a relationship with a public agency. Table 5.3 displays the source for each of the interest rate values utilized within the stochastic model.

Table 5.3 Interest Rate Sources for the Stochastic Model

Source	Interest Rate (%)
Kauffman et al. 2012	3
Atcheson 1993	8
Gransberg et al. 2006	6.75
Peurifoy and and Schexnayder 2002	8
Park 2011	12, 16
Caterpillar Inc. 2011	16
Minnesota Municipal Bonds (May 20, 2014)	3, 3.38, 2.5, 4, 5
Sabetghadam 2012	12

The stochastic equipment LCCA model was developed using equipment cost inputs prescribed by the Peurifoy and Schexnayder (2002) and engineering economic. The equipment costs were calculated on an annual basis using Equations 1 through 8. Equation 1 was employed to determine the annual life-cycle costs, and Equations 2 through 8 were employed to calculate the operating and ownership costs.

The stochastic model that was employed for this research includes nine stochastic inputs that range from direct quantities to factors within an equation. Table 5.4 shows the stochastic parameters that were applied for the analysis. The only values that utilized a deterministic variable were the initial cost, useful life, depreciation, and fuel consumption factor.

Table 5.4 Stochastic Inputs Range of Values

Parameter		Range of Values
Fuel Price*	Gas	\$2.91 - \$3.96
	Diesel	\$3.38 - \$4.13
Interest Rate		3% - 16%
Time Factor		25% - 100%
Engine Factor		17% - 100%
Salvage Value		5% - 30%
R&MC		35% - 80%
Tire Cost		Varied by Machine
Tire Repair Cost		12% - 16%
Annual Usage		1560hrs. - 2600hrs.
*\$/gal.		

The selection of historical fuel data is a significant issue within the stochastic model to ensure accuracy. Applying an abundance of historical fuel data may disrupt the model and take into account economic influences that are not present in this research. Also, the selection of only a few data points may not correctly quantity the fuel prices. Thus, finding the most appropriate time period for the data is vital to the accuracy of the model.

The historical fuel data was Accessed every sixth month to determine a variation within the data points. The F-test and the P-value determination were utilized to define the most appropriate time period for the fuel data. Table 5.5 and 5.6 show the mean, standard deviation, variance, and P-value for each specified month for gasoline and diesel fuel prices. The P-value is used to determine an appropriate time period for the fuel price sample population by calculating the significance to the null hypothesis. "P-values simply provide a cut-off beyond which we assert that the findings are 'statistically significant' (Davies and Crombie 2009). The null hypothesis is the assumption that there is no difference between two sample populations (Davies and Crombie 2009).

Table 5.5 Historical Diesel Prices with Statistical Analysis

Parameters	Number of Months									
	6	42	43	44	45	46	47	48	54	60
Mean	\$3.89	\$3.93	\$3.93	\$3.92	\$3.91	\$3.90	\$3.88	\$3.86	\$3.77	\$3.67
Std.	\$0.06	\$0.10	\$0.10	\$0.11	\$0.14	\$0.17	\$0.20	\$0.23	\$0.35	\$0.45
Variance	\$0.00	\$0.01	\$0.01	\$0.01	\$0.02	\$0.03	\$0.04	\$0.05	\$0.13	\$0.20
P-Value (%)			94.22	51.64	5.52	0.15 < 5%	0.00	0.00	0.00	0.00

Table 5.6 Historical Gasoline Prices with Statistical Analysis

Parameter	Number of Months									
	6	42	43	44	45	46	47	48	54	60
Mean	\$3.66	\$3.63	\$3.63	\$3.62	\$3.61	\$3.60	\$3.58	\$3.57	\$3.49	\$3.41
Std.	\$0.11	\$0.18	\$0.17	\$0.18	\$0.19	\$0.21	\$0.23	\$0.25	\$0.34	\$0.40
Variance	\$0.01	\$0.03	\$0.03	\$0.03	\$0.04	\$0.04	\$0.05	\$0.06	\$0.11	\$0.16
P-Value (%)			93.79	87.40	58.12	29.63	9.64	2.5 < 5%	0.00	0.00

Tables 5.5 and 5.6 show that the cut-off point where adding additional data points does not increase the statistical significance of the sample in the 45th month for diesel and 47th month for gas. By convention, five percent significance was applied to the study to determine the statistical significance (Davies and Crombie 2009). Thus, any P-value less than five percent is found "unlikely to have arisen by chance and we reject the idea that there is no difference between the two treatments (reject the null hypothesis)" (Davies and Crombie 2009). For the diesel prices the 45 month time period was found to be the cut-off range, and for the gasoline prices the 47 month time period was found to be the most significant. Consequently, the 45 and 47 month range were applied for the fuel analysis.

5.3 Results

Various types of equipment from the MPWFSD equipment fleet were employed in the stochastic model to determine the most sensitive variables. The following pieces of equipment were applied to the model; 2008 Ford F250, 2007 Chevrolet Impala, 2006 Ford Escape XLT, 2005 Sterling LT9513 tandem dump truck, 2006 Volvo L90F Art loader 2.5 yard, and a 2006 Volvo L150E Art loader 5 yard. The Chevrolet Impala, Ford F250, and Ford Escape are grouped into the administrative vehicles, and the Sterling dump truck and the two Volvo loaders are grouped as construction equipment.

The determination of the most sensitive inputs to the stochastic model utilized a sensitivity analysis within commercial software. Figure 5.1 displays the sensitivity analysis output for the 2008 Ford F250. The range in the values is represented in dollar amounts, with the wider the range the more volatile the input. The sensitivity of each variable is related to the mean of the annual life-cycle cost associated with the piece of equipment. For the 2008 Ford F250 the time factor was the most fluctuating input to the stochastic model with a range from $9,645 to $35,495. Therefore, just the time factor variable could make the annual costs vary by about $25,000.

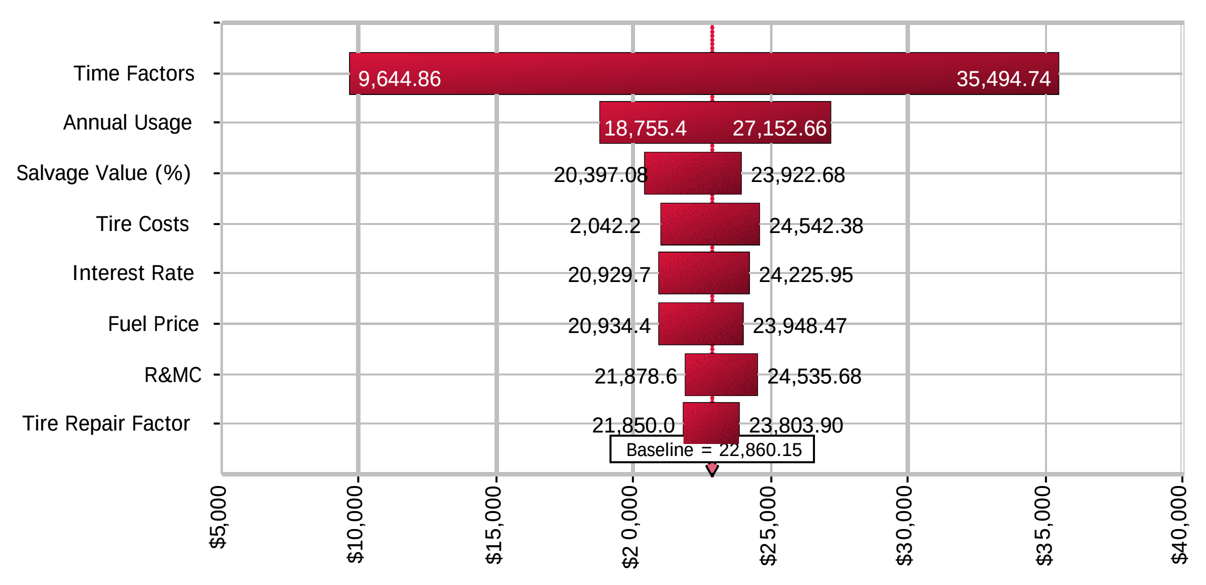


Figure 5.1 Sensitivity Analysis for the 2008 Ford F250

Next, ranking system was employed to further examine the sensitivity analysis. Since there are a total of nine input variables for the construction equipment and eight variables for the administrative vehicles, each stochastic input will be ranked with one being the most sensitive and eight or nine being the least sensitive. This will allow the determination of the most sensitive variable to each piece of equipment; Table 5.7 displays the ranking for each machine.

Table 5.7 Sensitivity Ranking of each Variable within the Sensitivity Analysis

Input Variable	Piece of Equipment					
	2008 Ford[1]	2007 Chevrolet[2]	2006 Ford[3]	2005 Dump Truck[4]	2006 Volvo Loader[5]	2006 Volvo Loader[6]
Time Factor	1	1	1	2	2	1
Engine Factor	N/A	N/A	N/A	3	1	2
Interest Rate	5	4	5	1	4	4
Salvage Value	3	6	4	4	5	5
Annual Usage	2	2	2	9	6	9
Tire Costs	4	7	8	7	3	3
Tire Repair Costs	9	8	6	8	9	8
R&MC	8	5	7	6	7	7
Fuel price	7	3	3	5	8	6
[1]F250, [2]Impala, [3]Escape XLT, [4]Sterling LT9513, [5]L90F Art 2.5yd., [6]L150E Art 5yd.						

The ranking from each piece of equipment was averaged to find the most significant input factors. Table 5.8 contains the results from the average ranking for each stochastic input factor. These results are directly related to Table 5.7 and the sensitivity analysis that was performed.

Table 5.8 Ranking of the Input Variables from the Sensitivity Analysis

Input Variable	**Average Ranking of Input Variables**
Time Factor	1.2
Engine Factor	1.7
Interest Rate	4.2
Salvage Value (%)	4.5
Annual Usage	4.3
Tire Costs	5.2
Tire Repair Costs	7.8
R&MC	7.0
Fuel price	6.0

The results from Table 5.7 and 5.8 indicate that the time and engine factors are the most sensitivity variables to the stochastic life-cycle cost model for the construction equipment. The two factors are utilized in the same calculation and have a major impact on the life-cycle costs. For the administrative vehicles, the time factor and annual usage are the most sensitive to the model. Once again, the annual usage is applied in the same calculation as the time factor so they may influence each other. The time factor is vastly unknown due to variability with idle time and productivity. Thus, the engine and time factors displayed significant uncertainty due to such things as downtime and harsh working conditions.

The percent of total horsepower used, which is a component of the engine factor, may vary extensively from project to project within an agencies fleet. Also, the amount of total horsepower may vary depending on the usage of a machine. For example, if a dump truck is hauling heavy material this may cause more usage of the engine horsepower. Thus, the uncertainty associated with the input is considerable and is evident in the sensitivity analysis.

The two sedans displayed inputs that were closely related when ranking the sensitivities. However, the repair and maintenance costs were one of the least influential inputs to the model for all pieces of equipment. The results contradict the common assumption about repair and maintenance costs, "repair cost normally constitutes the single highest operating cost" (Atcheson 1993). Also, both of the Volvo loaders exhibited the tire costs as the third most influential input due to the relative high cost of tires for that piece of equipment when compared to the cost of sedan and dump truck tires.

Within the stochastic model, fuel costs are a function of annual usage, fuel price, engine factor, horsepower, time factor, and fuel consumption factor. Thus, the size of the engine and the time factor directly impact fuel costs and are related to fuel efficiency, because the consumption factor goes down as an engine's fuel efficiency increases. The engine and time factors are variables that a fleet manager may not directly control. Therefore, applying the inputs deterministically would allow the analysis of the other variables that managers may influence.

Table 5.9 displays an example of the impact that the engine and time factor with the annual usage have on equipment costs. In this example the fuel costs were calculated with varying horsepower, either 400 hp or 300 hp, and a varying combined factor consisting of the engine and time factor. Additionally, the fuel consumption factor and annual usage were applied uniformly for all the pieces of equipment. The results displayed by Machine B and D show that the fuel costs are drastically lower when applying a piece of equipment with less horsepower and lower combined factor consisting of the engine and time factor. Therefore, this further reinforces the importance of engine efficiency and life-cycle costs.

Table 5.9 Fuel Consumption Factor Comparison of Engine Efficiency

Fuel Cost ($/gal)	Equipment A[1]	EquipmentB[2]	EquipmentC[3]	EquipmentD[4]
$3.00	$48,000	$24,000	$36,000	$18,000
$3.50	$56,000	$28,000	$42,000	$21,000
$4.50	$64,000	$32,000	$48,000	$24,000
$4.50	$72,000	$36,000	$54,000	$27,000
$5.00	$80,000	$40,000	$60,000	$30,000
[1]400hp 0.5 factor, [2]400hp 0.25 factor, [3]300hp 0.5 factor, [4]300hp 0.25 factor				

5.4 Conclusions

Based on the results obtained from the Monte Carlo simulation, the time and engine factors were the most sensitive input variables to the equipment taken from the MPWFSD. The uncertainty with each factor is a major reason why the discrepancy occurred during the simulations. The sensitivity of the time and engine factors is not vital for a fleet manager since they cannot control the input of each element. Thus, each factor has a major impact on the LCCA but is not significant in equipment fleet decision concerning repairs and overhauls.

Equipment fleet managers may use the sensitivity results of the time and engine factor to determine equipment purchases. When deciding to replace a piece of equipment, engine efficiency should be a high priority due to the costs associated with the time factor, engine factor, and annual usage. Equipment that is able to perform well in all work conditions has a lower horsepower, and high engine efficiency should be considered.

For a public agency's equipment fleet manager the influence of the time and engine factors are not essential to fleet decisions. Idle time, working conditions, and engine efficiency are not variables that an equipment fleet manager can influence. Thus, employing the inputs as deterministic is the most practical determination. Such inputs as the repair and maintenance uncertainty are more vital to equipment decisions because the fleet manager can control those inputs more closely. These inputs should remain stochastic within the model to optimize the results. Consequently, the study identified variables to be deterministic and stochastic within an equipment LCCA model to aid public agency equipment fleet managers.

Chapter 6

Optimizing Public Agency Equipment Economic Life using Stochastic Modeling Techniques

6.1 Introduction

A public agency's equipment fleet consists of many different types of machines, for example the TxDOT Fleet ranges from compact sedans to motorized ferries (TxDOT 2008). Also, many agencies have "a uniform process in its approach to determine equipment replacement criteria" (TxDOT 2008). The methods for determining a replacement age are based on deterministic approaches that don't account for uncertainty with inputs that affect equipment LCCA (West et al. 2013). To take into account uncertainty, a stochastic approach has been employed to define a viable economic life of equipment within a public agency.

Many studies have been completed on equipment replacement optimization. A study using dynamic programming, based on the Bellman and Wagner approaches, was employed to determine the replacement age of vehicles (Fan et al. 2013). The Florida Department of Management Services uses a minimum equipment replacement standard to determine the replacement age of the equipment (2009). Fan and Jin applied a decision tree to determine the significant factors in the economic life determination of construction equipment (2011).

Research completed by Mitchell applied cumulative cost models to aid managers with determining repair costs for equipment (1998, 2011). His work focused on the private sector and using regression models to analyze the repair costs for equipment fleet. Also, the use of regression models was employed by Ghadam to determine the economic life of earth moving equipment (2012). Soft computing methods using LCCA tools were applied to transportation infrastructure management to aid in management decisions (Flintsch and Chen 2004). Additionally, LCCA for infrastructure systems was established with the optimal service life and safety level characteristics (Furuta et al. 2003).

The utilization of EUAC was employed to determine the optimal disposal age, or economic life, of six equipment classes for the North Carolina Department of Transportation (DOT) (Kauffman et al. 2012). The research included the following varied input parameters to the EUCA model; interest rate, initial market value (MV), MV decline rate, mileage decline, cost per mile, and annual cost increase rate (Kauffman et a. 2012). A sensitivity analysis was performed for each of the varied parameters and was evaluated based on mean, standard deviation, coefficient of variation, and magnitude of the slopes for each response line (Kauffman 2012).

Barringer performed Monte Carlo simulations to calculate life-cycle costs for American petroleum institute (API) pumps (1997). The work included failure costs found by Monte Carlo simulations and net present value (NPV) calculations to determine the life-cycle costs (Barringer 1997). Barringer's work was completed using commercial software, similar to this research, but it was finalized for process equipment not construction equipment. Also, Barringer completed research based on reliability principles and computing life-cycle costs in 2001.

6.2 Input Data and Equipment LCCA

The calculation of the equipment life was performed using deterministic and stochastic input variables. The usage of the PSM was employed to calculate the life-cycle costs. The method was altered to reflect public agency practices. This was done because the PSM is operated by private entities and public agencies operate with different constraints.

The input parameters utilized in the PSM to formulate the stochastic model consist of solely cost variables. The costs are analyzed on an annual basis for all the parameters. The stochastic and deterministic LCCA models use Equation 2 through 6 to determine the operating costs for the equipment (Peurifoy and Schexnayder 2002, Park 2011).

6.2.1 Economic Life Analysis

The determination of the economic life for equipment fleet is a critical component of the LCCA. The economic life or the optimal time to sell a piece of equipment requires the usage of EUAC calculations. To properly utilize EUAC, the ownership costs and operating costs must be calculated on an annual basis in the correct year, using Equations 9 through 12 (Park 2011).

The calculation of the EUAC is done over the entire life span for a piece of equipment. In most instances the lowest EUAC in a given year will be the optimal economic life. This will be the determination used in the deterministic and stochastic evaluation of equipment fleet, but the stochastic model will use confidence levels associated with the output. Also, the stochastic economic life evaluation will use the same equations as the deterministic method but apply stochastic inputs.

The last 47 months were used for the range of the diesel fuel prices, determined by the F-test and P-value statistical assessment, reference Table 5.5 from Chapter 5. Table 6.1 summarizes the stochastic inputs that were applied to the economic life calculations. Other than the fuel prices and the tire cost, the values displayed in Table 6.1 were obtained from the literature review (Gransberg et al. 2006, Atcheson 1993, Puerifioy and Schexnayder 2002, Park 2011).

Table 6.1 Stochastic Values for the Inputs used in the Economic Life Determination

Parameter	Range of Values
Interest Rate	3% - 16%
Tire Cost	Varied by Machine
R&MC	35% - 80%
Change in Market Value	8% - 15%
Diesel Fuel Prices	\$3.38/gal. - \$4.13/gal.
Tire Repair Factor	12% - 16%

The stochastic economic life will be determined by a range of confidence levels associated with EUAC. The range for the confidence levels will be from 70% - 90%. Then a sensitivity analysis will be applied to determine the sensitivity of the change in market value and the repair and maintenance costs. When the sensitivity for the repair and maintenance costs exceeds the sensitivity of the change in market value, this will be an indicator for equipment fleet managers. Figure 6.1 shows an example of the trigger point based on the sensitivity analysis.

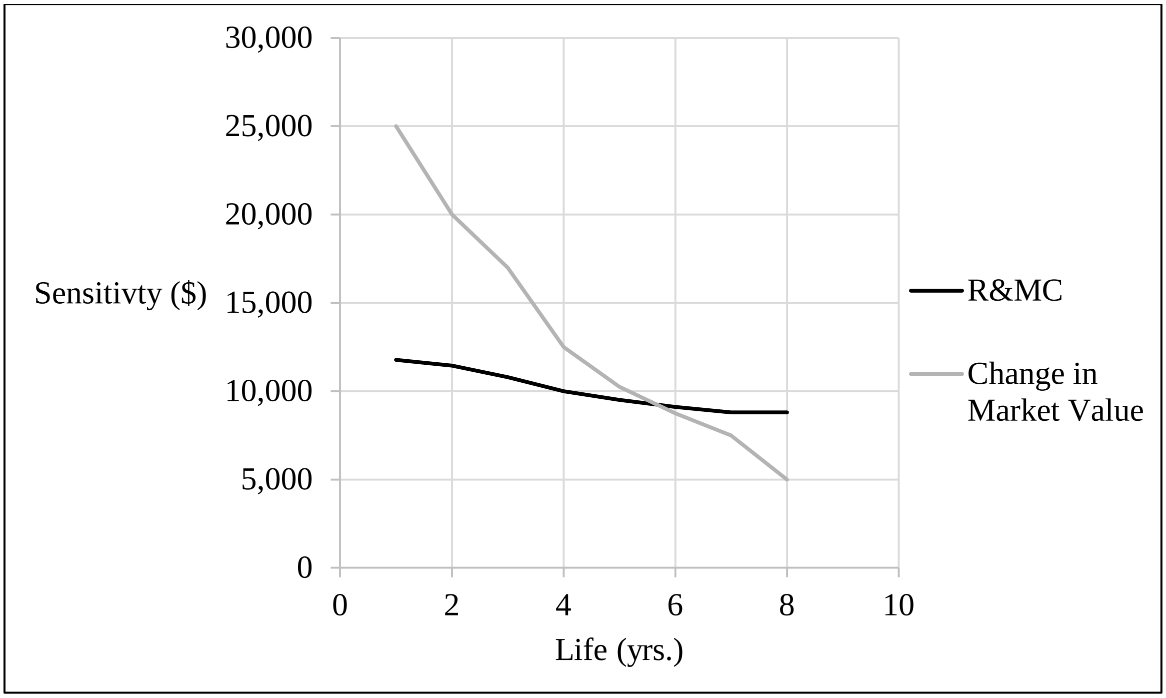


Figure 6.1 Trigger Point Determination Based on Sensitivity Analysis

The trigger point in Figure 6.1 is identified by the dashed line at year 6. This is the point in time when the sensitivity of the repair and maintenance costs intersects with the sensitivity of the change in market value. The trigger point signifies that the repair and maintenance costs are more uncertain at this point in time than the market value.

6.3 Results

The results for the research include deterministic and stochastic economic life calculations, and a sensitivity analysis of the stochastic output. An example using a loader, from the MPWFD equipment fleet, is provided to demonstrate the results that were obtained. Lastly, the usage of the stochastic economic life is discussed and compared with the deterministic method.

6.3.1 Deterministic Economic Life

The deterministic economic life was calculated to compare the results with the stochastic determination. Figure 6.2 displays the deterministic economic life of a 2006 loader, a piece of equipment within the MPWFD fleet. The economic life of the loader was found to be 4 years using the lowest EUAC. The variation between the two methods of calculating the economic life is discussed later in the research.

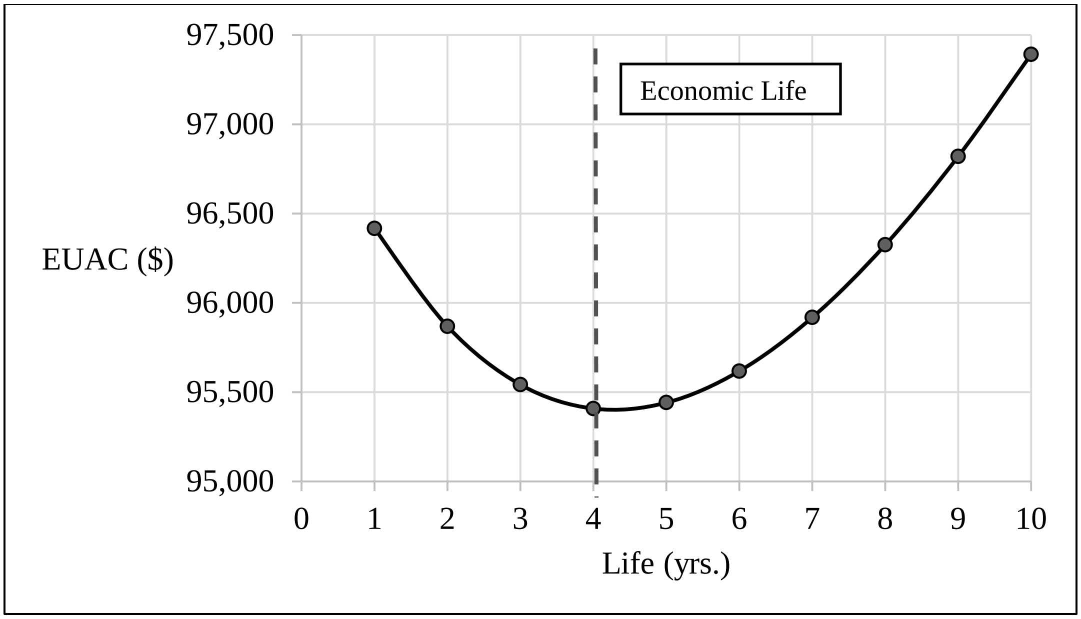


Figure 6.2 Deterministic Economic Life of the 2006 Volvo Loader

6.3.2 Stochastic Economic Life

The stochastic determination of the economic life for the 2006 Volvo loader is depicted in Figure 6.3. The confidence levels are shown with the optimal replacement age specified by the lowest EUAC. The economic life for the loader varies from year 5 to 8 depending on the confidence level.

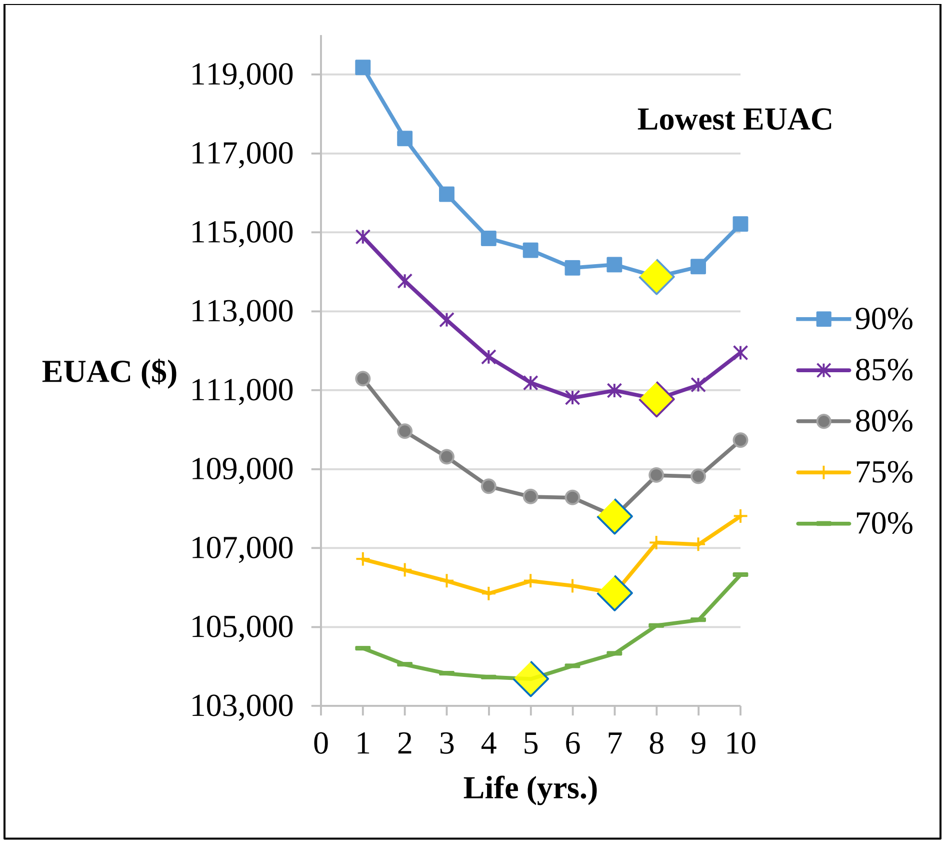


Figure 6.3 Stochastic Economic Life of the 2006 Volvo Loader

The economic life range for the loader supplies more detail than a deterministic determination. Using the range of values for the input parameters provides a more certain calculation of the economic life. Additionally, the range offers the fleet manager options to assess the replacement of equipment.

6.3.3 Sensitivity Analysis

Monte Carlo simulations were employed to determine the sensitivity of the inputs for the economic life calculation. Based on the sensitivity results of the change in market value and repair and maintenance costs, a trigger point for the machines was established. The sensitivity of each variable is related to the mean of the annual life-cycle cost associated with the piece of equipment. The range in the values is represented in dollar amounts. The wider the range the more sensitive the input is to the mean.

Figure 6.4 displays the results from the sensitivity analysis performed in the seventh year of the 2006 Volvo loader. The results show that the change in market value is more sensitive than the repair and maintenance costs given the year under investigation.

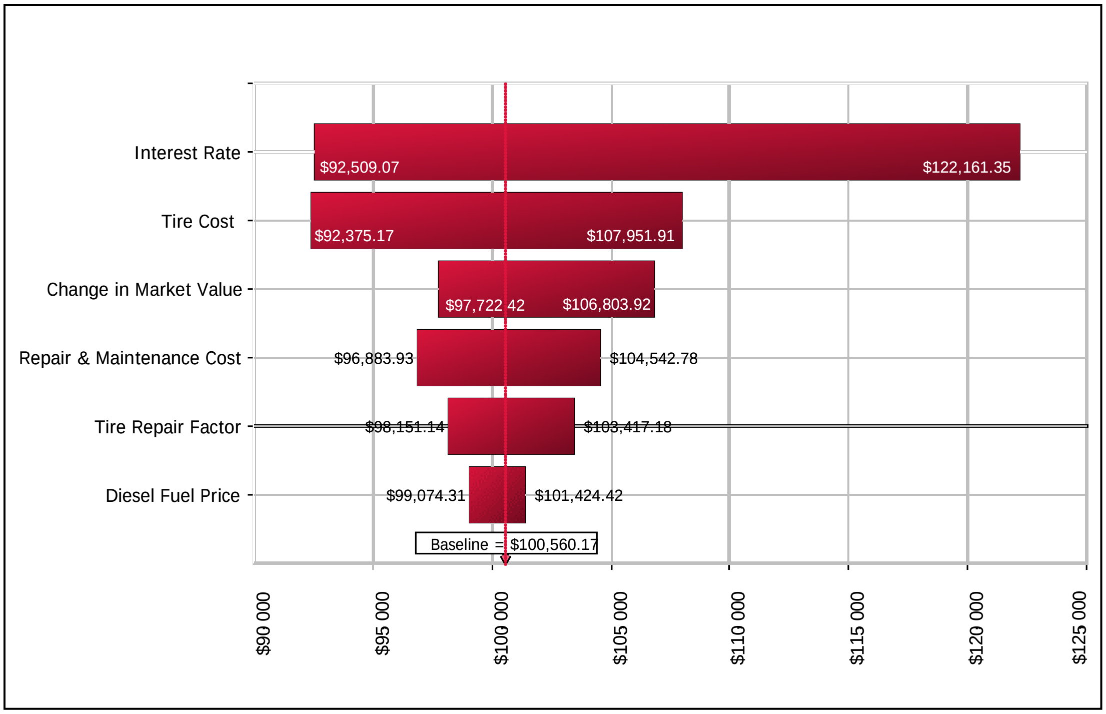


Figure 6.4 Sensitivity Analysis for the 2006 Volvo Loader in Year 7

Figure 6.5 contains the results from the sensitivity analysis performed in the eighth year of the Volvo loader. The results indicate that the repair and maintenance costs are more sensitive than the change in market value. This would indicate that the trigger point would be in year 8, due to the results differing from Figure 6.4.

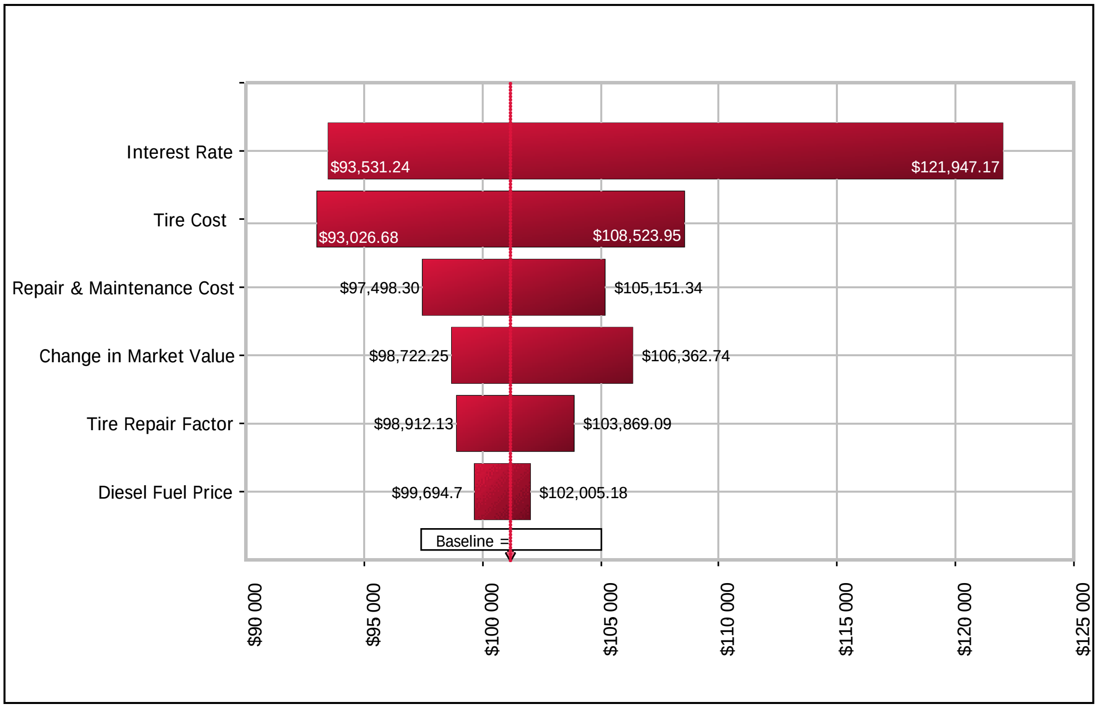


Figure 6.5 Sensitivity Analysis for the 2006 Volvo Loader in Year 8

Figure 6.6 contains the plot of the sensitivity fluctuations for the change in market value and the repair and maintenance costs for the 2006 Volvo loader. The results correlate with the Figures 15 and 16, indicating a trigger point in the eighth year.

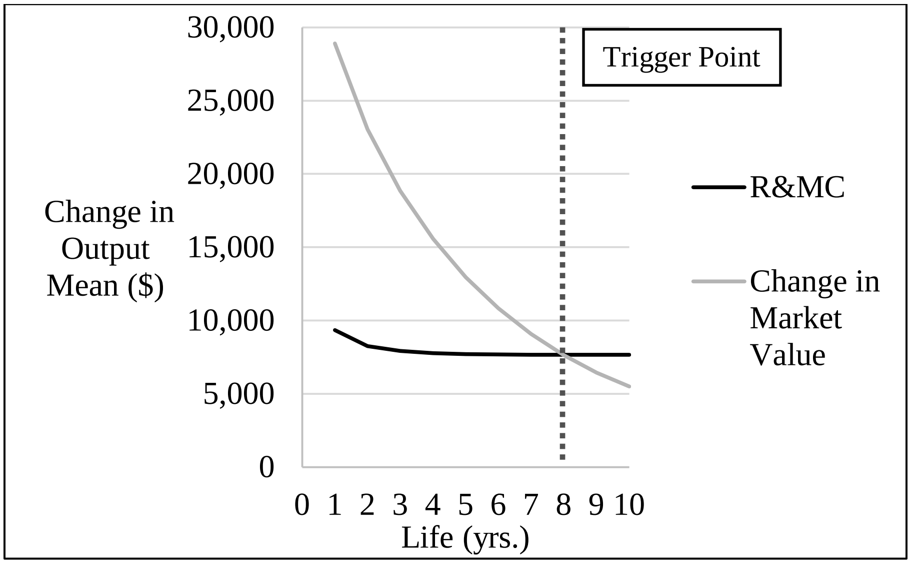


Figure 6.6 Change in the Output Mean for 2006 Volvo Loader 5 yd.

The results displayed in Figure 6.6 indicate that the sensitivities of the two inputs intersect at year 8, signifying the change in the sensitivity. The intersection of the two parameters is the trigger point for equipment fleet managers. Fleet managers may use this information to aid in equipment decisions.

Table 6.2 contains the results of the machines that were investigated within the MPWFD fleet. The economic life is shown with the deterministic and the stochastic methods for comparison. Also, the sensitivity analysis trigger year is displayed, and the service life of each machine is displayed.

Table 6.2 Economic life of MPWFD Equipment Fleet

Equipment	Deterministic Economic Life (yrs.)	Stochastic Economic Life Range (yrs.)	Sensitivity Analysis Trigger (yrs.)	Service Life (yrs.)
2002 Dump Truck	13	11 - 14	13	14
2012 Loader	4	3 - 8	6	10
2006 Loader 2.5 yd.	4	3 - 7	7	10
2006 Loader 5 yd.	4	5 -8	8	10

Since public agencies must make equipment replacement decisions years in advance, 5 years for the MPWFD, the economic life range allows fleet managers to plan the replacement with certain levels of confidence. For example, if the fleet manager uses an 80% confidence associated with the economic life for the 2006 loader 5 yd. they may plan the replacement at year 2, because at 80% confidence the economic life would be at year 7.
Based on the results from Table 6.2 the sensitivity analysis of the economic life determination may be used as a trigger point for equipment fleet managers. The sensitivity of the maintenance and repair costs is higher than the market value at the trigger point. Indicated by the shift in the two input parameters, the likelihood of a major failure for a piece of equipment increases as the machine ages. Therefore, implementing the trigger point would allow fleet managers to identify the correct age to implement preventative maintenance steps or support a replacement decision.

The budget constraints within a public agency's equipment fleet allow for strict replacement policies. This results in keeping equipment past the optimal economic life, increasing the repair and maintenance costs during the service life of equipment. The fleet manager has to manage these costs and identify the correct maintenance strategy at the correct time period. By having a trigger point within the service life of the fleet, it allows the management of the repair and maintenance costs, and use of resources.

6.4 Conclusions

A stochastic equipment LCCA model was applied to determine the economic life of equipment within a public agency. Using the PSM and engineering economics with stochastic functions the optimal replacement age was determined. The results displayed a different output than traditional deterministic methods. The model accounts for uncertainty within input parameters, different than deterministic methods that only have discrete input values. Accounting for the uncertainty within the input parameters allow fleet managers to make more certain equipment decisions because a more certain output is obtained.

The usage of Monte Carlo simulations provided a sensitivity analysis to be performed during the stochastic economic life determination. The outcomes displayed a change in the sensitivity from year-to-year in the change in market value and the repair and maintenance costs. The variation between the two input variables occurred within the optimal replacement age which is indicated from the confidence levels calculated. The sensitivity of the change in market value becomes less over time while the repair and maintenance cost increases over time. The point in time is an indicator that replacement of the equipment may be considered because repair and maintenance costs are more uncertain. Therefore, the confidence levels along with the sensitivity analysis provide a viable range to replace a piece of equipment.

Fleet managers may use this method as an indicator for replacement or as a trigger point to implement preventative maintenance strategies. Since public agencies must make equipment replacement decisions years in advance, the economic life range allows fleet managers to plan the replacement with certain levels of confidence. Also, due to budget constraints, public agencies must maximize the life of equipment fleet. By implementing a trigger point based on stochastic economic life determination, this may aid fleet managers more effectively than deterministic methods.

Chapter 7

Consolidated Conclusions and Recommendations

Deterministic and stochastic models were developed for public agencies to calculate equipment fleet life-cycle costs and the optimal economic life. This was achieved by modifying the PSM to fit the public agency equipment fleet environment and applying basic engineering economic principles to find optimal life-cycle cost solutions. When the stochastic model was applied to a piece of equipment using fluctuating interest rates and fuel prices, the sensitivity of the model's input variables were determined. The interest rate was found to have a greater impact on economic life output than fuel prices for a dump truck illustrated in Chapter 4. The fuel volatility did impact the life-cycle costs when applying the stochastic confidence levels. Therefore, allowing fuel prices to range probabilistically in the analysis provided a means to quantify the certainty of the equipment replacement decision.

With the increasing cost of diesel fuel, the issue of upgrading to a more fuel-efficient model of equipment using the latest technology has become an increasingly important element of the replace/repair decision. Therefore, employing the stochastic inputs allows the analyst to determine the impact of the most sensitive component of the model. This was illustrated in Chapter 5, where common input values were made stochastic to determine their impact on the public sector-adapted PSM equipment LCCA model. Based on Monte Carlo simulation sensitivity analysis results, the time factor and engine factor were the most sensitive input variables to the LCCA model. This leads to the conclusion that when deciding to replace a piece of equipment, engine efficiency should be a high priority due to the costs associated with the time factor, engine factor, and its subsequent annual usage.

Applying that conclusion to the public sector, one must realize that once a given piece of equipment is added to a public agency's equipment fleet, the equipment fleet manager can no longer influence many of the model's variables. These include the equipment's idle time, its working condition, and its engine efficiency. Thus, while accounting for uncertainty was shown to add value to the overall decision, making all the input variables stochastic introduces a level of complication that is not necessary. Therefore, it is concluded that employing the inputs as deterministic is the most practical determination. Such inputs as repair and maintenance uncertainty are more critical to equipment decisions because the fleet manager can control those inputs more closely. Consequently, Chapter 5 determined which variables to include in the equipment LCCA model as deterministic values and which were better portrayed as stochastic variables to aid public agency equipment fleet managers.

Lastly, Chapter 6 contained a stochastic equipment LCCA model that produced different output results than deterministic methods for a public agency's fleet. The stochastic model accounted for uncertainty within input parameters, unlike deterministic methods that only use discrete input value assumptions. A range for the optimal replacement age was formulated within a 70% to 90% confidence level. Since public agencies must make equipment replacement decisions years in advance, the economic life range allows fleet managers to plan the replacement with certain levels of confidence. The use of Monte Carlo simulations provided for a sensitivity analysis performed in conjunction with the stochastic economic life determination. The outcomes displayed a change in the sensitivity from year to year in the change in market value and the repair and maintenance costs. The variation between the two input variables occurred within the economic life range developed by the confidence levels. Therefore, the confidence levels along with the sensitivity analysis provide a trigger point that signals when the equipment manager should consider replacing a piece of equipment as it nears the end of its optimum economic life.

Chapter 8

Recommendations for Future Research

Due to the nonexistence of stochastic modeling for equipment LCCA within public agencies this research is the first of its kind. Thus, the expansion for this thesis is critical to increase the knowledge of equipment fleet management. The following is a list of possible research projects that may be formulated from this thesis:

- Using the stochastic equipment LCCA model, the development of a replacement time period may be established for public agency's equipment fleet. The time period could replace current replacement plans, such as the 5-year replacement plan for MPWFD. The adjusted replacement period would be based on the confidence levels associated with the stochastic economic life determination. For example, the 70% to 90% economic life range is between year 11 and 14 for the dump truck illustrated in Chapter 4. The three year range, from year 11 to 14, could be the determination of a three year replacement plan for MPWFD.
- Applying the stochastic equipment LCCA for private entities. Adjusting the model for the private sector, and use the confidence levels to develop an optimal replacement age.
- Case study analysis using the stochastic equipment LCCA from the thesis for other public agencies. Since the thesis has been adapted for MPWFD, the model could be analyzed for a different equipment fleet to justify the results obtained in the thesis.

References

1. M. Antich, (2010). “Top 10 Challenges Facing Public Sector Fleets in CY-2011.” *Government-Fleet*, Online available at: http://www.government-fleet.com/channel/fuel-management/article/story/2010/11/top-10-challenges-facing-public-sector-fleets-in-cy-201/page/2.aspx Accessed November 27, 2014
2. D. Atcheson, (1993). *Earthmoving Equipment Production Rates and Costs*. Norseman Publishing, Venice, FL.
3. P. Barringer, (1997). “Life-cycle Cost & Reliability for Process Equipment.” *Proceedings*, 8th Annual Energy Week Conference & Exhibition, American Society of Mechanical Engineers, January 28-30, Houston, Texas. http://www.barringer1.com/pdf/lcc_rel_for_pe.pdf Accessed April 15, 2014.
4. P. Barringer, (2001). “How to Justify Equipment Improvements Using Life-cycle Cost and Reliability Principles.” Barringer & Associates, Inc., http://www.barringer1.com/pdf/BarringerPower_Machinery&Compressor_Paper.pdf Accessed April 15, 2014
5. P. Barringer, (2005). "How to Justify Equipment Improvements Using Life-cycle Cost and Reliability Principles." *North American Association of Food Equipment Manufactures Conference*, June 12-15, 2005. Miami, Florida.
6. Caterpillar Inc. (2011). “*Caterpillar Performance Handbook*.” 41st edition, Caterpillar Inc. Peoria, IL
7. City of Minneapolis. (COM) (2014). “Financial Management Policies.” 2014 Mayor’s recommended Budget, Online available at: http://www.ci.minneapolis.mn.us/www/groups/public/@finance/documents/webcontent/wcms1p-113465.pdf Accessed November 27, 2014.
8. H. T. Davies, and I. K**.** Crombie, (2009). “What are confidence interval and p-values?” Online available at: http://www.medicine.ox.ac.uk/bandolier/painres/download/whatis/what_are_conf_inter.pdf Accessed October 2, 2014.
9. J. Douglas, (1975). “*Construction Equipment Policy*.” McGraw-Hill, New York, NY.
10. J. Douglas, (1978). “Equipment Costs by Current Methods.” *Journal of Construction Division ASCE* 104 (C02), 191-225.

11. H. Fan, and Z. Jin, (2011). “A Study on the Factors Affecting the Economical Life of Heavy Construction Equipment.” *Proceedings of the 28th ISARC*, July 1-2, 2011, Seoul, Korea, pp. 923-928.
12. W. Fan, M. Gemar, and R. Machemehl, (2013). “Equipment Replacement Decision Making: Challenges and Opportunities.” *Journal of Transportation Research Forum*, 52(3), No. 3, 79-90.
13. G. Flintsch, and C. Chen, (2004). “Soft Computing-Based Infrastructure Life-Cycle Cost Analysis Tools.” *Computational Intelligence* 1-15.
14. Florida Department of Management Services; Division of Specialized Services. (2009). "Minimum Equipment Replacement Criteria." Online available at: http://www.dms.myflorida.com/content/download/96061/559801/DMS_Minimum_Equipment_Replacement_Criteria.pdf Accessed April 15, 2014.
15. H. Furuta, T. Kameda, Y. Fukuda, and D. Frangopol, (2003). “Life-Cycle Cost Analysis for Infrastructure Systems: Life-Cycle Cost vs. Safety Level vs. Service Life.” *Life-Cycle Performance of Deteriorating Structures*, 19-25.
16. P. Ghadam, M. Ravanshadnia, S. Ramezani, (2012). “Determining Economic Life of Earth Moving Equipment by Using Life-cycle Cost Analysis: Case Study.” Online available at: http://www.academia.edu/2032383/Determining_Economic_Life_of_Earth_Moving_Equipment_by_Using_Life_Cycle_Cost_Analysis_Case_Study Accessed April 15, 2014.
17. J.S. Gillerspie, and A. S. Hyde (2004). T*he Replacement/Repair Decision for Heavy Equipment*. Report VTRC 05-R8, Virginia Transportation Research Council, Charlottesville, VA
18. D. Gransberg, R. Popescu and R. Ryan, (2006). *Construction Equipment Management for Engineers, Estimators, and Owners*. 1st Ed., Taylor & Francis Group, Boca Raton, FL
19. D.D. Gransberg, (2009). “Life-cycle Cost Analysis of Surface Retexturing with Shotblasting as a Pavement Preservation Tool.” *Transportation Research Record 2108,* pp.46-52.
20. D.D. Gransberg, and Scheepbouwer. E, (2010). “Infrastructure Asset Life-cycle Cost Analysis Issues,” *2010 Transactions*, AACE, Int‘l, Atlanta, Georgia, June, 27-30, 2010, pp. CSC.03.01- CSC.03.8.

21. D.D. Gransberg, and E.J. Kelly, (2008). “Quantifying the Uncertainty Due to Construction Material Price Volatility Using Monte Carlo Simulation.” *Cost Engineering,* Vol. 50 (6)14-21.
22. H. Haldorsen and E. Damsleth, (1990). “Stochastic Modeling” *Society of Petroleum Engineers* 42(4)
23. P.A. Jensen, and J.F. Bard, (2002). *Operations Research Models and Methods*. Wiley, New York.
24. P. Kauffman, E. Howard, J. Yao, D. Harbinson, N. Brooks, R. Williams, C. Gurganus, (2012). “Criteria for Fleet Management: Identification of Optimal Disposal Points with the Use of Equivalent Uniform Annual Cost.” *Transportation Research Record* 2292, 171-178.
25. Lang, J. (2008). “Financial Management.” American Public Works Association. Online available at: http://www.apwa.net/c/documents/education/institutes/ppt/finance.ppt Accessed November 29, 2014.
26. D. LeBlanc, (2004). *Statistics: Concepts and Applications for Science*. Jones and Bartlett Publishers. Sudbury, MA.
27. M.A. McCarthy, M.A. Burgman, and S. Ferson, (1995). “Sensitivity analysis for models of population viability.” *Biological Conservation* 73: 93-100.
28. Z. Mitchell, (1998). *A Statistical Analysis of Construction Equipment Repair Costs Using Field Data and the Cumulative Cost Model*. Virginia Polytechnic Institute. Blacksburg, VA
29. Z. Mitchell, J. Hildreth, and M.Vorster, (2011). ”Using the Cumulative Cost Model to Forecast Equipment Repair Costs: Two Different Methodologies.” *Journal of Construction Engineering and Management.* 137(2). 817–822.
30. C. Mooney, (1997). *Monte Carlo Simulation*. Sage Publications, Inc. Thousand Oaks, CA.
31. Moss Motors. (2014). “Bringing a Car out of Storage.” Tech Articles, Moss Motors, Ltd. Online available at: http://www.mossmotors.com/SiteGraphics/Pages/out_of_storage.html Accessed November 29, 2014

32. Municipal Bonds. (2014). “Byron Minnesota Independent School District School Building Series A.” Online available at http://minnesota.municipalbonds.com/bonds/recent/ Accessed May 20, 2014
33. Municipal Bonds. (2014). “Northern Municipal Power Agency Minnesota Electrical Series A.” Online available at http://minnesota.municipalbonds.com/bonds/recent/ Accessed May 20, 2014
34. Municipal Bonds. (2014). “University Minnesota Series A.” Online available at http://minnesota.municipalbonds.com/bonds/recent/ Accessed May 20, 2014
35. Municipal Bonds. (2014). “Wayzata Minnesota Independent School District School Building Series B.” Online available at http://minnesota.municipalbonds.com/bonds/recent/ Accessed May 20, 2014
36. Municipal Bonds. (2014). “Westonka Minnesota Independent School District School Building Series A.” Online available at http://minnesota.municipalbonds.com/bonds/recent/ Accessed May 20, 2014
37. Neuendorf, K.A. (2002). *The Content Analysis Guidebook*, Sage Publications, Thousand Oaks, CA
38. A. N. Oppenheim, (1992). *Questionnaire Design, Interviewing and Attitude Measurement*. Pinter, London and New York.
39. C. Park, (2011). *Contemporary Engineering Economics*. 5th Ed., Prentice Hall, NJ
40. R. Peurifoy, and C. Schexnayder, (2002). *Construction Planning, Equipment, and Methods*. Sixth edition, McGraw-Hill, New York.
41. M. Pinsky, and S. Karlin, (2011). *An Introduction to Stochastic Modeling*. 5th edition, Elsevier Inc. Burlington, MA.
42. D.M. Pittenger, D.D. Gransberg, M. Zaman, and C. Riemer. (2012). “Stochastic Life-cycle Cost Analysis for Pavement Preservation Treatments.” *Transportation Research Record No. 2292*, 45-51.
43. S. Richardson, (2007). “Economics of Commuter Rail Alternatives.” *Transportation Research Record* 99-105.
44. C.J. Schexnayder, (1980). “Heavy Construction Equipment Replacement Economics.” Doctoral Dissertation, Purdue University, West Lafayette, IN

45. J. S. Taylor, (1923). “A Statistical Theory of Depreciation Based on Units Cost.” *Journal of the American Statistical Association*, 1010-1023.

46. Texas Department of Transportation (TxDOT). (2008). *TxDOT Equipment Replacement Model*; Austin, TxDOT.

47. The Bond Exchange. (2010). “Bank Line of Credit, Their Benefits and How they Affect your Surety Bond Capacity.” The Bond Exchange; and Insurance Agency. Online available at: http://www.thebond-exchange.com/Pages.aspx/Bank-lines-of-credit-and-how-they-affect-your-surety-bond-capacity. Accessed November 29, 2014.

48. U.S. Department of Energy. (2014). “Gasoline and Diesel Fuel.” Update, April 28, 2014. http://www.eia.gov/petroleum/gasdiesel/ Accessed May 5, 2014

49. R. West, N. Tran, M. Musselman, J. Skolnik, and M. Brooks, (2013). *A Review of the Alabama Department of Transportation’s Policies and Procedures for Life-cycle Cost Analysis for Pavement Selection*. National Center for Asphalt Technology at Auburn University, Report 13-06. Auburn, AL.

Appendix A

Case Study Results

The case study results were obtained from a structured interview questionnaire. Three agencies were investigated for the case study analysis; city of Minneapolis, city of Eagan, and Dodge county. This section contains the questionnaire that was applied and the results from each case study.

Structured Case Study Questionnaire

The following contains the questions that were used during the case study analysis.

CONDITIONS: This interview can either be conducted in person or via telephone. The following protocol shall be followed during its administration:

1. The questionnaire shall be sent to the respondent at least 1 week prior to the interview via email.
2. To maximize the quality and quantity of information collected, the primary respondent should be encouraged to invite other members of his/her organization to be present during the interview. Thus, a single transportation agency response can be formulated and recorded.
3. The interviewer will set the stage with a brief introduction that emphasizes the purpose of the research, the type of information expected to be collected, and the ground rules for the interview.
4. Once the interviewees indicate that they understand the process at hand, the interview will commence.
5. The interviewer will read each question verbatim and then ask if the interviewee understood the question before asking the interviewee to respond.
6. Each question contains a specific response that must be obtained before moving to the next question. Once that response is obtained, the interviewer can record as text additional cogent information that may have been discussed by the interviewees in working their way to the specific response.
7. Upon conclusion of the interview, the interviewer will ask the interviewees if they have additional information that they would like to contribute and record those answers as text.
8. The interviewer will assemble a clean copy of the final interview results and return them to the interviewee for verification.

STRUCTURED INTERVIEW:

I. Agency and Interviewee General Information:

1. Interviewee name:
2. Interviewee job position in the agency:
3. Interviewee telephone number:
4. City and state in which the respondent agency is headquartered:

A. Name of Agency:

5. What type of organization do you work for?
   ☐ State DOT ☐ Other public transportation agency ☐ Other: {explain}
6. Approximate number of pieces of heavy machinery and equipment:
7. Approximate number of pieces of light vehicles (sedan, pickups, vans, etc):
8. Approximate average annual budget for equipment purchase:
9. Approximate average annual budget for equipment repair, rehabilitation, and maintenance:

II. Equipment Decision Techniques:

1. Does your agency currently use a formal decision-making process to make equipment maintenance, repair, and/or replacement decisions on individual pieces of equipment?
   ☐ Yes ☐ No ☐ Don't Know
2. If yes, which methods are used? What process best describes your procedures?
   - ☐ Life-cycle Cost Analysis
   - ☐ Minimum Cost Method
   - ☐ Mathematical Modeling Method
   - ☐ Payback Period Method
   - ☐ Other(s)
   - ☐ Economic life of the investment
   - ☐ Maximum number of hours
   - ☐ Output from software-based analysis
   - ☐ Don't know
3. If your agency utilizes a software-based analysis for fleet management decisions, what software program is used?

III. Major Equipment Decision Tool:

1. How does your agency decide when to replace a piece of equipment?
2. How does your agency decide when to repair a piece of equipment?
3. How does your agency decide between replacing and repairing a piece of equipment?
4. How long in advance does your agency need to know when to buy a new piece of equipment?
5. What is your definition of economic life?
6. What is your definition of service life?
7. What information do you need to make equipment management decisions based on the life-cycle of the equipment?
8. What are the major life-cycle components that factor into replacement or maintenance decisions for heavy equipment?
   - ☐ Acquisition Costs
   - ☐ Annual Usage
   - ☐ Depreciation
   - ☐ Equipment Horsepower
   - ☐ Fuel Costs
   - ☐ Insurance Costs
   - ☐ Interest Costs
   - ☐ Lubrication Costs
   - ☐ Oil Costs
   - ☐ Oil Life Expectancy
   - ☐ Other(s):
   - ☐ Operator Costs
   - ☐ Purchase Price
   - ☐ Maintenance Costs
   - ☐ Tire Costs
   - ☐ Tire Maintenance Costs
   - ☐ Tire Life Expectancy
   - ☐ Total Expected Life
   - ☐ Salvage Value
   - ☐ None
9. What are the major life-cycle components that factor into replacement or maintenance decisions for light equipment?
   - ☐ Acquisition Costs
   - ☐ Operator Costs

☐ Annual Usage
☐ Depreciation
☐ Equipment Horsepower
☐ Fuel Costs
☐ Insurance Costs
☐ Interest Costs
☐ Lubrication Costs
☐ Oil Costs
☐ Oil Life Expectancy
☐ Other(s):
☐ Purchase Price
☐ Maintenance Costs
☐ Tire Costs
☐ Tire Maintenance Costs
☐ Tire Life Expectancy
☐ Total Expected Life
☐ Salvage Value
☐ None

IV. Equipment Data:

1. What are the most common pieces of heavy equipment that your agency owns (5-6)?
2. What are the most common pieces of light equipment that your agency owns (5-6)?
3. Which pieces of equipment would be most beneficial for Life-cycle Cost Analysis?
4. Is there anything you would like to add that you think would be valuable to the researchers in this study?

Case Study Analysis Results

The following section contains the results for each of the case studies that was completed for this thesis. Each of the case studies has three parts; replacement evaluation process, repair evaluation process, and equipment life-cycle information.

City of Minneapolis

Replacement Evaluation Process: The replacement evaluation process for the City of Minneapolis includes three major aspects including; equipment life-cycle, equipment utilization, and business need of equipment. The equipment life-cycle requirement is based on 50% to 60% of the initial value of the piece of equipment. If a piece of equipment is below or at the optimal value than it would be considered for replacement. The equipment utilization is a factor due to the usage and need for certain tasks. For example, a police vehicle may be utilized more than a snow plow in the summer. The business need is the least important factor in the replacement evaluation process. An example of business need for the city of Minneapolis would include, a specific type of excavator is needed to build ponds and now the city needs a different type of excavator to maintain the ponds. Therefore, the replacement of an excavator which is needed to build ponds would not be necessary.

The replacement evaluation entails a ten, five, and two year replacement plan. These plans are developed to specify replacement needs and when they will be executed. The ten year plan is a rough estimate of what will be replaced in the future. The five year plan has a firm idea of what pieces of equipment will be replaced. The five year plan includes changes due to accidents and repairs. The two year plan includes the specific data for replacement. The two year plan finalizes and calculates all the replacement decisions that will be made.

Repair Evaluation Process: The repair process is specified by 50% to 60% of the original value of a piece of equipment. If a piece of equipment is above the optimal range of the initial value than the equipment is repaired. This is standard for all pieces of equipment within the fleet. Although, utilization of the equipment fleet is a major driving force in the determination between repairing and replacing a piece of equipment.

Equipment Life-cycle Information: The most vital pieces of information that are needed to make equipment decisions based on the life-cycle of equipment for the city of Minneapolis include; age, utilization, and fuel consumption. The major life-cycle components that factor into replacement or maintenance decisions for heavy pieces of equipment include:

- Acquisition Costs
- Depreciation
- Insurance Cost (same for all pieces of equipment)
- Maintenance Costs (includes tire cost and tire maintenance cost)
- Total Expected Life
- Salvage Value
- Up-fitting Costs

The major life-cycle components that factor into replacement or maintenance decisions for light pieces of equipment include:

- Acquisition Costs
- Annual Usage
- Insurance Cost (same for all pieces of equipment)
- Operator Costs
- Purchase Price
- Maintenance Costs (includes tire cost and tire maintenance cost)
- Total Expected Life
- Salvage Value
- Safety Factors

The most common pieces of heavy equipment that the city of Minneapolis owns are dump trucks, loaders (3yd and 5yd), skid steer loaders, and numerous others. The most common pieces of light equipment includes sedans, particularly the Ford Escape and Ford Focus.

City of Eagan

Replacement Evaluation Process: Eagan utilizes a minimum replacement standard for all pieces of equipment. The standard entails a specific age, mileage or hour requirement that must be met before a piece of equipment can be replaced. An example for a light piece of equipment is a sedan that must reach 10 years old or 100,000 miles before it may be classified for replacement consideration. An example of a heavy piece of equipment is a backhoe that must reach 20 years old or 6,000 hours of operation before it may be replaced.

After the minimum standards have been met, the replacement evaluation process includes the following pieces of information, Vehicle Condition Index (VCI), age (years, mileage, or operating hours), and operational considerations. The VCI takes into account the following parameters; age, mileage or hours, reliability, maintenance and repair costs, condition, cost per mile, and risk factor. These considerations will be reviewed by city employees to make the replacement decision. Furthermore, deviations from this policy must be reviewed and approved by city administrators.

The time frame for future replacement decisions for the equipment fleet is dictated by the budget period. The budget period for the city of Eagan is from May through December which allows for most of the replacement decisions to take place in December.

Repair Evaluation Process: All pieces of equipment are repaired and maintained until they reach the minimum standards set by the replacement evaluation process. This is true for both light and heavy pieces of equipment.

Equipment Life-cycle Information: All information and data regarding decisions based on the life-cycle of equipment is generated from FleetFocus, an equipment fleet software program. The major life-cycle components that factor into replacement or maintenance decisions for both heavy and light pieces of equipment include:

- Acquisition Costs
- Purchase Price
- Maintenance Costs
- Tire Costs
- Tire Life Expectancy

The most common pieces of heavy equipment that the city of Eagan owns are snow plows and fire trucks. The city currently has approximately 40 snow plows and 20 fire trucks within their equipment fleet. The most common pieces of light equipment includes sedans and light pick-ups.

Dodge County

Replacement Evaluation Process: Pieces of equipment are replaced based on the needs of the county and the allowable budget. Once a piece of equipment is needed to be replaced, the county decides if the budget has the funds to replace the equipment.

Repair Evaluation Process: Pieces of equipment are repaired when they are broken or need fixing. There is no standard policy for the repair evaluation process.

Equipment Life-cycle Information: The information that Dodge County needs to make equipment management decisions based on the life-cycle of equipment are repair costs and costs to replace. The major life-cycle components that factor into replacement or maintenance decisions for both heavy and light pieces of equipment include:

- Acquisition Costs
- Annual Usage
- Depreciation
- Purchase Price
- Maintenance Costs
- Salvage Value

The most common pieces of heavy equipment that Dodge County owns are snow plows, loaders, excavators, and graders. The most common pieces of light equipment light pick-ups.

Appendix B

National Survey Results

An online survey was distributed to benchmark the usage of LCCA and other parameters in agency fleet management programs. The following contains the questionnaire and results that for the survey that was completed for this thesis.

Survey Questionnaire

1. Please specify the following pieces of information.

	Response
Agency Name	
City	
Approximate number of pieces of heavy machinery and equipment	
Approximate number of pieces of light vehicles (pickup, vans, etc.)	
Approximate average annual budget for equipment purchase	
Approximate average annual budget for equipment repair, rehabilitation, and maintenance	

2. Does your agency currently use a formal decision-making process to make equipment maintenance, repair, and/or replacement decisions on individual pieces of equipment?

☐ Yes ☐ No ☐ Don't Know

3. If yes, which methods are used? What process best describes your procedures?

- ☐ Life-cycle Cost Analysis
- ☐ Minimum Cost Method
- ☐ Mathematical Modeling Method
- ☐ Payback Period Method
- ☐ Other(s)
- ☐ Economic life of the investment
- ☐ Maximum number of hours
- ☐ Output from software-based analysis
- ☐ Don't know

4. Which of the following fleet management software programs are or have been utilized by your agency? Please check all that apply.

- ☐ collectiveFleet
- ☐ Maintenance Connection
- ☐ eMaint X_3
- ☐ Maintenance Coordinator
- ☐ Maintenance5000
- ☐ Maintenance Pro
- ☐ Accruent 360Facility
- ☐ Fleetmatics
- ☐ Fleet Maintenance Pro
- ☐ J.J. Keller's Maintenance Manager™
- ☐ collectiveShop™
- ☐ Service Pro Field Service and Repair Center
- ☐ AgileAssets® Fleet & Equipment Manager™
- ☐ Other(s):
- ☐ Infor EAM
- ☐ 4Site
- ☐ Guide TI
- ☐ ManagerPlus
- ☐ TMT Fleet Maintenance
- ☐ iMaint
- ☐ Maintenance Assistant CMMS
- ☐ TMT Fleet Maintenance Software
- ☐ FleetFocus
- ☐ collectiveFleet™
- ☐ MH Fleet
- ☐ MS Excel
- ☐ None

5. Which of the parameters listed in the table does your agency collect and maintain in your equipment fleet management database? For those parameters in your database, please rate your sense of how reliable the data in the database is currently.

Parameters	Available Electronically	Available on Paper	Not Available	Data Reliability					
				Totally Unreliable	Mostly Unreliable	Mostly Reliable	Reliable	Very Reliable	Don’t Know
Purchase Price									
Acquisition Costs									
Annual Usage in Hours									
Total Expected Life									
Equipment Horsepower									
Salvage Value									
Maintenance Costs									
Insurance Costs									
Interest Costs									
Depreciation									
Operator Costs									
Tire Cost									
Tire Maintenance Cost									
Tire Life Expectancy									
Oil Life Expectancy									
Oil Costs									
Fuel Costs									
Lubrication Costs									

6. Which of the following parameters do you use when making equipment fleet management decisions, like purchases, major repairs, etc.? Please rate the impact on the final decision for each parameter that you use. For example, if the original purchase price for the piece of equipment carries the heaviest weight in a decision to invest in a major repair or to purchase a new piece of equipment, then rate it as “highest impact.” On the other hand if it is not considered, rate its impact as “none.”

Parameter	Decision-making Impact				
	None	Little	Some	High	Highest
Purchase Price					
Acquisition Costs (i.e. plates, licensing, etc.)					
Annual Usage in Hours					
Total Expected Life					
Equipment Horsepower					
Salvage Value					
Maintenance Costs					
Insurance Costs					
Interest Costs					
Depreciation					
Operator Costs					
Tire Cost					
Tire Maintenance Cost					
Tire Life Expectancy					
Oil Life Expectancy					
Oil Costs					
Fuel Costs					
Lubrication Costs					

7. Would you be willing to allow the researchers to use the information in your database and allow them to interview you on your program? ☐ Yes ☐ No

If yes, please indicate the name, phone number and email address of your agency's point of contact.

Survey Results
The subsequent tables contain the results of the survey. The table below shows the agency respondents and the corresponding equipment fleet information. The number of pieces of equipment and budget are shown in the table. Also, the last column of the table shows if the agency uses a formal decision-making process for the equipment fleet.

Table. Agency Responses and Equipment Fleet Information

Agency Name:	City:	Approximate number of pieces of heavy machinery and equipment:	Approximate number of pieces of light vehicles (sedans, pickups, vans, etc.):	Approximate average annual budget for equipment purchase:	Approximate average annual budget for equipment repair, rehabilitation, and maintenance:	Does the Agency Utilize a Formal Decision-Making-Process for Equipment Decisions?
Village of Algonquin	Algonquin	50	100	$150,000-$250,000	$850,000	Yes
City of Woodland	Woodland	100	200	$600,000	$1,000,000	No
City of Solon	Solon	25	10	$80,000	$20,000	No
Central Fleet	Manchester NH	220	240	$3,000,000	$3,000,000	No
Department of Public Works	City of Largo, Florida	75	300	$3,500,000	$2,000,000	Yes
City of Durham, NC	Durham, NC	578	937	$5,500,000	$2,300,000	Yes
City Of West Des Moines	West Des Moines	100	200	$1,200,000	$1,600,000	Yes
Pierce County Public Works Equipment Services	Tacoma WA	223	201	$3,500,000	$4,581,000	Yes
City of Decatur	Decatur	151	210		$2,715,547	No
City of Dubuque	Dubuque	160	100	$500,000	$500,000	Yes
City of Dubuque	Dubuque					Yes
City of Troy	Troy	70	200	$1,600,000	$2,900,000	Yes

The table corresponds to the methods utilized within the formal decision-making process that the agency has in place. Since eight of the eleven respondents utilize a formal decision-making process, the table has the results of only those eight. The respondents were allowed to pick more than one method, and the percent column is based on the total percent for that method, not cumulative of all the methods.

Table. Method's Utilized for Equipment Fleet Decision-Making

Method	Responses*	%
Life-cycle Cost Analysis	8	100%
Minimum Cost Method	0	0%
Mathematical Modeling Method	3	38%
Payback Period Method	1	13%
Economic Life of Investment	6	75%
Maximum Number of Hours	4	50%
Output from Software-based Analysis	5	63%
Don't Know	0	0%
Other(s)	0	0%

*Respondents were allowed to pick more than one method

Based on the results from table, the life-cycle cost analysis method is the most prominent method utilized by the responding agencies. The second highest response rate was the economic life of investment, and following that was output from software-based analysis.

The table below contains the results from the software programs that are being utilized by the various agencies that responded to the survey. The respondents were allowed to pick more than one software program, thus the percentages are not cumulative of all software programs. The most prominent software programs were MS Excel and Faster as shown in the table.

Table. Fleet Management Software Programs that have been or are being Utilized

Software	Results*	%
MS Excel	5	36%
collectiveFleet	1	7%
None	2	14%
Other:	11	79%
Faster, CCGSystems	6	55%
Jetfleet	1	9%
Sungard	1	9%
RTA	1	9%
C.F.A. Computerized fleet analysis	1	9%
PRECISION	1	9%

*Respondents picked more than one software if applicable

The table below shows the availability of the input data for the LCCA model. The parameters are the input data for the model and the other columns are the availability based on electronically availability, paper availability, or not available. A total of eleven agency responses are contained in table and they were allowed to pick more than one availability option.

Table. Availability of Input Data for LCCA Model

Parameter	Available Electronically	Available on Paper	Not Available	Total Responses
Purchase Price	9	6	0	15
Acquisition Costs	7	6	1	14
Annual Usage in Hours	9	2	1	12
Total Expected Life	9	4	0	13
Equipment Horsepower	5	2	2	9
Salvage Value	9	2	2	13
Maintenance Costs	10	2	1	13
Insurance Costs	3	3	4	10
Interest Costs	2	2	4	8
Depreciation	5	1	3	9
Operator Costs	4	2	4	10
Tire Maintenance Cost	8	2	1	11
Tire Life Expectancy	4	2	3	9
Oil Life Expectancy	6	3	2	11
Oil Costs	8	3	1	12
Fuel Costs	9	2	1	12
Lubrication Costs	8	1	2	11

The table below contains the results of the reliability characteristics of the available data for the LCCA model inputs. The parameters for the table are the LCCA model inputs and the other columns relate to the reliability. Each agency could pick one characteristic for a given parameter. Most of the results for each data point were mostly reliable as shown.

Table. Reliability of Input Data for LCCA Model

Parameter	Totally Unreliable	Mostly Unreliable	Mostly Reliable	Reliable	Very Reliable	Don't Know	Total Responses
Purchase Price	1	0	5	1	3	0	10
Acquisition Costs (i.e. plates, licensing, etc.)	1	1	4	2	2	0	10
Annual Usage in Hours	0	0	6	1	2	0	9
Total Expected Life (In hours or years)	0	0	6	1	2	0	9
Equipment Horsepower	1	0	4	1	1	1	8
Salvage Value	1	5	1	1	2	0	10
Maintenance Costs	0	2	5	1	2	0	10
Insurance Costs	1	2	2	1	1	0	7
Interest Costs	0	1	3	1	0	1	6
Depreciation	1	1	3	1	1	1	8
Operator Costs	0	1	3	1	2	1	8
Tire Maintenance Cost	0	1	5	1	2	0	9
Tire Life Expectancy	1	1	3	1	1	1	8
Oil Life Expectancy	1	2	3	1	2	0	9
Oil Costs	0	1	6	1	2	0	10
Fuel Costs	0	1	6	1	2	0	10
Lubrication Costs	0	2	5	1	2	0	10

The table below displays the impact of the input data for the LCCA model. Each agency was to rank the impact from no impact to highest impact. The parameters that received the most responses with the highest impact were; purchase price, annual usage in hours, and total expected life. The parameters that received the most responses corresponding with no impact included; acquisition costs, insurance costs, interest costs, and depreciation.

Table. Impact of Input Data for LCCA Model

Parameter	No Impact	Little Impact	Some Impact	High Impact	Highest Impact	Total Responses
Purchase Price	0	0	2	1	6	9
Acquisition Costs	5	1	2	1	1	10
Annual Usage in Hours	0	0	3	4	2	9
Total Expected Life	0	0	3	4	3	10
Equipment Horsepower	1	4	4	0	1	10
Salvage Value	2	5	1	2	0	10
Maintenance Costs	0	0	2	8	0	10
Insurance Costs	7	1	1	0	0	9
Interest Costs	5	2	2	0	0	9
Depreciation	4	2	3	0	0	9
Operator Costs	1	2	4	2	0	9
Tire Costs	2	2	4	1	0	9
Tire Maintenance Costs	1	3	4	1	0	9
Tire Life Expectancy	2	2	4	1	0	9
Oil Life Expectancy	2	1	6	0	0	9
Oil Costs	1	2	6	0	0	9
Fuel Costs	0	0	4	5	0	9
Lubrication Costs	2	2	6	0	0	10

Appendix C

Software Analysis

The table below contains the results of the content analysis and differentiates the capabilities of each software program. A check in a capability column indicates that the software program performs that certain task. This was completed to indicate the most software programs that would be most apt at providing meaningful out for equipment fleet LCA.

Table 4. Software Capabilities

Software	Capability												
	Multiple facilities	**Network support**	**Import/ Export**	**Auto Email**	**Maintenance Scheduler**	**Work order/ Request**	**Parts Inventory**	**Equipment log**	**Depreciation**	**Inspections**	**Life-cycle costs**	**Accident Reports**	**Multi-site**
Fleetmatics	x				x								x
TMT Fleet Maintenance Software			x				x	x					
Fleet Maintenance Pro (by IMS)		x	x		x	x	x	x	x	x			
(AgileAssets®) Fleet & Equipment Manager™					x	x	x		x		x		
FleetFocus (by AssetWorks)		x			x	x	x			x	x	x	
J. J. Keller's Maintenance Manager™ Software			x		x	x	x	x					
collectiveFleet™			x	x	x	x	x		x	x	x	x	
MH Fleet by MH Equipment		x			x								
Maintenance Connection	x												
eMaint X$_3$	x	x		x	x	x	x	x	x			x	
Maintenance Coordinator	x	x	x	x	x	x	x	x	x				
Maintenance5000					x	x							
Maintenance Pro		x	x		x	x	x	x		x			
Accruent 360Facility					x	x	x			x	x	x	
Infor EAM					x	x	x	x		x	x		
4Site					x		x	x					
Guide TI			x					x					
ManagerPlus			x		x	x	x					x	
iMaint (Fleet)					x	x	x					x	
Maintenance Assistant CMMS			x	x	x	x		x		x			x
MSI Service Pro Repair Center and Field Service					x	x	x	x					x
Fleetio				x	x								
TATEMS					x	x	x						
FleetCommander						x							
Arsenault, Dossier Fleet Maintenance					x	x	x	x			x	x	
RTA Fleet Management						x	x	x					
FleetWave/RoadBASE			x		x	x	x			x			
FleetWise VB					x		x	x					

Table. Software Capabilities Cont'd

Software	Capability												
	Cost Tracking/ Control	Customiz-able	Bar code	Fuel Mgnt	Risk Mgnt	Integrate with CAD	Equipment Tracking	History Recording	MX Mobile Solution	Track Vehicle Maint History	Track Tires	Integration GPS	Mobile Wireless Handheld
Fleetmatics	x			x			x	x		x		x	
TMT Fleet Maintenance Software	x	x	x	x			x				x	x	
Fleet Maintenance Pro (by IMS)	x			x			x	x		x	x		
(AgileAssets®) Fleet & Equipment Manager™				x			x					x	x
FleetFocus (by AssetWorks)	x		x									x	x
J. J. Keller's Maintenance Manager™ Software				x			x			x	x		
collectiveFleet™													
MH Fleet by MH Equipment							x						
Maintenance Connection													
eMaint X_3								x	x				
Maintenance Coordinator													
Maintenance5000	x							x					
Maintenance Pro							x	x					
Accruent 360Facility	x					x							
Infor EAM	x				x								
4Site	x												
Guide TI			x					x					
ManagerPlus	x		x										
iMaint (Fleet)	x	x	x	x									
Maintenance Assistant CMMS		x											
MSI Service Pro Repair Center and Field Service							x						
Fleetio	x			x			x	x		x			
TATEMS				x									
FleetCommander	x	x		x	x							x	
Arsenault, Dossier Fleet Maintenance	x			x				x		x			
RTA Fleet Management	x			x			x				x		
FleetWave/RoadBASE								x					
FleetWise VB				x									

Appendix D

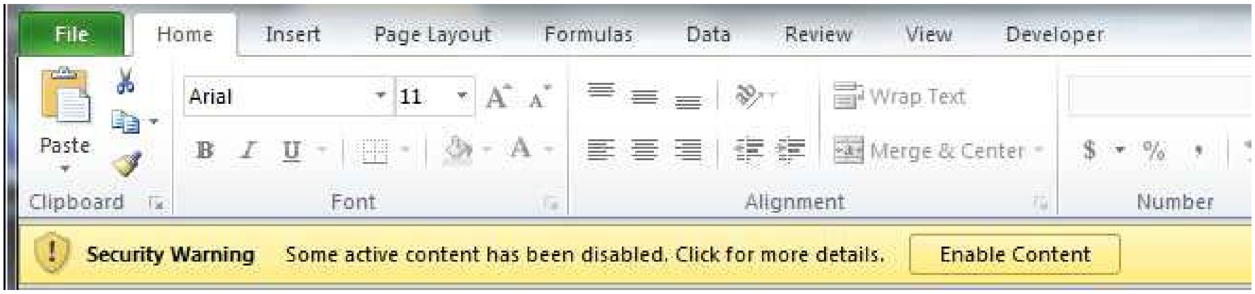
Major Equipment Stochastic LCCA Guide

This report contains the users' guide for the Microsoft Excel workbook containing the major equipment LCCA model that was developed in Task #4. The Excel workbook utilizes the model with the fuel data being the stochastic function and all other parameters being deterministic. The guide will provide step-by-step instructions to display the model's capabilities.

Objective 1	**Enter Data and Run Model**
Task 1.1	Open Excel Workbook
Task 1.2	Run LCCA Model
Objective 2	**Run the Stochastic Component of the Model**
Task 2.1	Stochastic Excel Add-in
Task 2.2	Run Stochastic Excel Add-in and View Results

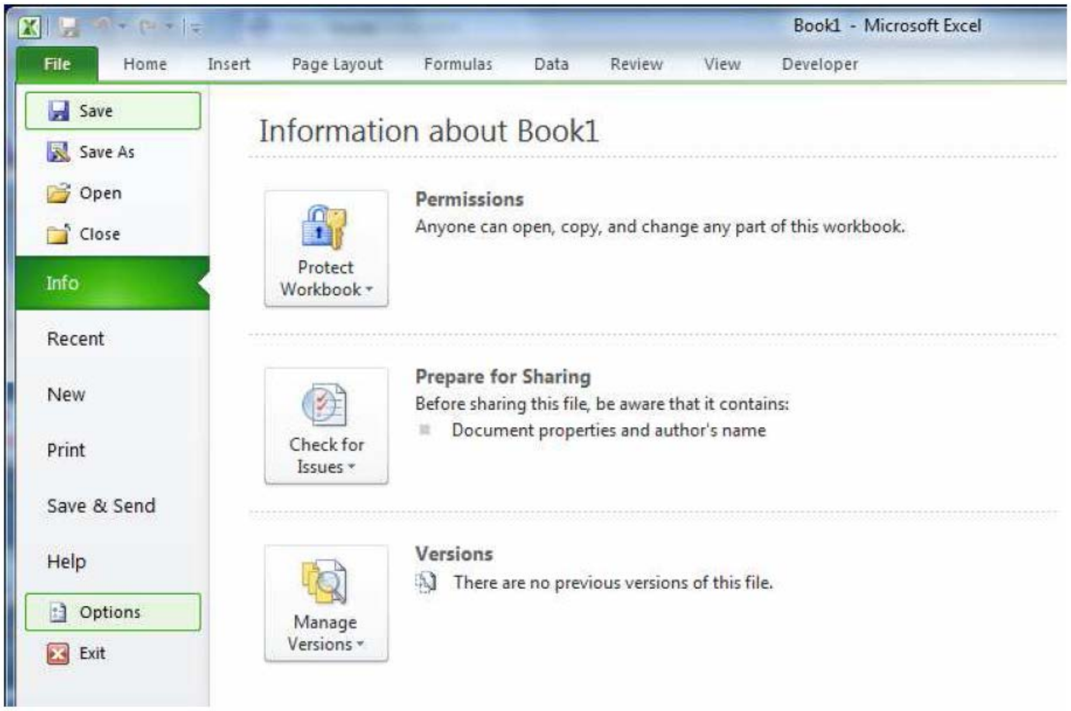
1.1 Open Excel Worksheet

The first step of the users' guide will be to open the Microsoft Excel workbook named Task#5.MnDOT.Equipment_LCCA_Model.073114.xlsm. The workbook is a macro-enabled workbook, thus one of two actions must be completed. The first option may include a security warning on the top of the workbook. If the following image is displayed when opening the workbook, click **Enable Content** as shown in the image below.



Security Warning Some active content has been disabled. Click for more details.

The second option includes the following steps:
Step 1. Select **File** on the menu bar in the upper left hand corner and select **options**.



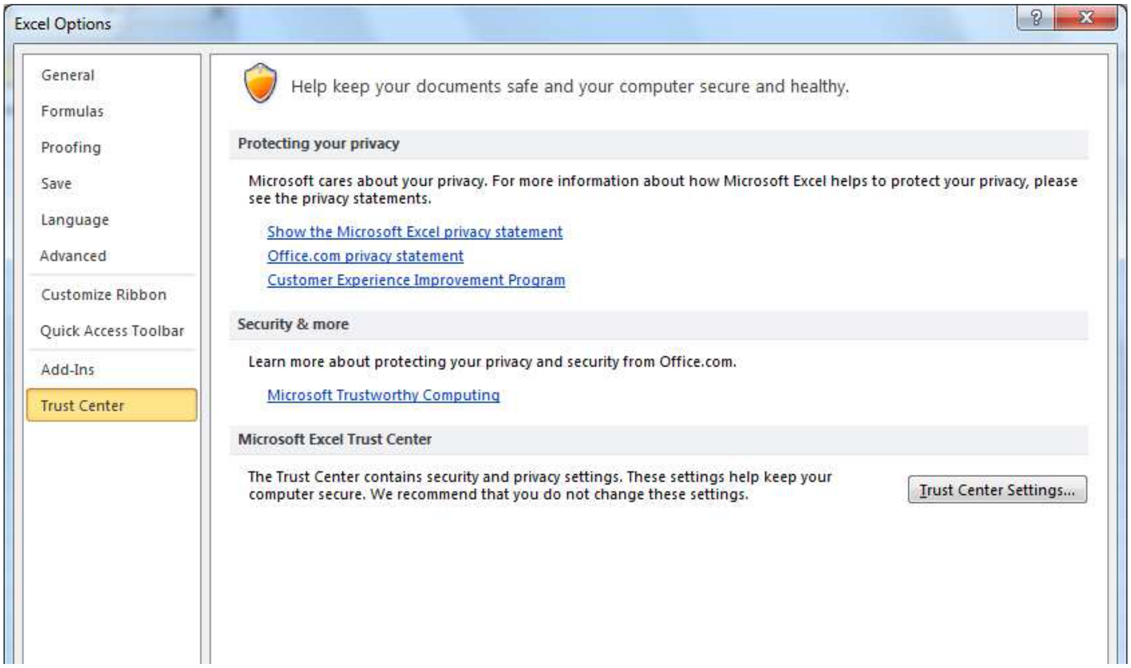
Information about Book1

Permissions
Anyone can open, copy, and change any part of this workbook.

Prepare for Sharing
Before sharing this file, be aware that it contains:
- Document properties and author's name

Versions
There are no previous versions of this file.

Step 2. Select the **Trust Center** tab on the left side of the pop up window. Then select on the **Trust Center Settings** button located on the right side of the widow.



Help keep your documents safe and your computer secure and healthy.

Protecting your privacy

Microsoft cares about your privacy. For more information about how Microsoft Excel helps to protect your privacy, please see the privacy statements.

Show the Microsoft Excel privacy statement
Office.com privacy statement
Customer Experience Improvement Program

Security & more

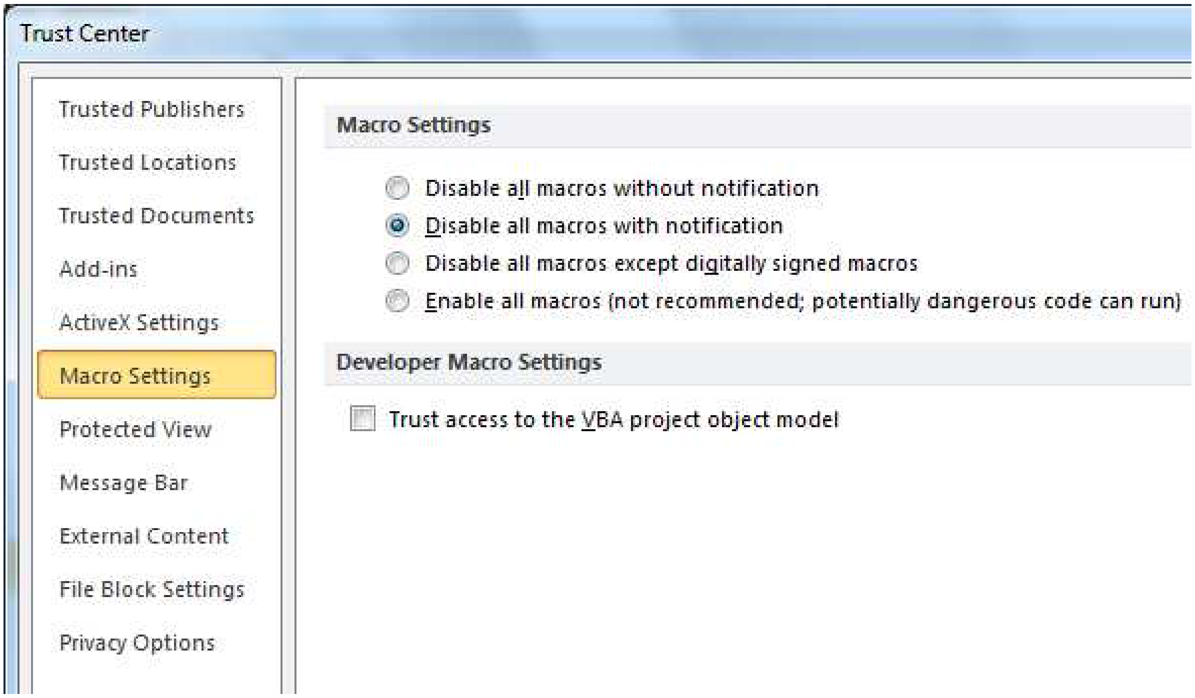
Learn more about protecting your privacy and security from Office.com.

Microsoft Trustworthy Computing

Microsoft Excel Trust Center

The Trust Center contains security and privacy settings. These settings help keep your computer secure. We recommend that you do not change these settings.

Step 3. Select **Macro Settings**, select **Disable all macros with notification**, and then select the **OK** button to apply the changes and exit the window.



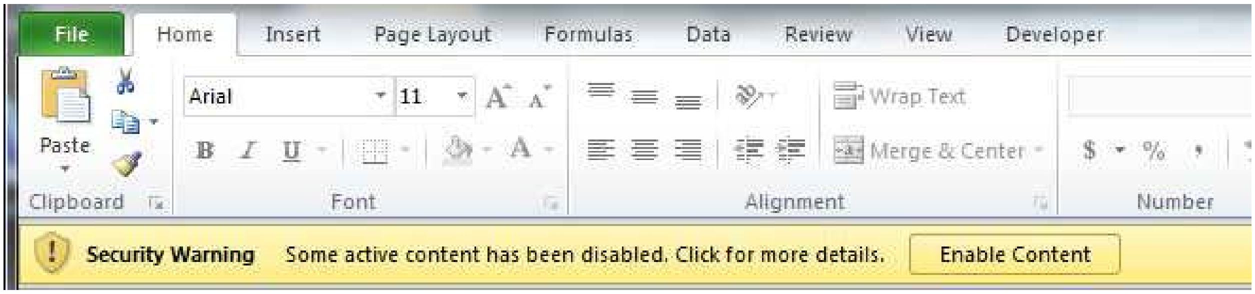
Macro Settings

○ Disable all macros without notification
● Disable all macros with notification
○ Disable all macros except digitally signed macros
○ Enable all macros (not recommended; potentially dangerous code can run)

Developer Macro Settings

☐ Trust access to the VBA project object model

Step 4. Close the Excel workbook, reopen the workbook, and click the **Enable Content** button.



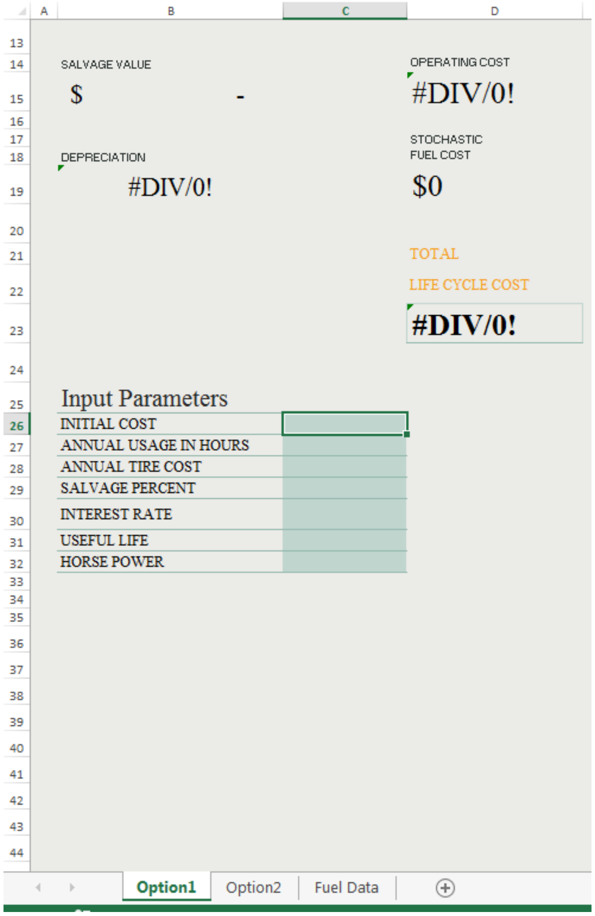
Security Warning Some active content has been disabled. Click for more details.

1.2 Run LCCA Model

Step 1. Choose an Analysis Options
The workbook has three Excel sheets; Option 1, Option 2, and Fuel Data. Option 1 contains the stochastic annual life-cycle costs with fuel prices from 2010 to 2014. Option 2 encompasses the stochastic annual life-cycle costs with fuel prices defined by the user. The Fuel Data Excel sheet contains the data utilized for Option 1 and allows the user to view the available fuel prices.

Step 2. Define Input Parameters

The procedure to run either model is the same. Option 1 will be chosen to demonstrate the capabilities of the workbook. To properly utilize either option the user must define each of the **Input Parameters** shown in the image below.



SALVAGE VALUE
$ -

OPERATING COST
#DIV/0!

DEPRECIATION
#DIV/0!

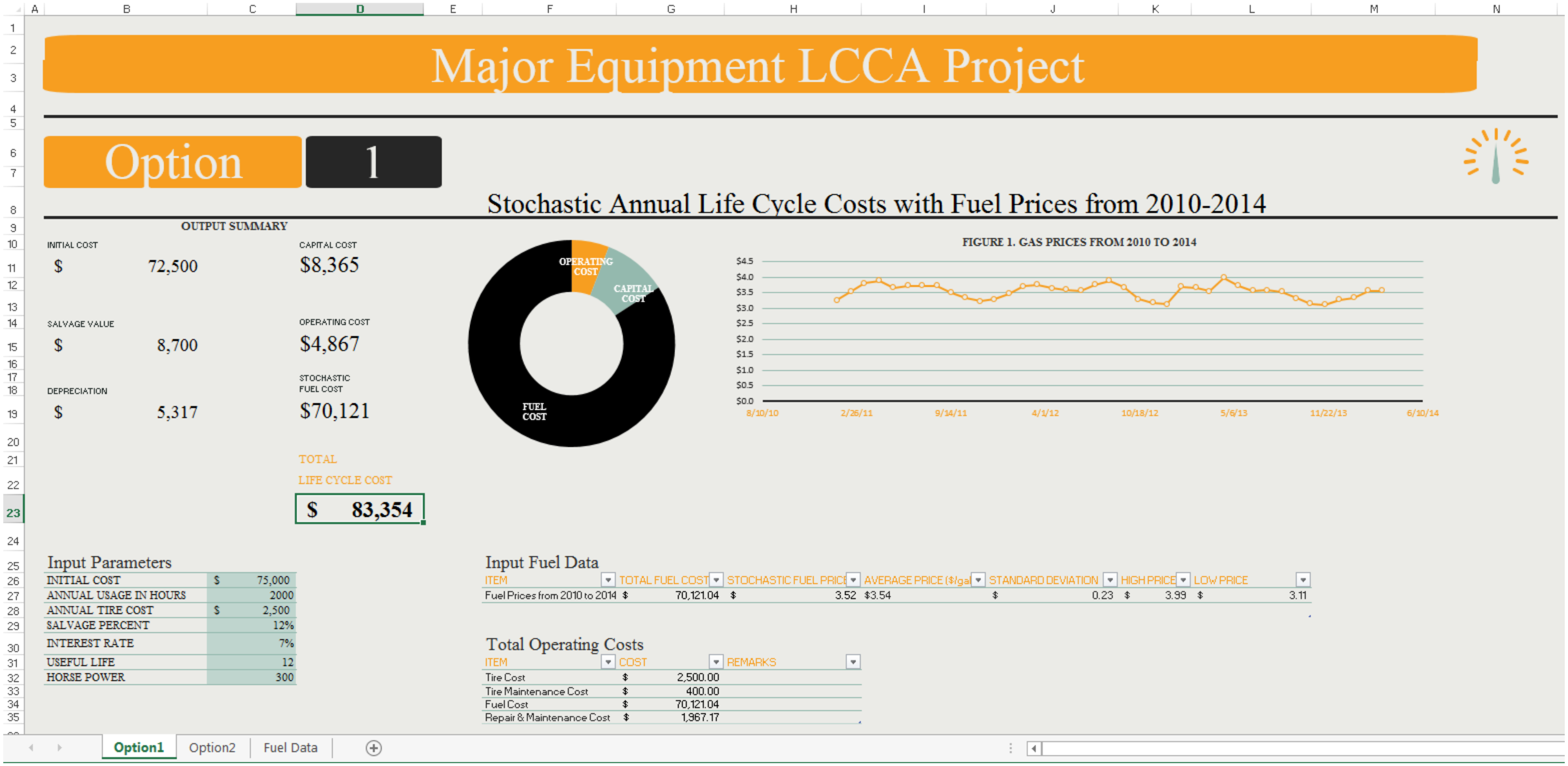
STOCHASTIC FUEL COST
$0

TOTAL
LIFE CYCLE COST
#DIV/0!

Input Parameters

INITIAL COST	
ANNUAL USAGE IN HOURS	
ANNUAL TIRE COST	
SALVAGE PERCENT	
INTEREST RATE	
USEFUL LIFE	
HORSE POWER	

The following image is an example of what Option 1 should look like when the input parameters have been specified. Note: This is purely an example and the output that the user views may have different quantities.



Major Equipment LCCA Project

Option 1

Stochastic Annual Life Cycle Costs with Fuel Prices from 2010-2014

OUTPUT SUMMARY

INITIAL COST $ 72,500	CAPITAL COST $8,365
SALVAGE VALUE $ 8,700	OPERATING COST $4,867
DEPRECIATION $ 5,317	STOCHASTIC FUEL COST $70,121
	TOTAL LIFE CYCLE COST $ 83,354

Input Parameters

INITIAL COST	$ 75,000
ANNUAL USAGE IN HOURS	2000
ANNUAL TIRE COST	$ 2,500
SALVAGE PERCENT	12%
INTEREST RATE	7%
USEFUL LIFE	12
HORSE POWER	300

Input Fuel Data

ITEM	TOTAL FUEL COST	STOCHASTIC FUEL PRICE	AVERAGE PRICE ($/gal	STANDARD DEVIATION	HIGH PRICE	LOW PRICE
Fuel Prices from 2010 to 2014	$ 70,121.04	$ 3.52	$3.54	$ 0.23	$ 3.99	$ 3.11

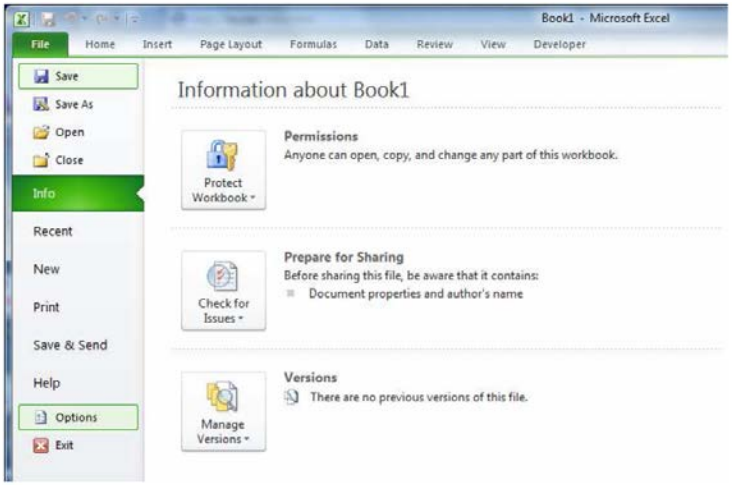
Total Operating Costs

ITEM	COST	REMARKS
Tire Cost	$ 2,500.00	
Tire Maintenance Cost	$ 400.00	
Fuel Cost	$ 70,121.04	
Repair & Maintenance Cost	$ 1,967.17	

2.1 Stochastic Excel Add-in

Step 1. Make sure Add-Ins Tab is located on Excel Ribbon

If the user is able to view the Add-Ins tab at the top of the excel sheet than this step may be skipped. If the Add-Ins tab is not available, select **File** on the menu bar in the upper left hand corner and select **options**.



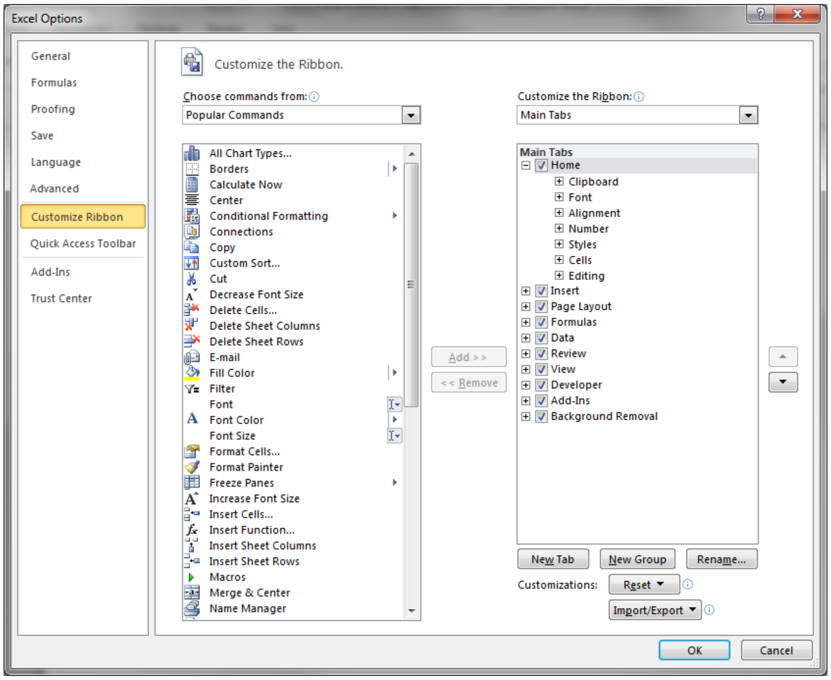
Information about Book1

Permissions
Anyone can open, copy, and change any part of this workbook.

Prepare for Sharing
Before sharing this file, be aware that it contains:
Document properties and author's name

Versions
There are no previous versions of this file.

Than select **Customize Ribbon** and check the **ADD-INS** tab. Select **OK**, proceed to the next step.



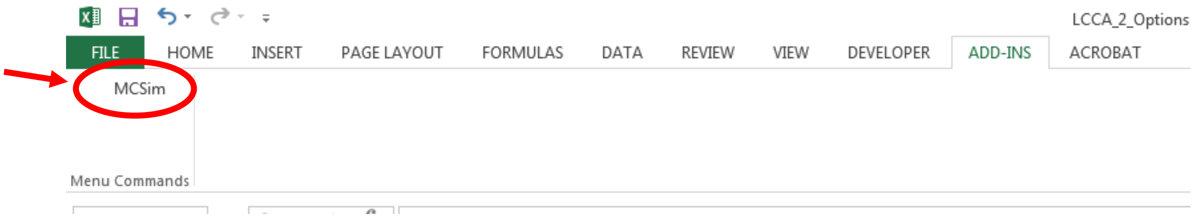
Customize the Ribbon.

Choose commands from: Popular Commands

Customize the Ribbon: Main Tabs

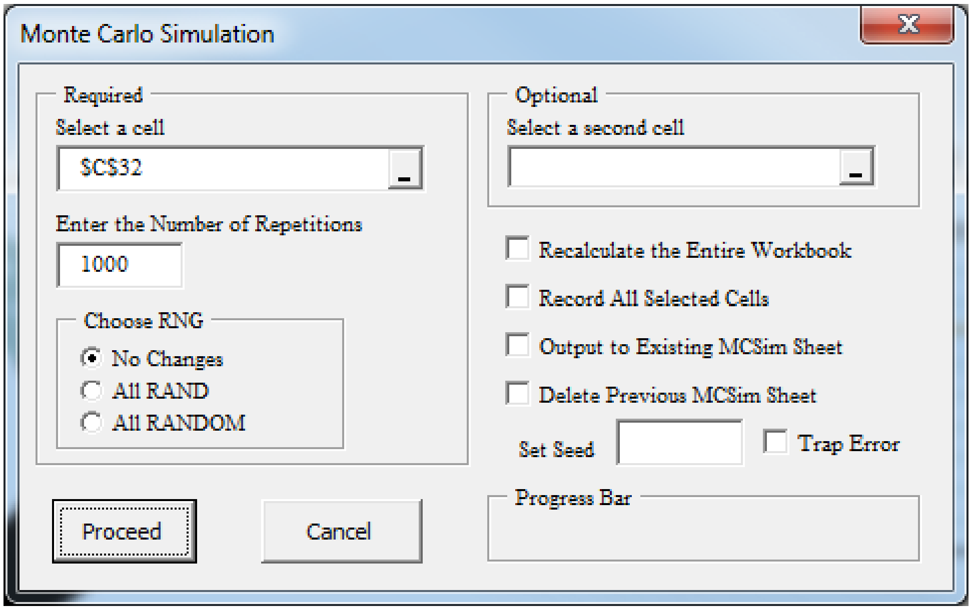
Step 2. Locate and Open Stochastic Add-In

Click on the **ADD-INS** tab at the top of the Excel workbook. Click on the item called **MCSim** located within the tab.



Step 3. Make sure Monte Carlo Simulation Window is Open

If your screen does not have the flowing window open go back to Step 1.



Select a cell: $C$32

Enter the Number of Repetitions: 1000

Choose RNG
- ● No Changes
- ○ All RAND
- ○ All RANDOM

- ☐ Recalculate the Entire Workbook
- ☐ Record All Selected Cells
- ☐ Output to Existing MCSim Sheet
- ☐ Delete Previous MCSim Sheet

Set Seed ☐ Trap Error

2.2 Run Stochastic Excel Add-in and View Results

Step 1. Specify Output Cell

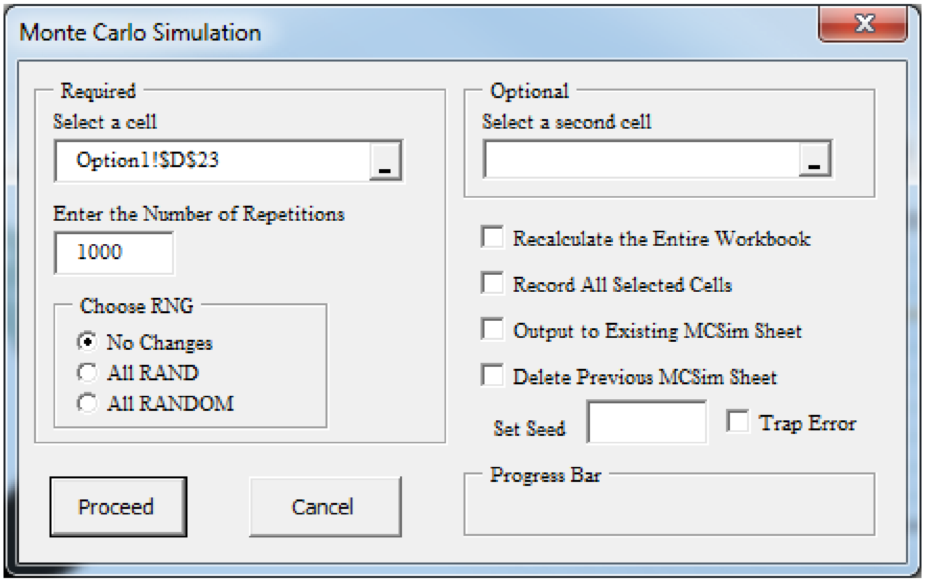
In the **Select a Cell** field click on the drop box to select the output cell, a small window will appear. Delete any and all text within the small window. Then select the **Total Life-cycle Cost** cell in the Excel sheet, the green cell with the bold black numbering. After the cell has been chosen select the following icon ▣.

Option1!$D$23

Step 2. Run Stochastic Model

After the output cell has been chosen, the Monte Carlo Simulation window should appear once again. The user may specify the number of repetitions. The more repetitions the more accurate the simulation will be. After the user has set the

Required iterations, click on the **Proceed** button on the lower left hand of the window.



Monte Carlo Simulation

Required

Select a cell

Option1!$D$23

Enter the Number of Repetitions

1000

Choose RNG

● No Changes

○ All RAND

○ All RANDOM

Optional

Select a second cell

☐ Recalculate the Entire Workbook

☐ Record All Selected Cells

☐ Output to Existing MCSim Sheet

☐ Delete Previous MCSim Sheet

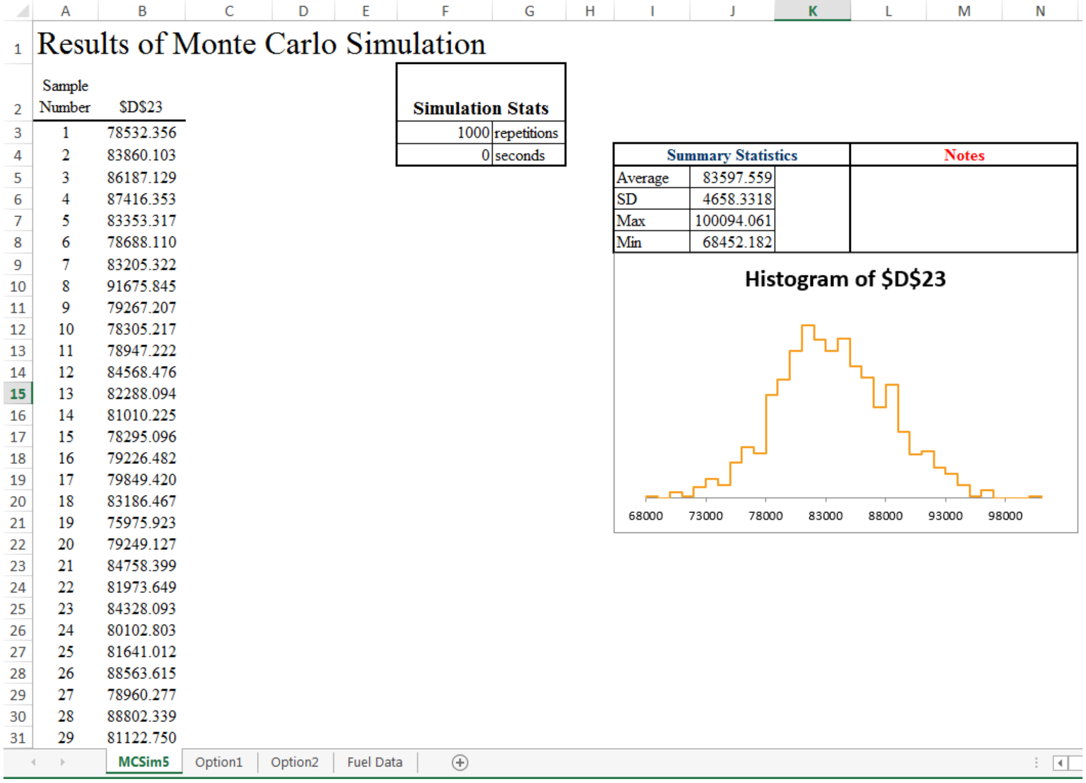
Set Seed

☐ Trap Error

Progress Bar

Step 3. View Results

A new Excel sheet will automatically open with the Monte Carlo Simulation results. The two columns on the far left of the sheet display the iterations that occur during the simulation. The summary statistics display the mean, standard deviation, maximum value, minimum value, and a histogram of the results.



Results of Monte Carlo Simulation

Sample Number	$D$23
1	78532.356
2	83860.103
3	86187.129
4	87416.353
5	83353.317
6	78688.110
7	83205.322
8	91675.845
9	79267.207
10	78305.217
11	78947.222
12	84568.476
13	82288.094
14	81010.225
15	78295.096
16	79226.482
17	79849.420
18	83186.467
19	75975.923
20	79249.127
21	84758.399
22	81973.649
23	84328.093
24	80102.803
25	81641.012
26	88563.615
27	78960.277
28	88802.339
29	81122.750

Simulation Stats	
1000	repetitions
0	seconds

Summary Statistics		Notes
Average	83597.559	
SD	4658.3318	
Max	100094.061	
Min	68452.182	

Histogram of $D$23