



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**A COST BENEFIT ANALYSIS OF RADIO FREQUENCY
IDENTIFICATION (RFID) IMPLEMENTATION AT THE
DEFENSE MICROELECTRONICS ACTIVITY (DMEA)**

by

James B. Gerber

December 2011

Thesis Co-Advisors:

Kenneth Doerr

Tali Freed

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2011	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE A Cost Benefit Analysis of Radio Frequency Identification (RFID) Implementation at the Defense Microelectronics Activity (DMEA)			5. FUNDING NUMBERS	
6. AUTHOR(S) James B. Gerber				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _____N/A_____.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release, distribution is unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) <p>This thesis focuses on the Defense Microelectronics Activity (DMEA) and its need to reduce its budget through becoming more efficient. There are many means for becoming more efficient; this report will analyze the adoption of radio frequency identification (RFID) technology as one way in which DMEA can achieve cost savings. The goal was to construct a working model to simulate factory conditions at electronics manufacturers' facilities, regardless of the size or breadth of production. The end state was to identify all major variables associated with the costs of RFID implementation, and the derived annual benefits, thereby giving decision makers an idea of the relative financial attractiveness of RFID.</p>				
14. SUBJECT TERMS Radio Frequency Identification, RFID, Defense Microelectronics Activity, DMEA, Cost Benefit Analysis, Costs, Benefits, Savings			15. NUMBER OF PAGES 121	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

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ACTIVITY (DMEA)**

James B. Gerber
Captain, United States Marine Corps
B.A., Washington State University, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MANAGEMENT

from the

**NAVAL POSTGRADUATE SCHOOL
December 2011**

Author: James B. Gerber

Approved by: Kenneth Doerr
Thesis Co-Advisor

Tali Freed
Thesis Co-Advisor

William R. Gates
Dean, Graduate School of Business and Public Policy

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ABSTRACT

This thesis focuses on the Defense Microelectronics Activity (DMEA) and its need to reduce its budget through becoming more efficient. There are many means for becoming more efficient; this report will analyze the adoption of radio frequency identification (RFID) technology as one way in which DMEA can achieve cost savings. The goal was to construct a working model to simulate factory conditions at electronics manufacturers' facilities, regardless of the size or breadth of production. The end state was to identify all major variables associated with the costs of RFID implementation, and the derived annual benefits, thereby giving decision makers an idea of the relative financial attractiveness of RFID.

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TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	INTRODUCTION.....	1
B.	DEFENSE MICROELECTRONICS ACTIVITY.....	1
C.	RESEARCH QUESTIONS.....	2
D.	METHODOLOGY.....	3
II.	BACKGROUND.....	5
A.	WHAT IS RFID?.....	5
B.	RFID HARDWARE.....	6
1.	Tags.....	6
2.	Readers.....	7
3.	Antennas.....	8
C.	SOFTWARE.....	8
D.	APPLICATIONS.....	9
E.	COSTS.....	10
F.	BENEFITS.....	10
G.	DISADVANTAGES.....	12
H.	CONCLUSION.....	14
III.	MODEL.....	15
A.	INTRODUCTION.....	15
B.	BENEFITS.....	15
1.	Physical Count.....	15
2.	Shrinkage Reduction.....	16
3.	Quality Savings.....	16
a.	<i>Products with Defects and Caught Internally.....</i>	<i>16</i>
b.	<i>Products with Defects and Caught Externally (Warranty Failures).....</i>	<i>17</i>
c.	<i>Conditions Relevant to Benefits.....</i>	<i>18</i>
4.	Model Variables.....	18
a.	<i>Physical Count.....</i>	<i>18</i>
b.	<i>Shrinkage Reduction.....</i>	<i>19</i>
c.	<i>Cost of Quality Savings.....</i>	<i>19</i>
C.	COSTS.....	19
1.	Capital Expenditures.....	20
a.	<i>Bays.....</i>	<i>20</i>
b.	<i>Readers.....</i>	<i>20</i>
c.	<i>Antennas.....</i>	<i>21</i>
d.	<i>Tags.....</i>	<i>21</i>
e.	<i>Computers.....</i>	<i>21</i>
f.	<i>Printers.....</i>	<i>22</i>
g.	<i>Software.....</i>	<i>22</i>
2.	Implementation Costs.....	22

3.	Training Costs	23
4.	Cost Variables	23
a.	Capital Expenditures.....	23
b.	Implementation Costs	24
c.	Training Costs	24
D.	INTEGRATION INTO COMPUTER MODEL	24
1.	Introduction.....	24
2.	Benefits.....	25
a.	Tracking and Control.....	25
b.	Shrinkage Reduction.....	26
c.	Cost of Quality Savings.....	28
3.	Costs	31
a.	Capital Expenditures.....	31
b.	Implementation Costs	32
c.	Training Costs	33
IV.	SCENARIOS	35
A.	INTRODUCTION.....	35
B.	SCENARIOS	36
1.	Scenarios One through Eight.....	36
a.	One through Four.....	37
b.	Five through Eight.....	38
2.	Scenarios Nine through Sixteen.....	39
a.	Nine through Twelve.....	39
b.	Thirteen through Sixteen.....	40
3.	Scenarios Seventeen through Twenty-Four.....	41
a.	Seventeen through Twenty.....	41
b.	Twenty-One through Twenty-Four	42
4.	Summary.....	43
C.	RESULTS	45
1.	Changes in Product Quality, Complexity and Inventory	45
2.	Costs, Benefits and Payback Period	49
V.	CONCLUSIONS	59
A.	INTRODUCTION.....	59
B.	CONCLUSIONS	59
C.	SUMMARY	61
APPENDIX.	SCENARIO DATA	63
LIST OF REFERENCES		99
INITIAL DISTRIBUTION LIST		101

LIST OF FIGURES

Figure 1.	RFID Process	5
Figure 2.	Tracking and Control	26
Figure 3.	Shrinkage Reduction	28
Figure 4.	Cost of Quality Savings	30
Figure 5.	Capital Expenditure Setup Options	32
Figure 6.	Implementation Costs	33
Figure 7.	Training Costs	34
Figure 8.	Scenario 1 Capital Expenditures	47
Figure 9.	Scenario 3 Capital Expenditures	47
Figure 10.	Scenario 1 Implementation Costs	48
Figure 11.	Scenario 3 Implementation Costs	48
Figure 12.	Total Cost Distribution for Scenario 1	50
Figure 13.	Total Benefit Distribution for Scenario 1	51
Figure 14.	Payback Distribution for Scenario 1	51
Figure 15.	Scenario 1 Total Costs	63
Figure 16.	Scenario 1 Total Benefits	63
Figure 17.	Scenario 1 Payback	64
Figure 18.	Scenario 2 Total Costs	64
Figure 19.	Scenario 2 Total Benefits	65
Figure 20.	Scenario 2 Payback	65
Figure 21.	Scenario 3 Total Costs	66
Figure 22.	Scenario 3 Total Benefits	66
Figure 23.	Scenario 3 Payback	67
Figure 24.	Scenario 4 Total Costs	67
Figure 25.	Scenario 4 Total Benefits	68
Figure 26.	Scenario 4 Payback	68
Figure 27.	Scenario 5 Total Costs	69
Figure 28.	Scenario 5 Total Benefits	69
Figure 29.	Scenario 5 Payback	70
Figure 30.	Scenario 6 Total Costs	70
Figure 31.	Scenario 6 Total Benefits	71
Figure 32.	Scenario 6 Payback	71
Figure 33.	Scenario 7 Total Costs	72
Figure 34.	Scenario 7 Total Benefits	72
Figure 35.	Scenario 7 Payback	73
Figure 36.	Scenario 8 Total Costs	73
Figure 37.	Scenario 8 Total Benefits	74
Figure 38.	Scenario 8 Payback	74
Figure 39.	Scenario 9 Total Costs	75
Figure 40.	Scenario 9 Total Benefits	75
Figure 41.	Scenario 9 Payback	76
Figure 42.	Scenario 10 Total Costs	76

Figure 43.	Scenario 10 Total Benefits.....	77
Figure 44.	Scenario 10 Payback	77
Figure 45.	Scenario 11 Total Costs	78
Figure 46.	Scenario 11 Total Benefits.....	78
Figure 47.	Scenario 11 Payback	79
Figure 48.	Scenario 12 Total Costs	79
Figure 49.	Scenario 12 Total Benefits.....	80
Figure 50.	Scenario 12 Payback	80
Figure 51.	Scenario 13 Total Costs	81
Figure 52.	Scenario 13 Total Benefits.....	81
Figure 53.	Scenario 13 Payback	82
Figure 54.	Scenario 14 Total Costs	82
Figure 55.	Scenario 14 Total Benefits.....	83
Figure 56.	Scenario 14 Payback	83
Figure 57.	Scenario 15 Total Costs	84
Figure 58.	Scenario 15 Total Benefits.....	84
Figure 59.	Scenario 15 Payback	85
Figure 60.	Scenario 16 Total Costs	85
Figure 61.	Scenario 16 Total Benefits.....	86
Figure 62.	Scenario 16 Payback	86
Figure 63.	Scenario 17 Total Costs	87
Figure 64.	Scenario 17 Total Benefits.....	87
Figure 65.	Scenario 17 Payback	88
Figure 66.	Scenario 18 Total Costs	88
Figure 67.	Scenario 18 Total Benefits.....	89
Figure 68.	Scenario 18 Payback	89
Figure 69.	Scenario 19 Total Costs	90
Figure 70.	Scenario 19 Total Benefits.....	90
Figure 71.	Scenario 19 Payback	91
Figure 72.	Scenario 20 Total Costs	91
Figure 73.	Scenario 20 Total Benefits.....	92
Figure 74.	Scenario 20 Payback	92
Figure 75.	Scenario 21 Total Costs	93
Figure 76.	Scenario 21 Total Benefits.....	93
Figure 77.	Scenario 21 Payback	94
Figure 78.	Scenario 22 Total Costs	94
Figure 79.	Scenario 22 Total Benefits.....	95
Figure 80.	Scenario 22 Payback	95
Figure 81.	Scenario 23 Total Costs	96
Figure 82.	Scenario 23 Total Benefits.....	96
Figure 83.	Scenario 23 Payback	97
Figure 84.	Scenario 24 Total Costs	97
Figure 85.	Scenario 24 Total Benefits.....	98
Figure 86.	Scenario 24 Payback	98

LIST OF TABLES

Table 1.	RFID Tag Attributes	7
Table 2.	Comparison of RFID and Bar Code.....	13
Table 3.	Scenario Summary	44
Table 4.	Effect of Product Quality Increase on Mean Yearly Benefit.....	45
Table 5.	Effect of Complexity Change on Mean Costs	46
Table 6.	Effect of Time Spent on Inventory on Mean Benefits	49
Table 7.	Expected Payback	56
Table 8.	Payback Confidence Intervals.....	57

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LIST OF ACRONYMS AND ABBREVIATIONS

COTS	Commercial-off-the-Shelf
DMEA	Defense Microelectronics Activity
ERP	Enterprise Resource Planning
DoD	Department of Defense
GPS	Global Positioning System
HF	High Frequency
LF	Low Frequency
MES	Manufacturing Execution System
NPV	Net Present Value
OSD	Office of Secretary of Defense
RFID	Radio Frequency Identification
UHF	Ultra-High Frequency
WORM	Write Once, Read Many

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EXECUTIVE SUMMARY

As the military enters 2012, the looming prospect of budget cuts to the Defense Department are forcing all agencies and activities to look hard at their financial strategies in order to find more efficient ways to operate. One such organization, the Defense Microelectronics Activity, hopes to increase their efficiency through the implementation of radio frequency identification (RFID) technology that will provide valuable, quantifiable benefits for years into the future. RFID is a recently emerged technology that is making large gains in the manufacturing industry, and DMEA is in a position to take advantage of the benefits.

This study examined the underlying costs associated with the implementation of RFID technology, as well as benefits that could be quantified in terms of dollar values. The author then created a model with the defined cost and benefit variables, and ran twenty-four simulations of the model in order to survey the financial benefits of RFID for electronics manufacturers who vary in facility size and breadth of production. The three cost drivers that the study focused on were capital expenditures (hardware and software), the installation of all equipment and training for employees to use the equipment. The three financial benefits that were examined savings resulting from conducting fewer inventories, a reduction in inventory shrinkage and a reduction in the number of production errors.

The study found that the most important factors to consider whether to adopt RFID are the size of the plant and the amount of time spent conducting inventories. The major cost driver that affected payback time was the amount of complexity involved in the RFID implementation (number of readers, antennas, tags).

Finally, the results of the study found that for small manufacturers like DMEA, a non-complex installation of RFID can be very beneficial to providing future savings.

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ACKNOWLEDGMENTS

First and foremost, thanks must be given to my wife, Amy, who endured and supported me through this thesis deployment. Second, to my four children who saw less of me than I intended during the past couple of months: Alyssa, Brooklyn, Cody and Delaney. Third, to my advisors, Dr. Kenneth Doerr and Dr. Tali Freed, whose advice, leadership and knowledge were vital to the successful completion of this report. Finally, a thank you to the personnel at DMEA, who were very gracious in opening their facility and knowledge up to me.

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I. INTRODUCTION

A. INTRODUCTION

As the military enters 2012, looming budget cuts are forcing the Department of Defense to look toward cutting unnecessary or overly expensive programs, while paring down costs and/or increasing the efficiency of needed programs. The Defense Microelectronic Activity (DMEA), considered to be in the field of electronic contract manufacturing, is one such government organization that is planning on increasing its efficiency in order to cut costs, and plans on doing this through implementation of Radio Frequency Identification (RFID) technology. The purpose of this report is to identify all variables associated with the costs and benefits of an RFID implementation. The goal is to create a working model that can simulate factory conditions at DMEA, or other electronics manufacturing facilities, in order to provide a basis for cost-benefit analysis of an RFID implementation. The model will be demonstrated on twenty-four scenarios, constructed to represent a range of operating conditions at electronics manufacturers. The end result is a demonstration of how an agency that seeks to improve efficiency through RFID implementation might use the model to assess the economic feasibility of the implementation.

B. DEFENSE MICROELECTRONICS ACTIVITY

As a government activity that falls directly under the Office of the Secretary of Defense (OSD), DMEA is ideally situated to provide microelectronics and services to the military. Originally created in 1981 as a small unit in the Air Force, DMEA officially joined the OSD in 1997, and currently reports to the Director, Defense Research and Engineering. DMEA is located in Sacramento, California, which positions it close to the Silicon Valley to better support its mission.

DMEA's mission is to provide microelectronics support to current, future and legacy weapon systems within the military. Three factors affect military requirements, making DMEA's mission critical. First, security for military weapons systems is jeopardized by the rapid pace of technological developments. This rapid pace ensures

that the commercial world of microelectronics will not be able to support existing platforms into the future due to their need to continually keep up with new developments. DMEA meets this need by maintaining an ability to design, fabricate, and produce limited quantities of microelectronics for systems which are no longer supported. Second, new advances in potential adversary's weapon systems require the U.S. to maintain superiority through upgrading and/or designing and purchasing new systems. In a financially austere environment, these costs can be prohibitive. DMEA meets this need by redesigning and reengineering existing systems to make them superior to the adversary's systems. Third, the Department of Defense (DoD) often has requirements for very low volume electronics with an extended timeframe of support. Commercial and DoD enterprises find this requirement to be costly and unsupportable. DMEA meets this need through not only designing the required electronics, but saving the designs and maintaining the ability to reproduce the designs at any later date.

As important as DMEA is to DoD, fiscal obligations require all institutions to become better stewards of taxpayer dollars. DMEA hopes to accomplish this through instituting an RFID implementation that will provide valuable, quantifiable benefits for years into the future. These benefits initially will be confined to improved inventory controls and increasing the efficiency of work-in-process, but might also bring future benefits through improved chemical tracking, improved reporting and automated shipping.

C. RESEARCH QUESTIONS

1. What are the underlying costs of an RFID implementation in an electronics manufacturing setting?
2. What are the benefits in an electronics manufacturing setting that can be quantified in dollar values?
3. Can the costs and benefits be described in a mathematical model?
4. Can the mathematical model be captured in a spreadsheet template and applied to realistic manufacturing scenarios?

D. METHODOLOGY

This research paper models costs and benefits associated with an RFID implementation and applies that model to twenty four specific scenarios. These scenarios relate to the size of the plant and, consequently, the size of the implementation, the volume of production within the plant, the degree to which the manufacturing facility experiences shrinkage and the quality of the end products, as measured by defect rates. The intent is to assume as little as possible about individual performances of manufacturing facilities. Therefore, the scenarios will reflect small, medium and large plant sizes, with each plant having varying degrees of production volume, shrinkage and defect rates. The identified costs are divided into hardware and software purchase, installation of hardware and training costs. Benefits are described in terms of inventory count savings, reductions in shrinkage and an increase in product quality. The intent of this scenario analysis is to provide a proof-of-concept of the economic model, demonstrating how it might be applied in a realistic setting, and the data requirements to implement it. The scenarios do not represent a random, or even a systematic sample of electronics manufacturing businesses, so the results of the analysis should not be seen as an attempt to predict or describe the economic utility of RFID across the electronics manufacturing sector.

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II. BACKGROUND

A. WHAT IS RFID?

RFID is one of the technologies grouped in the category of automatic identification technologies, along with barcodes, magnetic stripes, smart cards and biometrics. RFID uses radio wave technology to wirelessly transmit the unique identity of a tagged item to a tracking system or program. It does this through the use of tags, readers, antennas and the necessary software to provide a user interface (see Figure 1).

The key to the technology behind RFID is that it allows companies to leverage real-time information on their system processes. By tagging tools, equipment, inventory and work-in-process, managers can have instant access to reports that identify where all inventory currently resides, what inventory is currently in process and which tools or machines are in use and/or have reached their processing ceiling and need to be recalibrated or serviced. In addition, RFID has the potential, if applied correctly, to identify and flag work-in-process items that have arrived at the wrong work-station and consequently might have defects.



Figure 1. RFID Process

B. RFID HARDWARE

1. Tags

RFID tags are the computer chips that are placed onto objects for identification purposes. Each tag has a unique identification number, and other manufacturing information, which is sent to the reader. Tags are usually composed of at least two components – an integrated circuit that modulates radio frequencies and then stores and processes that information, and an antenna that can receive and transmit radio transmissions using backscatter technology. When the tag comes into range of a reader, the modulator reads the radio signal and the antenna transmits its' identification number to the reader.

Tag configurations come in passive, semi-passive, and active. Table 1 illustrates the differences between active and passive tags.

Passive tags remain inert until they come within close proximity of a reader, in which case they transmit their signal. Passive tags do not need batteries; they merely use the power received from the reader to broadcast their signal. This limits the range of the tag antenna but results in a longer shelf life (Dipert, 2004).

A subset of passive tags is semi-passive tags, which act like passive tags but have a local power source. This power source can be used to extend the range of the antenna, and to track local environmental conditions.

Active tags, like semi-passive tags, use batteries to power their circuits, but they continuously broadcast their signals. The local power provides additional capabilities, such as expanded range, processing power, and the ability to interact with other devices such as a Global Positioning Device (GPS).

Tags can use frequencies ranging from Low Frequency (LF) to High Frequency (HF) and Ultra High Frequency (UHF) depending on the application. Higher frequencies require more power but have a longer transmission range (Dipert, 2004). Lower frequencies require much less power and are generally used in passive tag applications with high-water content, such as fruit.

Table 1. RFID Tag Attributes

	Active RFID	Passive RFID
Tag Power Source	Internal to tag	Energy transferred using RF from reader
Tag Battery	Yes	No
Availability of power	Continuous	Only in field of reader
Required signal strength to tag	Very low	Very high
Range	Up to 100m	Up to 3–5 m, usually less
Multi-tag Reading	1000's of tags recognized – up to 100mph	Few hundred within 3m of reader
Data Storage	Up to 128Kb or read/write with sophisticated search and access	128 bytes of read/write

In an effort to standardize tags, and to reduce their cost, a consortium of industry leaders started EPCglobal, short for Electronic Product Code. They have classified tags into 6 categories based on the capabilities of the tag (Baudin). The classes and capabilities are:

Class 0: Read Only – Programmed by the factory that manufactures the tag

Class 1: Write Once, Read Many (WORM) – Programmed by the factory or the user

Class 2: Read / Write - Can be programmed over and over based on requirements

Class 3: Read / Write with on-board sensors – to record parameters such as temperature

Class 4: Read / Write with integrated transmitters – can communicate independent of readers

Class 5: Read / Write with integrated transmitters – All Class-4 capabilities along with the ability to communicate with passive devices

2. Readers

Like tags, readers can be categorized into passive and active, and are also called interrogators.

Passive UHF readers are used in applications requiring long-range reading of passive tags, and can reach around thirty feet. Passive HF readers can read up to three feet away, and passive LF readers need to be within one foot of the tag.

Active readers are used for tracking of tags at much longer distances, with reader distances very strongly correlated to the strength of the power source in the tag. HF frequencies can be as low as 100 KHz, and UHF frequencies can get as high as 5.8 GHz (Asif & Mandviwalla, 2005).

Beyond active and passive tags, readers can further be categorized into fixed, handheld, and mobile (Boeck, Lefebvre, L. & Lefebvre, E. 2008). Fixed readers are best utilized for the tracking of mobile tags through a defined, conveyor-belt type of process. Handheld readers are small in size, easily moved around, and can be an asset when portability is required. Mobile readers are of higher durability and can be mounted to vehicles or equipment.

3. Antennas

As with all RFID technologies, antennas come in a large range of sizes, from under a square centimeter to larger than a square meter (Asif & Mandviwalla, 2005). The gain of an antenna represents the operating range; the higher the gain, the farther the antenna can reach. UHF antennas can be single-direction receivers or circular receivers. Antennas that are single-direction have higher gain, and will reach farther distances, while omni-directional antennas cover less area due to the larger signal spread.

C. SOFTWARE

Software for RFID is generally divided into middleware and back-end solutions such as Enterprise Resource Planning (ERP), with a new emerging category being “smart” readers that don’t require middleware.

Simply speaking, middleware is a layer of software between the RFID reader and the back-end application, and is considered to be the brains of the RFID system because it manages all aspects of it (Boeck, Lefebvre, & Lefebvre, 2008). It has three main functions. One, it connects to the reader to extract data, or events, and interprets this

data. Two, it filters the data and aggregates it to read junk or repetitive data. Three, it sends the relevant data to the final application to be acted upon.

Back-end applications can take the form of ERP's, Manufacturing Execution Systems (MES's), or any other custom end-user application. These applications can serve many functions such as tracking equipment and labor, inventory management, costing, defect and resolution monitoring, and controlling warehouse activities such as shipping, receiving, and storing.

D. APPLICATIONS

It is important to note how current manufacturers have adopted and implemented from the implementation of RFID technology. Generally speaking, benefits within manufacturing usually involve fully automated identification of objects to improve visibility, inventory tracking, reducing errors, automating warehousing functions such as shipping and receiving, and tracking labor, parts, and consumables. Two examples of real companies show these benefits in action.

In an effort to maintain an edge on their competitors, in 2002 Harley Davidson developed and instituted a plan to implement RFID tracking of major motorcycle components. Their goal was to improve efficiency and reduce errors throughout the assembly process. They decided on an asset-tracking system called AVIS, and tracked their major components with tags that carried model number, serial number, and the required operations at each stage of the manufacturing process. As each component moved through the process, stationary RFID readers read the tags and displayed the information on computer screens at each workstation to ensure that the component was at the right workstation and completing the right operation. The resulting benefits of this RFID implementation were decrease in errors of ninety percent, improved manufacturing efficiency, and increased ability to track and improve product designs.

In a case of strict, exacting demands from their customers, Johnson Controls implemented an RFID solution to drastically increase their efficiency and reduce errors in shipping. Johnson Controls' customers required daily delivery of truck and car seats to be in an exact order and exact quantity. Due to the seats being delivered directly to a

vehicle production line, out-of-order seats would bring the production line to a standstill. The use of LF tags helped the company track their seats even though there was a high amount of metal present, and allowed tag tracking through production, testing, and inspecting. The greatest benefit came after the inspection phase, when the RFID software could automatically place the seats in proper shipping order, thus saving time and money.

E. COSTS

RFID tags have a wide range of prices, and costs are very much dependent on the application. Tags that act primarily as smart labels can be applied to cases and pallets for as little as 50 cents (Mehrjerdi, 2011). However, active tags with additional capabilities and local power supplies can be much more expensive, and can reach to over \$100 per tag. This generally should not be thought of as prohibitive, since these expensive tags can be reprogrammed thousands of times, resulting in a very high return on investment.

RFID readers have some variation in their pricing based on frequency, with UHF readers being generally more expensive. UHF readers tend to range between \$500 and \$2000, dependent on the level of capability desired in a reader. HF readers range between \$200 and \$500, while LF readers will be a little higher at \$350 to \$750 each.

Antennae's are essential to expanding the range of the readers, and generally cost about \$200.

Software costs are truly the wildcard factor when discussing implementation costs of hardware and software. Considerations should include whether the software is intended to act as middleware by sending information to a back-end application or whether the software is the final product. Small, one-reader applications that are not meant to connect to back-end applications can cost as little as \$800 to \$1000. Larger applications are so diverse that average prices cannot be determined, but it is common for licenses to be greater than \$100,000.

F. BENEFITS

Tracking machine usage, components, and employee labor hours has long been one of the most obvious benefits of RFID. through the use of tags placed directly onto

products going through a manufacturing process, these products have the ability to identify whether they are at the correct machine, whether the correct process is being performed, and whether the correct technician is performing the process. In the case of process deviations, the software program can either stop the process or sound an alarm to alert technicians. This is vitally important, especially in smaller-scale, electronics' manufacturing facilities where certain processes are repeated on a single product, resulting in a higher likelihood of errors (Hozak & Hill, 2010). In some cases, technicians are required to be certified in order to operate certain machinery, and RFID technology allows for the identification and pairing of compatible products and technicians.

Tracking tools can be highly beneficial, and can result in significant cost savings. The benefits include keeping track of all tool locations – and notification when tools are removed from authorized locations, automatic identification when tools require calibration, and identifying instances where tool usage is redundant, thereby allowing a total reduction in tool numbers (Violino, 2008).

Another high-visibility benefit is the cost savings in the reduction of scrap rates. In the case of electronics manufacturers, circuit boards and other components can be very expensive to throw away. RFID has shown that tracking products through the manufacturing process results in fewer errors due to ensuring that the products are in the right place at the right time. The direct result of a decreased scrap rate is an increase in yield, allowing the production company to use fewer materials to produce the same output and thereby reduce costs (Boeck, Lefebvre, & Lefebvre, 2008).

Other benefits are less quantifiable, but can still be very positive for the company. By allowing the process to be fully automated, RFID reduces and can sometimes eliminate the need for paperwork to track completed processes and labor hours. This saves the time spent on preparing a document to travel the process with the product, on technicians signing the traveler after each completed process, and the time technicians spend reviewing the traveler for accuracy. In addition to accurately determining how much time a technician spends on a certain machine with a certain job, RFID can track the actual machine usage.

Some benefits of RFID in a manufacturing setting cannot, or should not be quantified in dollar units (Doerr, Gates & Mutty, 2006). For example RFID, particularly when coupled with micro-electronic mechanical sensors (MEMS) can be used to detect changes in operating conditions which might cause problems with worker safety. Improvements in worker safety have an intrinsic utility which cannot be adequately assessed in dollar terms. Likewise, and RFID implementation creates learning opportunities both about the RFID technology itself, and the manufacturing process which can have strategic advantages, and network externalities that are difficult to capture, and even more difficult to measure in dollar terms with any precision. Multiple-criteria models can be built to assess the utility of these benefits against the dollar costs of the implementation (Doerr, Gates & Mutty, 2006). But in this project, we will attempt to capture the main dollar benefits in a systematic way, without quantifying non-dollar benefits. Decision makers can then compare the net dollar benefits (or costs) predicted by the model against the non-dollar benefits separately.

Sometimes, process improvements through RFID implementation are requested from customers (Gambon, 2010). This can be simply to ensure that customers know that the absolute best process is being used to produce the parts. In other cases, customers might require immediate delivery of a product. In this case, RFID can easily track the product and save valuable time that would have been spent looking for the product.

G. DISADVANTAGES

The main rival technology to RFID is barcoding, which is very cheap, easy to use, and can have a high return on investment if the implementation is on a very large scale. With barcodes, companies have a solution that is easy to learn and use, and is almost universal in its application. RFID, however, is not universal, is considerably more expensive to design and implement, and requires more training to use it. The cost of barcoding is cheap in the short term, while the expensive start-up costs sometimes overshadow the eventual savings in cost benefits. Table 2 compares the benefits between RFID and barcoding.

Table 2. Comparison of RFID and Bar Code

Read rate	Many tags can be read simultaneously – high productivity	Read one tag at a time and manually
Line of sight	Not required	Certainly required
Human capital	Once system is designed and set up then it is completely automated and do not need too much human help	Needs human capital to scan each tag
Read/write capability	Ability to read, write, modify, and update	Read ability only
Durability	High – it can be used in harsh environments	Low – it cannot be used when it is dirty or greasy
Security	High	Low
Event triggering	Capable to trigger certain events	Not capable of triggering events

Another disadvantage is the variability of RFID technology. There are many different tags, readers, antennae and software to choose from, all with their own described advantages, and sometimes the very act of choosing an implementation can become time-consuming and expensive. In addition, conditions within the manufacturing process must be considered. Whereas barcodes are read upon direct interaction with a scanner, RFID tags transmit sometimes indiscriminately. This can lead to multiple tags responding at the same time to a reader, resulting in multiple reads or missed reads.

Manufacturing environments can have a detrimental impact on RFID reliability. The presence of metal can make higher frequency signals bounce around, resulting in multiple reads (Ng, Leong, & Cole, 2008). Humid or moist environments can absorb certain frequency signals, which can result in missed reads. In addition to these, electromagnetic noise generated from nearby machinery can interfere with the ability to transmit radio frequency signals. These environmental issues can be mitigated through the use of proper frequencies, and sometimes through creative process refinement that changes the environment enough to allow frequency signals to be sent and read.

The data that is produced using RFID can itself be a hindrance to effective implementation. RFID, if widely used, can result in massive amounts of data being

directed to the middleware and back-end programs. Without efficient programming of the software, data overload can slow the process and result in inaccurate reports. Generally, the middleware is responsible for synthesizing and cleaning the data before sending it to the back-end program, and this requires knowledgeable RFID installers to program the software.

H. CONCLUSION

Radio Frequency Identification is a growing and improving technology that has the ability to provide previously unheard of benefits and cost reductions to the manufacturing industry. Although successful implementation and integration is dependent on many factors, the potential is great enough that the industry would do itself a great disservice by overlooking RFID.

III. MODEL

A. INTRODUCTION

This section will introduce the underlying concepts of the costs and benefits, and why they are important enough to be measured. After each concept is described, the mathematical variables relating to that concept will be described. Finally, and since Excel does not precisely translate these variables, a discussion will follow on how these variables are depicted and manipulated in an Excel spreadsheet, with the optional use of the Crystal Ball add-on.

B. BENEFITS

The benefits gained from the implementation of RFID technology in an electronics manufacturing setting will be categorized into three main components:

- Tracking and control
- Shrinkage reduction
- Cost of quality savings

1. Physical Count

The physical count savings represents savings achieved through a reduction in labor-hours. Reductions in labor hours can be achieved several ways. One, RFID eliminates the need for workers to manually input lot information into the computer system every time a lot reaches a new tool, or finishes work at a tool. Two, the need for a traveling document to keep track of the process flow for individual lots is eliminated. Instead, the new technology allows for the inputting of the process flow into the computer system at the time of initiation, and does not require further follow-up. Third, inventory tracking and counting becomes automated. This eliminates the need for workers to physically count each lot at each tool at the end of the day or to perform a physical check to find a specific lot in the case that a customer inquires into its status.

The measurement of these savings can be obtained through knowing the average hourly cost of labor and multiplying it by a difference factor. The difference factor is the

change in labor-hours from non-RFID manual entry and count compared to the RFID-enhanced model. This difference factor is a physical measurement of decreased labor-hours and, when multiplied by the hourly cost of labor, will result in the savings amount achieved.

2. Shrinkage Reduction

RFID tags, working in conjunction with the computer monitoring software, will track all movements of tagged inventory. This system will lower the probability of lost and missing inventory under the pre-RFID system of manual inventory tracking. In addition, RFID will enhance the ability of the company to find those items that are lost or missing, thereby returning value back to the company.

3. Quality Savings

Quality savings are those savings that are achieved through the reduction and/or elimination of errors in the process. When implemented on a shop floor, RFID can help control the routing of material, to ensure that jobs are processed on the right machines, by the right workers, in the right operating conditions. This kind of precision in tracking and control can help prevent errors. The benefit of this error reduction will depend on the existing level of quality control in the plant. These errors can be caught internally while still in process, or externally by the customer. In the case of internal errors, the resultant costs are either repair costs or replacement costs. In the case of external (or warranty) errors, the costs will involve the replacement of the product and the additional costs of handling and processing return material. There is also a loss of customer goodwill involved in external failures which is difficult to quantify. Quality savings fall into one of two categories: products with defects and caught internally, and products with defects caught externally.

a. Products with Defects and Caught Internally

The majority of products that have defects will be caught internally, and there are several associated costs. Rework costs are those costs involved with moving a product to some prior point in the process to correct an error. Scrap costs are the costs

incurred if a particular product is unable to be reworked; if this is the case, the product material must be scrapped and a new product begun. In either case, the products will also incur costs of re-inspection and re-testing.

Benefits will be achieved through the use of RFID to more securely track the progress of materials in the production process. To measure the benefits, the user will first need to know the company's actual defect rate. With the defect rate, total volume of production and cost of goods, the model will be able to accurately reflect the cost of defects without RFID. To then measure the benefit, the user can either manually input the anticipated reduction of costs or choose to model the reduction using a distribution that takes into account current manufacturing conditions.

b. Products with Defects and Caught Externally (Warranty Failures)

A minority of products with defects will escape the system and be caught externally, or not at all. These costs can be quite high depending on the product and its intended use. At the least, these costs can include processing of customer complaints, customer returns, warranty claims to rework or replace the product, additional damages due to the product causing system failure of a larger product, and the possibility of recalling all related products.

External costs are harder to estimate due to the nature of these costs being outside the purview of the manufacturer, and because there is a possibility that not all external warranty failures will be reported back to the manufacturer. To estimate these costs, the user will first need to input the external failure rate into the model or choose to model the failure rate using a distribution that takes into account current manufacturing conditions. Second, the cost per failure will need to be inputted. This can be a manually entered value, or it can be modeled with an appropriate distribution to account for the variation in item values. Finally, like the internal failures, the user can either manually input the anticipated decrease or choose to model it.

c. *Conditions Relevant to Benefits*

In making these benefit assessments, three specific conditions must be met to ensure that the model is accurate and reasonable. These conditions are assumed to be true for any manufacturing company that has an established and successful quality control program. First, the quality assurance costs will necessarily be higher than the costs of internal failures, which in turn will necessarily be higher than the costs of external failures. Second, the percentage of products without errors will always be higher than the percentage of products with errors, and that the percentage of products with errors and are caught internally will always be higher than the percentage of products with errors that are caught externally. Third, and to ensure mutual exclusivity, the percentage of products without errors, with internal failures and with external failures will equal 100%.

Generally speaking, for companies which have established quality assurance programs, the higher the amount of money that they have invested in error prevention, the lower their costs of internal and external failures. For companies that are just beginning or improving their quality assurance programs, they can expect that initial costs for internal and external failures will exceed the costs of their quality assurance program.

4. *Model Variables*

$$(K_1 * \Delta L_1) + [K_2 * P(S \& R)] + [K_3 * \Delta P(Q)] + [K_4 * \Delta P(D)] + [K_5 * \Delta P(W)]$$

a. *Physical Count*

The physical count savings can be described as $K_1 * \Delta L_1$.

K_1 is the hourly labor rate, and can be manually selected by a user or modeled with a uniform distribution to represent current accepted labor rates.

ΔL_1 is the change (reduction) in the number of labor hours. ΔL_1 is computed from the difference of L_1 , the number of labor hours needed in a manual entry and count inventory tracking system, and L_1' , the number of labor hours needed to conduct manual entry and inventory in an RFID-enabled system.

b. Shrinkage Reduction

The probability of shrinkage reduction can be described as $K_2 * P(S \cap R)$.

K_2 is the average cost of a single production item.

$P(S \cap R)$ is the probability of that an item is lost (shrinkage) and subsequently recovered.

c. Cost of Quality Savings

The savings from a quality assurance program can be described as $[T * ([K_3 * \Delta P(D)] + [K_4 * \Delta P(W)])]$, where

T is the throughput rate, or total volume of production per time period K_3 equals the cost of rework and/or scrap of a single defective item that is caught in-house.

$P(D)$ is the probability that defective materials will produced and caught in-house. $\Delta P(D)$ is the difference in the probability that a defective item will be caught in-house once an RFID system is implemented.

K_4 is the cost of warranty failure for a single defective product that is caught by the customer.

$P(W)$ is the probability that defective materials will be produced and caught by the customer (a warranty failure). $\Delta P(W)$ is the difference (decrease) in the probability of a warranty failure, after an RFID system is implemented

$P(Q)$ is the probability of producing a quality (defect free) item, and $\Delta P(Q)$ is the difference (increase) in the percentage of quality items produced following the RFID implementation. Note that $P(Q) + P(D) + P(W) = 1$, and $\Delta P(Q) + \Delta P(D) + \Delta P(W) = 0$.

C. COSTS

The cost structure of RFID implementation is generally straightforward, and confined to three main areas:

- Capital expenditures
- Implementation costs

- Training

1. Capital Expenditures

Capital expenditures are the costs to acquire the physical components of the RFID system, including the software. Items that are required for a complete system are RFID readers, antennas, tags, computers, printers, and software.

Central to figuring out the cost of these expenditures is to determine the size of the implementation. Small to medium manufacturing facilities separate their plants into several distinct work sections, or bays, for the purpose of segregating their processes. Some of the reasons to do this include improving inventory control and flow, increasing space utilization, improved safety, and to allow for certain processes to be conducted in ISO standard clean rooms. Each work section will require separate readers, antennas, and computer systems. Determining the number of work sections or bays will therefore be critical to determining the cost.

a. Bays

The number of bays will be determined in one of two ways. First, the user can determine the number of bays by manually entering the appropriate number. Second, the user can choose to model the number of bays based on typical and current manufacturer facilities. If modeled, and based on a triangular distribution, three assumptions will be made: (1) the minimum number of bays; (2) the maximum number of bays; and (3) the most likely number of bays.

b. Readers

The most commonly used forms of RFID readers are UHF and HF. HF readers have antennas embedded into the reader, and are consequently more expensive.

Reader costs will be determined by first multiplying the number of bays by the number of desired readers per bay, with the number of readers per bay being either manually inputted or modeled. If the number of readers per bay is modeled, the model

will use a normal distribution based on current accepted RFID architecture. The resultant number of readers will then be multiplied by a constant reader price to determine the final reader costs.

c. Antennas

Separate antennas are not required for HF readers, so the only cost to be concerned about here is the cost of UHF antennas. Antenna costs will be determined by first designating the number of bays, as previously discussed, and multiplying that number by the number of antennas that are desired per bay. The user can manually enter the number of antennas per bay or choose to model the number. The model will use a normal distribution based on current accepted RFID architecture.

d. Tags

Tags come in many forms and can be used in many different ways. In manufacturing, however, the predominant tag is the active tag. The cost of this tag, in comparison to passive tags, is much more expensive.

The cost of the tags will be determined by either having the user manually enter the desired tag quantity or by modeling the number, based on a triangular distribution. For the distribution, three assumptions will be made: (1) the lowest priced available active tag; (2) the highest priced available active tag; and (3) the most-likely priced tag that an electronics manufacturer would purchase.

e. Computers

Computers in this application are primarily used as information centers to locate specific tags in the bay, perform queries on work in process, check machine and tool usage, and other computer-related functions. The default setting in the model is one computer per bay. The cost of computers for this model, based on a current search of relevant computer manufacturers, will be conservatively set at \$1,500 each.

f. Printers

RFID printers are used for printing passive tags. If the manufacturer needs this printing capability, the default setting will be one printer for the company. The cost of a printer for this model, based on a current search of relevant printer manufacturers, will be conservatively set at \$3,500.

g. Software

Software costs have a wide range of values, dependent on the scope of the implementation and whether or not the software is a lightly-modified, commercial-off-the-shelf (COTS) program or a software program heavily modified to work with the company architecture. In the case of small to medium scale electronics manufacturers, the cost of software can be as low as \$20,000 and as high as \$150,000. The scenarios in this report will use a range of uniform distributions to represent the difference between small and large software implementations. For purposes of this report, the software cost will include the upfront costs and any modifications.

2. Implementation Costs

Implementation costs are contractor associated costs that include the cost to install each piece of hardware and the hourly contractor labor costs. This report will determine the costs on a per individual hardware item basis. Thus, the total number of hardware items to install will determine the total cost of the installation of hardware. The user will have the option to manually select a range of values for the cost per individual hardware item, or can choose to model the cost using a distribution that takes into account current accepted costs within the RFID installation community.

Contractor labor costs are separate from the cost per individual hardware item, and are based on current accepted hourly rates for contractors. The user will have the option to manually select a range for hourly contractor rates or can choose to model the rate using a normal distribution that takes into account current hourly contractor rates. If the contractor does not apply both labor costs and per item installation costs, the one that is not needed in the model can be set to zero.

3. Training Costs

Training costs are those costs associated with bringing in RFID professionals to train the company's employees on how to properly use the RFID technology. These costs include training materials, contractor labor hours, and the labor costs of employees that participate in the training.

The RFID contractor costs are determined by multiplying the total number of training hours required by the hourly contractor labor rate. Costs for training materials, for purpose of this report, are aggregated into the contractor labor rate. Likewise, the employee labor costs are determined by multiplying the number of employees that are participating in the training by the average employee labor rate.

4. Cost Variables

$$[(R_B * R_K) + (A_B * A_K) + (C_B * C_K) + (T * T_K) + P + S] + [(K_6 * C_K) + (K_7 * L_2)] + [(K_8 * L_3) + (K_9 * L_4)]$$

a. Capital Expenditures

The cost of capital expenditures can be described by $[(R_B * R_K) + (A_B * A_K) + (C_B * C_K) + (T * T_K) + P + S]$.

R_B is the total number of RFID readers, and is a multiple of the number of bays.

R_K is the cost of a single reader.

A_B is the total number of RFID antennas, and is a multiple of the number of bays.

A_K is the cost of a single antenna.

C_B is the total number of computers, and is a multiple of the number of bays.

C_K is the cost of a single computer.

T is the number of RFID tags.

T_K is the cost of a single tag.

P is the cost of an RFID printer, and is a constant.

S is the cost of software, and is determined by modeling a uniform distribution from \$20,000 to \$120,000.

b. Implementation Costs

$$(K_6 * C_K) + (K_7 * L_2)$$

K_6 is the cost per component to install each piece of RFID hardware, and can be determined via user input or computer model.

C_K is the number of components that need to be installed.

K_7 is the hourly cost of contractor labor to install the RFID hardware.

L_2 is the per/component time block that is needed to install each piece of RFID hardware, and can be determined via user input or computer model.

c. Training Costs

$$(K_8 * L_3) + (K_9 * L_4)$$

K_8 is the contractor hourly labor rate, and is determined via either user input or computer model.

L_3 is the total number of contractor hours required to train company employees on the RFID technology, and is determined via computer model.

K_9 is the employee hourly rate, and is determined via user input or computer model.

L_4 is the number of employees that need to be trained.

D. INTEGRATION INTO COMPUTER MODEL

1. Introduction

The variables described in the preceding sections were transferred to Microsoft Excel in order to create a dynamic model of the problem. The user of the model can

manually input all variables into the spreadsheet and generate a cost-benefit analysis. Conversely, the user can choose to model some or even all of the variables. Even this option is dynamic, since the user can also change the assumptions of each model to better account for certain special considerations, such as geographic variation.

The math model, however, does not translate directly onto an Excel spreadsheet. Therefore, the language used on the Excel spreadsheet will differ from that used in the math model.

2. Benefits

a. Tracking and Control

The tracking and control section provides an area for the user to set options that will be used to determine the savings amount. These options include the number of employees, the standard number of hours that the employees work each week, and the amount of time that they spend performing inventory counts (see Figure 2), all of which are used in the calculation of the total number of inventory hours per year. The ΔL_1 difference factor is determined through the use of a reduction percentage, which is the estimated reduction of inventory hours that can be achieved. This figure can be entered manually or modeled. Once obtained, the reduction percentage can be multiplied against the total number of inventory hours to get the new amount of inventory hours, or L_1' . The difference in inventory hours, $L_1 - L_1'$, is multiplied by the average employee hourly rate to determine the total physical count savings.

Number of employees		Choose		
	Model	Manual		
<input type="text" value="5"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		10
			Minimum:	125
Model Parameters			Maximum:	200

Standard work hours/week		Choose		
	Model	Manual		
<input type="text" value="40"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		40
			Minimum:	30
Model Parameters			Maximum:	50
			Most Likely:	40

OR

Time spent on Inventory		Percent of Annual Time		
	Model	Manual		
<input type="text" value="3%"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		4.00%
			Minimum:	1.00%
Model Parameters			Maximum:	5.00%
			Most Likely:	4.00%

Time per Inventory Event		
Hours:	<input type="text" value="40"/>	Weekly <input type="text"/>

Anticipated Reduction %		Choose		
	Model	Manual		
<input type="text" value="80%"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		99%
			Minimum:	75%
Model Parameters			Maximum:	100%
			Most Likely:	80%

Figure 2. Tracking and Control

b. Shrinkage Reduction

The shrinkage reduction section begins with Inventory Settings, which is used to determine the annual size and cost of average inventory (see Figure 3). The volume per year is the average number of items produced each year, and can be modeled or manually inputted. This number is multiplied by the manually-inputted value of the item and is the determinant of the size and cost of inventory. The next section, Losing

Less, refers to the cost savings that can be achieved through preventing shrinkage. The reduction rate can be modeled or manually inputted, but the following shrinkage rate must be manually inputted as it is variable among different manufacturers. The third section is the Finding More section, which refers to the ability of RFID to help find shrinkage items that have been lost. The anticipated increase can be modeled or manually inputted, but the recovery rate is variable among manufacturers and must be manually inputted.

Inventory Settings

Choose

ModelManual

Volume (year)

2500

☒

☐

500

Model Parameters

Minimum:7500

Maximum:25000

Most Likely:15000

Single-item value

\$100

Volume2500

Losing Less

Shrinkage Rate

2.00%

Choose

ModelManual

Anticipated Reduction rate

80%

☒

☐

92%

Model Parameters

Minimum:75%

Maximum:100%

Most Likely:80%

Finding More

Recovery rate

20%

Choose

ModelManual

Anticipated Increase rate

80%

☒

☐

50%

Model Parameters

Minimum:75%

Maximum:100%

Most Likely:80%

Figure 3. Shrinkage Reduction

c. Cost of Quality Savings

The cost of quality savings is sectioned into the two designated areas of quality control savings, internal failure savings and external failure savings (see Figure 4).

Under internal failures, the cost of defects per item is a model-only variable. The cost is determined through a uniform distribution from \$1 to the cost of the item. The defect rate and anticipated reduction of the defect rate can both be modeled or can both be a manual input. The savings achieved is then computed through multiplying the defect rate (once as normal and once with the anticipated reduction) by the total volume of production, and then multiplying by the defect cost per item to get the total cost. The difference in cost is the savings attained.

Under external failure savings, the cost-per-warranty is a model-only variable. The cost is determined using a uniform distribution from the cost of the item to three times the cost of the item. The warranty failure rate and anticipated reduction variables can both be modeled or can both be a manual input. Savings can be determined by multiplying the warranty failure rate (once as normal and once with the anticipated reduction) by the total volume of production, and then multiplying by the warranty cost per item to get the total cost. The difference in cost is the savings attained.

Internal Failure Savings			
Defect cost / item			\$100
		Minimum:	\$1
	Model Parameters	Maximum:	\$100
		Choose	
		Model	Manual
Defect rate	0.50%	<input checked="" type="checkbox"/>	<input type="checkbox"/> 2.00%
		Minimum:	1.00%
	Model Parameters	Maximum:	5.00%
		Most Likely:	2.50%
Anticipated reduction	25.00%	<input checked="" type="checkbox"/>	<input type="checkbox"/> 50%
		Minimum:	0.10%
	Model Parameters	Maximum:	1.00%
		Most Likely:	0.50%
Warranty Savings			
Cost per warranty			\$100
		Minimum:	\$100
	Model Parameters	Maximum:	\$300
		Choose	
		Model	Manual
Warranty Failure Rate	0.010%	<input checked="" type="checkbox"/>	<input type="checkbox"/> 0.50%
		Minimum:	0.090%
	Model Parameters	Maximum:	0.110%
		Most Likely:	0.10%
Anticipated reduction	76%	<input checked="" type="checkbox"/>	<input type="checkbox"/> 50%
		Minimum:	75%
	Model Parameters	Maximum:	100%
		Most Likely:	80%

Figure 4. Cost of Quality Savings

3. Costs

a. Capital Expenditures

Capital expenditure options are necessary to provide the quantities of bays, tools, readers, antennas, tags, computers and printers, as well as the cost of software, to be used in the implementation. Each option can be manually selected by the user or can be modeled (see Figure 5). If modeled, the model parameters for all variables are all based on triangular distribution, except for the software costs, which is determined with a uniform distribution.

This section takes the determined quantities of hardware and sums up the total cost of the hardware and software. To do this, four variables have been defined in the Name Manager of Excel, and given costs commensurate with current cost structures: AntennaCost, ComputerCost, ReaderCost and TagCost. Each of these variables are used in the cost aggregation of hardware, and their values can be changed by entering into the Name Manager, selecting the variable and then choosing Edit.

		Choose		
		Model	Manual	
Bays	<div><div>4</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	8
				Minimum: 8
	Model Parameters			Maximum: 16
				Most Likely: 12
Tools / Bay	<div><div>9</div></div>			9
				Minimum: 5
	Model Parameters			Maximum: 15
				Most Likely: 9
Readers / Bay	<div><div>6</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	9
				Minimum: 25
	Model Parameters			Maximum: 50
				Most Likely: 30
Antennas / Bay	<div><div>10</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	9
				Minimum: 25
	Model Parameters			Maximum: 75
				Most Likely: 50
Tags	<div><div>2500</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	500
				Minimum: 7500
	Model Parameters			Maximum: 17500
				Most Likely: 12500
Software	<div><div>20,000</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	100,000
				Minimum: 80,000
	Model Parameters			Maximum: 150,000

Figure 5. Capital Expenditure Setup Options

b. Implementation Costs

The implementation options are used to determine the length of time that is necessary to install the hardware, and the associated costs of installation (see Figure 6). The component option designates the cost of installation for each item (K_6), the time in hours option is the length of time necessary to install that item, and the labor option is the cost of installing that item. If there is only a per-item charge without a time component, the time and labor can be set to zero, and vice versa.

Implementation options		Choose		
		Model	Manual	
Component cost	<div><div>25</div></div>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	0
		Minimum: 5		
	Model Parameters	Maximum: 100		
		Most Likely: 25		
Time (hrs) per item	<div><div>2</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	0
		Minimum: 0.5		
	Model Parameters	Maximum: 5		
		Most Likely: 2		
Contractor labor rate	<div><div>100</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	100
		Minimum: 25		
	Model Parameters	Maximum: 300		
		Most Likely: 100		

Figure 6. Implementation Costs

c. Training Costs

The training options are needed to determine the total number of hours of training (L_3) for purposes of summing up the contractor training costs and the employee training costs (see Figure 7). Each of the following variables can be both modeled and manually inputted: number of training hours, number of employees, and the employee hourly rate. Total training costs for the employees can thus be calculated. The contractor's cost of performing the training is obtained from the number of training hours required multiplied by the contractor hourly rate, which was determined in a previous section of the model.

<u>Training Options</u>		<u>Choose</u>		
		Model	Manual	
Training hours	<div><div>50</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	10
				<i>Minimum:</i> 10
	Model Parameters			<i>Maximum:</i> 100
				<i>Most Likely:</i> 50
# Employees	<div><div>5</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	48
				<i>Minimum:</i> 125
	Model Parameters			<i>Maximum:</i> 200
				<i>Most Likely:</i> 50
Employee hourly rate	<div><div>40</div></div>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	48
				<i>Minimum:</i> 25
	Model Parameters			<i>Maximum:</i> 75
				<i>Most Likely:</i> 50

Figure 7. Training Costs

IV. SCENARIOS

A. INTRODUCTION

The scenarios will adjust several variables within four general categories: size and volume of the manufacturing company, tracking of inventory, complexity of the RFID implementation and product quality of the company. Within the size and volume category, the number of bays, number of employees and product volume will be varied to represent small, medium and large companies. Within tracking of inventory, the percentage of time that employees spend on conducting inventory will be varied. For complexity, the number of components and the cost of software will be varied to represent varying degrees of implementation. For product quality, the internal defect rate and warranty failure rates will be varied to represent high and low quality products.

Several variables in the model remain constant throughout the scenarios due to the necessity to restrain the number of scenarios. The variables which are not selected for manipulation across scenarios were chosen by conducting a sensitivity analysis on the model. Using the base scenario, a tornado chart was built using Crystal Ball, which ranked the input variables in terms of their impact on the outcome variables (total investment, yearly benefit, and payback period). The input variables which had the least impact were not manipulated across scenarios.

For implementation costs, component cost is set to \$0, time that it takes to install each item is a triangular distribution from 0.5 to 5 hours with 2 hours being the most likely and contractor labor rate is a triangular distribution from \$25 to \$300 with \$100 being the most likely. For training options, the training hours are a triangular distribution from 10 to 100 with 50 being the most likely and the employee hourly rate is a triangular distribution from \$25 to \$75 with \$50 being the most likely. For tracking and control, the standard work week is set to a triangular distribution from 30 to 50 hours with 40 hours per employee being the most likely and the anticipated reduction of time spent on inventory is a triangular distribution from 75% to 100% with 80% being the most likely. For shrinkage reduction, the value of a single item of production is set to \$100, the

shrinkage rate is 2%, the anticipated reduction of the shrinkage rate is a triangular distribution from 75% to 100% with 80% being the most likely, the recovery rate is 20% and the anticipated increase in the recovery rate is a triangular distribution from 75% to 100% with 80% being the most likely. For cost of quality, the defect cost per item is a uniform distribution from \$1 to \$100 (the cost of the item), the anticipated reduction in the defect rate is a triangular distribution from 10% to 100% with 50% being the most likely, the cost per warranty is a triangular distribution from \$100 to \$300 (three times the cost of the item) and the anticipated reduction in the warranty failure rate is a triangular distribution from 75% to 100% with 80% being the most likely. The values of all parameters which do not vary across scenarios were selected to represent a reasonable range, based on the author's experience.

B. SCENARIOS

In the absence of data, these scenarios are meant to examine the cost benefit model across a wide range of possible electronics manufacturing settings, based on the experience of the author and his advisors. The purpose of this analysis is to examine which factors in the model most influence the payback period of an RFID investment. However, given the large number of input factors, an exhaustive analysis of all factors, across the entire range of their possible values, is not possible. Hence, these scenarios should be considered as a set of examples of possible electronic manufacturing situations, rather than a systematic study of RFID payback across every electronic manufacturing situation. In sum, the analysis examines the model (how the input variables affect payback period), not the implications of the model to manufacturing practice.

1. Scenarios One through Eight

Each scenario in this group will be based on the same small plant size. The number of working bays will be computed from a triangular distribution of 2 bays minimum, 8 maximum and with 4 being the most likely. The number of employees will be determined by a uniform distribution of employees from 5 to 25. The volume of production will be based on a triangular distribution of 1,500 items minimum, 3,500 items maximum and 2,500 items being most likely produced in a given year.

a. One through Four

Each scenario in this group will have the same amount of time spent on inventory. The percentage of time will be determined by using a triangular distribution with 1% minimum, 5% maximum and 2% the most likely. This distribution represents a low amount of time for conducting inventory.

Scenarios 1 and 2 are both small plants with low production and relatively little time spent on conducting inventory. These two plants also have the same complexity, with a normal number of components and a lower software cost, determined by a uniform distribution of \$20,000 minimum to \$80,000 maximum. Scenario 1 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 2 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

Scenarios 3 and 4 are both small plants with low production and relatively little time spent on inventory. Unlike the previous two plants, however, these plants will have complex implementation costs. The number of components will rise by a factor of five over a normal plant, and the software costs will be modeled with a uniform distribution of \$80,000 minimum to \$150,000 maximum. Scenario 3 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 4 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

b. Five through Eight

Each scenario in this group will have the same amount of time spent on inventory. The percentage of time will be determined by using a triangular distribution with 1% minimum, 5% maximum and 4% the most likely. This distribution represents a high amount of time for conducting inventory.

Scenarios 5 and 6 are both small plants with low production and a high amount of time spent on conducting inventory. These two plants also have the same complexity, with a normal number of components and a lower software cost, determined by a uniform distribution of \$20,000 minimum to \$80,000 maximum. Scenario 5 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 6 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

Scenarios 7 and 8 are both small plants with low production and a high amount of time spent on inventory. Unlike the previous two plants, however, these plants will have complex implementation costs. The number of components will rise by a factor of five over a normal plant, and the software costs will be modeled with a uniform distribution of \$80,000 minimum to \$150,000 maximum. Scenario 7 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 8 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

2. Scenarios Nine through Sixteen

Each scenario in this group will be based on the same medium plant size. The number of working bays will be computed from a triangular distribution of 4 bays minimum, 12 maximum and with 8 being the most likely. The number of employees will be determined by a uniform distribution of employees from 40 to 100. The volume of production will be based on a triangular distribution of 2,500 items minimum, 10,000 items maximum and 5,000 items being most likely produced in a given year.

a. Nine through Twelve

Each scenario in this group will have the same amount of time spent on inventory. The percentage of time will be determined by using a triangular distribution with 1% minimum, 5% maximum and 2% the most likely. This distribution represents a low amount of time for conducting inventory.

Scenarios 9 and 10 are both medium sized plants with medium production and relatively little time spent on conducting inventory. These two plants also have the same complexity, with a normal number of components and a lower software cost, determined by a uniform distribution of \$20,000 minimum to \$80,000 maximum. Scenario 9 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 10 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

Scenarios 11 and 12 are both medium sized plants with medium production and relatively little time spent on inventory. Unlike plants 9 and 10, these plants will have complex implementation costs. The number of components will rise by a factor of five over a normal plant, and the software costs will be modeled with a uniform distribution of \$80,000 minimum to \$150,000 maximum. Scenario 11 represents

a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 12 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

b. Thirteen through Sixteen

Each scenario in this group will have the same amount of time spent on inventory. The percentage of time will be determined by using a triangular distribution with 1% minimum, 5% maximum and 4% the most likely. This distribution represents a high amount of time for conducting inventory.

Scenarios 13 and 14 are both medium sized plants with medium production and a high amount of time spent on conducting inventory. These two plants also have the same complexity, with a normal number of components and a lower software cost, determined by a uniform distribution of \$20,000 minimum to \$80,000 maximum. Scenario 13 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 14 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

Scenarios 15 and 16 are both medium sized plants with medium production and a high amount of time spent on inventory. Unlike scenarios 13 and 14, however, these plants will have complex implementation costs. The number of components will rise by a factor of five over a normal plant, and the software costs will

be modeled with a uniform distribution of \$80,000 minimum to \$150,000 maximum. Scenario 15 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 16 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

3. Scenarios Seventeen through Twenty-Four

Each scenario in this group will be based on the same large plant size. The number of working bays will be computed from a triangular distribution of 8 bays minimum, 16 maximum and with 12 being the most likely. The number of employees will be determined by a uniform distribution of employees from 125 to 200. The volume of production will be based on a triangular distribution of 7,500 items minimum, 25,000 items maximum and 15,000 items being most likely produced in a given year.

a. Seventeen through Twenty

Each scenario in this group will have the same amount of time spent on inventory. The percentage of time will be determined by using a triangular distribution with 1% minimum, 5% maximum and 2% the most likely. This distribution represents a low amount of time for conducting inventory.

Scenarios 17 and 18 are both large plants with high levels of production and relatively little time spent on conducting inventory. These two plants also have the same complexity, with a normal number of components and a lower software cost, determined by a uniform distribution of \$20,000 minimum to \$80,000 maximum. Scenario 17 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 18 represents a low-

quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

Scenarios 19 and 20 are both large plants with high levels of production and relatively little time spent on inventory. Unlike plants 17 and 18, these plants will have complex implementation costs. The number of components will rise by a factor of five over a normal plant, and the software costs will be modeled with a uniform distribution of \$80,000 minimum to \$150,000 maximum. Scenario 19 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 20 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

b. Twenty-One through Twenty-Four

Each scenario in this group will have the same amount of time spent on inventory. The percentage of time will be determined by using a triangular distribution with 1% minimum, 5% maximum and 4% the most likely. This distribution represents a high amount of time for conducting inventory.

Scenarios 21 and 22 are both large plants with high levels of production and a high amount of time spent on conducting inventory. These two plants also have the same complexity, with a normal number of components and a lower software cost, determined by a uniform distribution of \$20,000 minimum to \$80,000 maximum. Scenario 21 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009%

minimum, 0.011% maximum and 0.01% the most likely. Scenario 22 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

Scenarios 23 and 24 are both large plants with high levels of production and a high amount of time spent on inventory. Unlike the previous two scenarios, however, these plants will have complex implementation costs. The number of components will rise by a factor of five over a normal plant, and the software costs will be modeled with a uniform distribution of \$80,000 minimum to \$150,000 maximum. Scenario 23 represents a high-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 0.1% minimum, 1% maximum and 0.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.009% minimum, 0.011% maximum and 0.01% the most likely. Scenario 24 represents a low-quality producing plant. The internal defect rate for this plant will have a triangular distribution of 1% minimum, 5% maximum and 2.5% the most likely. The warranty failure rate will also have a triangular distribution of 0.09% minimum, 0.11% maximum and 0.1% the most likely.

4. Summary

Table 3 summarizes the twenty-four scenarios in a tabular format. The number of bays, volume, time spent on inventory, internal defect rate and external defect rate are explained in terms of triangular distributions, and are displayed in a minimum / maximum / most likely format. For example, 2/8/4 represents 2 as the minimum number in the distribution, 8 as the maximum and 4 as the most likely. Number of employees and software are explained in terms of uniform distributions, and formatted as minimum / maximum. Components are explained in terms of either normal or X 5. Normal components have the standard number of readers, antennas and tags as scenario 1. The X 5 scenarios multiply each of these component numbers by five to represent increased complexity in the model.

Table 3. Scenario Summary

Scenario	Size / Volume			Tracking	Complexity		Product Quality	
	# Bays	Number of Employees	Volume	Time Spent on Inventory	Components	Software	Internal Defect Rate	External defect Rate
1	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/2	Normal	D: 20/80	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
2	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/2	Normal	D: 20/80	D: 1/5/2.5	D: 0.09/0.11/0.1
3	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/2	X 5	D: 80/150	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
4	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/2	X 5	D: 80/150	D: 1/5/2.5	D: 0.09/0.11/0.1
5	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/4	Normal	D: 20/80	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
6	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/4	Normal	D: 20/80	D: 1/5/2.5	D: 0.09/0.11/0.1
7	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/4	X 5	D: 80/150	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
8	D: 2/8/4	D: 5/25	D: 1500/3500/2500	D: 1/5/4	X 5	D: 80/150	D: 1/5/2.5	D: 0.09/0.11/0.1
9	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/2	Normal	D: 20/80	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
10	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/2	Normal	D: 20/80	D: 1/5/2.5	D: 0.09/0.11/0.1
11	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/2	X 5	D: 80/150	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
12	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/2	X 5	D: 80/150	D: 1/5/2.5	D: 0.09/0.11/0.1
13	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/4	Normal	D: 20/80	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
14	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/4	Normal	D: 20/80	D: 1/5/2.5	D: 0.09/0.11/0.1
15	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/4	X 5	D: 80/150	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
16	D: 4/12/8	D: 40/100	D: 2500/10000/5000	D: 1/5/4	X 5	D: 80/150	D: 1/5/2.5	D: 0.09/0.11/0.1
17	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/2	Normal	D: 20/80	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
18	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/2	Normal	D: 20/80	D: 1/5/2.5	D: 0.09/0.11/0.1
19	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/2	X 5	D: 80/150	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
20	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/2	X 5	D: 80/150	D: 1/5/2.5	D: 0.09/0.11/0.1
21	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/4	Normal	D: 20/80	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
22	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/4	Normal	D: 20/80	D: 1/5/2.5	D: 0.09/0.11/0.1
23	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/4	X 5	D: 80/150	D: 0.1/1.0/0.5	D: 0.009/0.011/0.01
24	D: 8/16/12	D: 125/200	D: 7500/25000/15000	D: 1/5/4	X 5	D: 80/150	D: 1/5/2.5	D: 0.09/0.11/0.1

C. RESULTS

1. Changes in Product Quality, Complexity and Inventory

The effects of changes in benefits due to changes in product quality are calculated by grouping the twenty-four scenarios into the twelve natural pairs that are only differentiated by product quality. For example, scenarios one and two are the same scenarios except for a change in product quality; scenario one is a plant with high quality products and scenario two is a plant with low quality products. Each succeeding group of pairs is likewise connected with each other.

Changes in product quality, at the given internal defect rates and warranty rates, do not have a significant impact on benefits. In general, scenarios one through eight (representing small manufacturing facilities) experienced higher benefits by increasing their product quality from poor to good than either the medium or large manufacturing facilities (see Table 4). However, due to the lower production volume of these facilities, the increased percentage represents a small increase in financial benefits. It is clear, though, that manufacturing facilities that are at least medium sized with a yearly volume of 5,000 products will not expect an increase of more than 3% in financial benefits.

Table 4. Effect of Product Quality Increase on Mean Yearly Benefit

Scenario	Mean	Δ Mean	Scenario	Mean	Δ Mean	Scenario	Mean	Δ Mean
1	\$39,277	4.37%	9	\$170,352	2.73%	17	\$401,956	2.75%
2	\$41,073		10	\$175,129		18	\$413,309	
3	\$39,360	3.27%	11	\$171,486	1.02%	19	\$402,368	1.96%
4	\$40,692		12	\$173,249		20	\$410,415	
5	\$47,513	3.63%	13	\$209,208	2.12%	21	\$495,067	2.10%
6	\$49,304		14	\$213,738		22	\$505,665	
7	\$47,470	3.41%	15	\$209,858	2.61%	23	\$493,633	2.16%
8	\$49,145		16	\$215,472		24	\$504,519	

The effects of changes in costs due to changes in complexity are calculated by grouping the twenty-four scenarios into six groups that represent the changes in complexity (see Table 5). Each group contains four scenarios; the first two scenarios are

normal complexity and the second two are multiplied by five. By averaging the first two scenarios, subtracting this from the average of the third and fourth scenarios and then dividing this sum by the average of the third and fourth scenarios gives the increase of costs, in percentage.

Table 5. Effect of Complexity Change on Mean Costs

Scenario	Mean	Δ Mean	Scenario	Mean	Δ Mean	Scenario	Mean	Δ Mean
1	\$160,454	63.53%	9	\$350,104	54.69%	17	\$649,194	48.19%
2	\$159,514		10	\$350,070		18	\$644,423	
3	\$438,246		11	\$773,727		19	\$1,250,996	
4	\$438,994		12	\$771,665		20	\$1,246,045	
5	\$160,537	63.38%	13	\$349,691	54.75%	21	\$649,997	48.11%
6	\$160,173		14	\$348,691		22	\$645,778	
7	\$438,286		15	\$771,838		23	\$1,246,210	
8	\$437,605		16	\$771,510		24	\$1,250,763	

Changes in complexity can be seen to have a very large impact on costs, with the small manufacturers having the largest increase. Percentage-wise, the small manufacturers have an increase of nearly two-thirds, medium sized manufacturers are slightly lower at around 55%, and large manufacturers come in with an increase of 48%. To demonstrate, Figure 8 shows the capital expenditure costs of a small manufacturer with high quality products but low complexity. Figure 9 shows the same manufacturer with high complexity. The difference in mean costs, simply from increasing the complexity of the installation of a small manufacturer, is \$176,973.

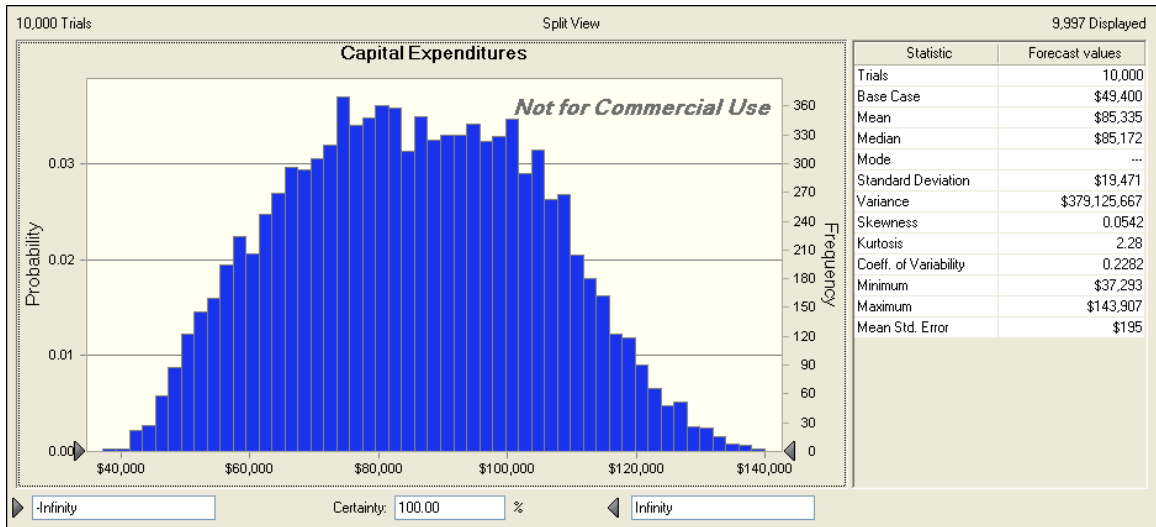


Figure 8. Scenario 1 Capital Expenditures

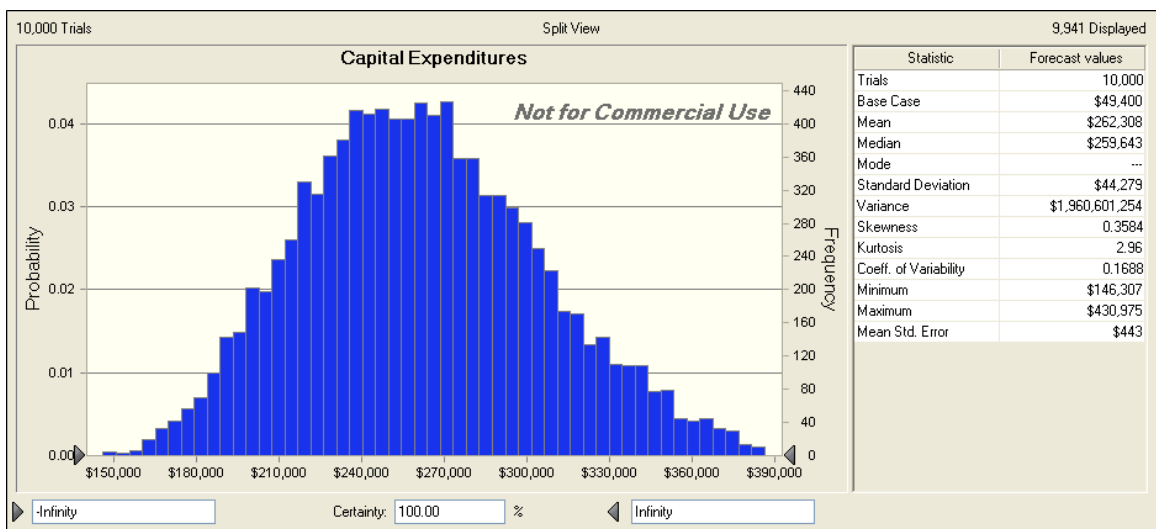


Figure 9. Scenario 3 Capital Expenditures

Not only does complexity affect the capital expenditures in a big way, it also affects the implementation costs to a large extent. Again, comparing small manufacturers highlights this point. Figure 10 shows the small, non-complex manufacturer with mean implementation costs of \$27,350. Figure 11 shows the same small manufacturer with complex implementation with mean implementation costs of \$128,348, an increase of over \$100,000.

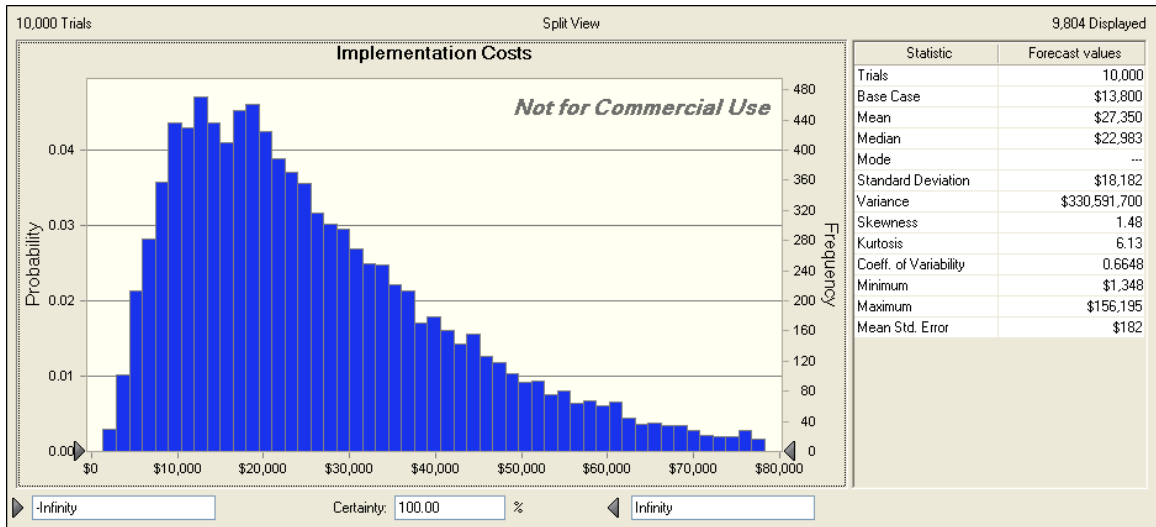


Figure 10. Scenario 1 Implementation Costs

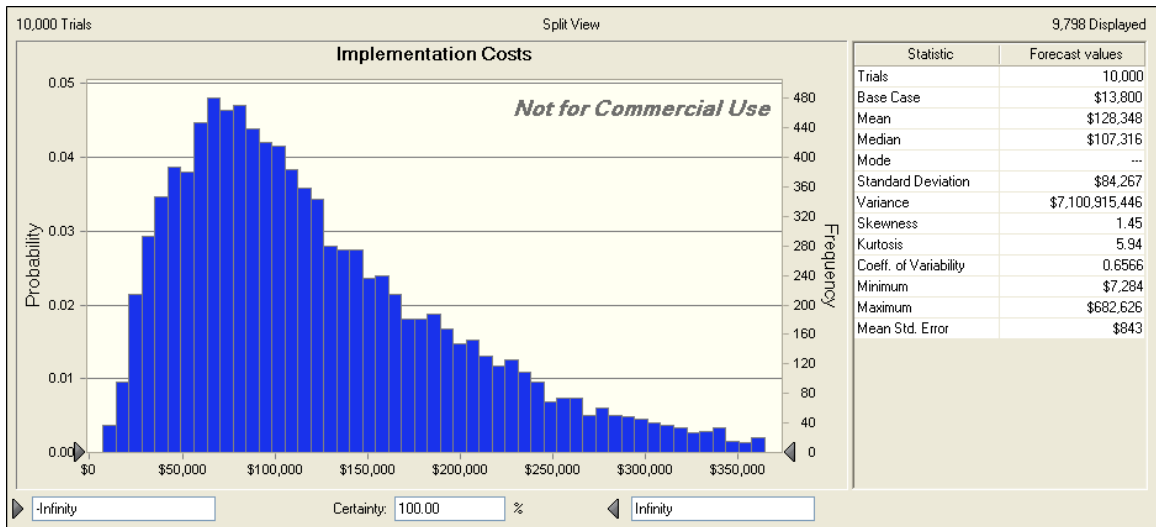


Figure 11. Scenario 3 Implementation Costs

The effects of changes in benefits due to changes in percentage of time that employees spend on inventory are determined by dividing the scenarios into the three segments identified by manufacturer facility size (see Table 6). Each of these groups contains two subgroups that are differentiated only by time spent on inventory. The first group, scenarios one through eight, has two subgroups identified as one through four and five through eight. Each of the first subgroups represents a lower amount of time spent on inventory, at 2%. The second subgroups represent a higher amount of time spent on

inventory, at 4%. The change in benefits is calculated by dividing the difference of the means of the first scenario in each subgroup, and then dividing the difference by the mean of the scenario in the second subgroup. For example, the difference in the means of scenario one and scenario five is \$8,236. This difference is then divided by the mean from the second subgroup, which is scenario five. The result is .1733, or 17.33%, from \$8,236 divided by \$47,513. Scenario 2 is then matched up with scenario 6, and so on.

The results of the calculations show that increases in time spent on inventory results in a very tight range of benefit increases from about 17% to 19%. For increases in time spent on inventory in facilities that have high product quality, as shown in scenarios one and five, nine and thirteen and seventeen and twenty-one, the increases are 17.33%, 18.57% and 18.81%, respectively. For increases in time spent on inventory in facilities that are highly complex and have high product quality, as shown in scenarios three and seven, eleven and fifteen and nineteen and twenty-three, the increases are 17.08%, 18.28% and 18.49%.

Table 6. Effect of Time Spent on Inventory on Mean Benefits

Scenario	Mean	Δ Mean	Scenario	Mean	Δ Mean	Scenario	Mean	Δ Mean
1	\$39,277	17.33%	9	\$170,352	18.57%	17	\$401,956	18.81%
2	\$41,073		10	\$175,129		18	\$413,309	
3	\$39,360	16.69%	11	\$171,486	18.06%	19	\$402,368	18.26%
4	\$40,692		12	\$173,249		20	\$410,415	
5	\$47,513	17.08%	13	\$209,208	18.28%	21	\$495,067	18.49%
6	\$49,304		14	\$213,738		22	\$505,665	
7	\$47,470	17.20%	15	\$209,858	19.60%	23	\$493,633	18.65%
8	\$49,145		16	\$215,472		24	\$504,519	

2. Costs, Benefits and Payback Period

Confidence intervals were constructed for the payback period of each scenario. Given the large number of iterations of each simulation, these confidence intervals are quite narrow. (See Table 8.)

Each scenario is also analyzed, in turn, for upside and downside risk. We examine risk with respect to payback period. Upside risk describes the possibility that expected payback period falls below the 10% percentile in the distribution of payback

period, thus indicating a faster rate of return on investment. Conversely, downside risk represents payback period results that fall above the 90% percentile in the distribution of payback period, and thus indicate a slower rate of return on investment. In the bootstrapping tool, each scenario was simulated 250 times with 500 trials in each simulation. Costs, benefits and expected payback are summed up in Table 7 and payback confidence intervals are summed up in Table 8.

Scenario 1: Average upfront cost is \$160,454 (Figure 12) and average yearly benefit is \$39,277 (Figure 13). The average expected payback period is 4.03 years with a 95% confidence interval from 4.03 years to 4.14 years. The upside benefit is a payback in 1.86 years with an 80% confidence interval from 1.75 years to 1.95 years. The downside is a payback in 10.87 years with an 80% confidence interval from 10.26 years to 11.47 years. Figure 14 shows the bootstrapping distribution results for scenario 1.

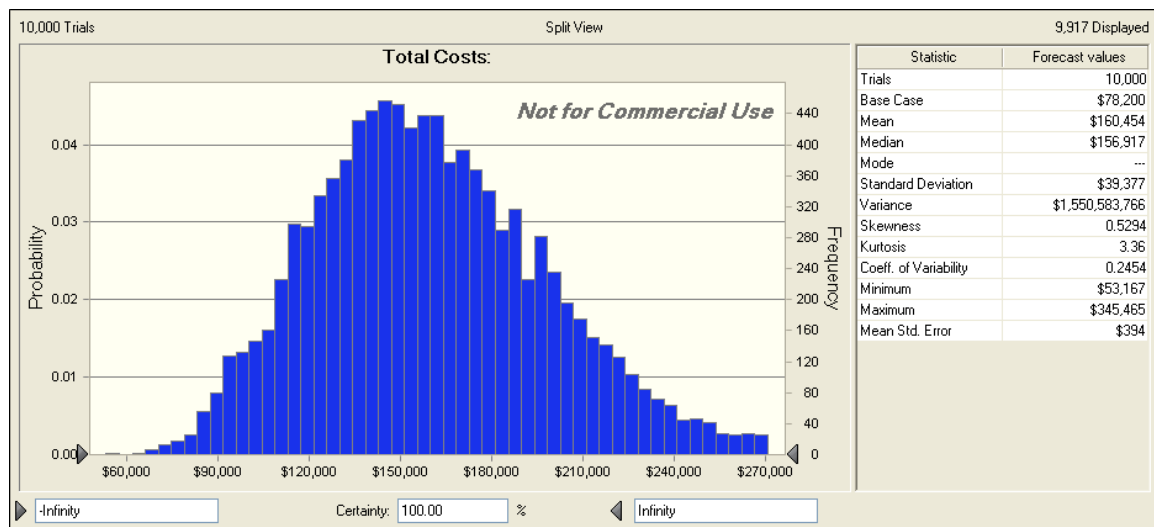


Figure 12. Total Cost Distribution for Scenario 1

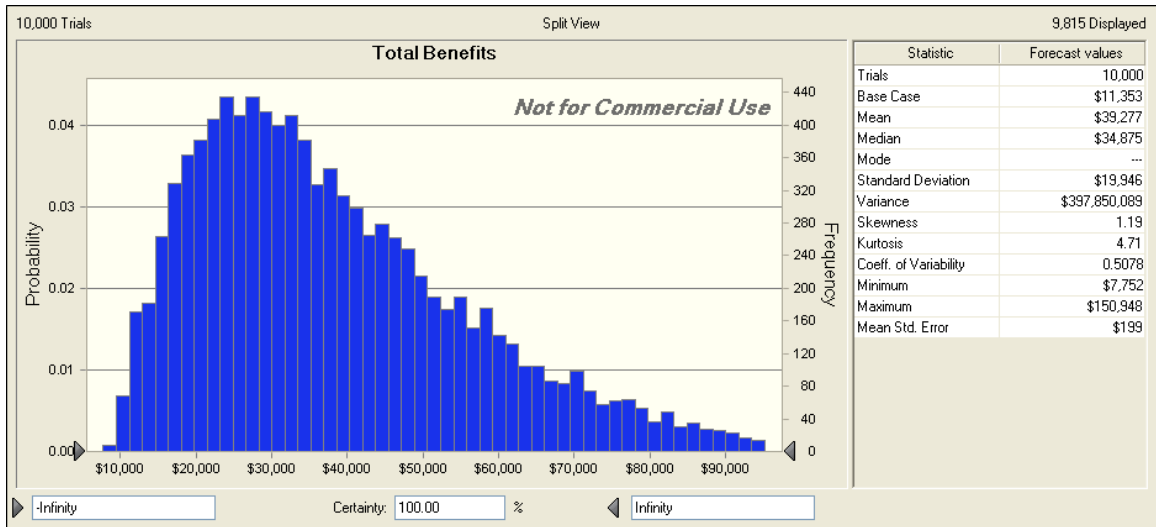


Figure 13. Total Benefit Distribution for Scenario 1

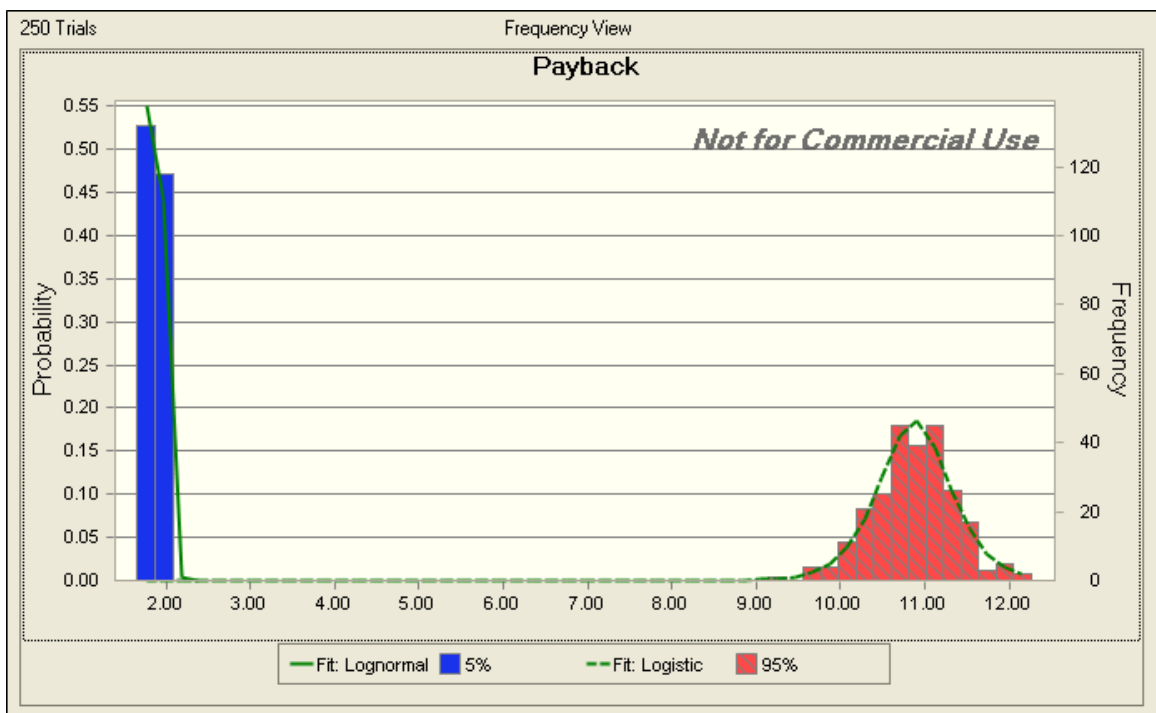


Figure 14. Payback Distribution for Scenario 1

Scenario 2: Average upfront cost is \$159,514 and average yearly benefit is \$41,073. The average expected payback is thus 3.88 years with a 95% confidence interval from 3.82 years to 3.94 years. The upside benefit is a payback in 1.81 years with

an 80% confidence interval from 1.7 years to 1.92 years. The downside is a payback in 9.92 years with an 80% confidence interval from 9.36 years to 10.51 years.

Scenario 3: Average upfront cost is \$438,246 and average yearly benefit is \$39,360. The average expected payback is 11.13 years with a 95% confidence interval from 10.94 years to 11.33 years. The upside benefit is a payback in 4.98 years with an 80% confidence interval from 4.67 years to 5.28 years. The downside is a payback in 30.23 years with an 80% confidence interval from 28.43 years to 32.27 years.

Scenario 4: Average upfront cost is \$438,994 and average yearly benefit is \$40,692. The average expected payback is 10.79 years with a 95% confidence interval from 10.63 years to 10.95 years. The upside benefit is a payback in 4.91 years with an 80% confidence interval from 4.64 years to 5.18 years. The downside is a payback in 27.83 years with an 80% confidence interval from 26.22 years to 29.52 years.

Scenario 5: Average upfront cost is \$160,537 and average yearly benefit is \$47,513. The average expected payback is 3.38 years with a 95% confidence interval from 3.32 years to 3.44 years. The upside benefit is a payback in 1.57 years with an 80% confidence interval from 1.47 years to 1.66 years. The downside is a payback in 9 years with an 80% confidence interval from 8.43 years to 9.58 years.

Scenario 6: Average upfront cost is \$160,173 and average yearly benefit is \$49,304. The average expected payback is 3.25 years with a 95% confidence interval from 3.19 years to 3.31 years. The upside benefit is a payback in 1.53 years with an 80% confidence interval from 1.45 years to 1.61 years. The downside is a payback in 8.34 years with an 80% confidence interval from 7.8 years to 8.82 years.

Scenario 7: Average upfront cost is \$438,286 and average yearly benefit is \$47,470. The average expected payback is 9.23 years with a 95% confidence interval from 9.08 years to 9.39 years. The upside benefit is a payback in 4.21 years with an 80% confidence interval from 4.01 years to 4.41 years. The downside is a payback in 25.17 years with an 80% confidence interval from 23.48 years to 26.93 years.

Scenario 8: Average upfront cost is \$437,605 and average yearly benefit is \$49,145. The average expected payback is 8.9 years with a 95% confidence interval

from 8.77 years to 9.04 years. The upside benefit is a payback in 4.15 years with an 80% confidence interval from 3.93 years to 4.33 years. The downside is a payback in 23.5 years with an 80% confidence interval from 21.91 years to 24.97 years.

Scenario 9: Average upfront cost is \$350,104 and average yearly benefit is \$170,352. The average expected payback is 2.06 years with a 95% confidence interval from 2.04 years to 2.07 years. The upside benefit is a payback in 0.96 years with an 80% confidence interval from 0.9 years to 1.02 years. The downside is a payback in 4.81 years with an 80% confidence interval from 4.58 years to 5.07 years.

Scenario 10: Average upfront cost is \$350,070 and average yearly benefit is \$175,129. The average expected payback is 2 years with a 95% confidence interval from 1.98 years to 2.02 years. The upside benefit is a payback in 0.95 years with an 80% confidence interval from 0.89 years to 1.01 years. The downside is a payback in 4.63 years with an 80% confidence interval from 4.36 years to 4.91 years.

Scenario 11: Average upfront cost is \$773,727 and average yearly benefit is \$171,486. The average expected payback is 4.51 years with a 95% confidence interval from 4.45 years to 4.57 years. The upside benefit is a payback in 2.18 years with an 80% confidence interval from 2.06 years to 2.29 years. The downside is a payback in 10.77 years with an 80% confidence interval from 10.17 years to 11.43 years.

Scenario 12: Average upfront cost is \$771,665 and average yearly benefit is \$173,249. The average expected payback is 4.45 years with a 95% confidence interval from 4.4 years to 4.51 years. The upside benefit is a payback in 2.14 years with an 80% confidence interval from 2.02 years to 2.26 years. The downside is a payback in 10.34 years with an 80% confidence interval from 9.84 years to 10.9 years.

Scenario 13: Average upfront cost is \$349,691 and average yearly benefit is \$209,208. The average expected payback is 1.67 years with a 95% confidence interval from 1.65 years to 1.69 years. The upside benefit is a payback in 0.81 years with an 80% confidence interval from 0.77 years to 0.86 years. The downside is a payback in 3.85 years with an 80% confidence interval from 3.63 years to 4.09 years.

Scenario 14: Average upfront cost is \$348,691 and average yearly benefit is \$213,738. The average expected payback is 1.63 years with a 95% confidence interval from 1.61 years to 1.65 years. The upside benefit is a payback in 0.8 years with an 80% confidence interval from 0.76 years to 0.84 years. The downside is a payback in 3.71 years with an 80% confidence interval from 3.49 years to 3.94 years.

Scenario 15: Average upfront cost is \$771,838 and average yearly benefit is \$209,858. The average expected payback is 3.68 years with a 95% confidence interval from 3.62 years to 3.74 years. The upside benefit is a payback in 1.85 years with an 80% confidence interval from 1.75 years to 1.95 years. The downside is a payback in 8.66 years with an 80% confidence interval from 8.11 years to 9.17 years.

Scenario 16: Average upfront cost is \$771,510 and average yearly benefit is \$215,472. The average expected payback is 3.58 years with a 95% confidence interval from 3.52 years to 3.64 years. The upside benefit is a payback in 1.82 years with an 80% confidence interval from 1.73 years to 1.9 years. The downside is a payback in 8.35 years with an 80% confidence interval from 7.88 years to 8.88 years.

Scenario 17: Average upfront cost is \$649,194 and average yearly benefit is \$401,956. The average expected payback is 1.62 years with a 95% confidence interval from 1.6 years to 1.63 years. The upside benefit is a payback in 0.79 years with an 80% confidence interval from 0.74 years to 0.83 years. The downside is a payback in 3.37 years with an 80% confidence interval from 3.19 years to 3.54 years.

Scenario 18: Average upfront cost is \$644,423 and average yearly benefit is \$413,309. The average expected payback is 1.56 years with a 95% confidence interval from 1.54 years to 1.58 years. The upside benefit is a payback in 0.78 years with an 80% confidence interval from 0.74 years to 0.82 years. The downside is a payback in 3.23 years with an 80% confidence interval from 3.07 years to 3.38 years.

Scenario 19: Average upfront cost is \$1,250,996 and average yearly benefit is \$402,368. The average expected payback is 3.11 years with a 95% confidence interval from 3.07 years to 3.15 years. The upside benefit is a payback in 1.62 years with an 80%

confidence interval from 1.53 years to 1.71 years. The downside is a payback in 6.54 years with an 80% confidence interval from 6.25 years to 6.83 years.

Scenario 20: Average upfront cost is \$1,246,045 and average yearly benefit is \$410,415. The average expected payback is 3.04 years with a 95% confidence interval from 3.02 years to 3.06 years. The upside benefit is a payback in 1.62 years with an 80% confidence interval from 1.55 years to 1.69 years. The downside is a payback in 6.44 years with an 80% confidence interval from 6.16 years to 6.74 years.

Scenario 21: Average upfront cost is \$649,997 and average yearly benefit is \$495,067. The average expected payback is 1.31 years with a 95% confidence interval from 1.29 years to 1.33 years. The upside benefit is a payback in 0.68 years with an 80% confidence interval from 0.64 years to 0.71 years. The downside is a payback in 2.72 years with an 80% confidence interval from 2.59 years to 2.87 years.

Scenario 22: Average upfront cost is \$645,778 and average yearly benefit is \$505,665. The average expected payback is 1.28 years with a 95% confidence interval from 1.26 years to 1.3 years. The upside benefit is a payback in 0.67 years with an 80% confidence interval from 0.64 years to 0.71 years. The downside is a payback in 2.71 years with an 80% confidence interval from 2.56 years to 2.85 years.

Scenario 23: Average upfront cost is \$1,246,210 and average yearly benefit is \$493,633. The average expected payback is 2.52 years with a 95% confidence interval from 2.5 years to 2.54 years. The upside benefit is a payback in 1.39 years with an 80% confidence interval from 1.33 years to 1.44 years. The downside is a payback in 5.32 years with an 80% confidence interval from 5.04 years to 5.6 years.

Scenario 24: Average upfront cost is \$1,250,763 and average yearly benefit is \$504,519. The average expected payback is 2.48 years with a 95% confidence interval from 2.44 years to 2.52 years. The upside benefit is a payback in 1.39 years with an 80% confidence interval from 1.33 years to 1.45 years. The downside is a payback in 5.26 years with an 80% confidence interval from 4.94 years to 5.58 years.

Table 7. Expected Payback

Payback Analysis				
Scenario	Costs	Benefits	Expected Payback (yrs)	
			Mean	95% CI
1	\$160,454	\$39,277	4.09	[4.03, 4.14]
2	\$159,514	\$41,073	3.88	[3.82, 3.94]
3	\$438,246	\$39,360	11.13	[10.94, 11.33]
4	\$438,994	\$40,692	10.79	[10.63, 10.95]
5	\$160,537	\$47,513	3.38	[3.32, 3.44]
6	\$160,173	\$49,304	3.25	[3.19, 3.31]
7	\$438,286	\$47,470	9.23	[9.08, 9.39]
8	\$437,605	\$49,145	8.90	[8.77, 9.04]
9	\$350,104	\$170,352	2.06	[2.04, 2.07]
10	\$350,070	\$175,129	2.00	[1.98, 2.02]
11	\$773,727	\$171,486	4.51	[4.45, 4.57]
12	\$771,665	\$173,249	4.45	[4.40, 4.51]
13	\$349,691	\$209,208	1.67	[1.65, 1.69]
14	\$348,691	\$213,738	1.63	[1.61, 1.65]
15	\$771,838	\$209,858	3.68	[3.62, 3.74]
16	\$771,510	\$215,472	3.58	[3.52, 3.64]
17	\$649,194	\$401,956	1.62	[1.60, 1.63]
18	\$644,423	\$413,309	1.56	[1.54, 1.58]
19	\$1,250,996	\$402,368	3.11	[3.07, 3.15]
20	\$1,246,045	\$410,415	3.04	[3.02, 3.06]
21	\$649,997	\$495,067	1.31	[1.29, 1.33]
22	\$645,778	\$505,665	1.28	[1.26, 1.30]
23	\$1,246,210	\$493,633	2.52	[2.50, 2.54]
24	\$1,250,763	\$504,519	2.48	[2.44, 2.52]

Table 8. Payback Confidence Intervals

Payback Analysis				
Scenario	10% Mean	CI - 10%	90% Mean	CI - 90%
1	1.86	[1.75, 1.95]	10.87	[10.26, 11.47]
2	1.81	[1.7, 1.92]	9.92	[9.36, 10.51]
3	4.98	[4.67, 5.28]	30.23	[28.43, 32.27]
4	4.91	[4.64, 5.18]	27.83	[26.22, 29.52]
5	1.57	[1.47, 1.66]	9	[8.43, 9.58]
6	1.53	[1.45, 1.61]	8.34	[7.8, 8.82]
7	4.21	[4.01, 4.41]	25.17	[23.48, 26.93]
8	4.15	[3.93, 4.33]	23.5	[21.91, 24.97]
9	0.96	[0.9, 1.02]	4.81	[4.58, 5.07]
10	0.95	[0.89, 1.01]	4.63	[4.36, 4.91]
11	2.18	[2.06, 2.29]	10.77	[10.17, 11.43]
12	2.14	[2.02, 2.26]	10.34	[9.84, 10.9]
13	0.81	[0.77, 0.86]	3.85	[3.63, 4.09]
14	0.8	[0.76, 0.84]	3.71	[3.49, 3.94]
15	1.85	[1.75, 1.95]	8.66	[8.11, 9.17]
16	1.82	[1.73, 1.9]	8.35	[7.88, 8.88]
17	0.79	[0.74, 0.83]	3.37	[3.19, 3.54]
18	0.78	[0.74, 0.82]	3.23	[3.07, 3.38]
19	1.62	[1.53, 1.71]	6.54	[6.25, 6.83]
20	1.62	[1.55, 1.69]	6.44	[6.16, 6.74]
21	0.68	[0.64, 0.71]	2.72	[2.59, 2.87]
22	0.67	[0.64, 0.71]	2.71	[2.56, 2.85]
23	1.39	[1.33, 1.44]	5.32	[5.04, 5.6]
24	1.39	[1.33, 1.45]	5.26	[4.94, 5.58]

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V. CONCLUSIONS

A. INTRODUCTION

To preface these conclusions, it should be noted once again that all conclusions are derived from a set of scenarios whose parameters were selected based on the experience of the author and his advisors, and are not meant to predict outcomes of specific, real-life situations. No data was given from any outside source; thus, all conclusions are drawn exclusively through modeling the chosen parameters.

B. CONCLUSIONS

Product quality differences between similar plants had little effect on derived benefits. Although this was hinted at during the model set-up process when product quality variables were very low in the tornado chart, the 2.68% average increase in benefits from poor quality to high quality products is slightly surprising. Equally surprising is the fact that smaller manufacturers benefit more from an increase in product quality; their average increase is 3.67%, compared to the average increase of large manufacturers of 2.24%.

Like product quality, complexity has more of an effect on smaller manufacturers than large manufacturers, albeit through higher costs instead of higher benefits. These added costs can be staggering, as evidenced by the nine to eleven year payback lengths. With this in mind, smaller companies attempting complex RFID implementations may find little financial benefit. On the other hand, medium to large sized manufacturers do not face these same payback lengths, so the amount of complexity should not be a limiting factor in their decision to implement RFID.

There are more savings to be had for manufacturers who spend significant portions of their time conducting inventory over those who spend less. However, these additional savings are very nearly equal across the realm of small to large manufacturers, demonstrated in the scenarios by a low of 16.69% (small manufacturer) to a high of

19.6% (medium manufacturer). The conclusion here is that RFID implementation is more beneficial for any manufacturer who currently spends a lot of time conducting inventories.

In terms of fitting the Defense Microelectronics Activity to a specific scenario, since the agency was reluctant to share specific cost or production data, the author will have to make a few assumptions based on his previous interactions with the agency. First, DMEA should be classified as a small manufacturer with low yearly volume and a low number of employees who need training. Second, it does not appear that DMEA will need a complex installation of RFID equipment based on their size, layout and overall intended use of the technology. This will mitigate a significant portion of costs identified in the model. Third, DMEA is a high-quality producer of electronics due to the stringent standards which they are required to meet in order to continue providing goods to the United States military.

These assumptions in mind, the author will select scenario one to be representative of DMEA. Scenario five is equally likely to be a close fit as well; although the benefits of scenario five are 17% higher per year due to greater savings in regards to time spent on inventory, scenario one is selected due to the more conservative idea of spending only 2% of employee time on inventory activities instead of 4%. The expected upfront cost of implementing scenario one is \$160,454. The expected annual benefit of scenario one is \$39,277, resulting in an expected payback period of 4.09 years.

To further examine the question of whether the implementation of RFID technology is a financially feasible option for DMEA, the author uses the widely accepted Net Present Value tool, or NPV. The NPV is calculated by projecting the annual benefit to ten years after year zero, in which year there are only the costs of implementation. While benefits are very likely to continue accruing after ten years, changes in technology and/or changes at DMEA might have an impact on RFID benefits, so therefore the benefits are limited to the first ten years. Assuming a 5% discount rate, the NPV of implementation of scenario one is \$142,833. The NPV with a 10% discount rate is \$80,886.

Of course, a business case analysis using DMEA data might find a different payback period, and a different NPV. But the organization should be able to use the method laid out in this project as a foundation for their own business case analysis.

C. SUMMARY

In this project, the author has developed a template to support the business case analysis of an RFID implementation at an electronics manufacturer. The genesis for the study was a proposed RFID implementation at DMEA, but DMEA was unable to deliver detailed data to the author to support the financial feasibility analysis. Instead, the author used the template to examine a wide set of manufacturing settings. The analysis reported here is thus an exploratory examination of the factors which would determine the relative financial attractiveness of RFID in electronics manufacturing. It appears the most significant factors are the size of the plant, and time spent on physical inventory tracking without RFID.

DMEA, as a member of the Department of Defense, can and should look at all options to reduce their budget through cost-cutting initiatives and by utilizing newer technologies to their advantage. While this activity is in no danger of being subsumed or outsourced to the civilian sector, it will still likely face the probability of a reduction in its budget. In addition, it is incumbent upon DMEA, as on all government agencies, to be good steward of the American taxpayer dollars. Therefore, it is the recommendation of this report that DMEA undertakes a detailed study of the implementation of RFID technologies using the methodology laid-out in this project, to become a more-efficient entity in order to meet the tougher financial standards that the future holds.

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APPENDIX. SCENARIO DATA

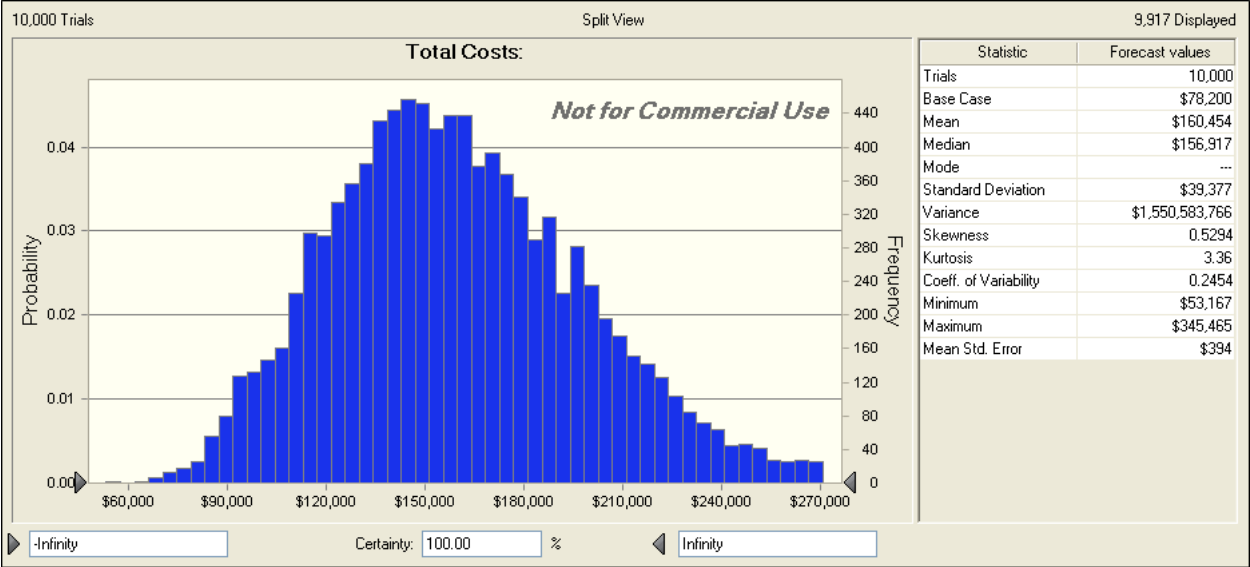


Figure 15. Scenario 1 Total Costs

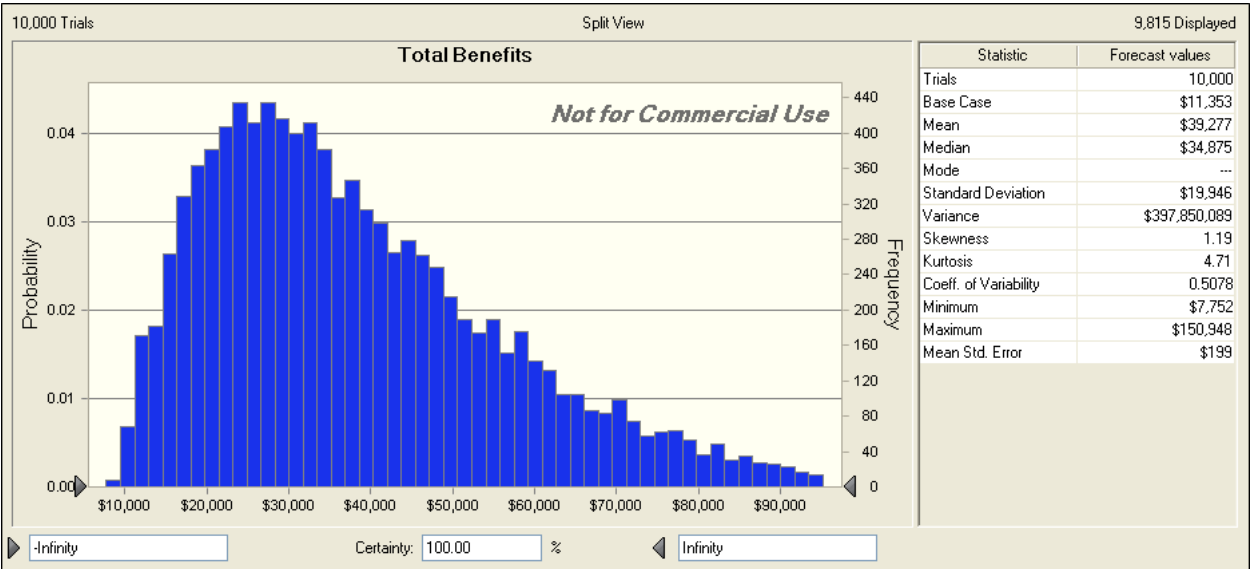


Figure 16. Scenario 1 Total Benefits

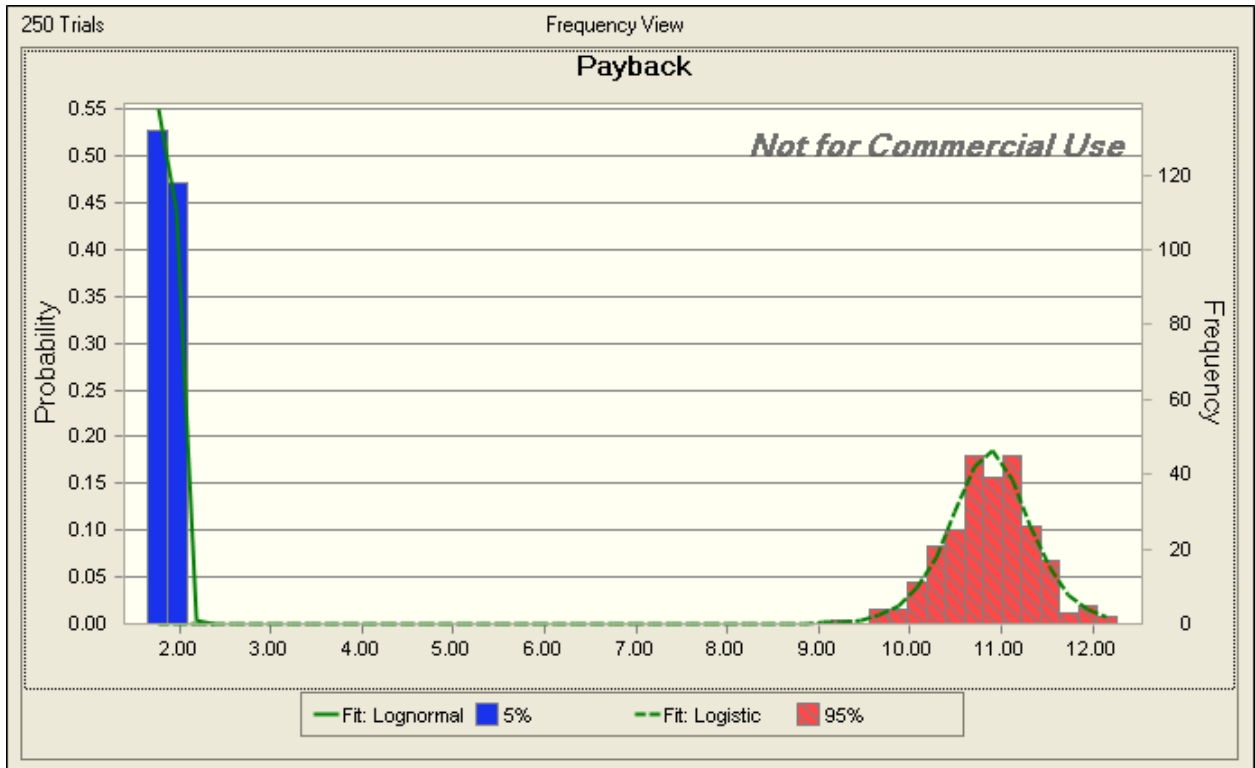


Figure 17. Scenario 1 Payback

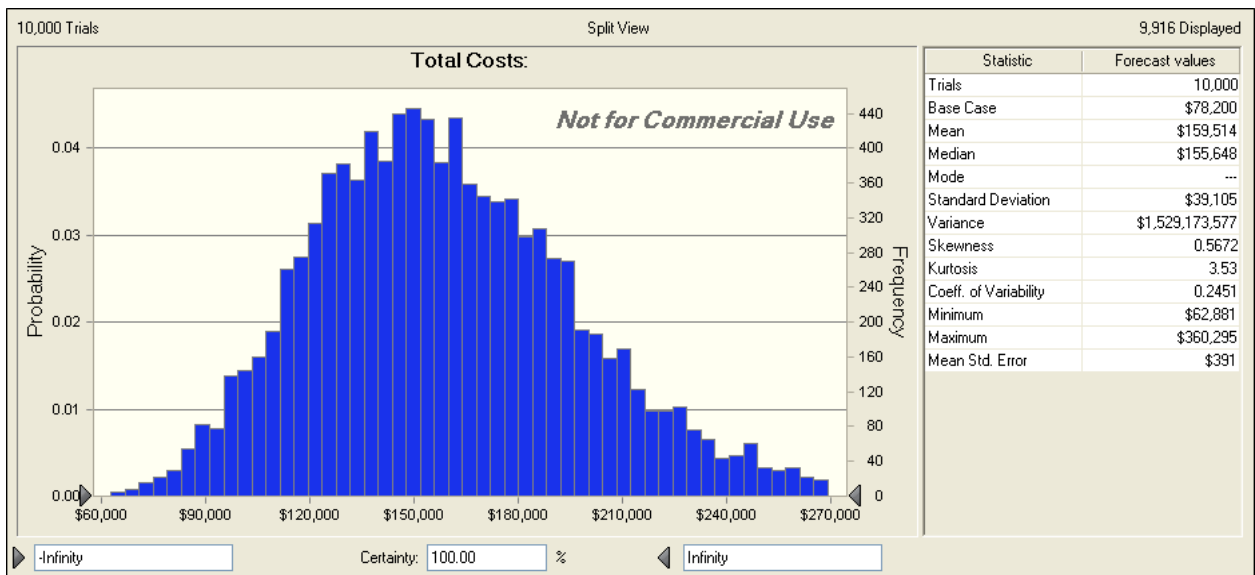


Figure 18. Scenario 2 Total Costs

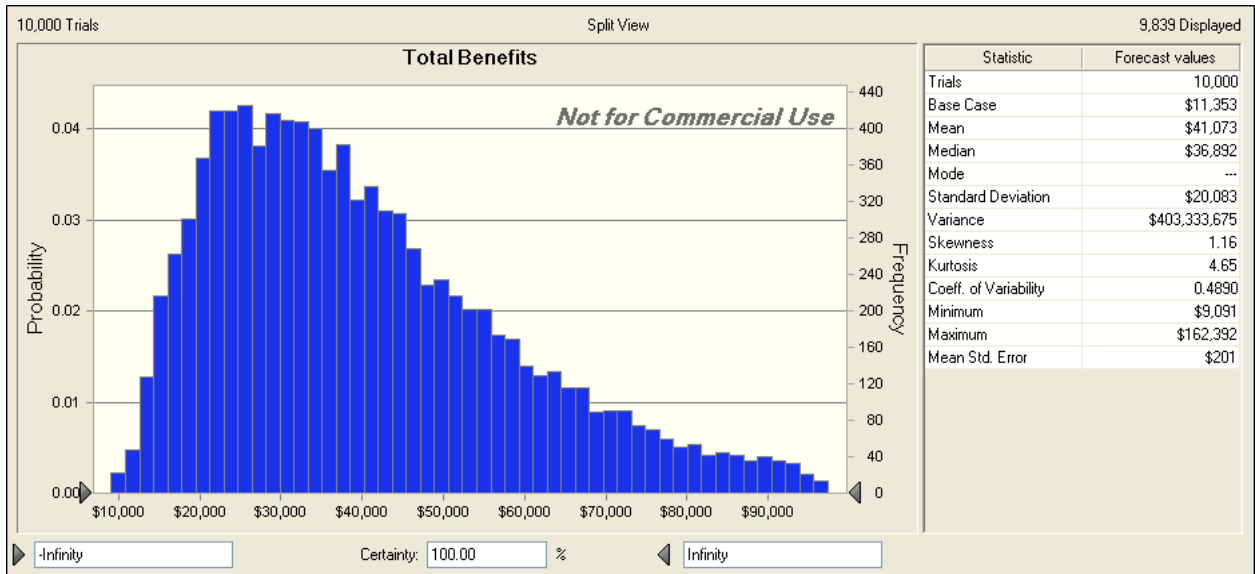


Figure 19. Scenario 2 Total Benefits

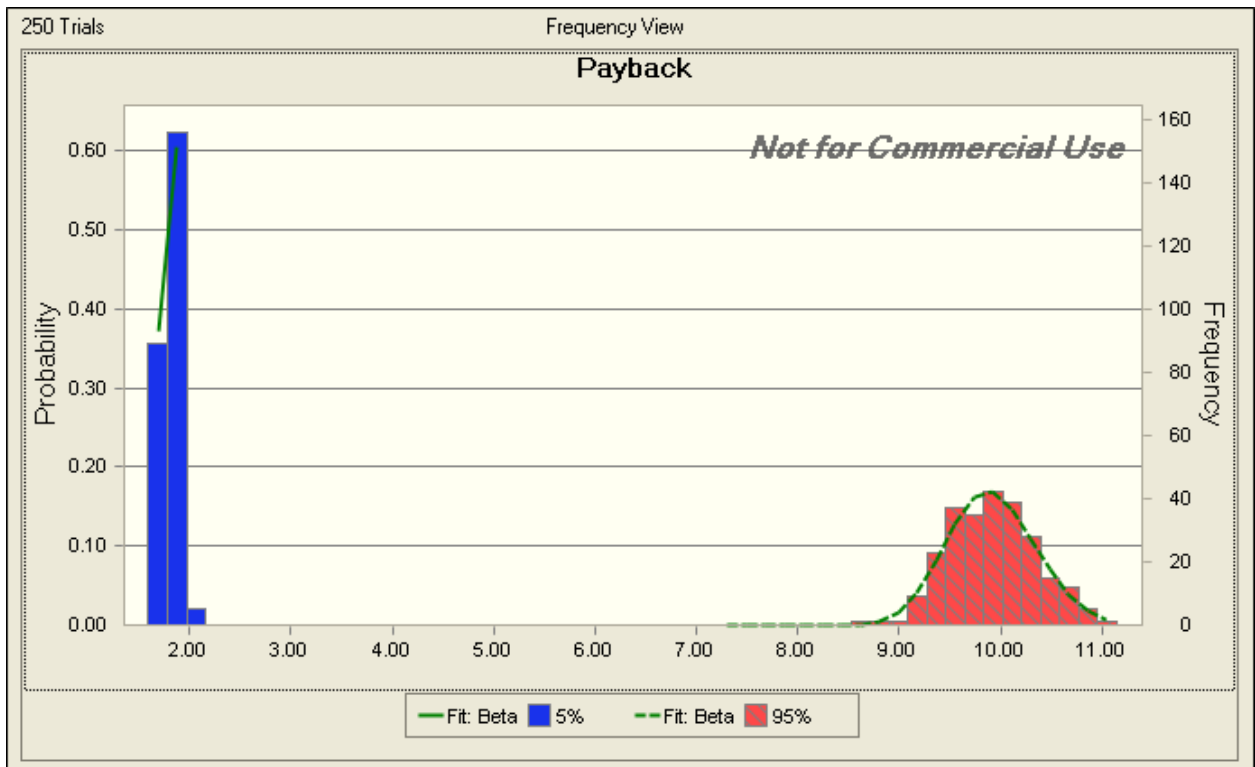


Figure 20. Scenario 2 Payback

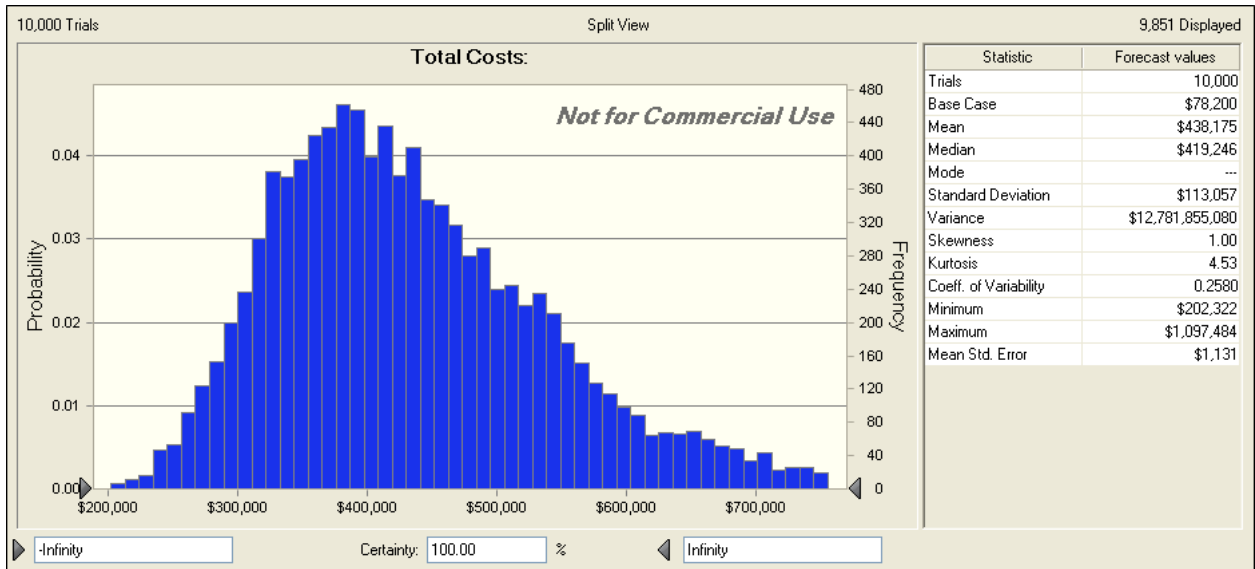


Figure 21. Scenario 3 Total Costs

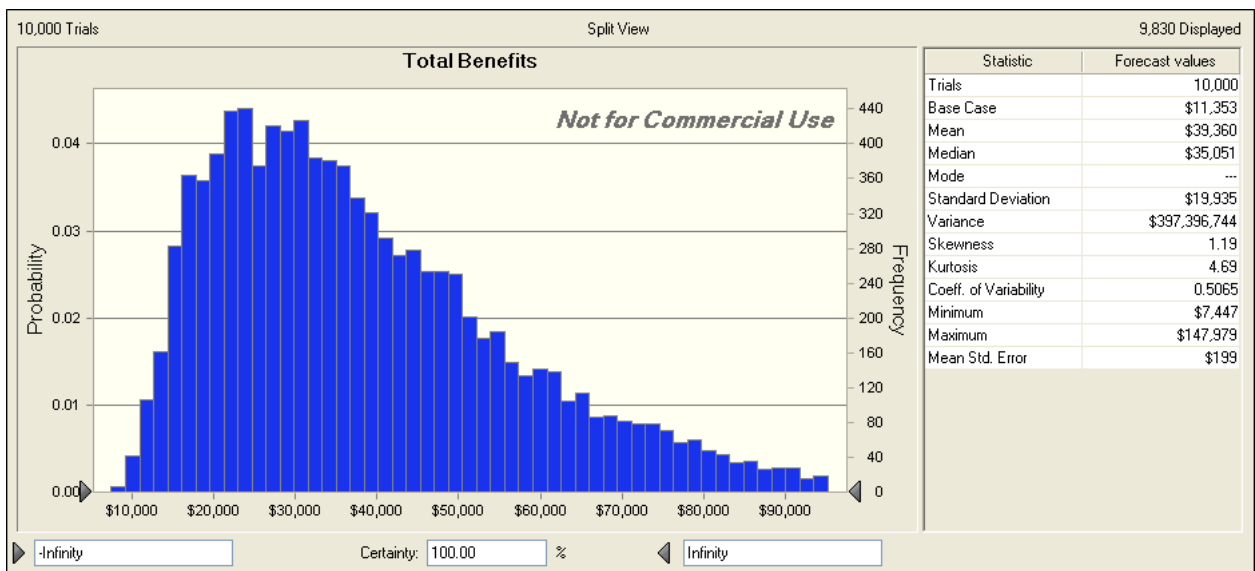


Figure 22. Scenario 3 Total Benefits

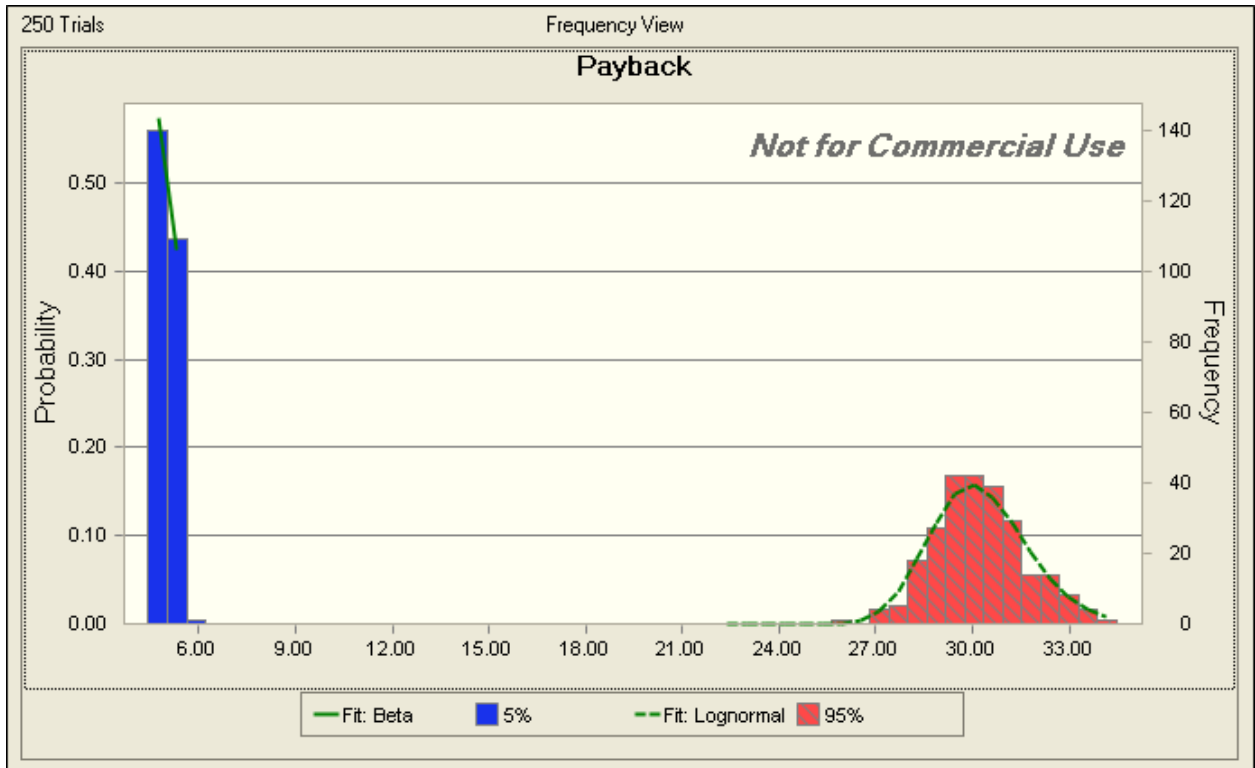


Figure 23. Scenario 3 Payback

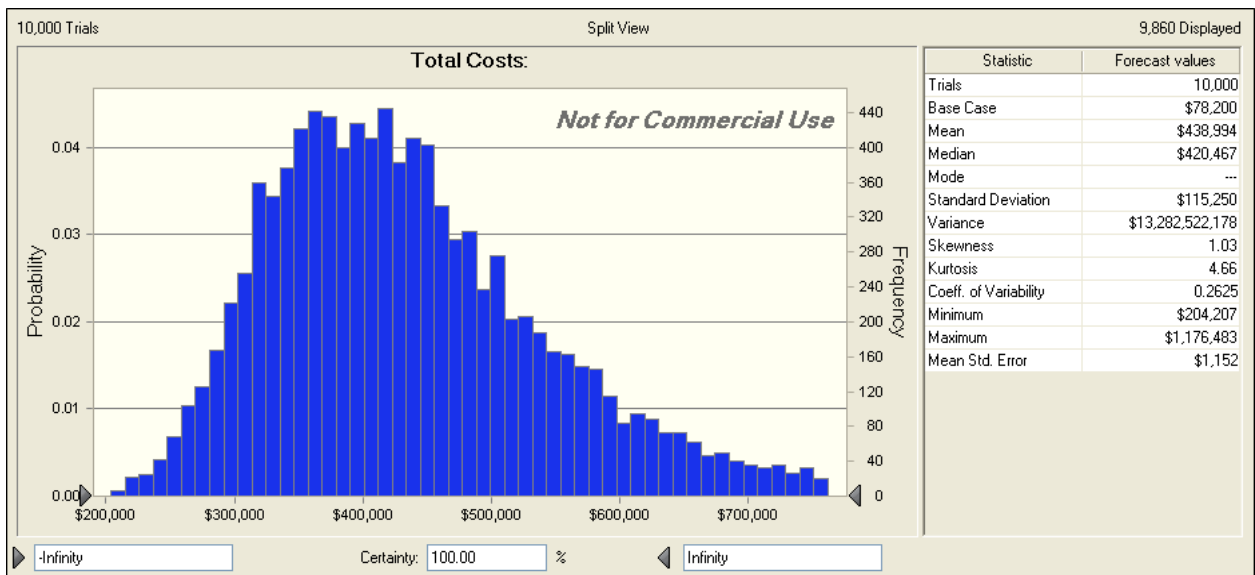


Figure 24. Scenario 4 Total Costs

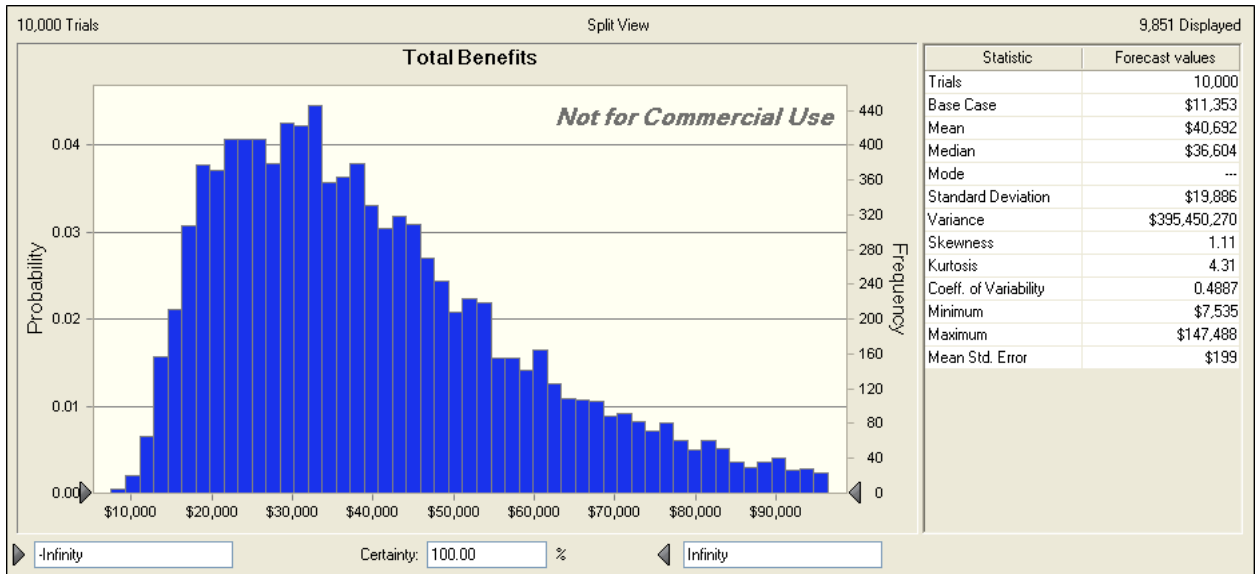


Figure 25. Scenario 4 Total Benefits

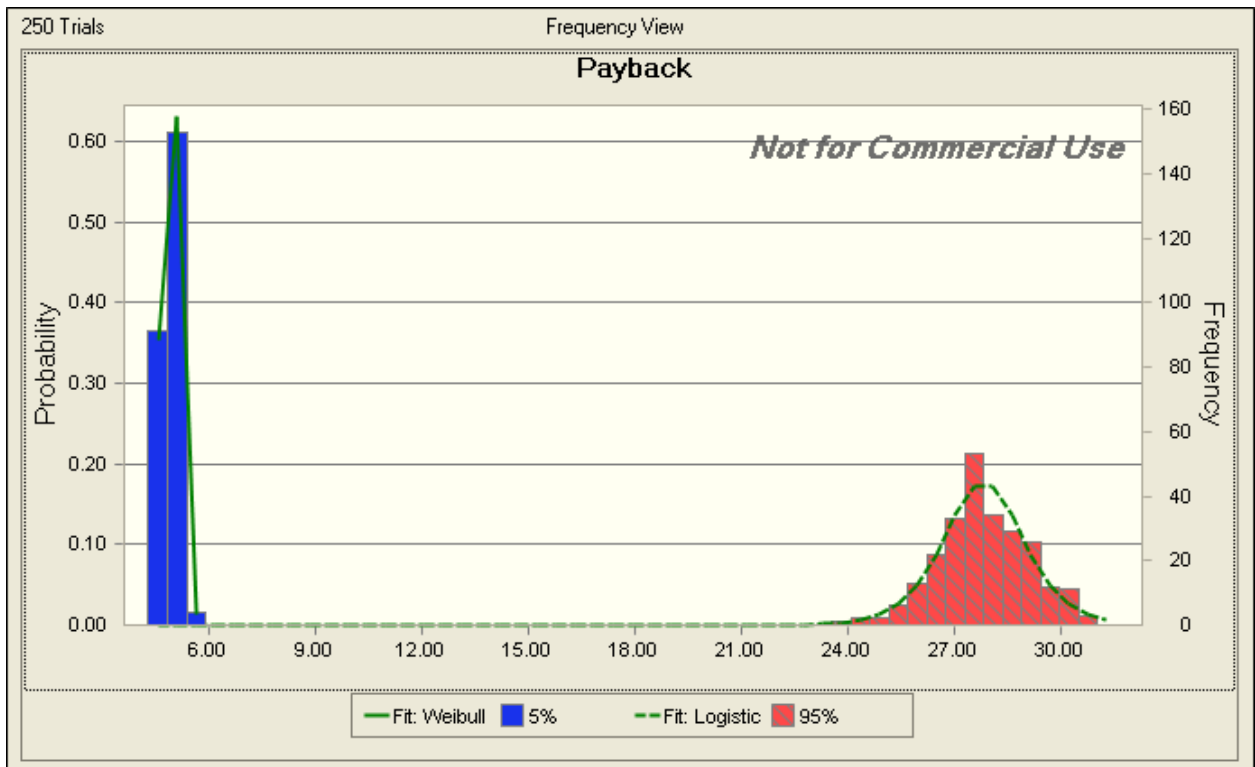


Figure 26. Scenario 4 Payback

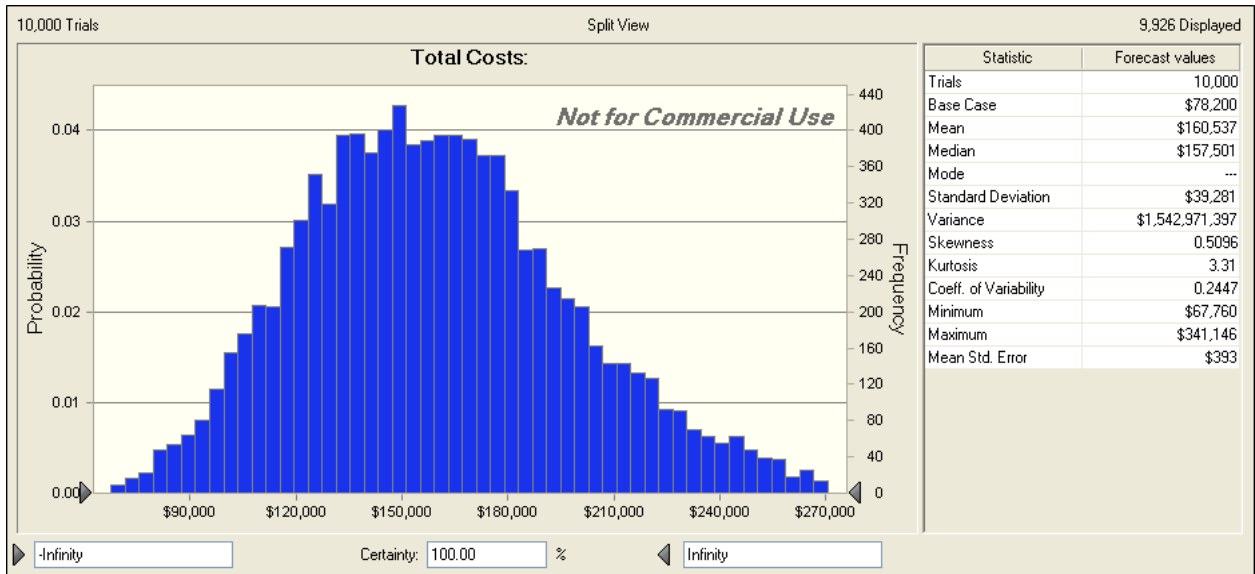


Figure 27. Scenario 5 Total Costs

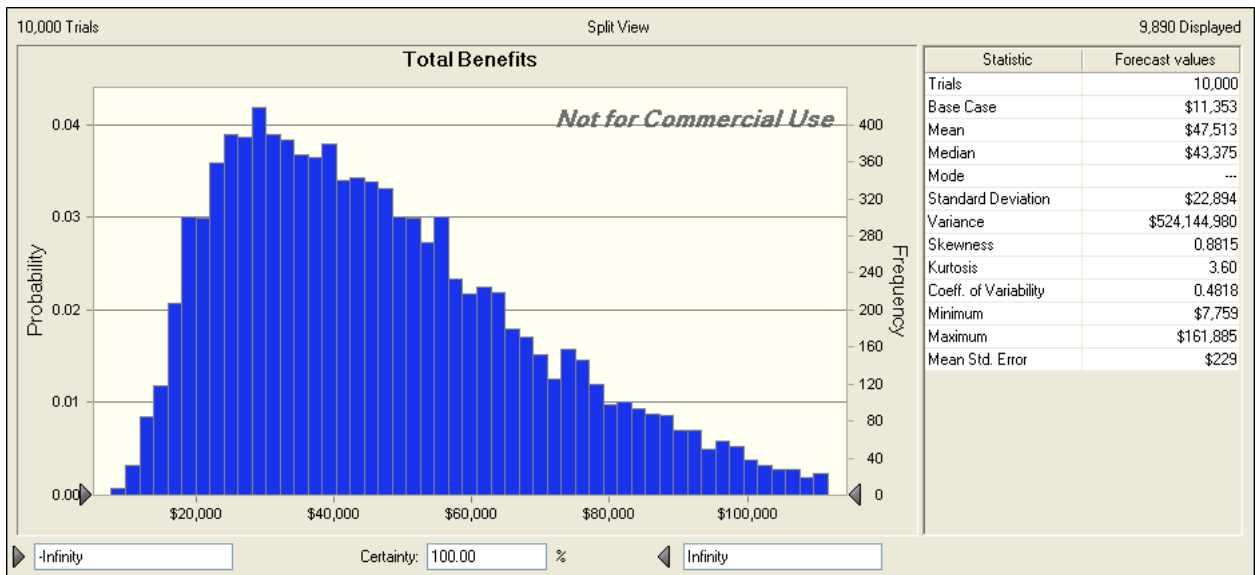


Figure 28. Scenario 5 Total Benefits

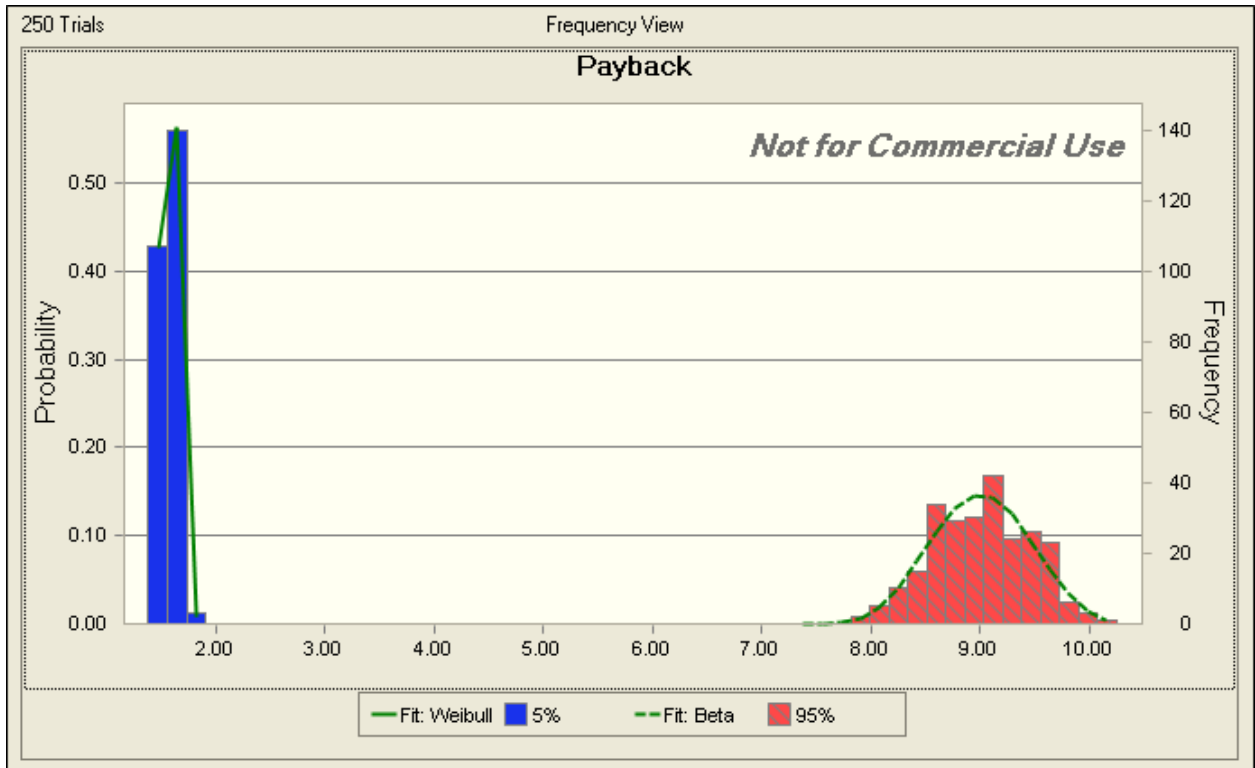


Figure 29. Scenario 5 Payback

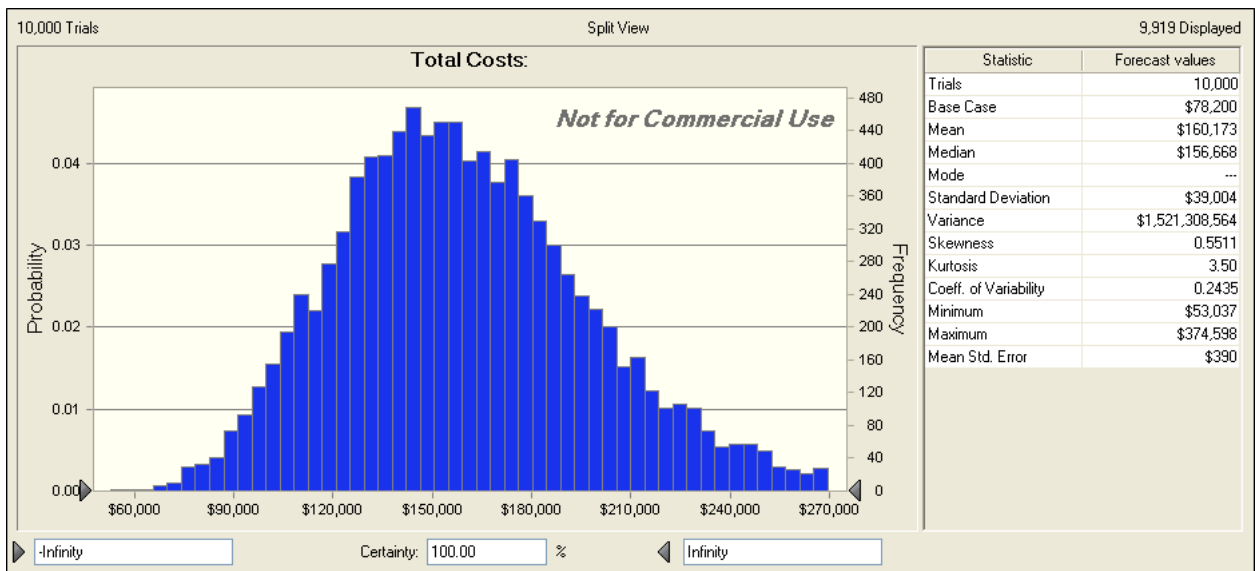


Figure 30. Scenario 6 Total Costs

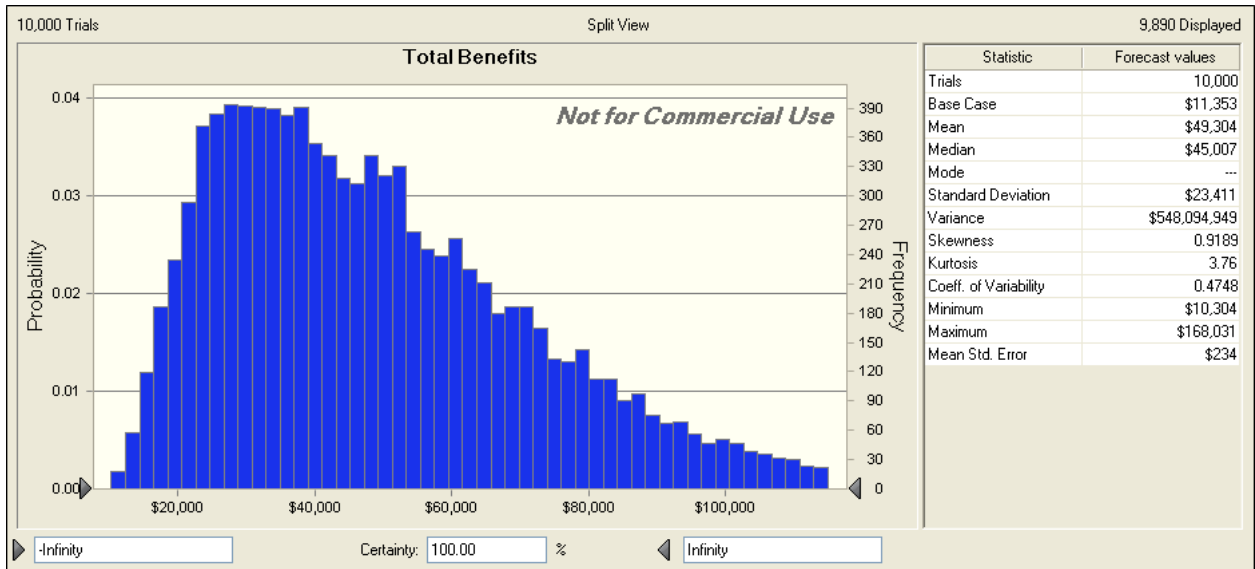


Figure 31. Scenario 6 Total Benefits

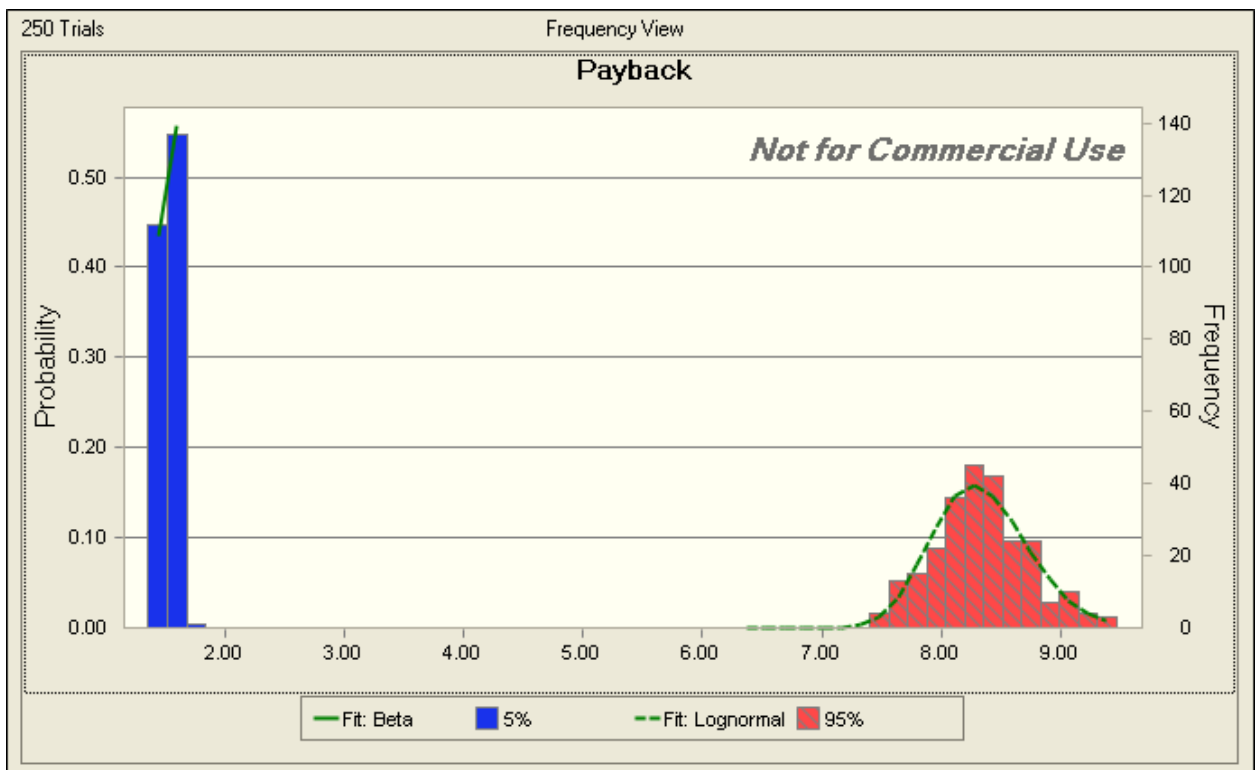


Figure 32. Scenario 6 Payback

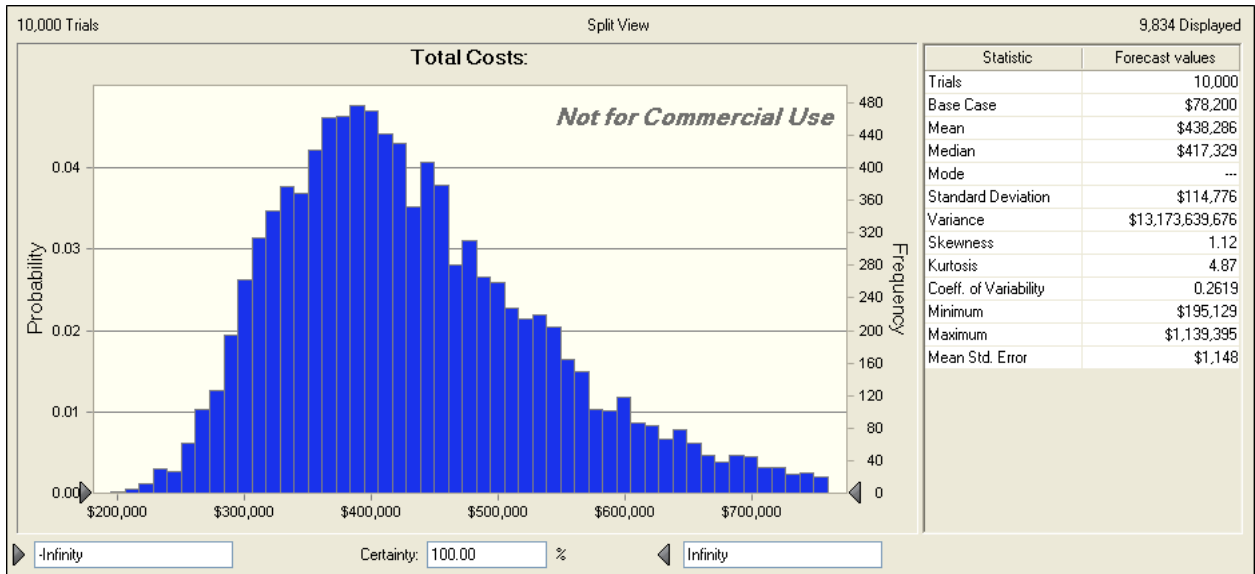


Figure 33. Scenario 7 Total Costs

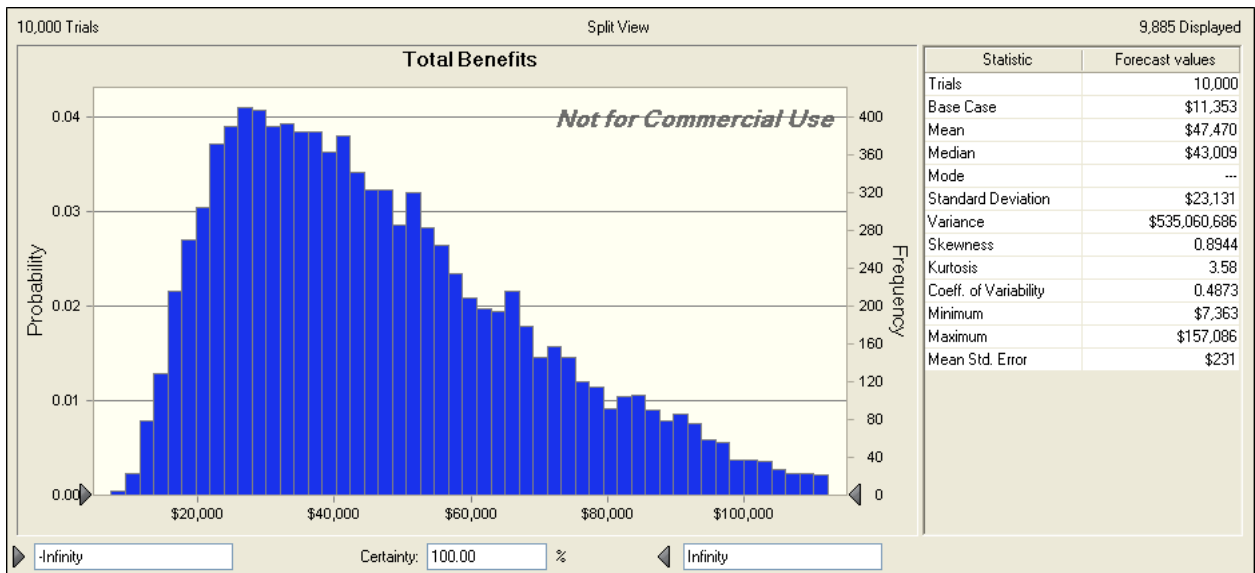


Figure 34. Scenario 7 Total Benefits

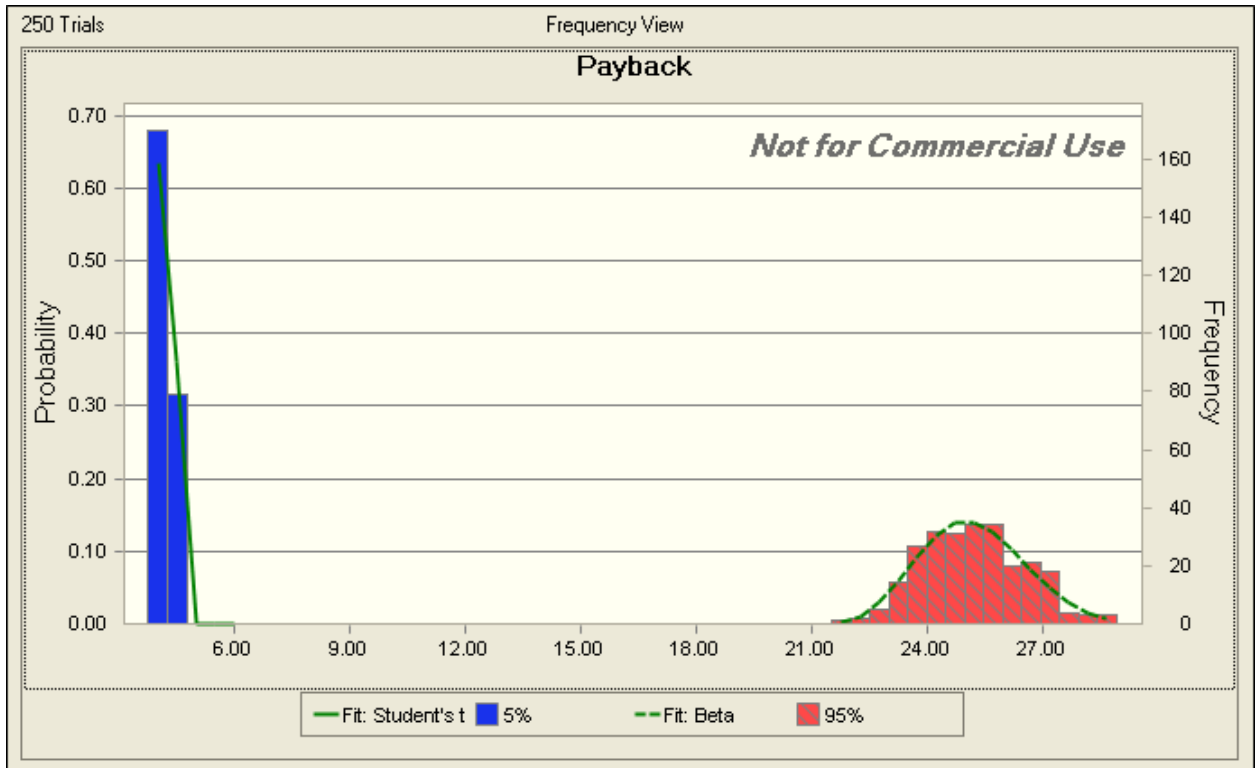


Figure 35. Scenario 7 Payback

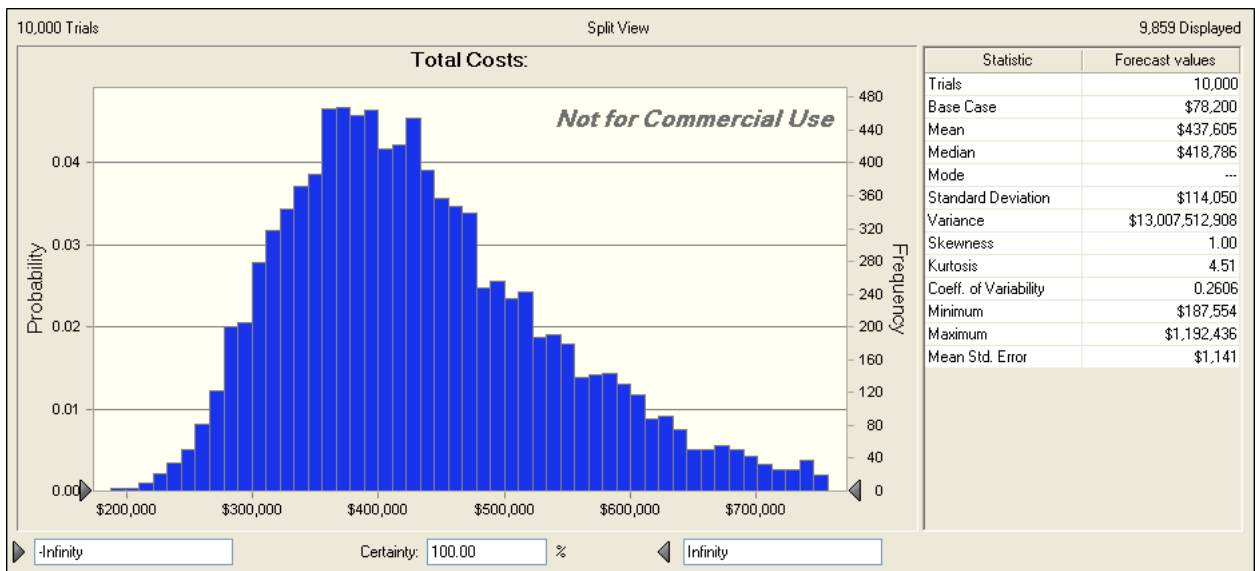


Figure 36. Scenario 8 Total Costs

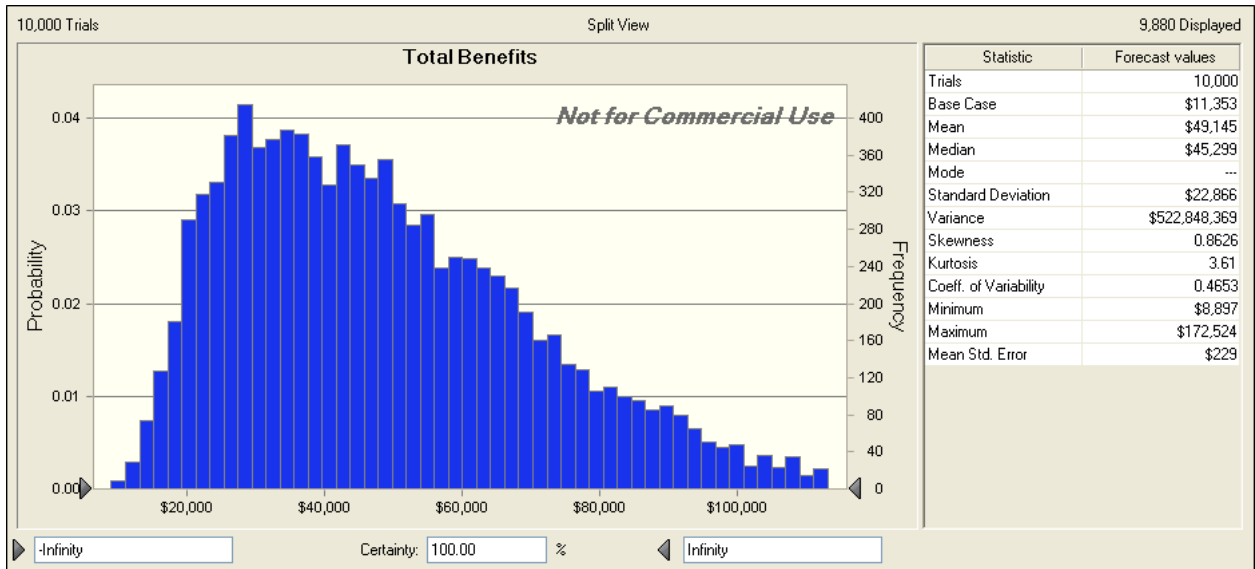


Figure 37. Scenario 8 Total Benefits

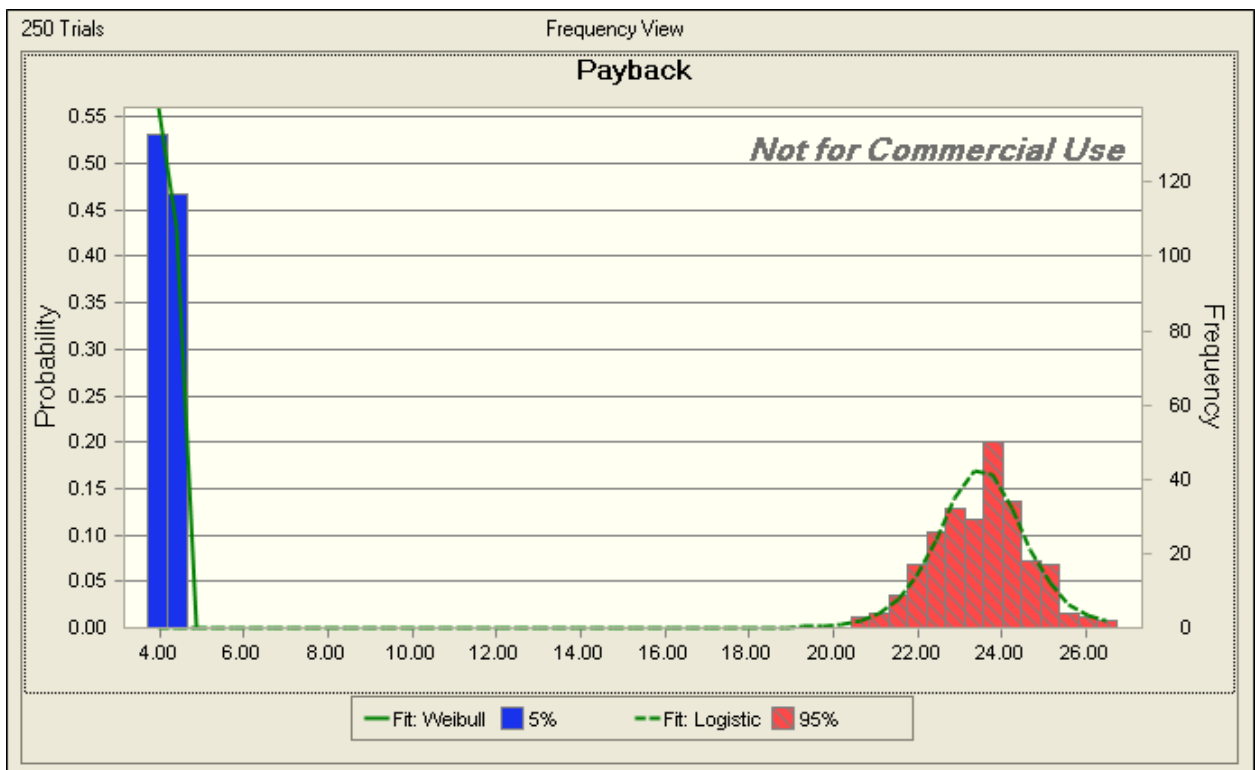


Figure 38. Scenario 8 Payback

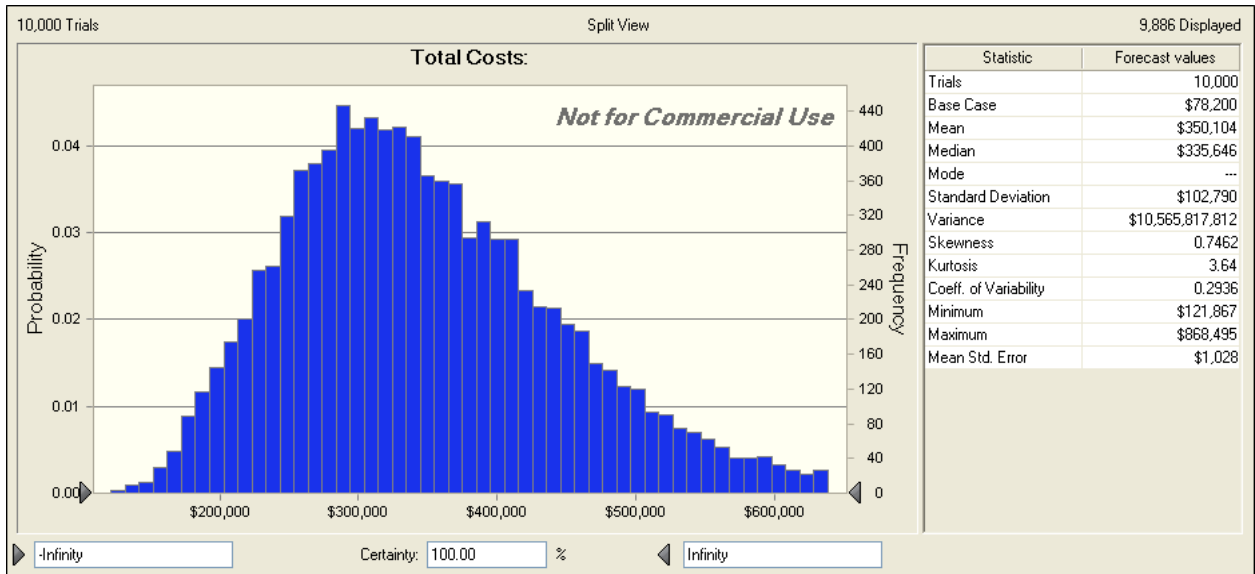


Figure 39. Scenario 9 Total Costs

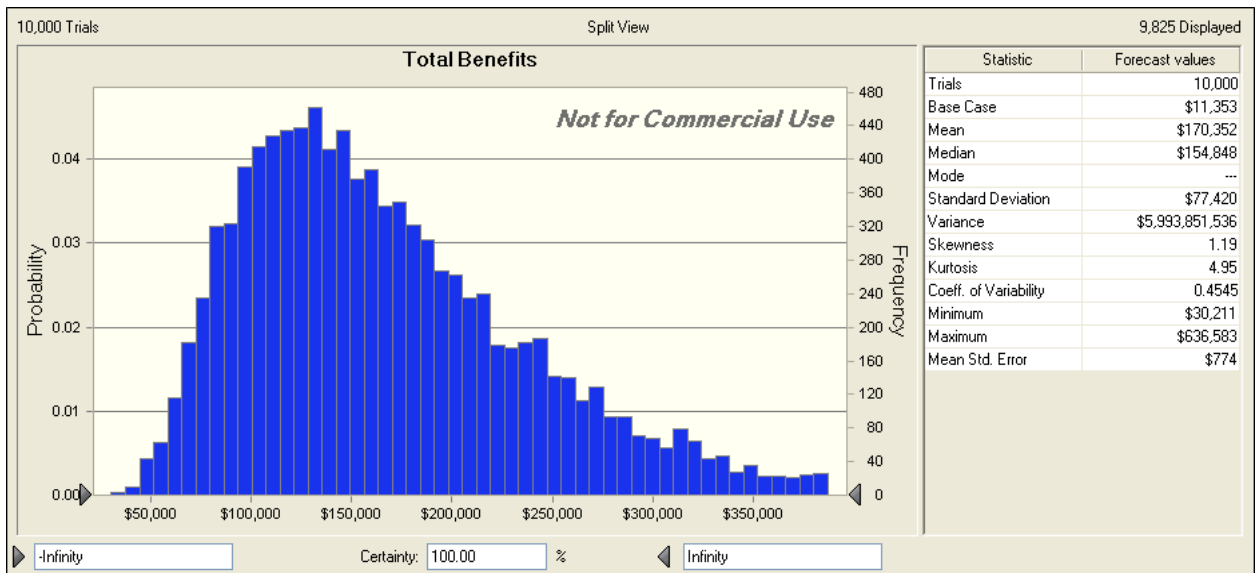


Figure 40. Scenario 9 Total Benefits

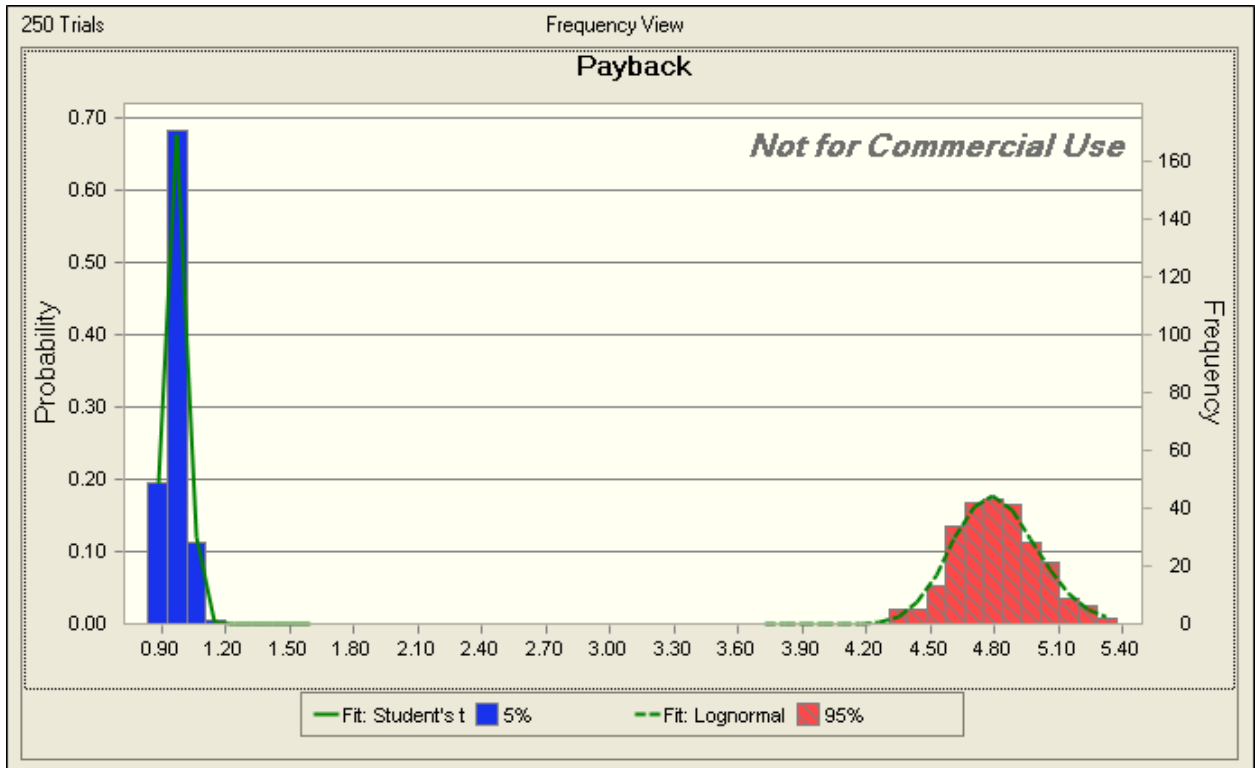


Figure 41. Scenario 9 Payback

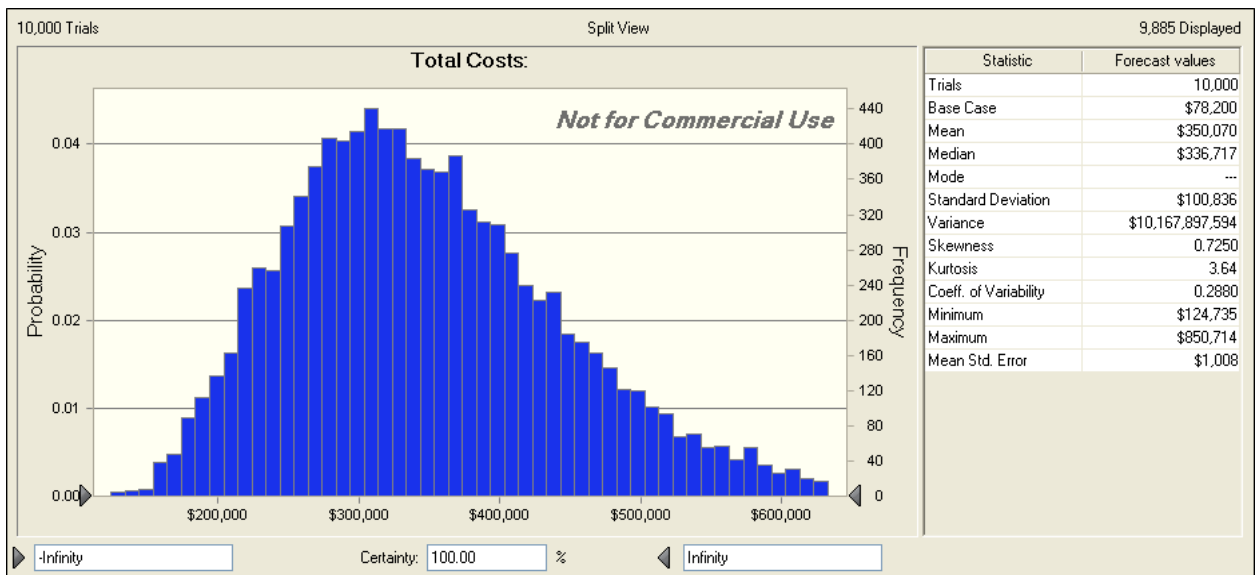


Figure 42. Scenario 10 Total Costs

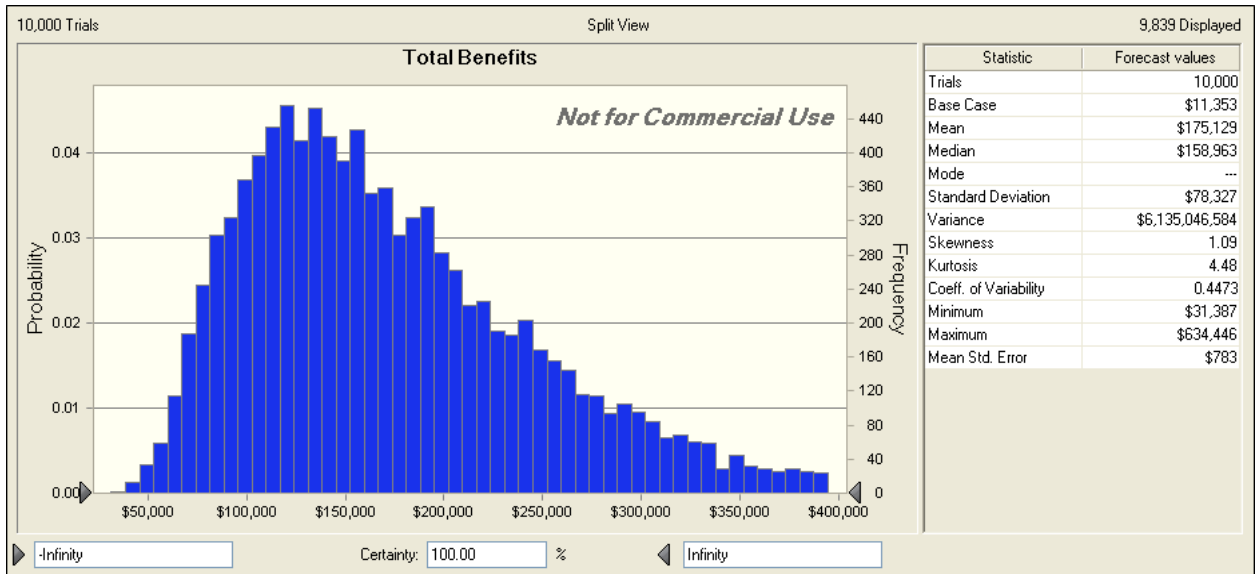


Figure 43. Scenario 10 Total Benefits

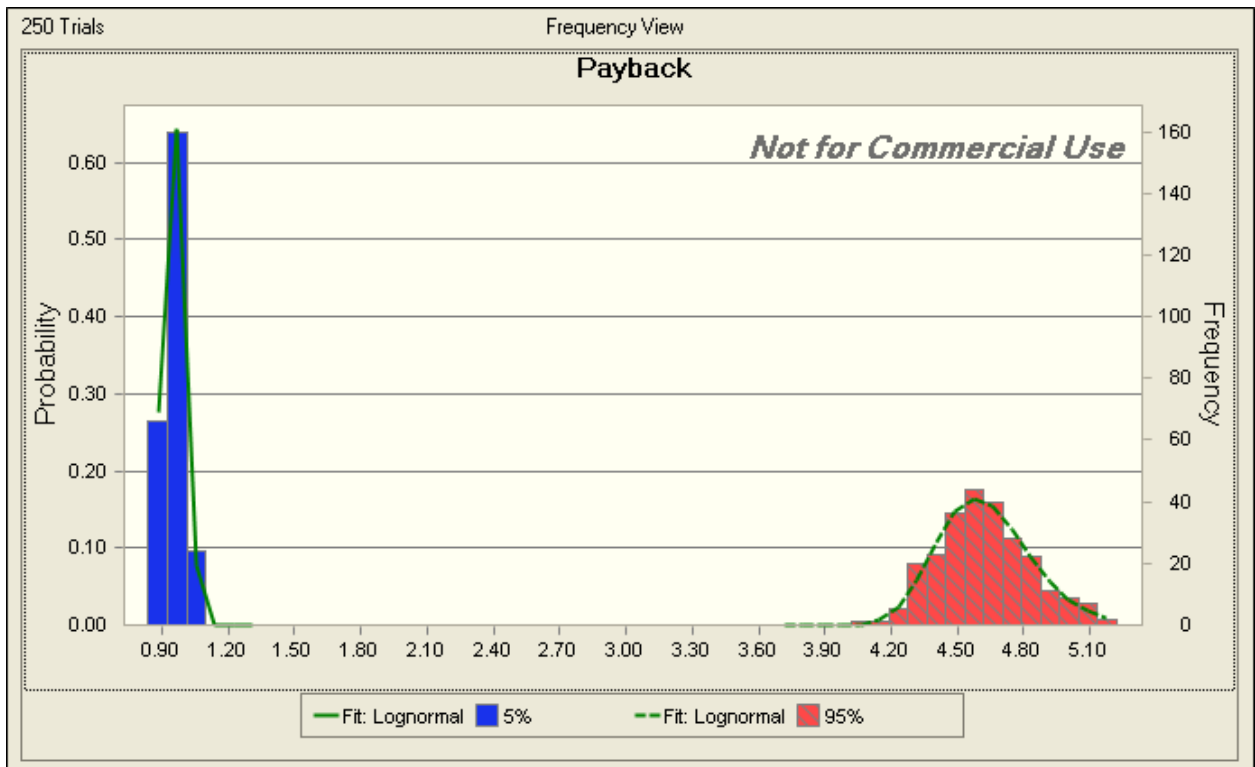


Figure 44. Scenario 10 Payback

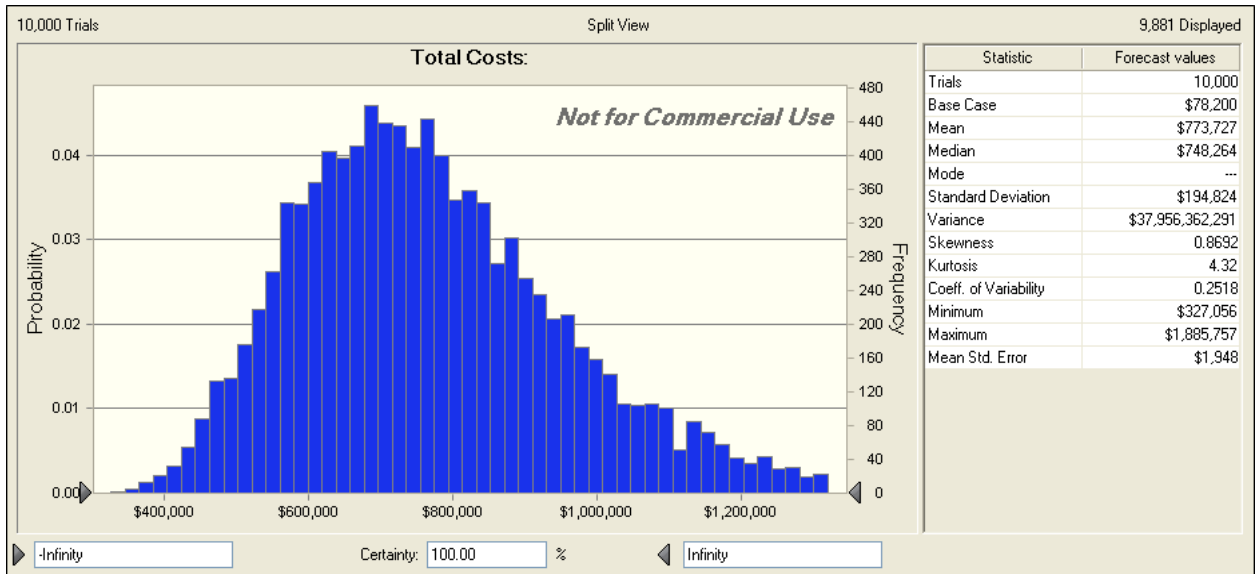


Figure 45. Scenario 11 Total Costs

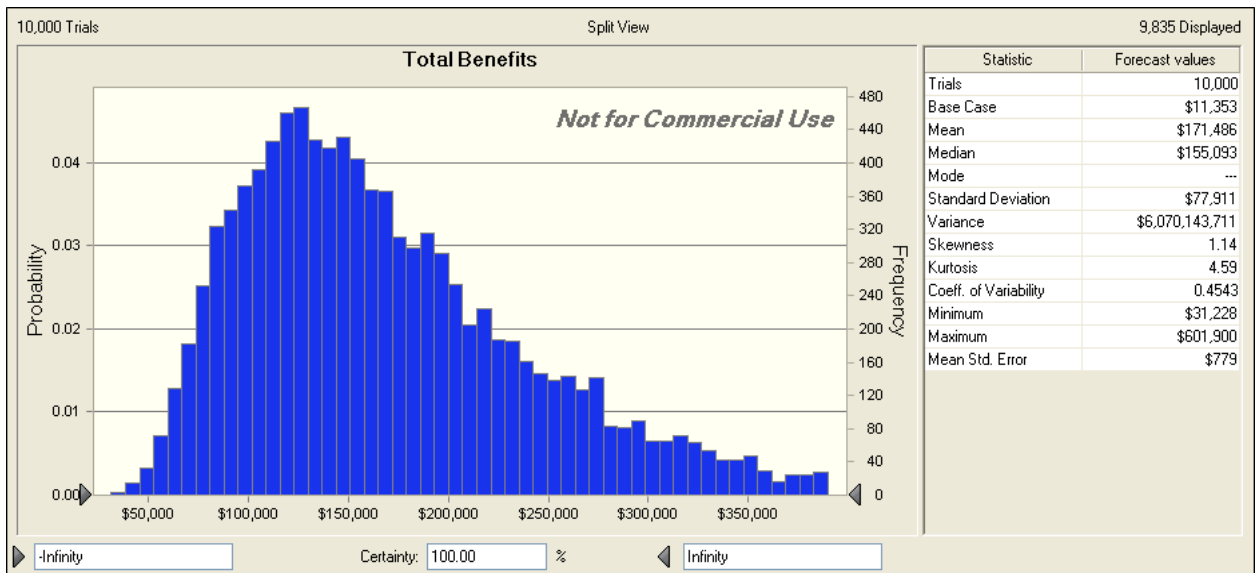


Figure 46. Scenario 11 Total Benefits

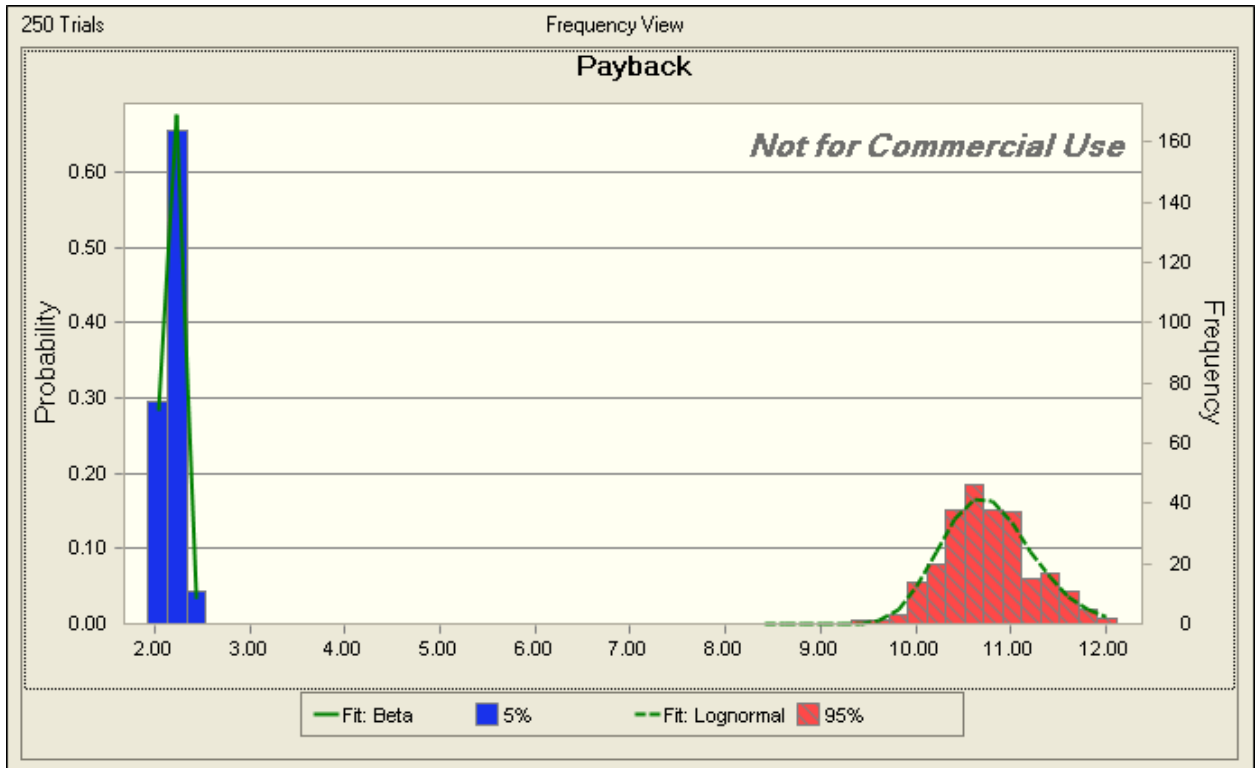


Figure 47. Scenario 11 Payback

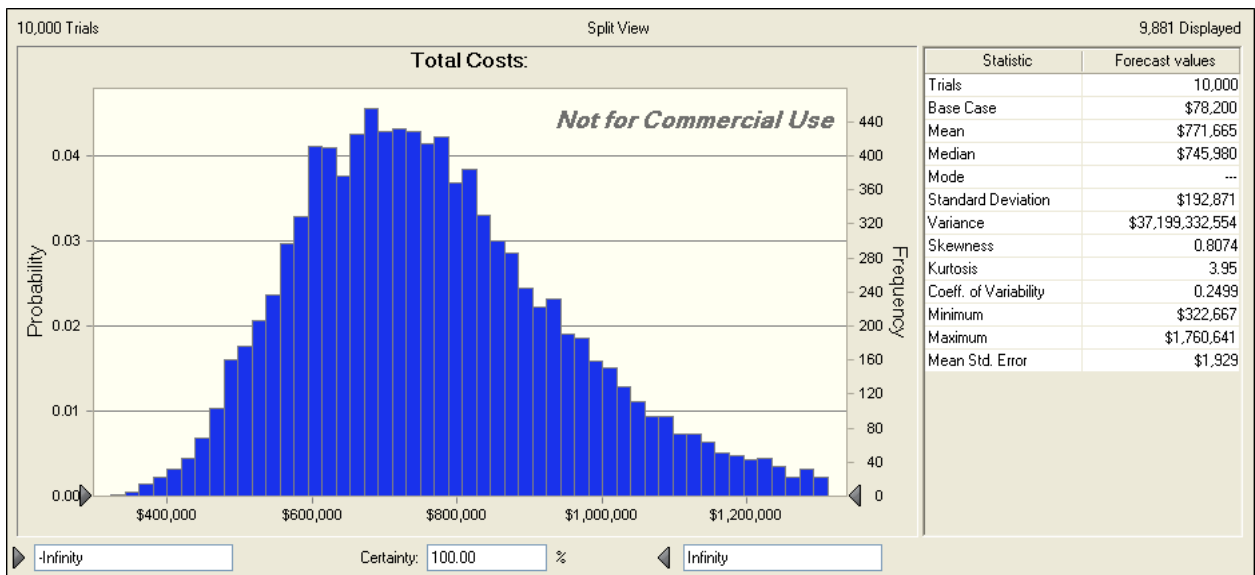


Figure 48. Scenario 12 Total Costs

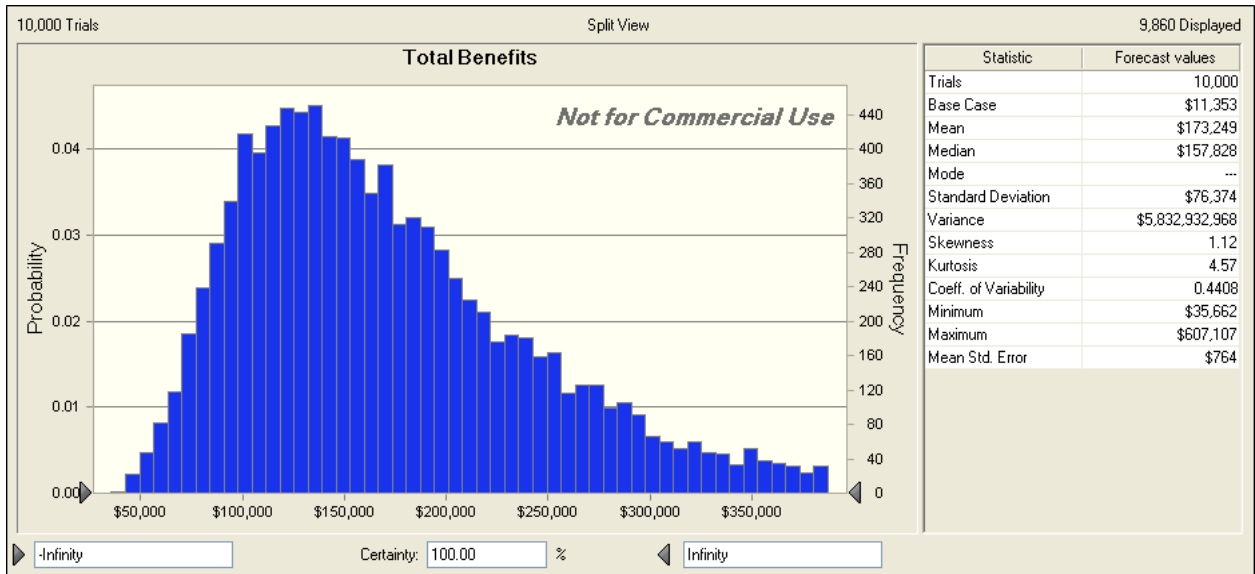


Figure 49. Scenario 12 Total Benefits

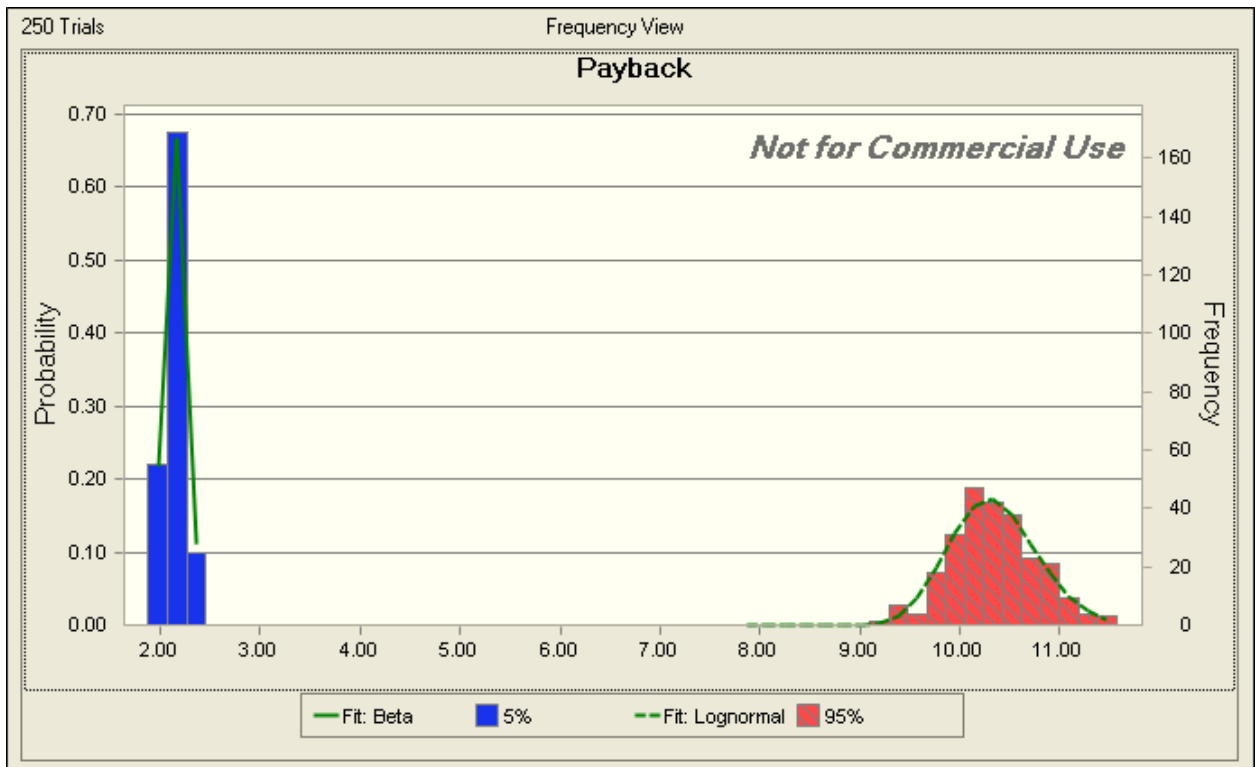


Figure 50. Scenario 12 Payback

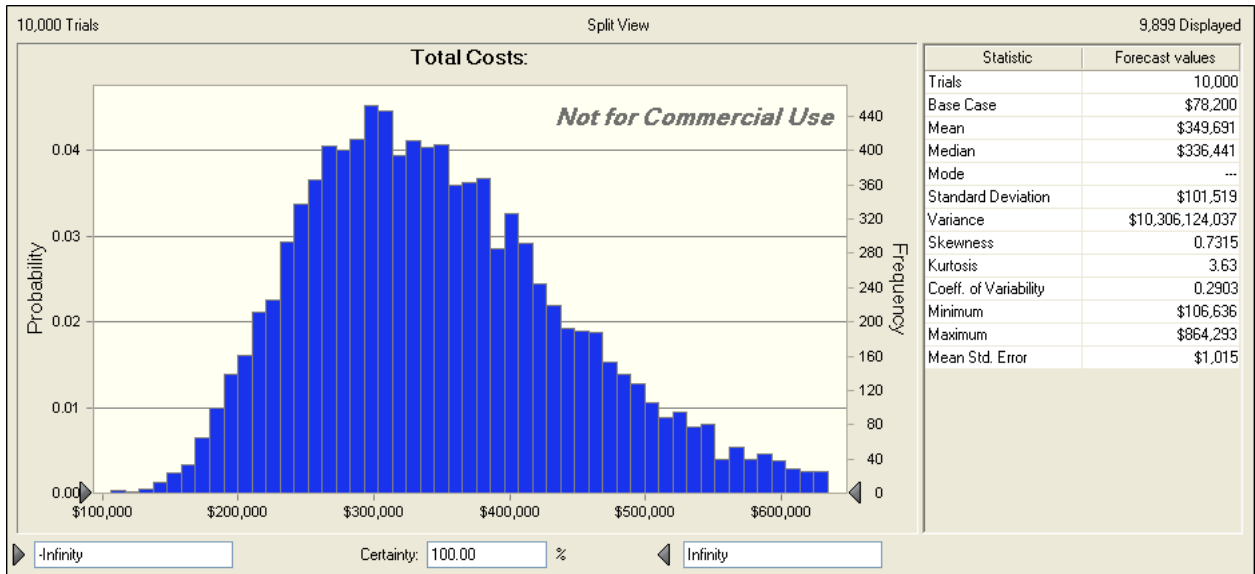


Figure 51. Scenario 13 Total Costs

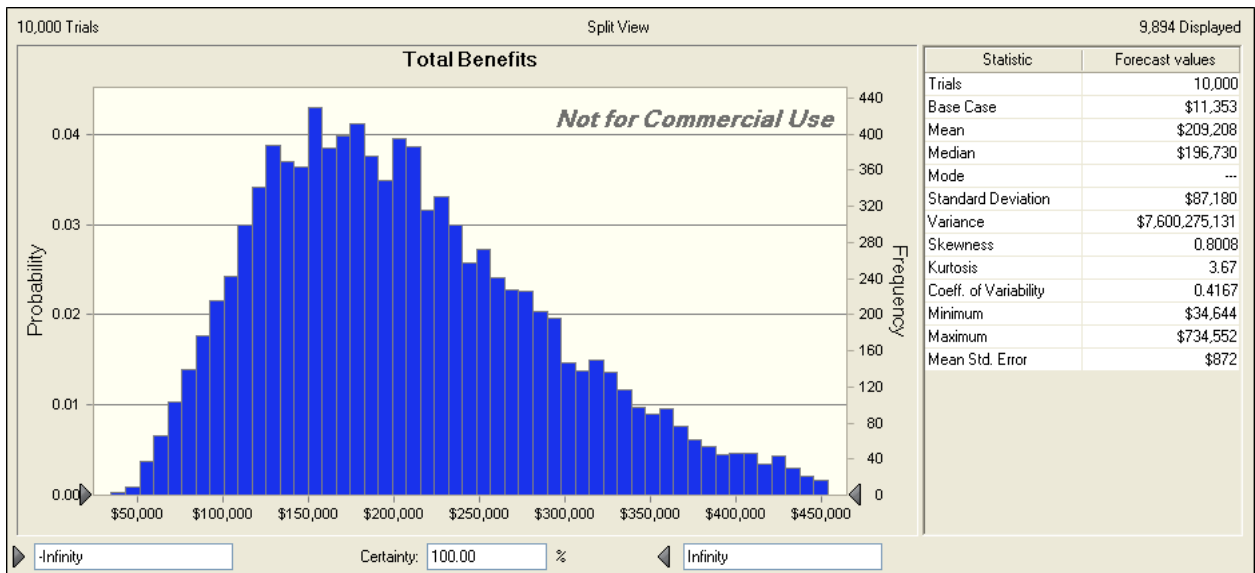


Figure 52. Scenario 13 Total Benefits

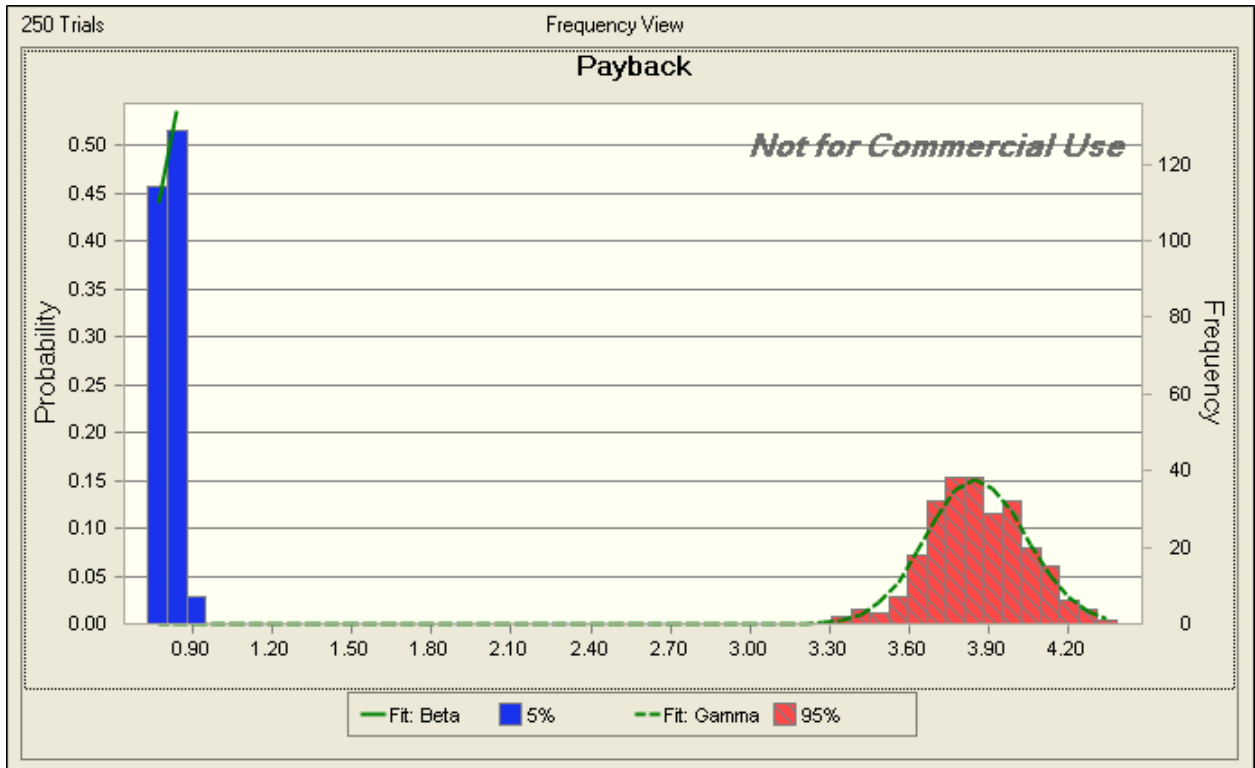


Figure 53. Scenario 13 Payback

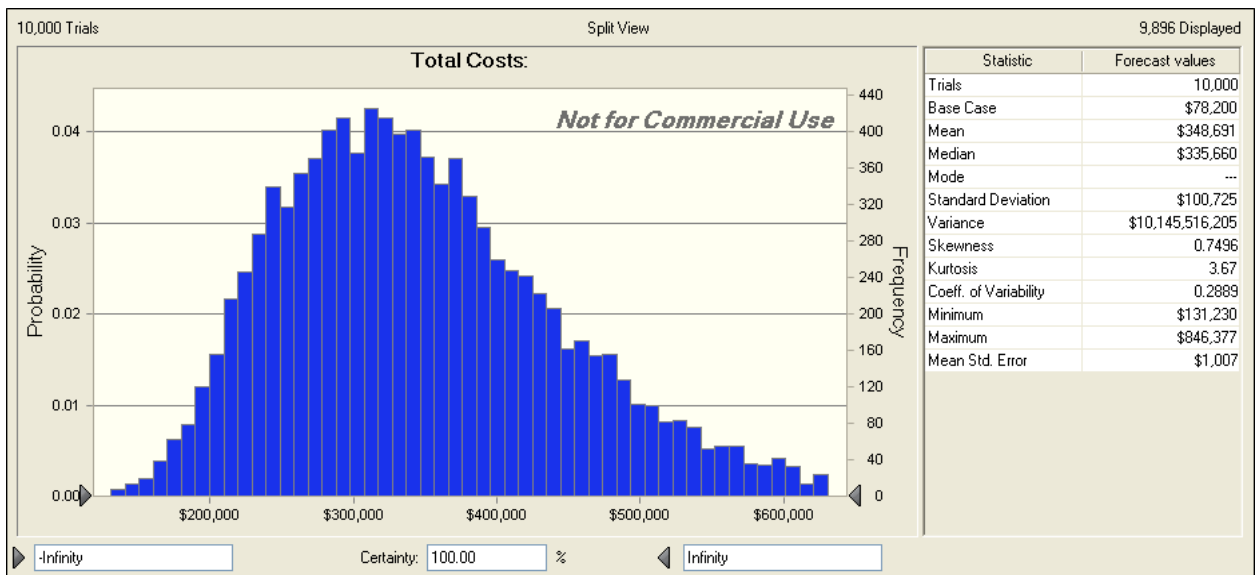


Figure 54. Scenario 14 Total Costs

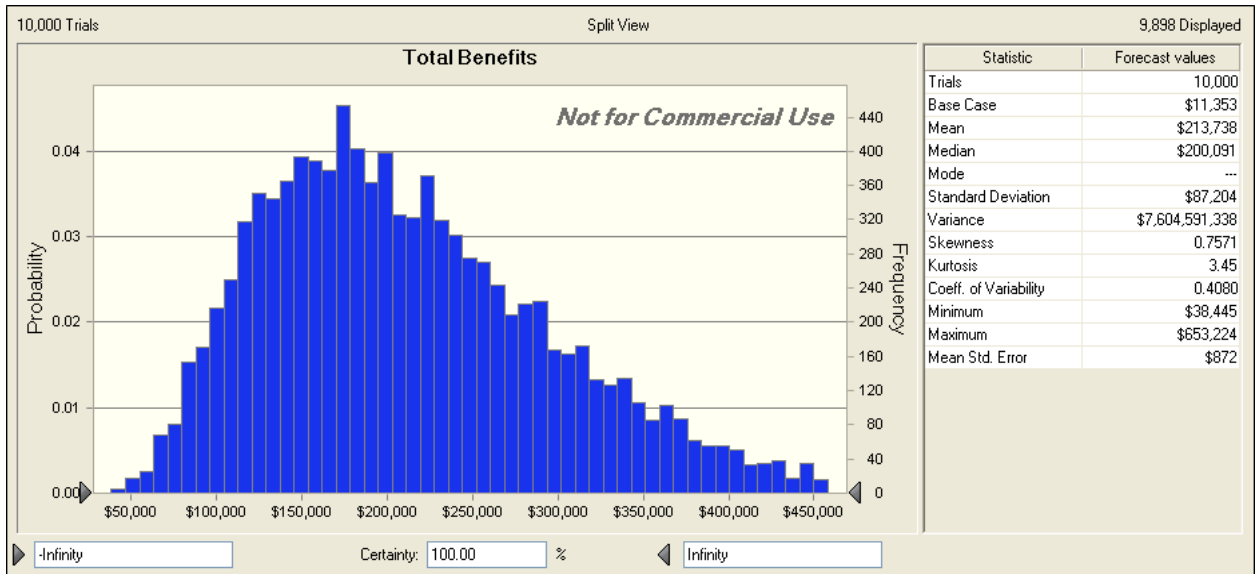


Figure 55. Scenario 14 Total Benefits

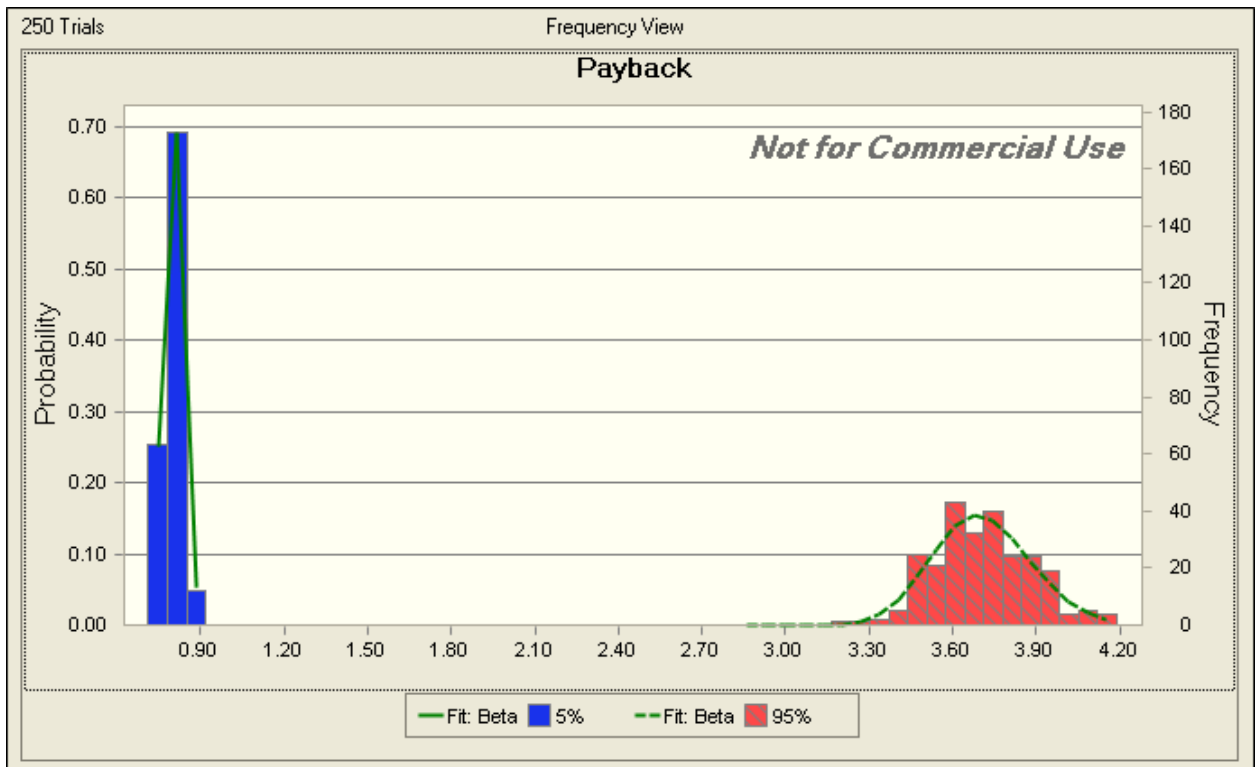


Figure 56. Scenario 14 Payback

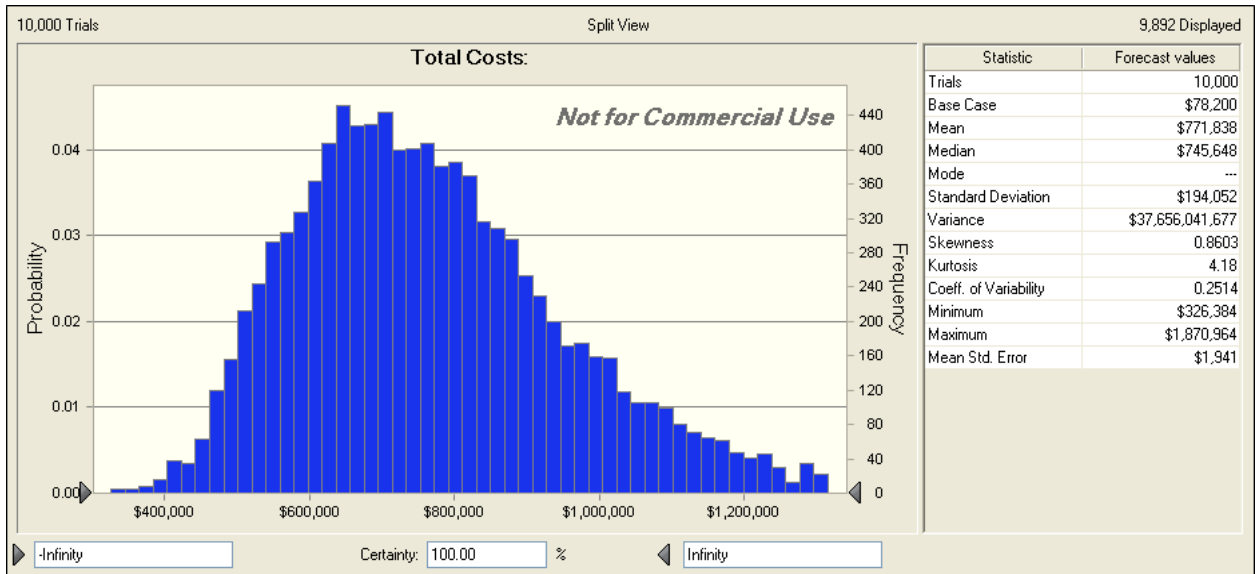


Figure 57. Scenario 15 Total Costs

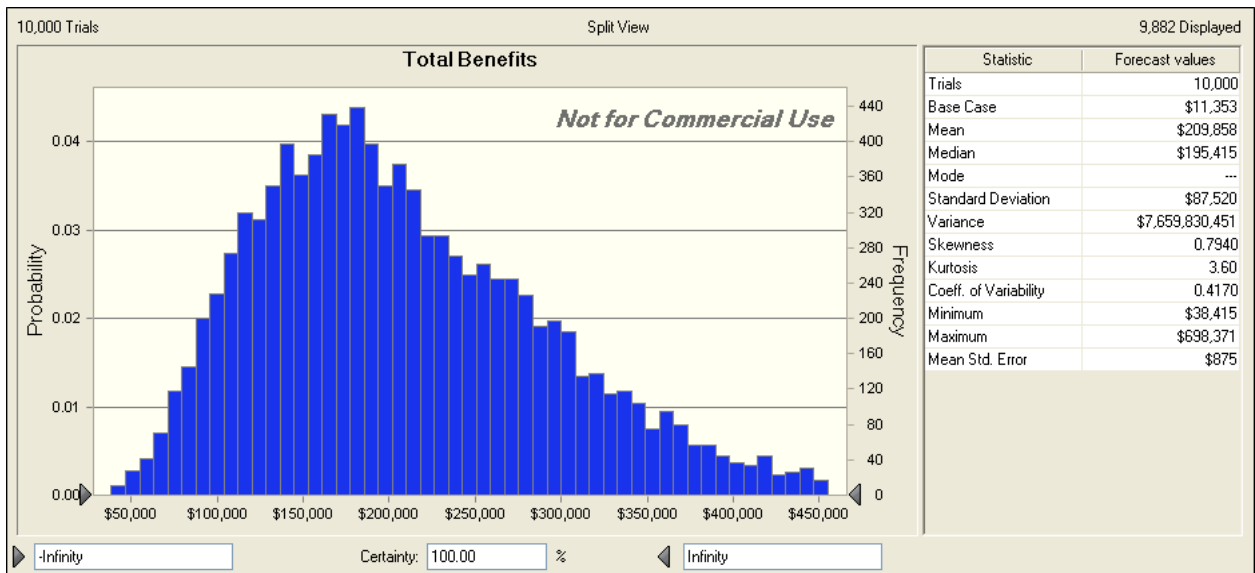


Figure 58. Scenario 15 Total Benefits

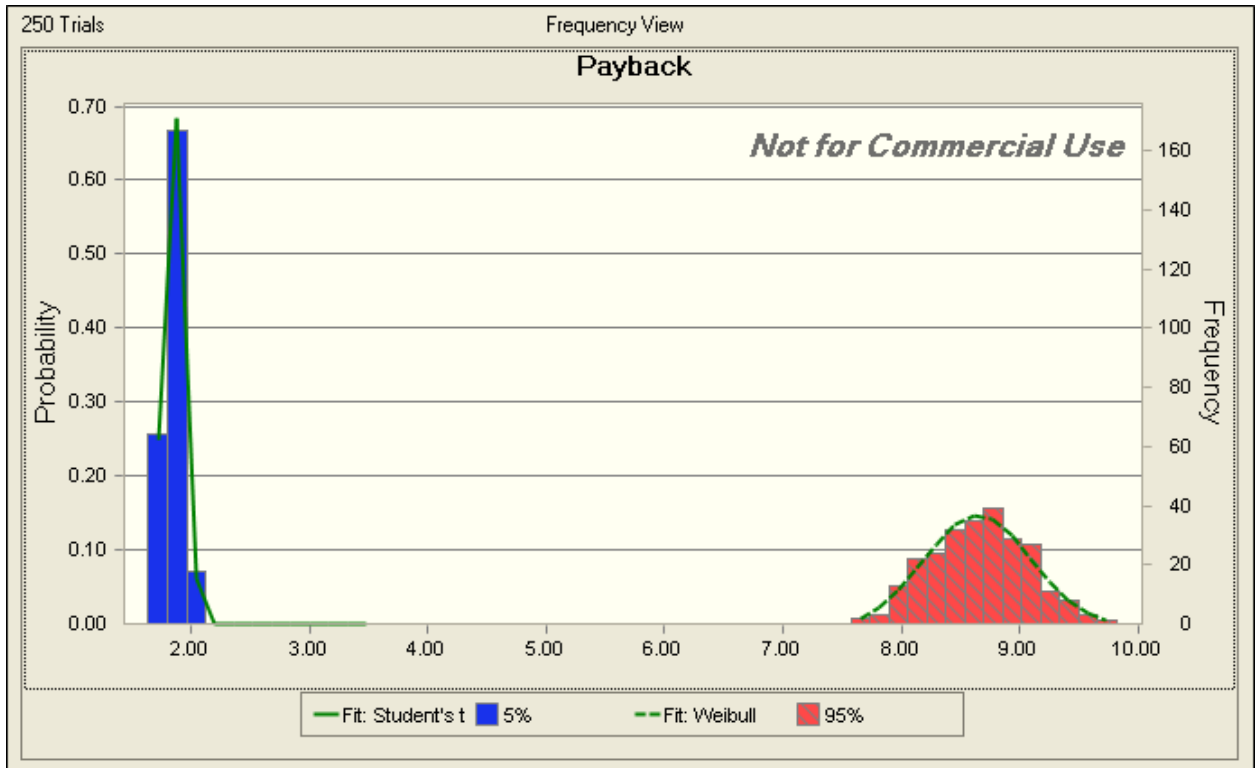


Figure 59. Scenario 15 Payback

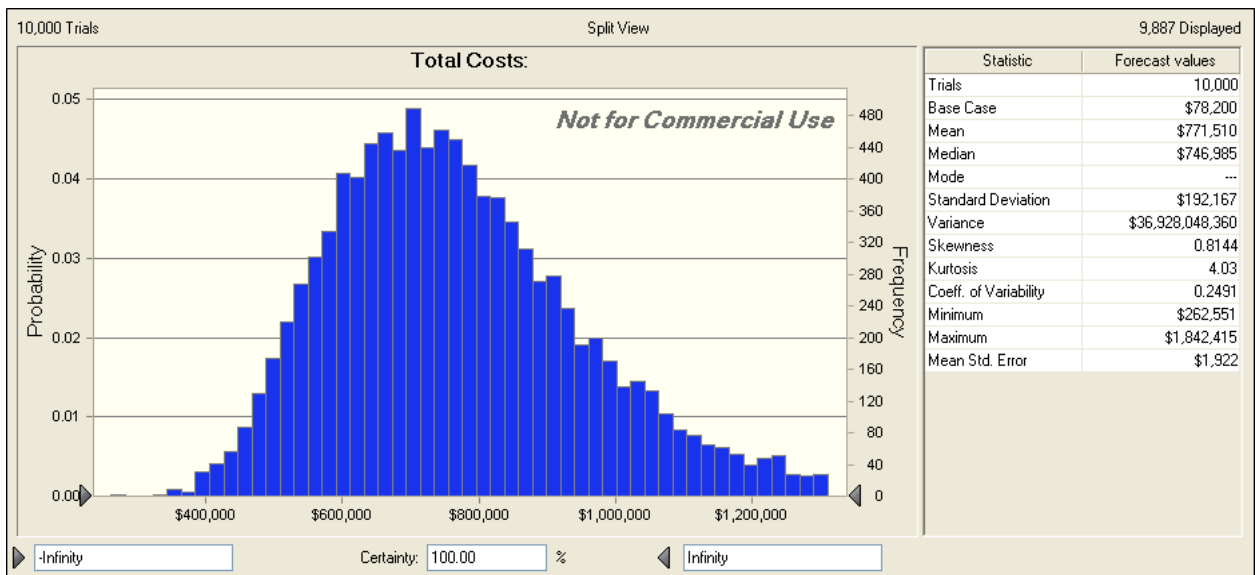


Figure 60. Scenario 16 Total Costs

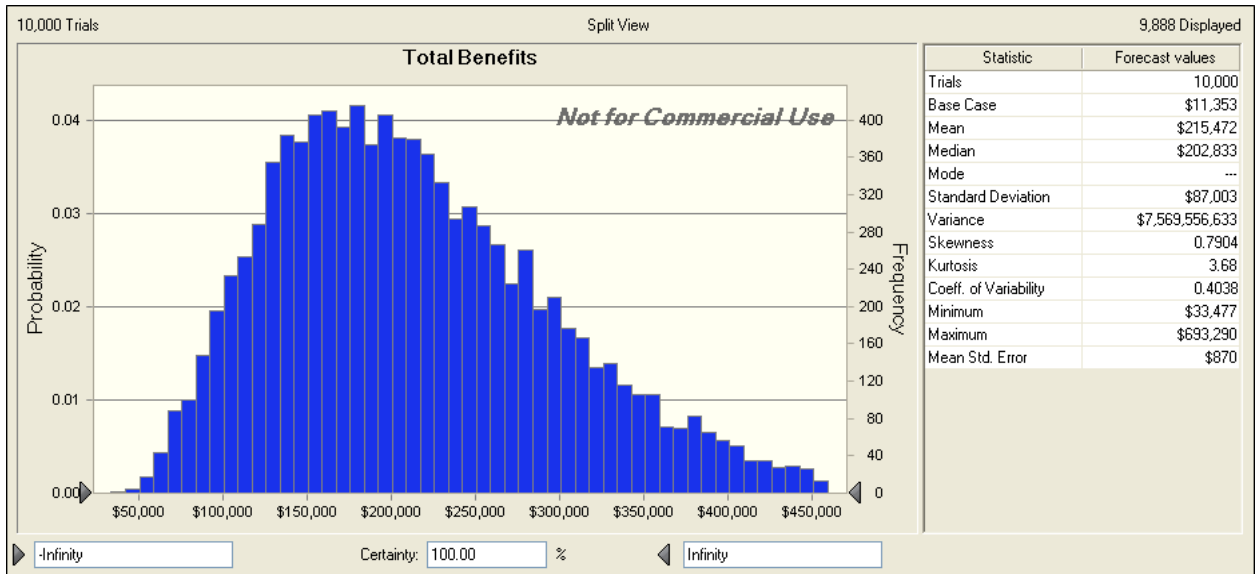


Figure 61. Scenario 16 Total Benefits

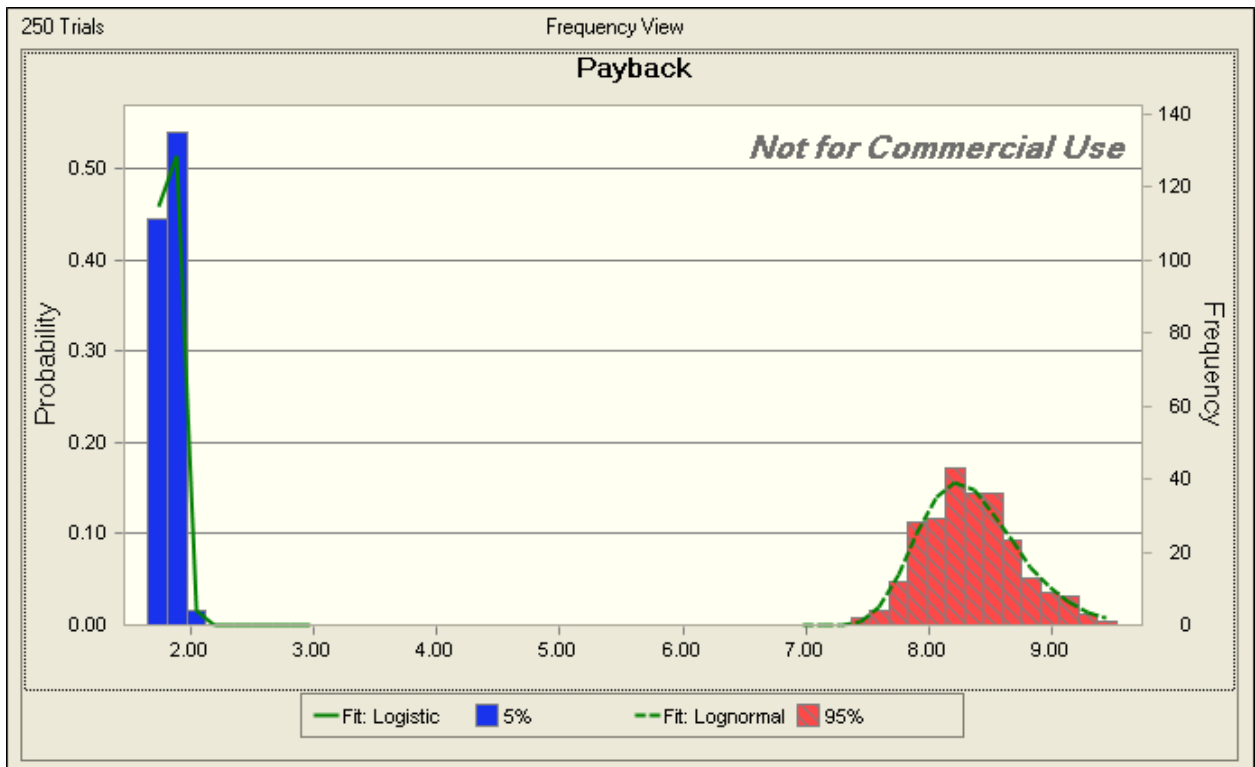


Figure 62. Scenario 16 Payback

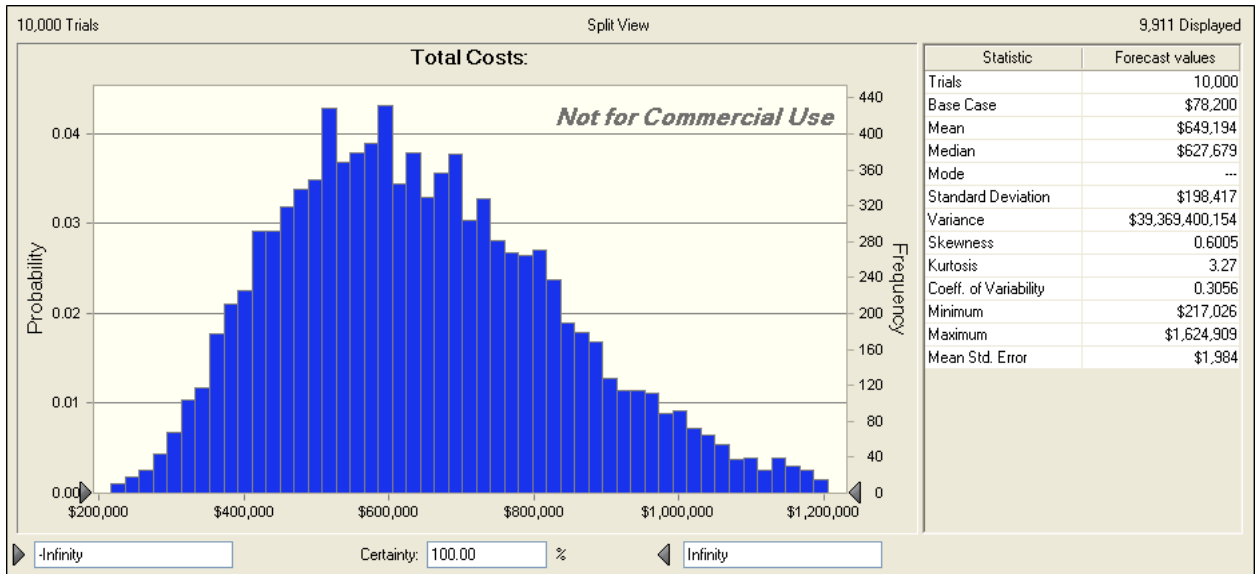


Figure 63. Scenario 17 Total Costs

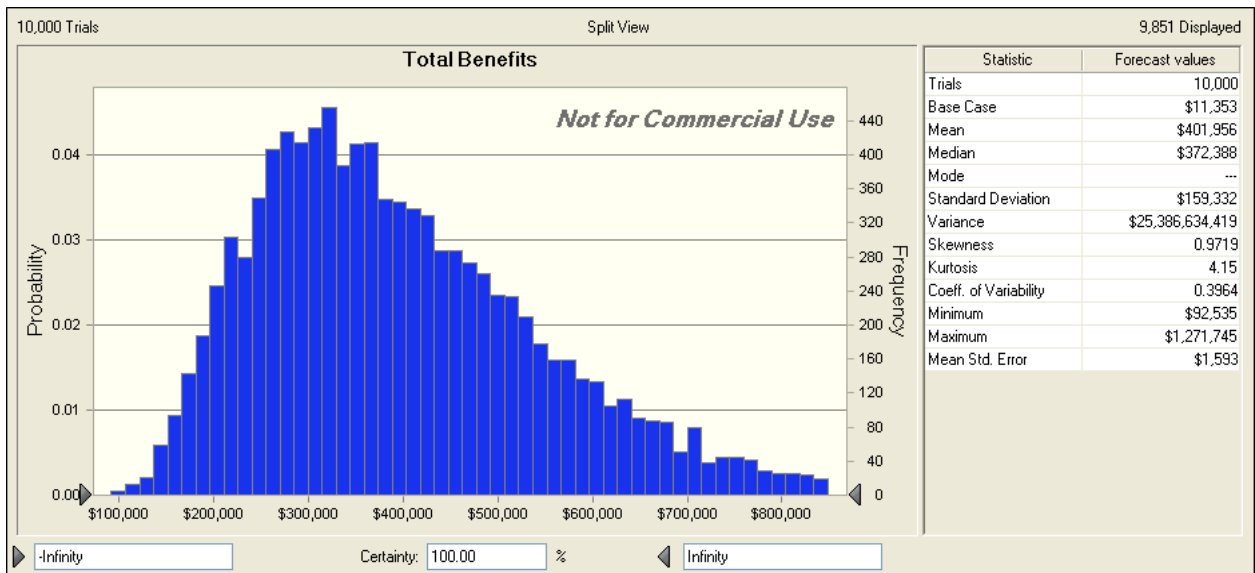


Figure 64. Scenario 17 Total Benefits

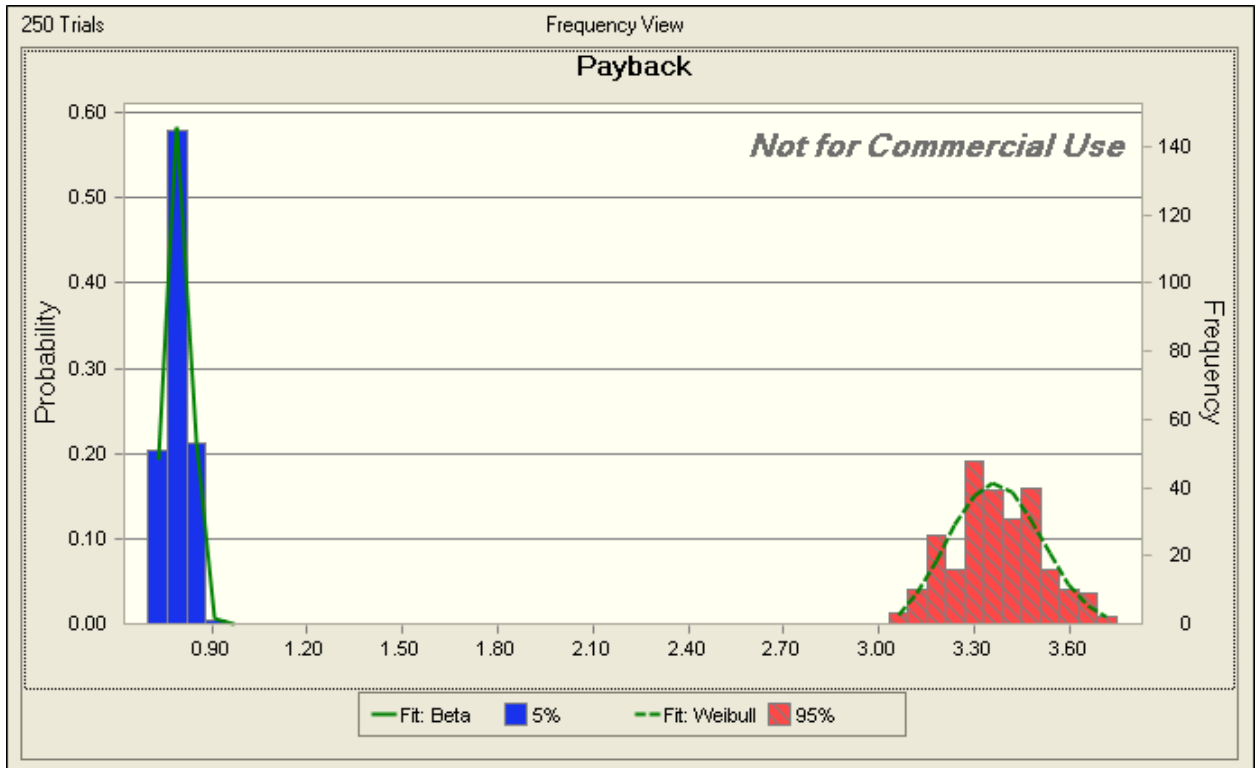


Figure 65. Scenario 17 Payback

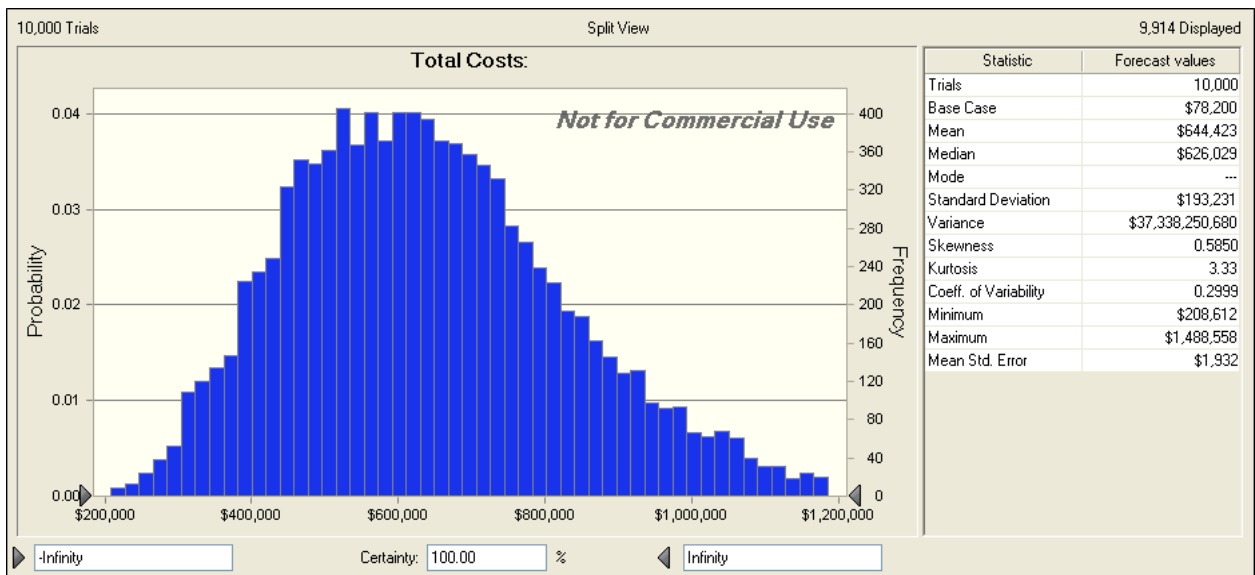


Figure 66. Scenario 18 Total Costs

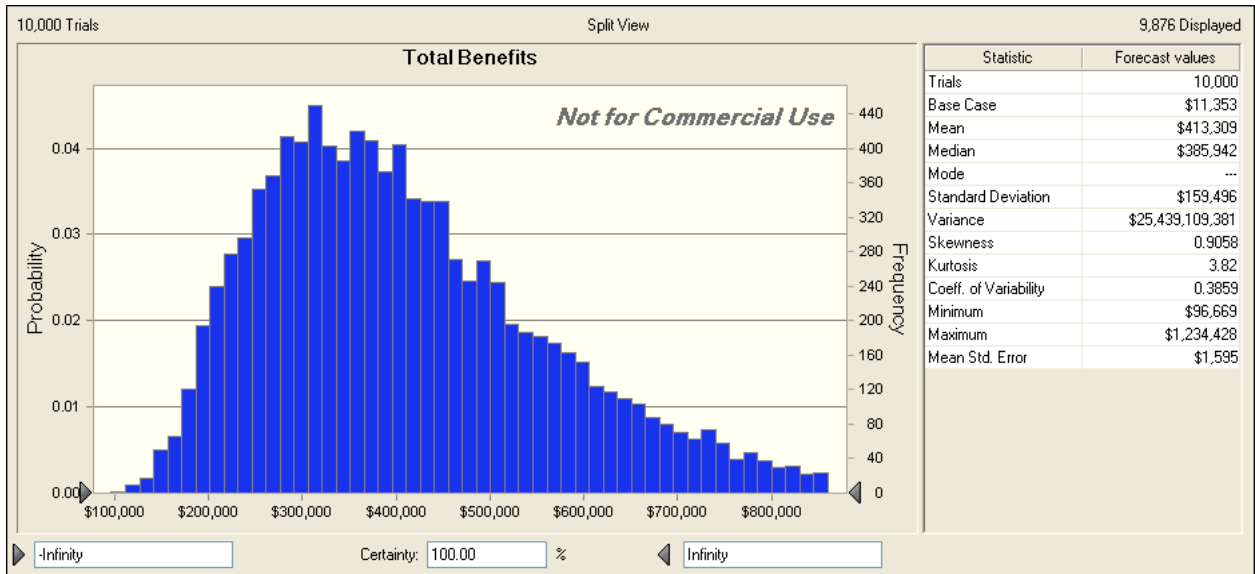


Figure 67. Scenario 18 Total Benefits

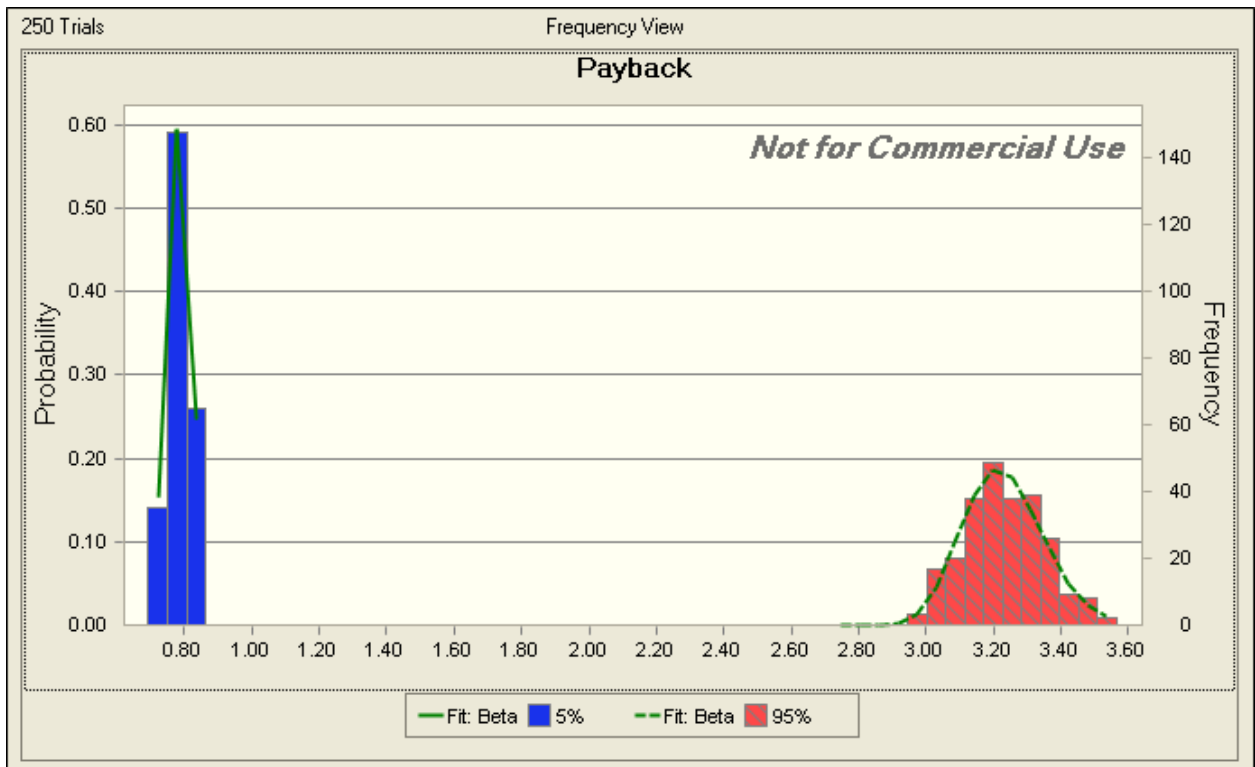


Figure 68. Scenario 18 Payback

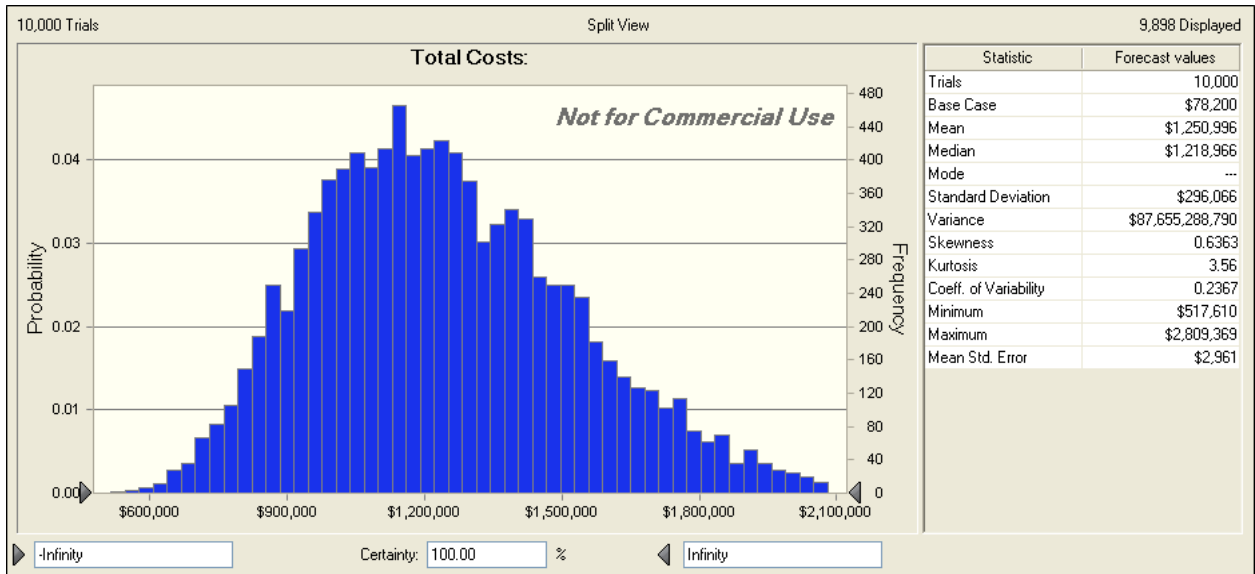


Figure 69. Scenario 19 Total Costs

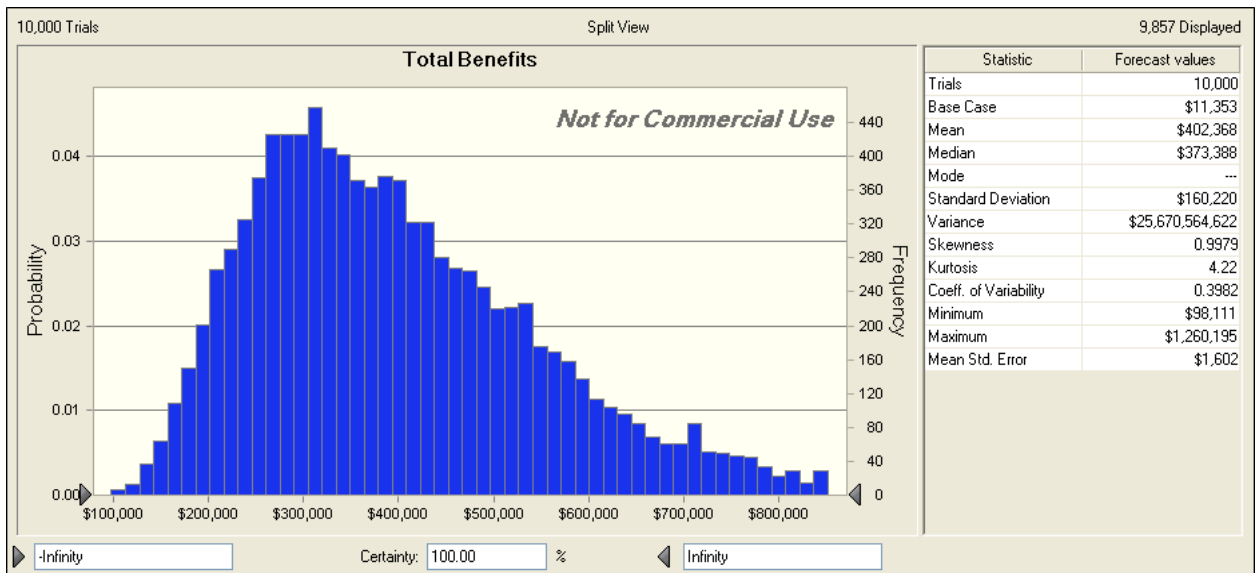


Figure 70. Scenario 19 Total Benefits

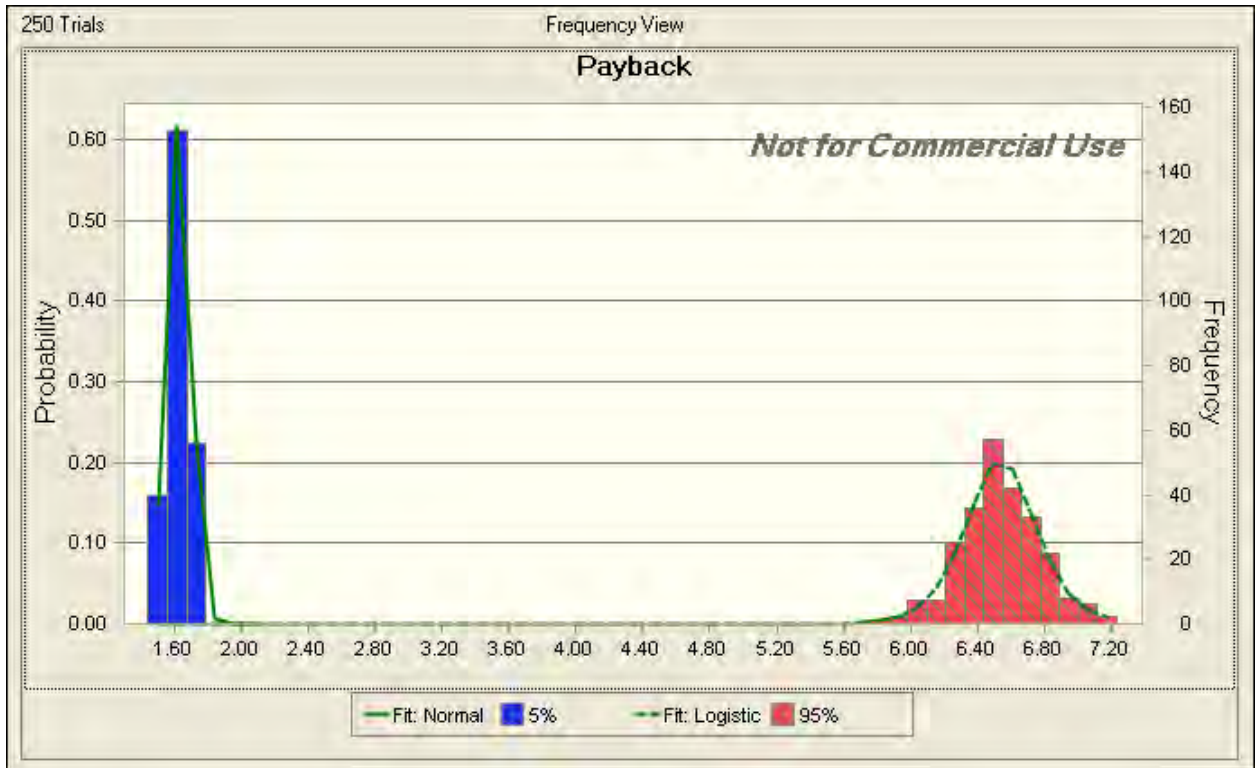


Figure 71. Scenario 19 Payback

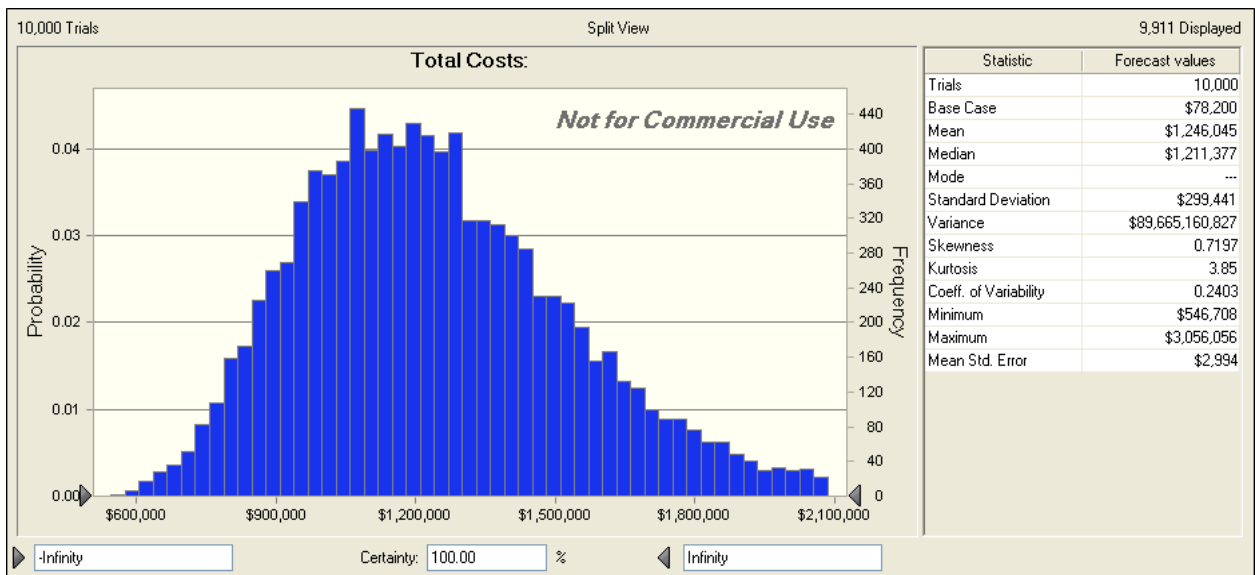


Figure 72. Scenario 20 Total Costs

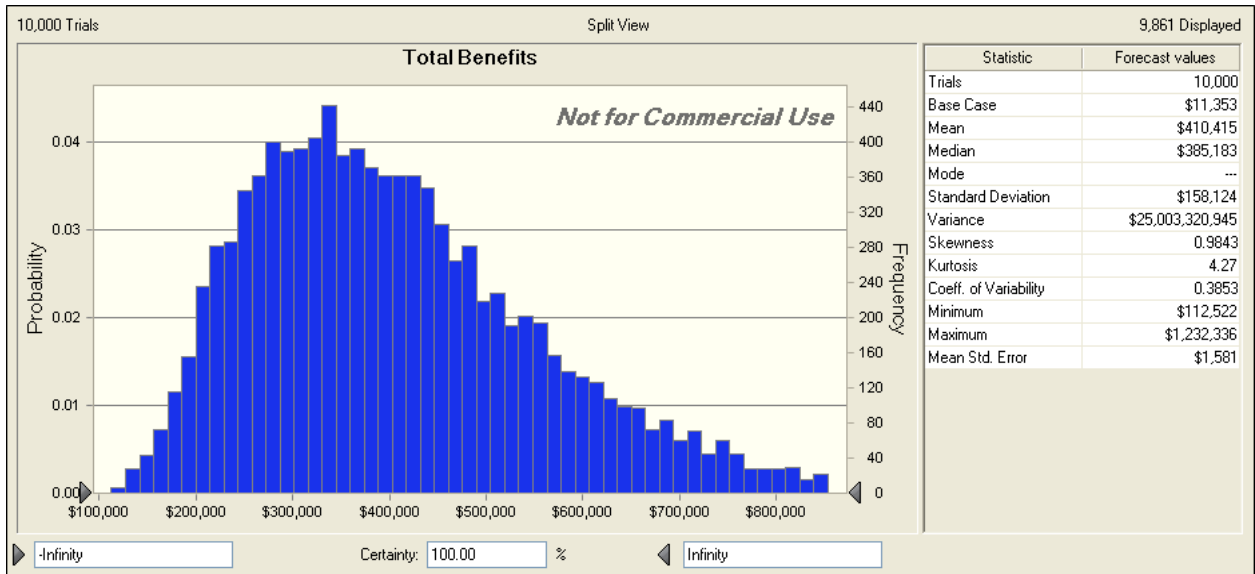


Figure 73. Scenario 20 Total Benefits

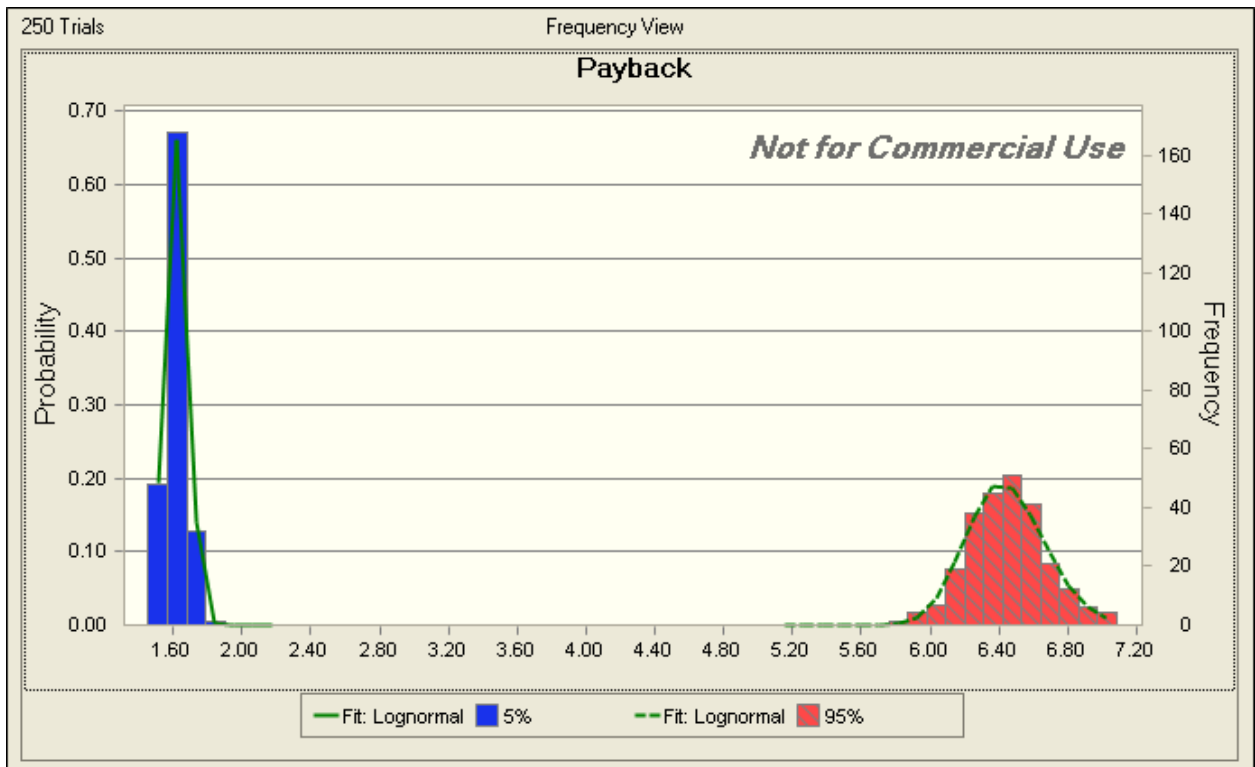


Figure 74. Scenario 20 Payback

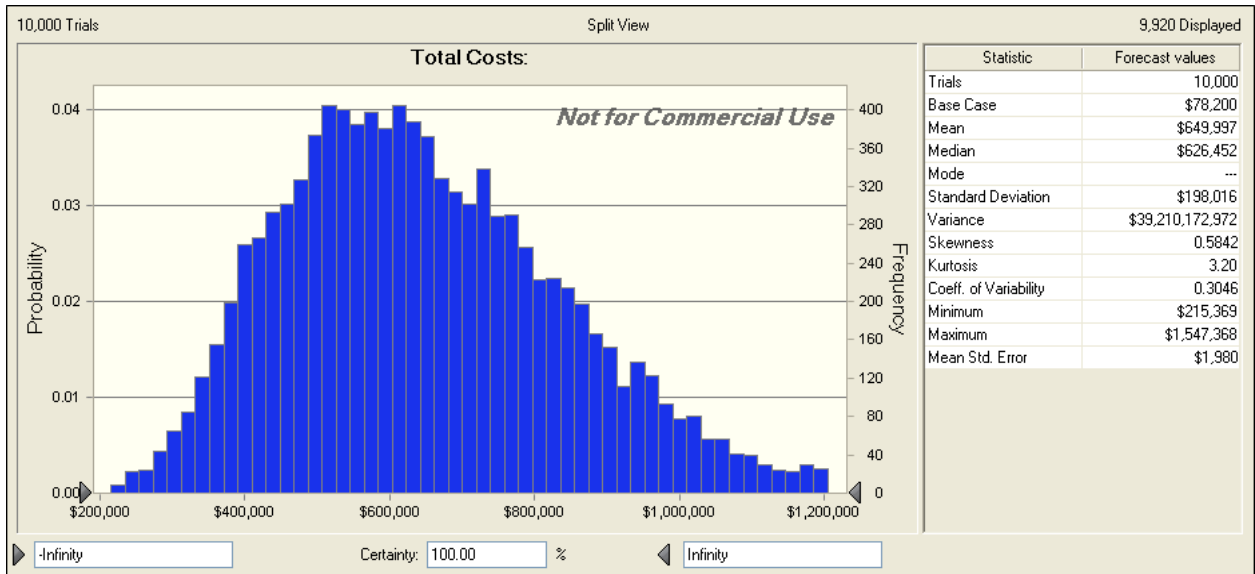


Figure 75. Scenario 21 Total Costs

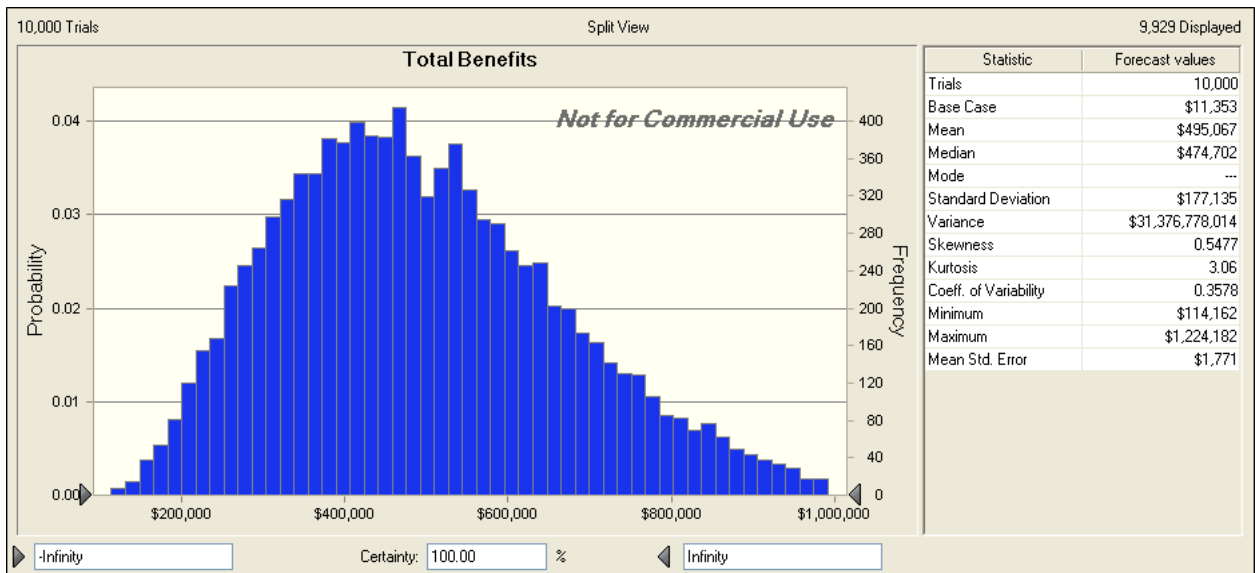


Figure 76. Scenario 21 Total Benefits

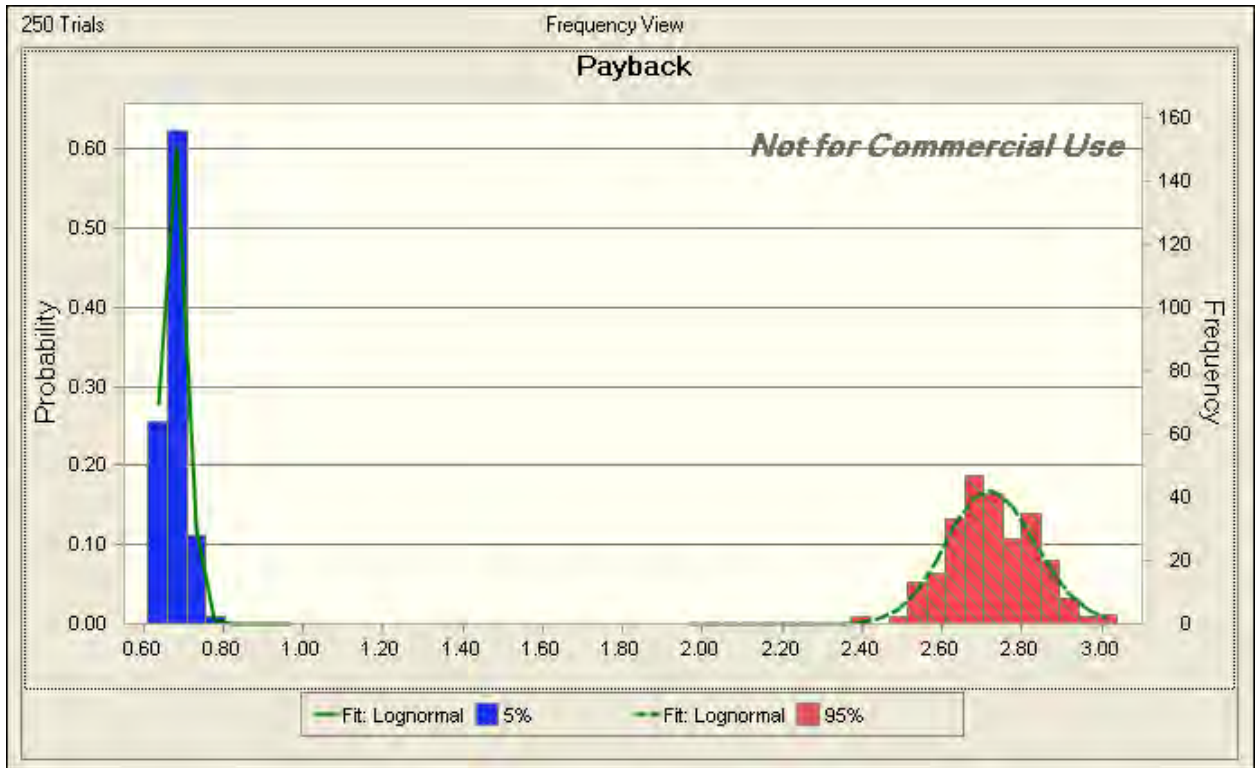


Figure 77. Scenario 21 Payback

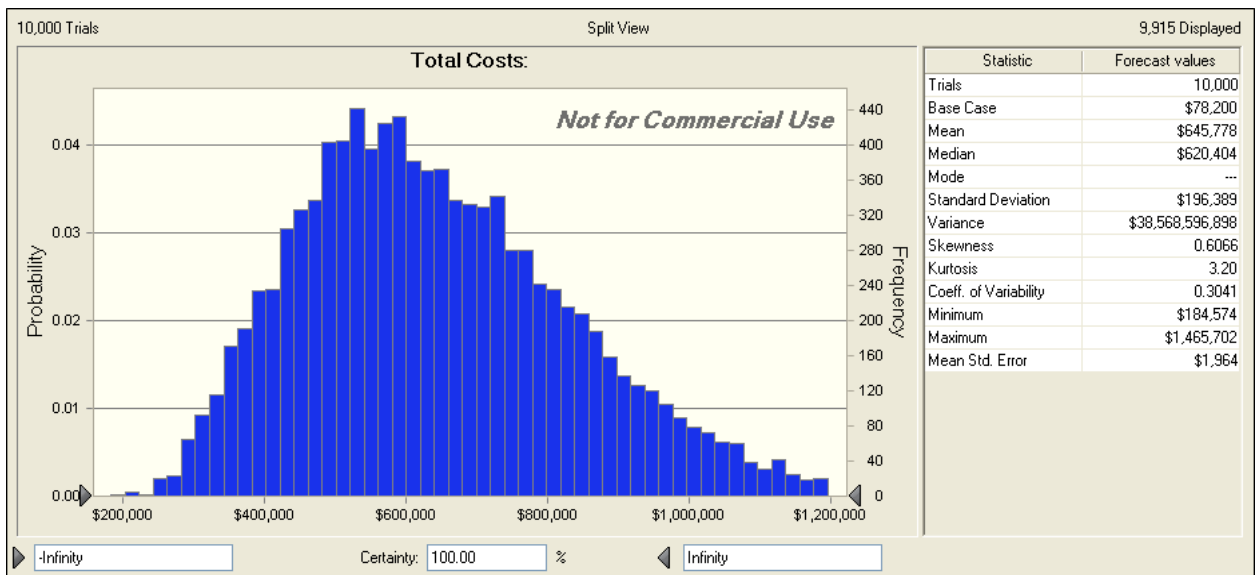


Figure 78. Scenario 22 Total Costs

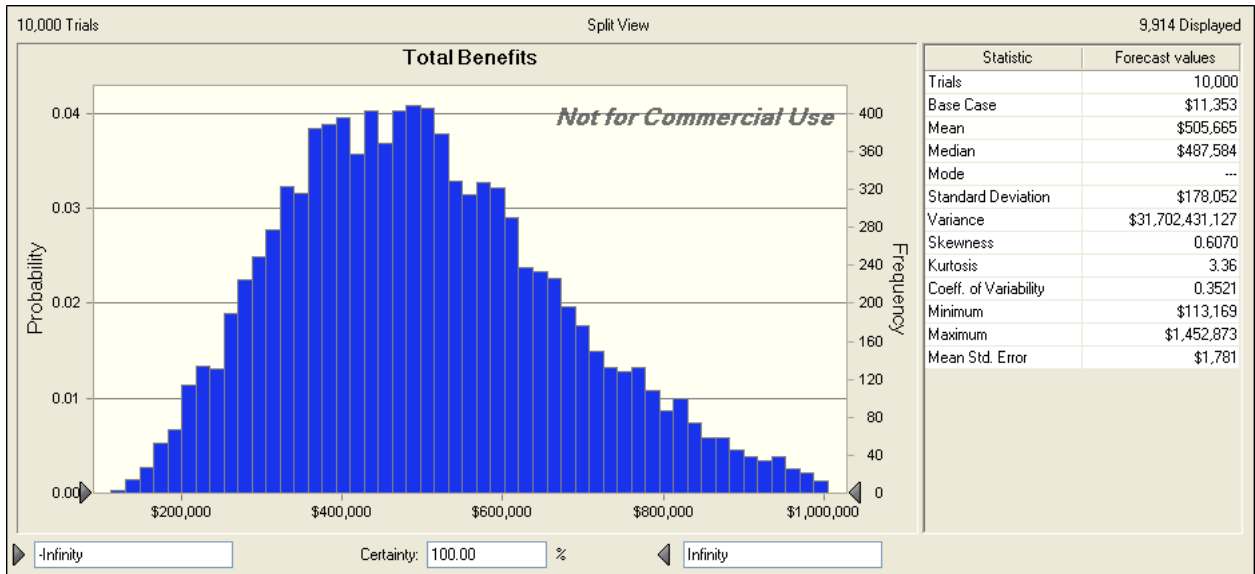


Figure 79. Scenario 22 Total Benefits

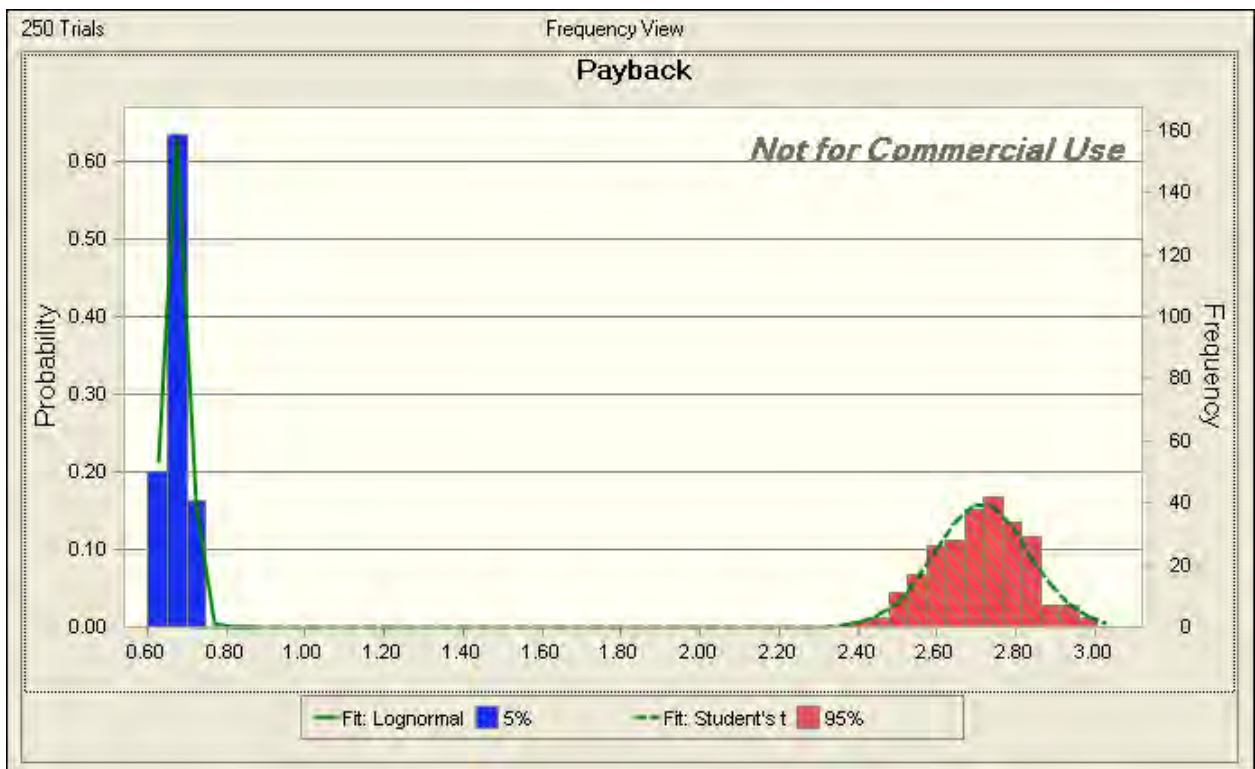


Figure 80. Scenario 22 Payback

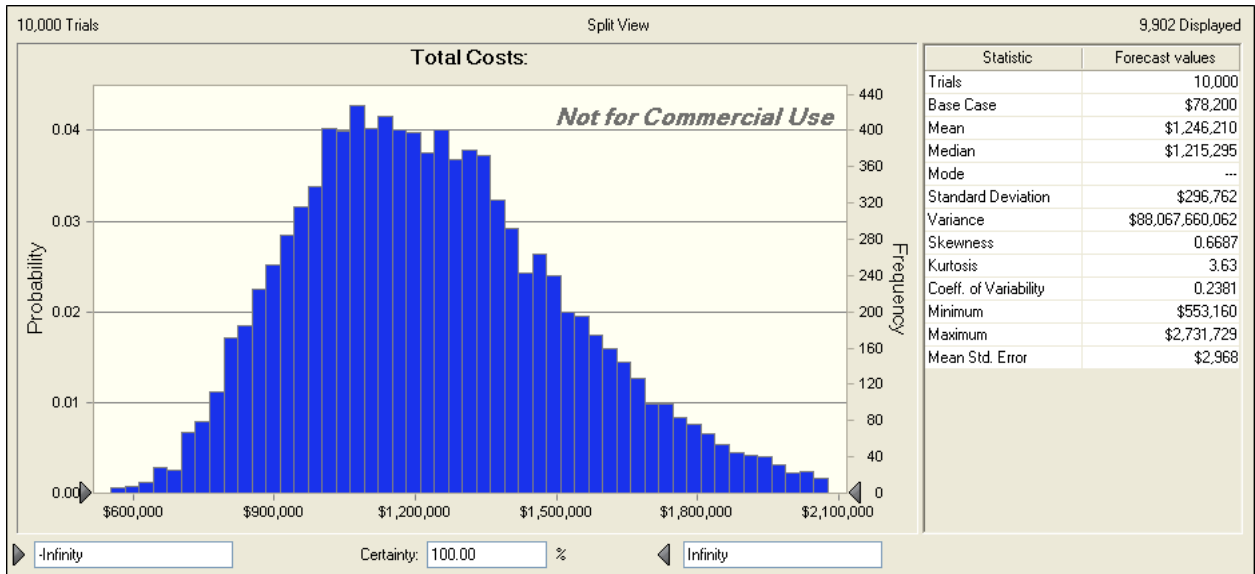


Figure 81. Scenario 23 Total Costs

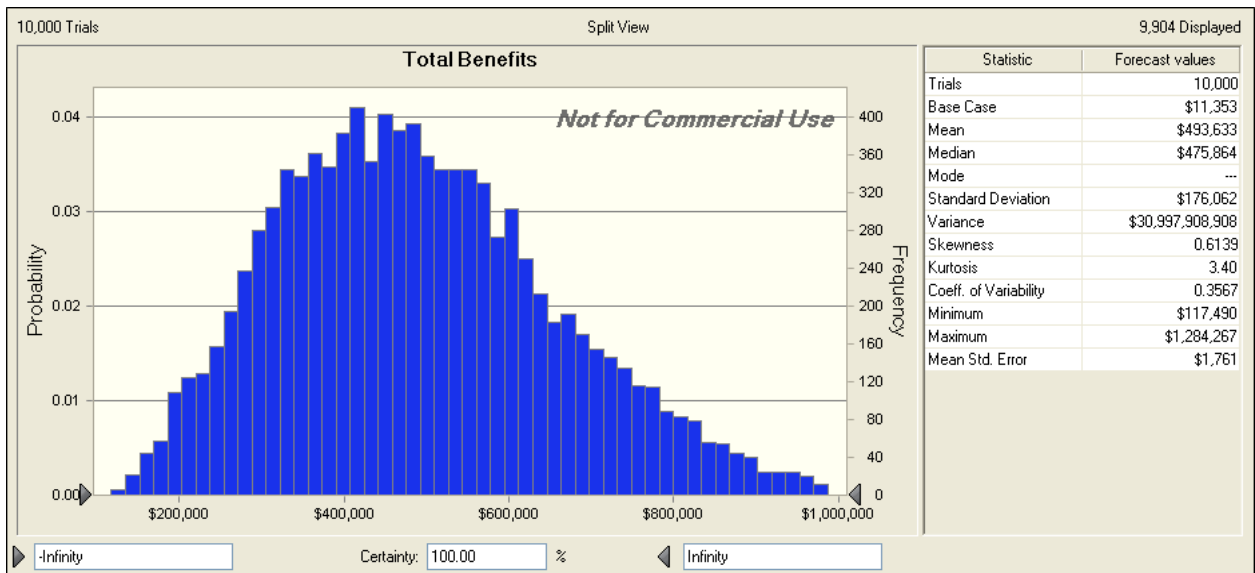


Figure 82. Scenario 23 Total Benefits

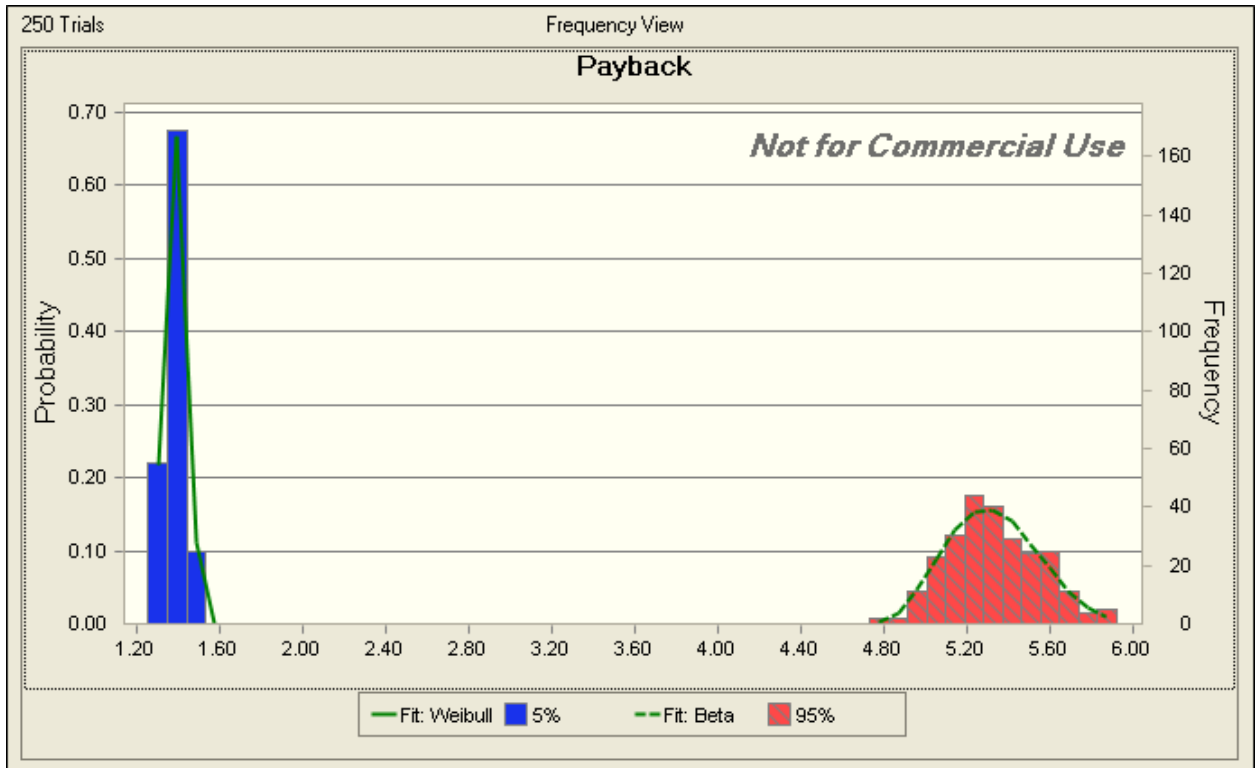


Figure 83. Scenario 23 Payback

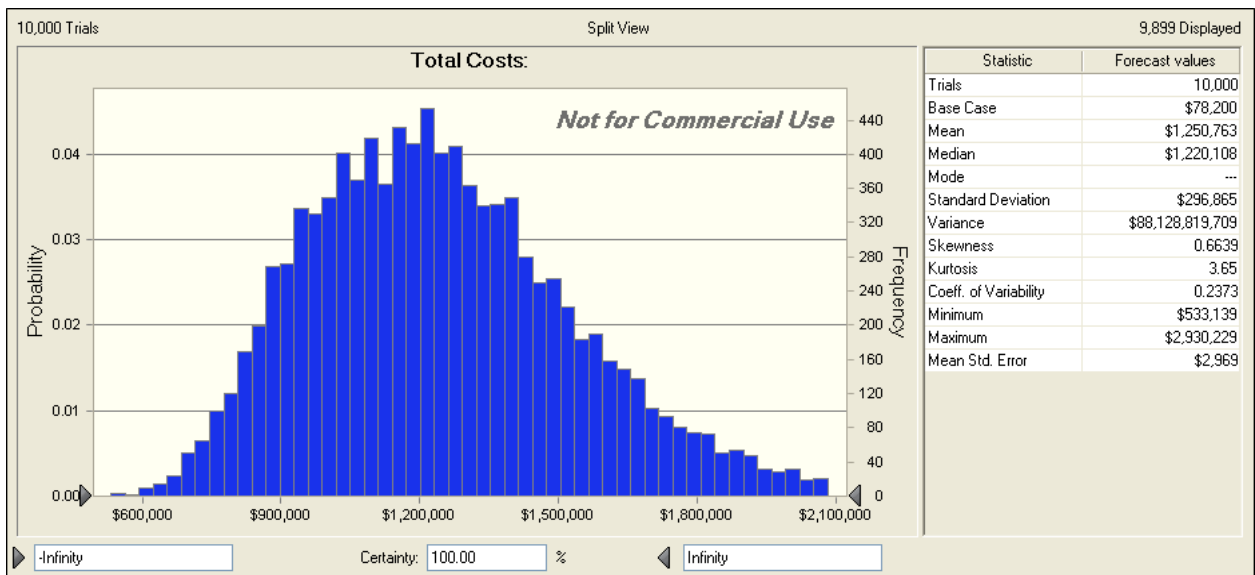


Figure 84. Scenario 24 Total Costs

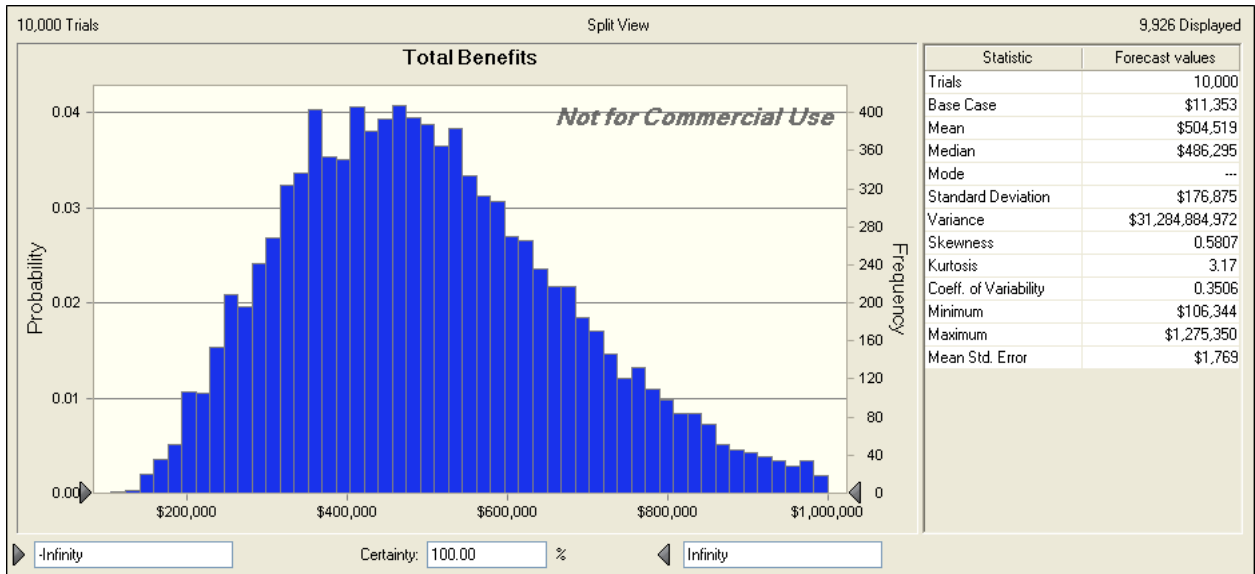


Figure 85. Scenario 24 Total Benefits

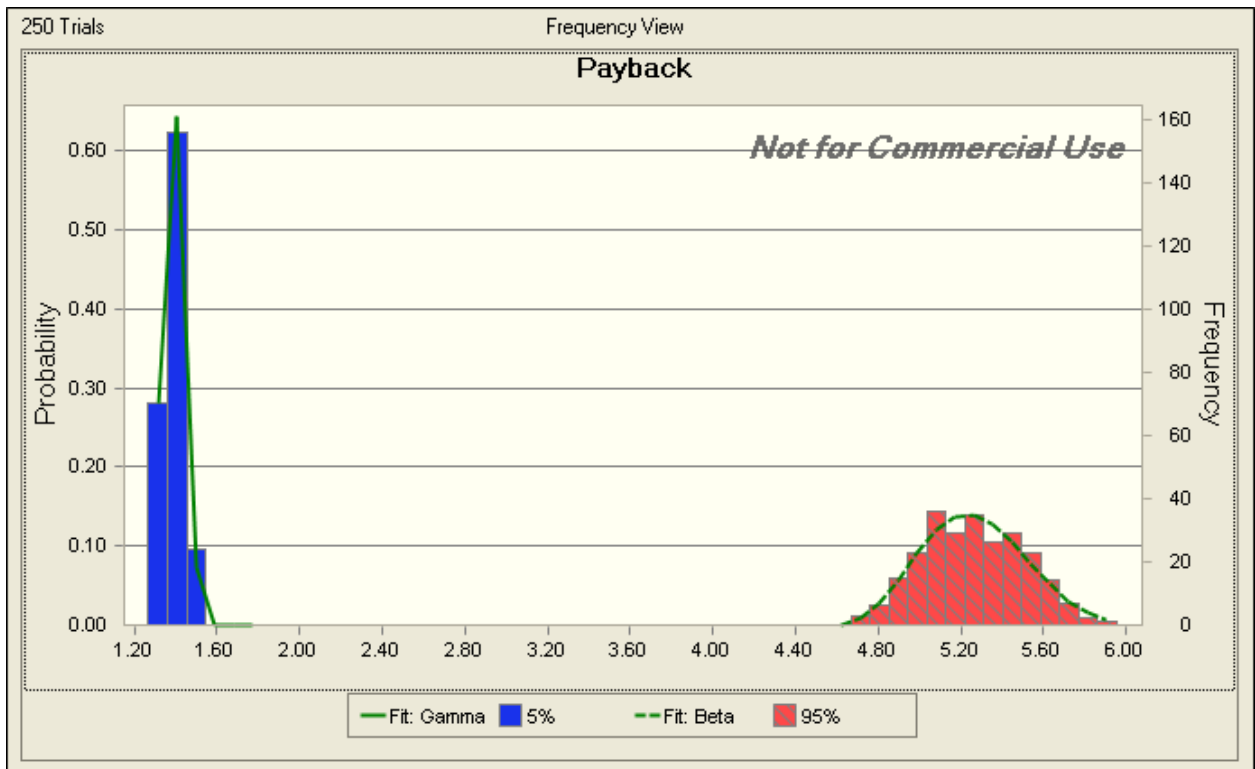


Figure 86. Scenario 24 Payback

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