THE

ENGINEERING ECONOMIST

A JOURNAL DEVOTED TO THE PROBLEMS OF CAPITAL INVESTMENT

2007 • Volume 52 • Number 3

A Joint Publication of the
Engineering Economy Divisions of the
American Society for Engineering Education
and the Institute of Industrial Engineers

THE ENGINEERING ECONOMIST

A JOURNAL DEVOTED TO THE PROBLEMS OF CAPITAL INVESTMENT

Abstracted and/or Indexed in: Business Periodical Index, Wilson Web, CSA-Mechanical and Transportation Engineering Abstracts, Civil Engineering Abstracts, Scopus, Compendex
The Engineering Economist (ISSN: 0013-791X) is published quarterly in March, June, September, and December for a total of 4 issues per year by Taylor and Francis Group, LLC, 325 Chestnut Street, Suite 800, Philadelphia, PA 19106. Periodicals postage paid (Permit no. 378-630) at Philadelphia, PA and additional mailing offices.

US Postmaster: Please send address changes to The Engineering Economist, Taylor & Francis Group, LLC, 325 Chestnut Street, Philadelphia, PA 19106.

Annual Subscription, Volume 52, 2007
Print ISSN - 0013-791X, Online ISSN - 1547-2701
Institutional subscribers: US $136, UK £82
Personal subscribers: US $73, UK £44
An institutional subscription to the print edition includes free access to the online edition for any number of concurrent users across a local area network.

Production and Advertising Office: 325 Chestnut Street, Philadelphia, PA 19106. Tel: 215-625-8900, Fax: 215-625-8563. Production Editor: Andrea McFadden.

Subscription offices
USA/North America: Taylor and Francis Group, LLC, 325 Chestnut Street, Philadelphia, PA 19106. Tel: 215-625-8900, Fax: 215-625-2940.
UK/Europe: Taylor and Francis Customer Services, Sheepen Place, Colchester, Essex CO3 3LP, UK. Tel: +44 (0)-20-7017-5544, Fax: +44 (0)-20-7017-5198.
For a complete guide to Taylor and Francis Group , LLC's journal and book publishing programs, visit our website: **www.taylorandfrancis.com.**

September 2007

IIE ENGINEERING ECONOMY DIVISION

M. Affan Badar
Director
Indiana State University

Heather Nactmann
Immediate Past Director
University of Arkansas

Alisha Youngblood
Program Chair
University of Alabama, Huntsville

Thomas Boucher
Awards Chair
Rutgers University

ASEE EUGENE L. GRANT AWARD COMMITTEE

Jane Fraser, Chair (2004-07)
University of Colorado-Pueblo

Paul Kauffman (2004-07)
East Carolina University

Kevin Dahm (2004-07)
Rowan University

Janis Terpenny (2005-08)
Virginia Tech

Jim Luxhoj (2005-08)
Rutgers University

William Peterson (2005-08)
Old Dominion University

Kate Abel (2006-09)
Stevens Institute of Technology

Scott Grasman (2006-09)
University of Missouri-Rolla

Ed Wheeler (2006-09)
University of Tennessee-Martin

The Eugene L. Grant Award is presented at the annual meeting of the Engineering Economy Division of the American Society for Engineering Education to the author(s) of the best paper published in the preceding volume of *The Engineering Economist.*

2006 Eugene L. Grant Award

Ravipim Chaveesuk and Alice Smith,
Dual Kriging: An Exploratory Use in Economic Metamodeling

2005	Joseph C. Hartman
	Ingrid Schafrick
2004	Heather Nactmann
	Kim LaScola Needy
2003	Hakan Erdogmus
2002	Ronald E. Shrieves
	John M. Wachowicz, Jr.
2001	Chan S. Park
	Hemantha S.B. Herath
2000	Joseph C. Hartman
1999	David E. Sartori
	Alice B. Smith
1998	Thomas O. Boucher
	Ozerk Gogus
	Elin M. Wicks
1997	Donald E. Malen
	Arturo Salazar
1996	Deborah L. Thurston
	Angela Locascio
1995	Hesham E. Shaalan
	Robert P. Broadwater
	Wolter J. Fabrycky
	Robert E. Lee
1994	Adedeji B. Badiru
	Bob L. Foote
	John W. Peters
1993	Thomas O. Boucher
	Elin L. MacStravic
1992	William G. Sullivan
1991	George C. Prueitt
	Chan S. Park
1990	Chan S. Park
	Young K. Sun
1989	Robert A. Thompson
	Gerald. J. Thuesen
1988	Anil Mital
	R. Vinayagamoorthy
1987	James R. Buck
	Ronald G. Askin
1986	Thomas O. Boucher
	William E. Stuckey
	Layek Abdel-Malek
1985	William G. Sullivan
	Thomas L. Ward
	Kyung S. Lee
1984	Richard H. Bernhard
1983	Thomas O. Boucher
1982	Robert V. Oakford
	Sultan A. Bhimjee
	Arturo Salazar
1981	C.R. Rao
	Kenneth Nowotny
	Paul McDevitt
1980	John Freidenfeld
	Michael Kennedy
1979	James R. Buck
	Glen H. Sullivan
	Phillip E. Nelson
1978	Peter G. Sassone
1977	Gerald J. Thuesen
1976	Nabil A. El-Ramly
	Richard E. Peterson
	K.K. Seo
1975	J. Morley English
1974	Lynn E. Bussey
	G.T. Stevens, Jr.
1973	William Rudko, Jr.
	Richard J. Tersine
1972	Raymond P. Lutz
	Harold A. Cowles
1971	James C.T. Mao
	John F. Brewster
1970	Robert F. Kleusner
1969	Gerald W. Smith
1968	L.C. Rosenberg
1967	Richard L. Norgaard
1966	J. Morley English

The Engineering Economist, 52: 285–303

ISSN: 0013-791X print / 1547-2701 online
DOI: 10.1080/00137910701503951

Taylor & Francis
Taylor & Francis Group

CASE STUDY: THE ENGINEERING ECONOMICS OF RFID IN SPECIALIZED MANUFACTURING

Erick C. Jones, Michael W. Riley, Rodrigo Franca, and Sheana Reigle

University of Nebraska—Lincoln, Nebraska, USA

Calibrated tools are essential to producing highly specialized, defect-free parts. These tools are used in many processes in specialty manufacturing operations. Personnel could use the improper tool if the calibrated tool has been lost or stolen. This results in reduced business productivity and increased cost due to poor quality. This study demonstrates the cost effectiveness of using a radio frequency identification (RFID) system to track calibrated tools throughout a production facility. The costs of RFID tool tracking are described and return on investments of plausible scenarios are determined. Also, sensitivity analysis is performed utilizing spider plot and tornado diagrams.

INTRODUCTION

In order to ensure the cost-effective production of specialized products, many companies use calibrated tools. Failure to use the proper calibrated tool can result in scrap and rework. This inefficiency results in events such as audit costs, higher labor costs, and loss of customer trust that translates into lost sales. Further, customers often sue companies that produce defective parts that cause injuries. These events not only produce negative publicity for the companies but may result in costly lawsuit settlements.

Calibrated tools are essential to producing quality products and should be efficiently tracked for optimal labor productivity. However, this practice is not always demonstrated. In this study, the observed company's management attributes financial losses each year to lost or stolen calibrated tools. A stolen tool is considered a lost tool for this analysis. Defective parts from using noncalibrated tools can trigger facility audits by customers as specified

Address correspondence to Erick C. Jones, 175 Nebraska Hall, University of Nebraska—Lincoln, NE 68588-0518.

in contractual arrangements. Consequently, failed audits may result in a contract fine if an operator is found to be using a noncalibrated tool.

In addition to the quality costs of an operator using a noncalibrated tool in production, there are also the costs of losing calibrated tools. First, there is the cost of the tool itself if the tool is never found. Second, there is the cost of the lost labor time spent searching for the tool. And finally, there is lost production time if the tool is needed immediately in production. We suggest that these latter costs could be alleviated by the use of radio frequency identification (RFID), which can provide real-time tracking of calibrated tools.

RFID can be used in an asset management system, such as those supported by enterprise resource planning (ERP) systems. Asset management systems should locate assets individually, allow for locating the correct assets at the correct time, and provide information about each individual asset and the physical status of the asset (RFID Wizards, Inc., 2003).

These uses are the foundation of RFID systems. A tag is placed on each asset that carries the information of the individual item. These tags contain an antenna, which allows information to be transmitted at the frequency identified by the reader. Readers are located throughout the production facility in coordination with their reading distance abilities. Software is used to capture the information transmitted to the reader. The reader sends the data to the inventory management system, which allows for parts to be tracked and located throughout the production facility (United States Department of Defense, 2004).

PROBLEM STATEMENT

The fundamental question for this study is "Will implementing an RFID-based system reduce some of the cost of poor quality incurred due to lost calibrated tools?" This analysis focuses on the labor costs, audit costs, and management time needed for implementing an RFID system. This article does not address lost quality due to other factors that management felt were not related problems that RFID could solve. These include training, wrong tool usage, and gauge precision. These are valid reasons for loss of quality but not explicitly related to the tracking of lost tools.

This article formulates a cost analysis of implementing an RFID system to track calibrated tools throughout a production facility. By comparing two different scenarios, the best plan of action is defined (Evans, Zhang, and Vogt 2004). The goal of a new system is to save the company money with increased traceability. The RFID system put in place must provide savings greater than the cost to implement and be innovative in nature so as to put the company ahead in the industry (Blanchard, 1992).

BACKGROUND

An armament and technical products manufacturing facility that has no current tracking system in place is analyzed. Increased costs due to audits, rework, and customer dissatisfaction have been identified by management as costs incurred by using the wrong tools or a noncalibrated tool. In order to place more control over the practice of wrong tool usage due to the loss of calibrated tools, the company evaluated an RFID tracking system. The facility has approximately 132,000 square feet and 200 total employees. Management personnel and production personnel costs are respectively about \$40/h and \$20/h including indirect costs. Approximately 2,000 calibrated tools are utilized in production.

A dedicated staff has the responsibility of calibrating and supplying the tools to the production workers. The communication between the production floor and calibration staff on the location of tools was identified as a problem; there was no effective tool tracking. Therefore, calibrated tools were difficult to find when needed and little feedback was available to production supervisors when production operators were unable to find a tool. This lack of feedback led to operators either looking for the tools or using the incorrect tool. The costs associated with using the incorrect tools including labor, scrap, rework, and failed audits are evaluated in this article.

COST JUSTIFICATION

This study presents two scenarios. The first scenario is the do-nothing option or the company remains status quo. This scenario describes the baseline costs for the study. Scenario two demonstrates the costs and benefits of implementing the RFID system over a 5-year period.

Scenario 1: Baseline

The first option the company has in regards to tracking its calibrated tools is to remain status quo, which we consider the baseline. This suggests that the costs the company is incurring will remain unchanged over the 5-year period considered in this article. In order to show the total cost, each cost is considered separately. These costs include audit costs, rework costs, scrap costs, management costs, and customer service costs.

AUDIT COSTS

External auditors periodically review processes and procedures at the company. These audits include governmental audits and environmental audits.

This study focuses on the audits that review the products created from calibrated tools. For each of these auditors who visit the plant, there is a cost to the company. The initial audit is always obligatory; therefore, the cost of the first audit is not considered. However, problems identified during the initial audit can lead to an additional audit for production areas that do not pass inspection. These secondary audit costs create additional company efforts such as management and operator time for communications about failed audits, delayed contracts, and possibly layoffs due to lost contracts.

There may be one or two more secondary audits throughout the year that would not have been needed previously. In order to estimate the cost of an additional audit, conditional probability trees are utilized to assess the probability of the company needing a second, third or fourth audit. The probabilities utilized were established through management interviews. Due to company privacy issues, this study does not display the histograms or show the distributions of the number of occurrences of error. Instead, only the distribution probabilities are shown in Figure 1 as conditional probability trees.

The expected value of the audit cost $E(X_i)$ is given as a function derived from the decision tree. The following equation will be in this study for the audit cost calculations.

$$E(X_i) = A_1D_1 + A_2B_1D_2 + A_2B_2C_1D_3 + A_2B_2C_2D \tag{1}$$

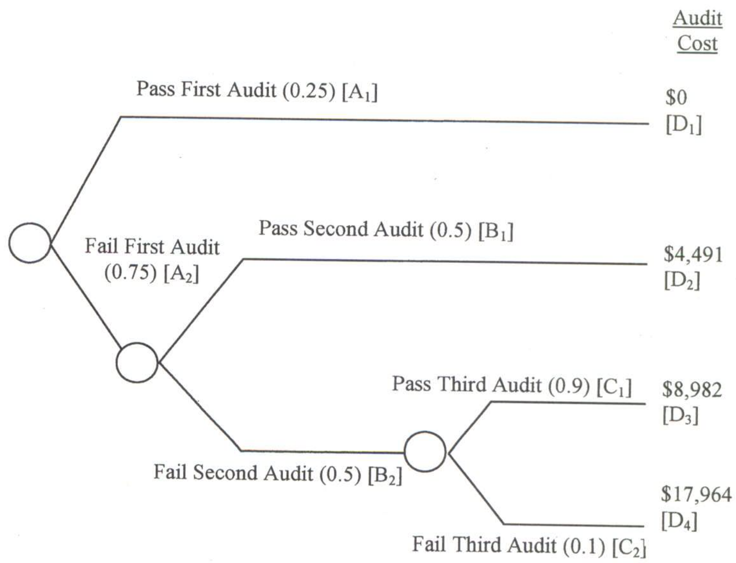

Figure 1. Audit conditional probability tree.

Table 1. Audit costs

Audit cost elements per audit	Scenario 1 ($)
Auditor	2,376
Travel	900
Lodging & food	1,215
Total cost	4,491

X_i is the audit cost of contract i. For the audit cost calculation, an additional penalty is given if the third audit is not passed represented as D_4 in Equation (1). The given cost is twice the cost of passing the third audit. This cost was included due to the additional cost of special efforts made by the company when an audit fails three times.

The costs include auditor labor and travel expenses. Each auditor is conservatively estimated to earn $25 per hour with 33% benefits or a total cost of approximately $33 per hour. Each audit takes approximately three days, and the auditors work 8 hours daily. Thus, the average number of hours worked per audit is 24 hours. Overall, the cost for an outside audit team with three members is $2,376 per audit.

In addition to the costs for the auditors, travel expenses were included. Travel expenses include air travel, lodging, and food. Given an audit team of three auditors, the total cost for airline tickets is $900 ($300 per airline ticket). Next, the audit team lodging and food cost were $100 per night for a hotel room and $35 a day for food over three days, such that the cost for three auditors would be $1,215. These costs are summarized in Table 1.

The total cost per extra audit is approximately $4,491. The expected ue for an audit with the given probability of failure is estimated to be $5,389.

$$E(X_1) = (0.25)(\$0) + (0.75)(0.5)(\$4,491) + (0.75)(0.5)(0.9)(\$8,982) + (0.75)(0.5)(0.1)(\$17,964) = \$5,389 \qquad (2)$$

The current company contracts that were audited the previous year were 27. The possible savings that can be achieved from audit reduction is the product of the expected audit cost and the number of audits. We use a conservative estimate of reducing the cost of 20 audits for a total cost savings for audit of $107,784.

REWORK COSTS

Another cost to consider is rework cost. Through this study, the company analyzed did not have data available to individually measure the different causes of rework specifically due to a missing calibrated tool. Management estimates that 90% of defects were reworked and the other 10% become scrap. The previous year's total defects were 3,800 including defects in the final product and in subassemblies. Given a fraction defective of 0.90 and estimating 10% of this fraction are defects related to the use of calibrated tool, we conservatively estimate that 342 defects were reworked. Rework included such things as retooling in order to fix the defect, complete reworking of a part, or fixing a broken piece. Management interviews support an average of 8 hours per defect reworked. A production worker makes approximately $15 per hour plus 33% benefits, which equates to a total hourly cost of $20. Therefore, with 342 defects per year reworked, 8 hours lost for each defect, at a cost of $20 per hour, the estimate average total rework cost per year is approximately $54,720. These costs are summarized in Table 2.

SCRAP COSTS

The estimated scrap cost was calculated by using the median price for the final products and multiplying them by a factor of 0.72. This factor was used because the profit and transportation costs were estimated as 28% of a final product's price. Other costs such as management, warehousing, and labor were inclusive in the cost factor. Parts at this company range from $400 to $200,000 per part. There are approximately 2,346 parts manufactured each year. The expected price value was estimated at $50,300 and the cost was estimated at $36,216.

Currently, 380 defects are scrapped each year. We cannot attribute all scrap to calibrated tools due to the fact they are only used in certain processes. The operation's specialized manufacturing production lines consist mainly of four processes. The use of calibrated tools occurs in the final two processes. The current scrap estimates from those two processes are between 10 and 17% of total scrap. For this study we conservatively estimate scrap at 10%.

We use this conservative estimate due to the fact that though the defects may result in a scrapped assembly, it may not result in a scrapped product. Theoretically, the scrap produced at the third stage is not considered final

Table 2. Annual rework costs

Rework cost elements	Scenario 1
Defects to rework	342
Rework hours	2,736
Operator cost	$20/h
Total cost	$54,720

Table 3. Annual scrap costs

Scrap cost elements	Scenario 1
Cost per product at fourth process	$36,216
Cost per product at third process	$30,784
Scrapped products at third process	23
Scrapped products at fourth process	15
Total cost	$1,294,722

product scrap and the value for this scrap can be reduced. Management estimates the added value of the last process at 15%. In other words, the in-process inventory's value increases from stage 3 to 4 due to the fact that it becomes a final product in the fourth process. This was not considered in our study. Of this calibrated tool scrap, 61.5% occurs at the third process and 39.5% at the fourth process. Thus, we estimate that 38 products are scrapped per year, 23 in the third process and 15 on the fourth. The final estimated cost of scrap is $1,294,722. These costs can be seen in Table 3.

MANAGEMENT COSTS

Management costs were estimated as a percentage of total management time. Currently there are five managers directly involved with the results of audits and other problems that arise from the production floor. In our study, the time of five managers is associated with lost calibrated tools. There are 2,080 work hours in a year, which equates to 10,400 hours per year of total management time available. The percentage of total time tilized to address audit concerns and production floor problems were 5%. Of this 5%, we assume that a minimum of 50% of this time, or 2.5% of total time, is dedicated to working with problems of rework and scrap. This percentage is a conservative estimate. The total time per year for five managers is 260 hours. Finally, the hourly cost per manager was determined to be $30 per hour with 33% benefits. Benefits increase the cost per manager about $40 per hour. The cost of management per year in regards to audits and production performance was found to be $10,374 per year. Table 4 summarizes those costs.

CUSTOMER SERVICE COSTS

The customer service cost considers the risk of losing the customer or contract. Conservatively, the article only considers the potential loss of a portion of a contract, not the loss of the complete contract. The customer may either cancel or reduce the contract at the end of the contract period.

Table 4. Annual management costs

Management cost elements	Scenario 1
Hours per year	2,080
# Managers	5
2.5% Total work time	260
Hourly cost	$39.90
Total cost	$10,374

Due to this risk, the range of values were considered. Contracts could potentially range from $1,000 to $11.8 million. The conditional probability trees consider the reduction of a contract due to a defect reaching the customer, and after two occurrences, the contract would be canceled. All these probabilities were considered in the conditional probability trees below in Figure 2.

The second conditional probability tree utilized in this article was for deriving the function for the expected customer service cost $E(Y_j)$.

$$E(Yj) = A_1D_1 + A_2B_1C_1D_2 + A_2B_2C_2D_3 + A_2B_2C_3D_4 + A_2B_2C_4D_5 \tag{3}$$

Equation (3) describes the expected customer service cost calculations. Y_j represents customer service cost for contract j. The conditional probability tree was based on the following assumptions from estimates of past occurrences. First, it was estimated that a minor defect on a first occurrence would cause the customer to reduce its contract by 10%. However, a major defect would cause the customer to reduce its contract by 25%. If a minor defect was found by a customer for a second time or more, the customer

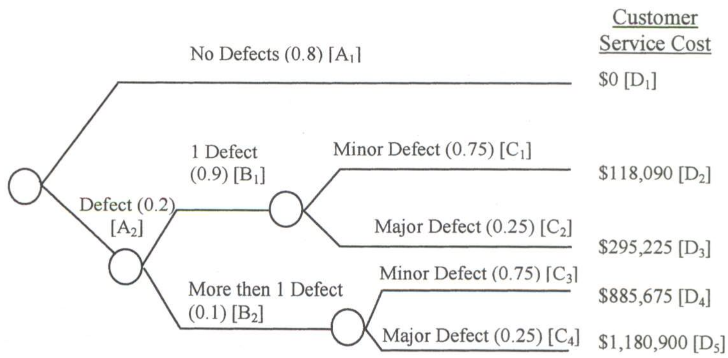

Figure 2. Customer service conditional probability tree.

was estimated to reduce its contract by 75%, but if the defect was major, the customer was likely to seek another company to do business with. Therefore, the company could potentially lose the entire contract on a second major defect. This penalty cost is given as D_5 in Equation (3). The penalty cost is quantified as the cost of completely losing the value of an expected contract.

In order to complete the conditional probability tree, an expected value of the contract price needed to be found. The smallest contract was considered to be 90% of the total contracts, with 10% being the contract of \$11.8 million. This gave a weighted average contract of \$1,180,900 as calculated below.

$$(\$1,000)(0.9) + (\$11,800,000)(0.1) = \$1,180,900 \tag{4}$$

These conditional probability tree calculations are demonstrated in Figure 2. The conditional probability tree was collapsed in order to find an expected cost for customer service of \$48,417.

$$\begin{aligned} E(Y_2) = {} & (0.8)(\$0) + (0.2)(0.9)(0.75)(\$118,090) \\ & + (0.2)(0.9)(0.25)(\$295,225) + (0.2)(0.1)(0.75)(\$885,675) \\ & + (0.2)(0.1)(0.25)(\$1,180,900) = \$48,417 \end{aligned} \tag{5}$$

Many assumptions were made with the inclusion of the customer service cost. However, it is a risk that the company takes every time it ships a product. Therefore, this cost needed to be included. This estimation has some limitations. The main one to note would be the lack of numerous occurrences. This cost was estimated on the assumption of one occurrence a year. The company is a government contractor and has lost no more than five contracts over the last 5 years to other plants, though audit costs have risen. This may be a low or high estimate and must be considered by any other companies looking into this model. Overall, this expected value fits this company well.

TOTAL ANNUAL COST

The total costs for scenario 1 are outlined in the table below (Table 5). The total cost is approximately \$2.1 million dollars per year. The implementation cost of scenario 1 was zero due to the fact that it is the current system. The total cost with its elements can be seen in Table 5.

Table 5. Total annual cost scenario 1

Cost elements	Scenario 1 ($)
Audit	107,820
Rework	54,720
Scrap	1,294,722
Management	10,374
Customer service (contracts lost)	48,417
Implementation	0
Total cost	1,516,017

Scenario 2: RFID Implementation

The second scenario evaluates the cost of implementing an RFID system to track calibrated tools. This implementation would be the greatest cost to the company for this scenario, as will be seen. In addition to the implementation cost, there will be a maintenance cost each year to keep the system in good working condition. Also taken into consideration with scenario 2 is the cost reduction linked to the implementation of the RFID system.

TAG COSTS

Tags are the transponders that carry the information in an RFID system. Passive RFID tag costs can range from $0.40 and $0.80 (United States Department of Defense 2004). Through this study, passive class 1 labels were used. These tags cost approximately $0.75 each. In order to implement the system, all 2,000 calibrated tools would be tagged. The tags would be used to store and pass data between systems devices, in this case the tag and the reader. The estimated total tag cost is $1,500. These costs can be seen in Table 6.

The cost of the tags will also include yearly replacement tags at the same value of the same amount of $1,500. The tags will have the ability to be programmed with such information as the unique tool number, type of tool, planned location, current location, and next scheduled tool calibration.

Table 6. Annual tag costs

Tag cost elements	Scenario 2
Cost per passive tag	$0.75
Number of tags	2000
Total cost	$1,500

READER COSTS

The reader is used to communicate with the RFID tags through electromagnetic waves. The information is relayed from the tag to the reader. There are both portable readers and fixed readers in the market today (Nobel 2004). In this case, the company would be using fixed readers placed at strategic locations throughout the plant. Considering that there are numerous rooms in the plant, 15 readers would be needed. All exits to the outside would be covered with a reader as well as other locations within the plant. Each reader would cost the company approximately $5,000. Therefore, the initial cost of the readers would be approximately $75,000.

In addition to the readers, 15 antennas would be purchased to boost the signal sent from the readers to the tags at various locations within the plant. A spectrum analyzer was used to conduct a site survey in order to determine the number antennas that would be used in this environment. The antennas would be used at ingress and egress of the rooms to provide optimal data capture of RFID tags.

These antennas would be used in areas where transmission through the material may be an issue. By adding antennas in these areas, the entire plant could be covered by the RFID network in order for all tags to be read when needed. An inventory search can be initiated at any time by activating the readers and antennas. The search would identify tools that are missing from the plant. There would be no readers placed within the offices. Therefore, engineering or tooling staff would need to confirm that they were moving a calibrated tool to an office in order to prevent alarming the system. Each antenna costs approximately $500. The cost for 15 antennas would be $7,500. Therefore, the total cost of the readers and antennas is $82,500. The installation cost is included in the implementation cost for the RFID system. Table 10 summarizes those equipment costs.

SOFTWARE COSTS

The final component of the RFID system is the middleware software. This software serves as a traffic cop to send the correct data to the ERP system currently in place at the company. This software typically costs approximately $25,000 and includes the cost of upgrades for up to 3–5 years. Currently the company purchases the tags and readers from a supplier that will include the supplier's software, commonly termed *edgeware*. The integration between the reader's edgeware, middleware software, and ERP are the typical software costs. Another consideration when purchasing middleware is that the software platforms must be compatible with the current ERP system. Possible costs include interface programmers in such languages as

Table 7. Annual reader costs

Reader cost elements	Scenario 2 ($)
Readers	75,000
Antennae	7,500
Total cost	82,500

C, C-sharp, and C++, which can be as high as $200/h, and the costs can exceed $50,000 for this type of software integration. For this study we conservatively estimate $25,000.

IMPLEMENTATION COSTS

We estimate implementation costs by assuming that two technical personnel are assigned the task to implement the RFID system over 6 months. These technical personnel cost $33 per hour fully burdened. Over 6 months (assume 20 work days per month) and assuming an 8-h work day, these two employees would work a total of 960 hours. This cost is $31,680 per technical personnel, or $63,360 for implementation of an RFID system over a facility of 132,000 square feet.

INVESTMENT FOR SCENARIO 2

The total cost for year one of the second scenario is shown below in Table 8. There is estimated to be a cost of approximately $172,360 for implementation of the RFID system. The cost elements for scenario 2 can be seen in Table 8.

In addition to the implementation costs of year one, there will also be a yearly maintenance cost. This includes replacing the tags and the labor needed to perform this task. In this study we conservatively estimate that yearly tag replacement costs would be the same as the initial tag costs. We use this yearly tag replacement cost throughout our 5-year analysis.

Table 8. Initial investment scenario 2

Cost elements for year 1	Scenario 2 ($)
Tags	1,500
Readers	82,500
Software	25,000
Implementation	63,360
Total cost	172,360

Table 9. Annual maintenance cost

Maintenance cost elements	Scenario 2 ($)
Tag replacement	1,500
Labor	1,334
Total cost	2,834

As mentioned earlier, the cost of the replacing 2,000 tags will be $1,500. The time of this project is estimated to take approximately two minutes per tool to both find the tool and replace the tag. With more than 2,000 tools it will take 4,000 minutes, or 67 hours. Employees performing this task will be making $15 hour. After 33% benefits were added to this labor cost, the personnel cost rose to $20 per hour. This brings the labor cost of maintenance to $1,334 per year and total costs to $2,834, as shown in Table 9.

COST EVALUATION FOR SCENARIO 2

In this section the cost elements of scenario 2 will be exposed and compared with those of scenario 1. The estimation of those cost is necessary to evaluate the economic viability of the proposed scenario.

First we are going to analyze the audit conditional probability tree elements. With the implementation of the RFID system to track tools, the expected cost for one audit is estimated as $4,320. The total cost for the 20 audits is then $86,807.

$$\begin{aligned} E(X_1) &= (0.35)(\$0) + (0.65)(0.6)(\$4,491) + (0.65)(0.4)(0.9)(\$8,982) \\ &\quad + (0.65)(0.4)(0.1)(\$17,964) = \$4,320 \end{aligned} \tag{6}$$

We estimated the number of parts that needed rework due to calibrated tools in scenario 2 as 279. With the same average of 8 hours per rework at a cost of $20 per hour we have the cost of $44,640.

The number of parts that were scrapped due to defects related to calibrated tools is now estimated as 31, with 60.5% of the scrap coming from the third stage and 39.5% from the last process. The estimated costs to the company are $30,784 and $36,216, respectively, giving the total scrap cost of $1,056,221.

For the management cost the fraction of the time dedicated to floor problems is again estimated to be 5%. The percentage of this time used to deal with problems related to work and scrap is now estimated to be 40%, giving a fraction of 2% of the total time of the managers. The total cost

Table 10. Cost elements comparison

Element	Scenario 1 ($)	Scenario 2 ($)	Difference ($)	Savings (%)
Audit	107,784	86,407	21,377	20
Rework	54,720	44,640	10,080	18
Scrap	1,294,722	1,056,221	238,501	18
Management	10,374	8,299	2,075	20
Customer service	48,417	35,583	12,833	27
Total	1,516,017	1,231,150	284,867	19

for management considering five managers working 2,080 hours per year each and receiving $39.90 per hour is $8,299.

The customer service conditional probability tree, an example of the audit tree, is estimated to have its probabilities modified. The new expected cost for customer service in scenario 2 is calculated as follows:

$$\begin{aligned} E(Y_2) = {} & (0.83)(\$0) + (0.17)(0.93)(0.8)(\$118,090) \\ & + (0.17)(0.93)(0.2)(\$295,225) + (0.17)(0.07)(0.78)(\$885,675) \\ & + (0.17)(0.07)(0.22)(\$1,180,900) = \$35,583 \end{aligned} \tag{7}$$

The summary of scenario 2 estimated savings compared to scenario 1 can be seen in Table 10. From this data it can be seen that the implementation of an RFID system for tracking calibrated tools gives an expected 19% savings compared with the do-nothing scenario.

The estimation of the savings promoted by RFID indicates that a one-time $172,360 investment can save about $284,867 yearly. For illustrative and pedagogical purposes, the savings in scenario 2 are analyzed at a conservative 5% of $284,867 for the present value analysis, so the yearly cost of scenario 2 is $1,517,628.

NET PRESENT VALUE COMPARISON

We use a net present analysis to compare the two alternatives. The assumptions applied here are that the cash flows are deterministic and they occur at the end of each period of time analyzed.

A reasonable range for the discount rate is between 18 and 20%. In this study the value we will use is 20%. The time period used is a 5-year period, which is the minimum considered by the company to compare the two projects. On this comparison there is no salvage value.

A further study analyzing the variability of the elements that compose the costs will be presented in the sensitivity analysis part.

For scenario 1, the total net present worth is approximately \$4.78 million, demonstrated using Equation (8).

$$\begin{aligned} \mathrm{PW}(20\%) &= \$1,516,017(\mathrm{P/A}, 20\%, 5) \\ &= \$4,553,819 \sim \$4.55 \text{ million} \end{aligned} \tag{8}$$

For scenario 2, the net present value was approximately \$4.72 million, as seen in Equation (9).

$$\begin{aligned} \mathrm{PW}(20\%) &= \$172,360 + (\$1,440,216 + \$2,834)(\mathrm{P/A}, 20\%, 5) \\ &= \$4,487,963 \sim \$4.49 \text{ million} \end{aligned} \tag{9}$$

Comparison

From the results of the net present value analysis above, RFID will provide an economic benefit to the company. The difference in the two net present values is approximately \$46,000. Due to this difference in the net present values as well as the initial savings, RFID would be a good choice for the company to pursue.

SENSITIVITY ANALYSIS

In order to justify the results of this study further, a sensitivity analysis was developed. This was done in order to justify the study and compensate for the large amounts of variability in the variables.

The term *sensitivity analysis* examines how uncertainty of the variables that compose the cash flows can influence the recommended decisions. The sources of uncertainty can be due to measurement error, unclear specification, or volatility of the future. The techniques used in this model are the spider plot and the tornado diagram. The spider plot has the advantage of showing the impact of each cash flow's uncertainty on the present worth of the project and also makes a comparison between the individual variables influence easier to identify. A spider plot should contain the limits of uncertainty for each cash flow element; the impact of each element on the PW and the identification of each element might change the recommendation (Eschenbach 2003, 1989).

The tornado diagram, on other hand, is to be used when a summary of the economic performance of the variables on the present worth is needed. This chart shows the variables that have the most influence on the present worth in descending order. This makes the diagram have a tornado shape. Normally this analysis assumes that the variables are statistically independent (Eschenbach 2006), which is assumed in this case.

Table 11. Limits of variables

Variable	Scenario 1	Scenario 2	Lower limit (%)	Upper limit (%)
Investment	—	$172,360	80	140
Yearly cost	$1,516,017	$1,440,216	60	120
Maintenance cost	—	$2,834	90	130
i	20%	20%	70	150
N	5	5	70	120

The lower and upper limits used in this case are demonstrated in Table 11. As we are dealing with two mutually exclusive scenarios, the sensitivity analysis was created using the differences between the present worth of the two scenarios.

We calculated the present value of the project and we utilized these data to construct a spider plot that demonstrates the effect on each variable when the others remain constant. The positive values indicate that scenario 2 is more attractive, whereas negative values indicate that scenario 1 is more attractive.

From Figure 3 it can be seen that, when uncertainty is taken in account, in some situations scenario 2 is more advantageous and in others scenario 1 is better. On Table 12 the breakeven point for the difference of each variable can be visualized. Particularly for low values of the yearly savings and high values of the initial investment, scenario 2 became less attractive. The

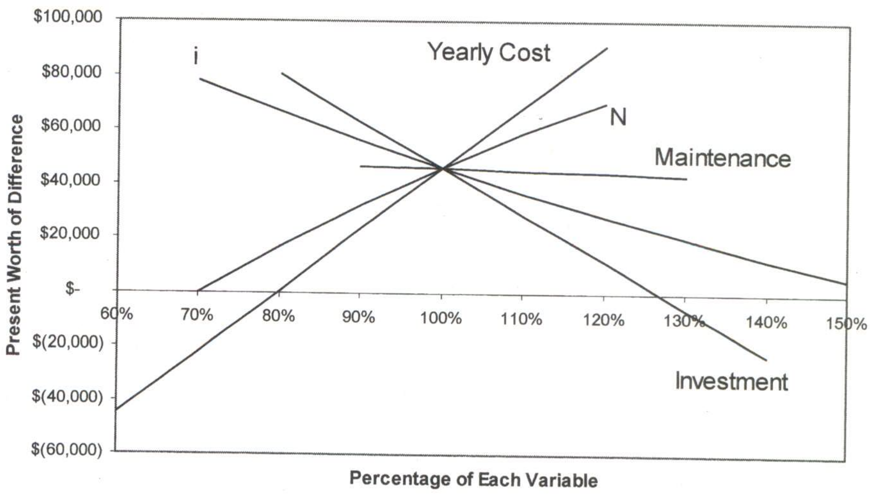

Figure 3. Spider plot of PW of difference of the two scenarios.

Table 12. Breakeven points

Variable	Breakeven ($)
Investment	$218,216
Year cost	$(60,468)
Maintenance cost	$18,167
i	32%
N	3.507

minimum difference of PW between the two scenarios is obtained when the yearly cost is set to its lower limit.

The breakeven for each variable expresses the value of that variable that makes the NPV assume the value zero. The point divides the positive NPV from the negative NPV; in other words, the attractive scenarios from the negative scenarios, respectively. Those values indicate that the minimum yearly savings necessary for this project to be attractive is about $60,000, or a 4% improvement.

To summarize the relative sensitivities of each variable, a tornado diagram (Figure 4) was then created. This diagram shows the variability accounted for each factor in descending order. From this chart can be seen the influence of each variable on the present worth.

From the above sensitivity analysis, this study shows that even with variability added into the model, there remains a substantial benefit in implementing an RFID system. The variables that have the most influence on the project are the yearly cost and the investment. Therefore, as long as

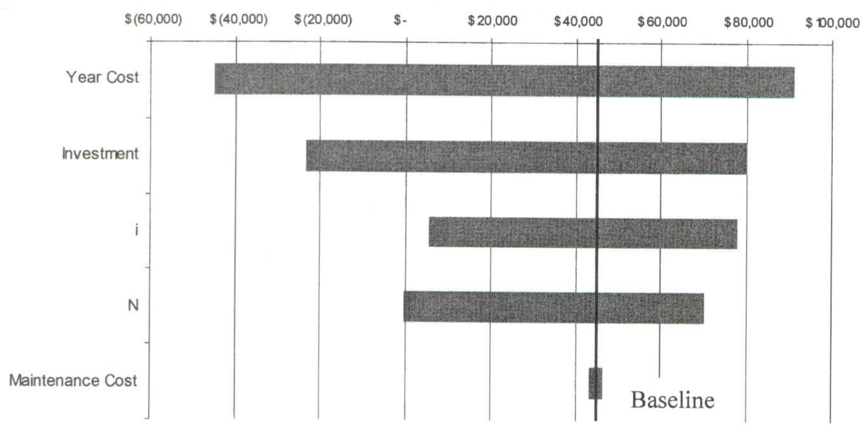

Figure 4. Tornado diagram.

those variables do not go beyond the respective breakeven values, scenario 2 represents a good alternative to the company.

LIMITATIONS

In this study there were several limitations. The cost of scrap associated with not using a calibrated tool was difficult to measure. Scrap costs can be further associated with inadequate training, improper workstation design, and other nonproductive practices. In order to limit this study to the impact of lost tools, we made the simplifying assumption that 10% of scrap was associated with using the wrong tool due to lack of availability of the correct calibrated tool. The cost to upgrade the RFID systems is not included in this analysis due to the fact that this will probably happen after 5 years, which exceeds our cost time horizon.

Finally, the high-level time study that yielded a projected 20% labor reduction due to RFID implementations has a significant effect on the study. Though managers were comfortable with these saving estimates, a more detailed time study was recommended by the researchers.

CONCLUSION

This study has outlined the current costs of using noncalibrated tools to the company. These costs have the potential to be reduced by implementing an RFID system to track the calibrated tools. RFID technologies are rapidly emerging as a useful technology and this company has the potential to use RFID in other areas besides calibrated tools. This could lead to other savings. This study outlined the cost of implementing an RFID system as well as the cost to maintain this type of system. We utilized the net present value analysis in order to evaluate the cost and benefits of RFID. The net present value analysis showed the difference between a do-nothing scenario and the scenario in which we implement RFID. The results demonstrated a savings of approximately $60,000 if the RFID system is implemented. Further, for illustrative purposes we conservatively used 5% of our estimated savings, which demonstrated a favorable return. Given this additional fact we suggest that the investment in RFID technology would be significantly advantageous for this company.

REFERENCES

Blanchard, B. (1992) *Logistics of engineering and management*, 2d ed. Englewood Cliffs, NJ: Practice Hall.

Eschenbach, T.G. (1989) *Cases in engineering economy*. New York: Wiley.

Eschenbach, T.G. (2003) *Engineering economy: Applying theory to practice,* 2d ed. Oxford, UK: Oxford University Press.

Eschenbach, T.G. (2006) Technical note: Constructing tornado diagrams with spreadsheets. *The Engineering Economist*, 51(2), 195–204.

Evans, J.L., Zhang, D., and Vogt, N. (2004) Investment analysis for automotive electronics manufacturing: A case study. *The Engineering Economist*, 49, 159–183.

Nobel, C. (2004) Sun, Sybase, IBM tackle RFID.*eWeek*, 21, 14–16.

RFID Wizards, Inc. (2003) *RFID equipment test results manufacturing.* RFID Wizards, Inc.

(2004) The need for total asset visibility. *ID TechEx*, Cambridge: Far Field House.

United States Department of Defense. *United States Department of Defense suppliers' passive RFID information guide*, November 14, 2004.

BIOGRAPHICAL SKETCHES

DR. ERICK C. JONES is an assistant professor at the University of Nebraska—Lincoln. Areas of specialization and teaching include: RFID and AIDC reliability testing, Six Sigma, logistics, and engineering management. Dr. Jones is the current Nebraska site director of a NSF I/URC CELDi and the director of the RFID Supply Chain Lab (RfSCL). He can be reached at ejones2@unl.edu

DR. MICHAEL RILEY, P.E., is a professor of industrial and management systems engineering of the University of Nebraska—Lincoln. His research areas include safety and ergonomics. He can be reached at mriley1@unl.edu

RODRIGO FRANCA received his B.S. in industrial engineering from the Universidade Federal do Ceará-Brazil and is currently pursuing an M.S. in industrial engineering from the University of Nebraska—Lincoln. His professional interests are engineering economy, supply chain modeling, and RFID applications. He can be reached at rbfranca@yahoo.com

SHEANA REIGLE received her B.S. in industrial engineering from the University of Nebraska—Lincoln. She is currently working for the Rolls-Royce Corporation as a Black Belt management trainee. She can be reached at sreigle11@gmail.com