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ORIGINAL ARTICLE

Application of AHP and Taguchi loss functions in evaluation of advanced manufacturing technologies

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Abstract The purpose of this study is to develop the decision model to help decision makers with their technology selection. Evaluation and selection of a new technology is a multi-criteria decision-making process encompassing various tangible and intangible factors. Thus, these factors should be identified for inclusion in the evaluation process. A thorough analysis of the impact, both positive and negative, of such factors on the organization is also required in the evaluation technique. Therefore, the first step in the development of a decision model for evaluation of technology alternatives is the identification of the pertinent factors. To accomplish this, both risks and benefits of implementing a new technology are identified for inclusion in the evaluation process. Once pertinent risks and benefits are identified, a mechanism for analysis of these factors is developed. Since these factors can be objective and subjective, a hybrid approach that applies to both quantitative and qualitative factors is used in the development of the model. Taguchi loss function is used to measure performance of each technology candidate with respect to the risk and benefit categories. Appropriate Taguchi loss functions are formulated based on the target value and the specification limits set by the decision maker. These loss functions are then used to calculate Taguchi loss scores for each technology alternative. Analytic hierarchy process (AHP) is used to determine the relative importance of the risks and benefits to the decision maker. The weighted loss scores are calculated for each technology alternative by using the relative importance as the weights. The composite weighted loss scores are then calculated and used for ranking of the technology alternatives. The technology with the smallest composite loss score is recommended for adoption. The proposed model provides guidelines for managers to make an informed decision regarding technology selection. In addition, combining Taguchi loss function and AHP provides a novel approach for ranking of the potential technology alternatives for implementation purposes.

Keywords Analytical hierarchy process · Weighted loss score · Technology ranking · Taguchi loss function · Advanced manufacturing technology

1 Introduction

To survive in a competitive environment and respond to customer demands, manufacturing companies have no choice but to invest in advanced technologies. Thus, there is a need by these manufacturers to have access to a decision model that thoroughly analyzes the impact of such investments and provide guidelines for evaluating several competing technology alternatives [1, 2]. The present study attempts to address the special needs of the manufacturers by developing a model that helps them with their technology selection and investment.

A manufacturer has to follow several stages to complete the process of adopting a new technology. The stages in a typical technological adoption process are identified as follows: generation/identification of technology alternatives, assessment of technology alternatives, prioritization of alternatives, emergence of a champion, resource allocation, and implementation of the selected technology. At each stage, there are barriers that act as gates that may not allow the process to continue. These barriers are summarized by Ordoobadi et al. [3] as follows:

Uncertainty
Lack of resources
Perception of payback
Priority scheme

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- Time constraints to make a decision
- Resistance to change
- Issues regarding the champion for the cause
- Success rate in past technology adoptions
- Current perceived need of the company for a new technology

The focus of this research is on two specific stages of the adoption process: assessment stage and prioritization stage. The attempt here is to address the difficulties that manufacturers face with regard to these two stages and develop a process that overcomes these barriers. To assess technology alternatives, there is a need to identify various classifications of advanced manufacturing technology (AMT). The AMTs are generally classified into three broad categories [4]: stand-alone systems such as computer-aided design, intermediate systems such as automated storage and retrieval systems (AS/AR), and integrated systems such as flexible manufacturing cells (FMC). For stand-alone systems where the purpose is to simply replace the old equipment, the standard financial justification techniques might be sufficient to evaluate their costs of investment and benefits and risks. However, for intermediate and integrated systems, realization of the potential benefits/risks and analysis of their impacts on all areas of the company are essential for justifying such investments. Thus, more sophisticated justification approaches that consider both financial and non-financial aspects are required. For the remainder of this paper, AMT refers to intermediate and integrated manufacturing systems.

Two observations can be made from analyzing the stages of technology adoption process and the barriers associated with each stage. First, the main barrier to technology implementation is the inability of the manufacturers to recognize all potential benefits/risks of a technology adoption. It is particularly so, if these benefits/risks are not measurable for inclusion in the traditional financial justification approaches. The second barrier is failing to realize the importance of the role of the decision maker's subjective judgments in the evaluation process. Thus, there is a need for an approach that addresses both issues. This is done in the present research by developing a mechanism for identifying potential benefits/risks of a technology adoption and also including the decision maker's subjective judgments in the evaluation process.

The rest of the paper is organized as follows: Background and research motivation are provided in Section 2. Section 3 covers the research design as well as the detailed description of the proposed model. An illustrative example is provided in Section 4 to illustrate the application of the proposed methodology. Finally, the paper is concluded with conclusions and suggestions for future research in Section 5.

2 Background and research motivation

Over the past 30 years, researchers have been actively involved in developing justification techniques for adoption of a new technology. Some of the developed techniques are purely financial and consider only tangible factors while others have the capability of including intangible factors. Furthermore, the models that allow the inclusion of intangible factors are divided into two categories: those that include intangible costs of adopting a new technology and those that include intangible benefits of such adoption. A brief overview of these justification techniques is provided below.

There are several traditional engineering economic analysis methods that are used for justifying new investments [5]. In net present value (NPV) method, all cash inflows and cash outflows resulted from a project are discounted to the present time at the desired interest rate to form the net present value of the project. A positive NPV justifies the investment. In the internal rate of return (IRR) method, the interest rate that equates the cash inflows to the cash outflows of an investment is calculated and is referred to as the IRR. IRR has to be greater than the minimum attractive rate of return or the hurdle rate of the company to make the investment desirable. Other methods include payback period which is a measure of speed with which an investment is recovered and the benefit/cost ratio which compares the ratio of the benefits to the costs of the project [6, 7].

The above-mentioned techniques primarily include the tangible financial costs and benefits. However, investment in a new technology is hard to justify by using the measurable cost and benefit data alone [8]. Investing in a new technology often result in uncertain future benefits that are very hard to estimate using a conventional financial analysis. In fact there is often lack of sufficient experience with AMT implementation, and it is not unusual for companies who have adopted AMTs to discover unexpected benefits [2]. In the literature, those categories of benefits that add value to a system but are not measurable in dollar value are referred to as "intangible benefits." It is essential to include these categories of benefits in the evaluation process since they may or may not make an investment attractive.

In order to address the above-mentioned issue, other models are developed that include intangible benefits of a new technology adoption [1, 9, 10]. These models are used to complement the purely financial evaluation techniques. A comprehensive bibliography on justification techniques is provided by Raafat [11]. Some researchers have developed analytical techniques [1, 12–16] while others have suggested procedures that one may refer to as strategic considerations [17–19]. Several researchers have focused on developing techniques for actual ranking of competing technology alternatives. Georgakellos [1] has proposed scoring techniques for screening candidates in equipment purchasing, while Arslan et al. [14] have used multi-criteria weighted average to rank alternatives for machine tool selection. Fuzzy axiomatic design has been used by Kulak et al. [15] for information technology project selection. Thomaidis et al. [16] have developed a fuzzy multi-criteria decision-making approach for evaluation of information technology projects. Kahraman et al. [20] have used fuzzy axiomatic design for evaluation and selection of renewable energy alternatives. The application of their proposed methodology is then illustrated through a case study for Turkey. Ordoobadi [21, 22] has addressed the issue of ranking of the technology alternatives through application of Taguchi loss function and analytic network process.

All of the above-mentioned techniques have included the intangible benefits in the evaluation process. However, none of these techniques considers the intangible risks of adopting a new technology. To fill this gap, several researchers have developed evaluation techniques that consider the risk factors associated with adoption of a new technology. Fit-viability framework is used by Liang et al. [23] to examine the success of the mobile technology applications in business. Christenson [24] provides a detailed study of instances where new technologies actually contribute to major failures in some companies because of unforeseen risks associated with them. Jones et al. [25] analyze the impacts of operational and strategic risks of adopting a new technology. The fact that introduction of a new superior technology does not guarantee its acceptance to replace the present inferior technology is brought up by Woodside [26]. The study by Dey et al. [27] illustrates the failure of several high profile information technology projects due to ineffective risk management. The significance of identifying and managing potential risks while developing an information system is clear from the study conducted by Maguire [28].

An empirical study conducted by Vehovar and Lesjak [29] shows the failure of investments in information–communication technology. The main reasons for the failure are stated as lack of careful analysis of the impact of such an implementation on factors like organizational structure and employee education. Au and Enderwick [30] study the impact of decision maker's perceived risk of a new technology on the investment decision, while Ryan and Harrison [31] point to the "hidden" costs of new technologies, specifically the human-related costs. Calculating opportunity costs of risks associated with adoption of a new technology and their inclusion in the evaluation process are subject of the study by Ordoobadi [32, 33]. The study conducted by Cannon et al. [34] reveals that one of the risks associated with adoption of radio-frequency identification technology is the uncertainty that accompanies such an adoption.

As can be seen from the review of the literature, there are numerous techniques for justification of investing in a new technology. Some models focus exclusively on benefits of technology adoption while others concentrate solely on risks of such adoption. However, very few attempts have been made to develop a justification technique that includes both benefits and risks of technology adoption in a single model. Such attempts are evidenced through the research conducted by Ordoobadi [9] and Small and Chen [35] where they provide discussion of risks and benefits of investing in AMT. However, none of the above-mentioned research provides a systematic way to identify both risks and benefits of adopting a new technology and a mechanism to quantify them for inclusion in the evaluation process. Specifically, no methodology is offered for technology selection when the result of the economic evaluation alone does not allow the rankings of the alternatives. The attempt of the present study is to address this issue by using intangible risks and benefits of adopting a new technology as distinguishing factors among technology alternatives with similar economic evaluation results.

The proposed evaluation technique is developed in a two-step process: first, identification of the intangible risks and benefits associated with adoption of a new technology and second, development of a methodology for evaluation and ranking of the technology alternatives based on these factors. The list of potential risks and benefits of adopting new technologies is compiled from the literature. The methodology is developed by applying Taguchi loss function to calculate loss scores for each technology alternatives. These loss scores are determined based on the target value, specification limits, and technology's performance with respect to the risks and benefits. Analytic hierarchy process (AHP) is used to determine the relative importance of these factors to the decision maker. The weighted loss scores are calculated for each technology by using the relative importance as the weights. The composite weighted loss scores are then used for rankings of the technologies. The technology with the highest ranking (minimum loss score) will be selected for adoption. The development of the proposed model is detailed in the next section.

3 Development of the evaluation technique

The model is developed by completing the following steps:

- Identifying the risk and benefit categories associated with technology adoption
- Determining the relative importance of each risk and benefit category
- Determining the performance of each technology with respect to the risk and benefit categories
- Developing a mechanism to quantitatively measure the technologies' performance with respect to all the pertinent risk and benefit categories
- Determining the rankings of the potential technologies and selecting the appropriate technology for adoption

These steps are shown in the process chart of Fig. 1 and detailed in the following sections.

3.1 Identifying risks and benefits of technology adoption

Implementation of a new technology has certain benefits and risks that should be included in the evaluation process. A careful review of the literature was conducted to uncover various categories of risks and benefits associated with a technology adoption. A list of possible benefits and risks that could materialize from a technology adoption is compiled from the available literature on the subject. Numerous benefits associated with adoption of a new technology are identified by researchers [2, 8, 13, 36–51]. A list of benefits along with their benefit indicators (how the benefits are measured) is provided in Table 1.

Some of the risks associated with adoption of a new technology cited in the literature [27–29, 31, 52–56] are:

- Reduction in versatility of personnel skills
- Incompatibility with current operations
- Low employee performance due to resistance to change
- Drop in future management support
- Project cost overrun
- Increase in absenteeism due to low employee morale
- Increase in learning costs
- Obsolescence due to poor timing of adoption
- Not completing the implementation
- Increase in labor contract costs

Of course not all the risks and benefits on the above lists are pertinent to every situation and/or every decision maker. The list of the benefits and risks is narrowed down to include only the relevant categories. This is accomplished through a calibration procedure where the decision maker is asked to identify the benefits/risks pertinent to his/her situation. In addition, the selected categories have different levels of importance to the decision maker. Thus, there is a need to determine the relative importance of each risk and benefit category. This is accomplished by completing the second phase of the model development explained in the following section.

3.2 Determining the relative importance of each risk and benefit category

The importance of each risk and benefit category is subjective and varies by the decision maker. To capture the subjective judgments of the decision maker, the AHP methodology is used. AHP introduced by Saaty [57] is widely used for solving multi-attribute decision-making problems. In the current research, the AHP methodology is used to determine the relative importance of various factors considered in the evaluation of the technology alternatives. Although AHP is used by researchers [58, 59] for actual ranking and selection of the alternatives, in the present research it is applied just to elicit decision maker's judgment on the importance of various criteria. Rankings of the alternatives through AHP methodology are based solely on the subjective information. Here we use Taguchi loss function to objectively measure the technologies' performances with respect to benefit/cost categories and AHP methodology to determine the relative importance of these factors. The

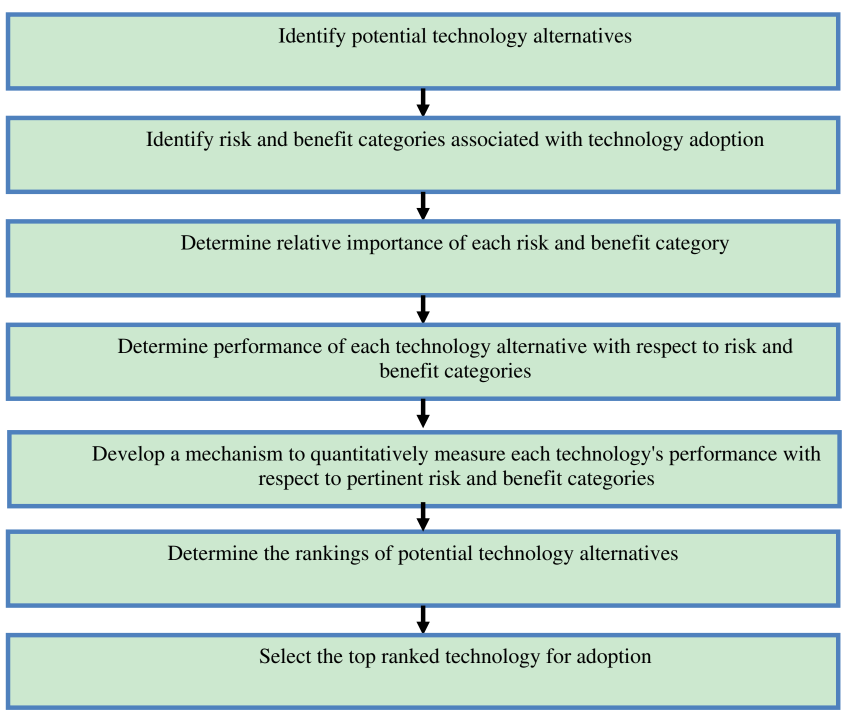

Fig. 1 Process flow chart for evaluation and selection of advanced manufacturing technology

Table 1 List of benefits of an advanced technology adoption

Benefit category	Benefit indicators
Increased flexibility	Number of product types, volume of parts, shorter cycle times and setups
	Decreased waiting time for parts, decreased work in progress
	Reduced lead times, reductions in inventory
	Increased machine utilization, reductions in idle cost
Increased quality	Lower defect rates, reduced scrap and rework decreased inspection costs
	Higher tolerance capability, improved control measures
Increased productivity	Decreased labor costs (direct and indirect)
	Decreased materials costs (direct and indirect)
	Decreased service costs of using capital
	Decreased floor space requirements
Expanded use of the technology	Increased number of products, increased product variety
	Number of other processes/areas in which the technology can be used
	Number of other departments/areas that can benefit from the technology
	Increase in the number of new ventures
Promotion of strategic objectives	Increased number of achieved goals
	Decreased risk of obsolescence, increased level of progress made on certain goals
Competitive strengths	Increased customer satisfaction, increased sales in target market areas
	Increase in the percent of the market share
Increased customer satisfaction	Improved delivery reliability, reduced delivery time, reduced lead times
	decreased customer complaints
Increased market opportunities	Faster response to changing market demands
	Increased speed for new product introduction
Increased ease of operation	Standardization of product designs within families of parts
	Shorter cycle times, increased machine utilization and efficiency
	Reductions in indirect labor
	Availability of real-time information
Improved employee relations	Increased employee morale/satisfaction, increased labor productivity
	Increased learning about advance technologies, decreased safety hazards

performances of the technologies are measured by their loss scores while the weights of the risk and benefit categories are determined by their pair-wise comparisons. By combining the two approaches, a mechanism for rankings of the technology alternatives is provided that is more objective than using the AHP methodology alone.

To determine the relative importance of the risk and benefit categories, several pair-wise comparisons are performed where the decision maker states the importance of one criterion over the rest of the criteria on the scale of (1–9), where 1 means least preferred and 9 means most preferred and numbers between the two extremes show moderate importance. The pair-wise comparisons are performed for the benefits/risks, and local priorities are calculated using the approach recommended by Saaty [57]. These priorities represent the relative importance of the benefit/risk categories. Once the importance of each risk and benefit category is determined, there is a need to find out how each potential technology performs with respect to these risk and benefit categories. This is achieved by completing the third phase of the model development as explained in the next section.

3.3 Determining performances of the technology alternatives with respect to the risk and benefit categories

Technologies' performances vary with respect to the pertinent risk and benefit categories. More importantly two decision makers might have different perceptions of the performance of the same technology with respect to the exact same risk or benefit category. Thus, inclusion of the subjective judgment of the decision maker in the evaluation process is crucial. To achieve this, an elicitation procedure is performed to solicit the decision maker's perceptions of technologies' performances. The decision maker often base such judgments on the historical data, reputation of the technology brand, the specifics of the situation at hand, etc. Once pertinent risk and benefit categories are selected and potential technologies are identified, the elicitation process is performed.

At this point, all the pertinent risks and benefits are identified, and the relative importance of each has been determined through the application of AHP methodology. Furthermore, the decision maker's perceptions of technologies' performances with respect to these risk and benefit categories have been elicited. However, to allow rankings of the technology alternatives, the results of the analysis performed so far should be combined and subjective perceptions ought to be quantified to come up with a single performance score for each technology. Taguchi loss function is considered as a means to accomplish this task as explained in the next phase of the model development.

3.4 Developing a mechanism to quantitatively measure technologies' performances with respect to risk and benefit categories

Taguchi loss function is used as a means to quantify the performance of the technologies with respect to the risk/benefit categories. The rationale for the use of Taguchi loss function is twofold. First, all the characteristics having different units of measurement and varying magnitude of scale can be converted into a common measurement: loss score. Second, since the loss function is quadratic and nonlinear, the loss becomes increasingly large as the value deviates from the target value. This second feature allows higher values to be placed on measurements (benefits/risks) that show lower variation from the target value. A brief overview of the Taguchi loss function is provided below.

Generally, three types of loss functions are used to calculate Taguchi loss [60–62]. First is the two-sided loss function where nominal value is the target and deviation from either side of the target is allowed as long as it remains within the specification limits. Any deviation from the target value will result in a loss and zero loss occurs only when the characteristic measurement is equal to the target value. The second and third types of loss functions are one-sided functions where deviations from the target are allowed only in one direction. These loss functions are referred to as "larger-is-better" and "smaller-is-better" with target values of infinity and zero, respectively. The "nominal-is-best" quality loss function is formulated as $L(X)=k\,(X-T)^2$ where X is a measurable quality characteristic with a specific target value, T is the target value, k is the proportionality constant (loss coefficient), and $L(X)$ is loss in dollars for specific value of X [62].

Taguchi loss function has been used extensively in multi-criteria decision-making problems. For instance, many vendor selection problems in a supply chain have been solved by applying the Taguchi loss technique. In particular, integration of Taguchi loss function and AHP methodology has proved to be successful for selection of the appropriate vendor. This is evidenced through the study conducted by several researchers. Taguchi loss function and AHP methodology are used by Liao [63] in order to solve supplier selection problem in an Asian food manufacturer. Magdalena [64] has used these techniques for supplier selection in a food industry in Bali, Indonesia. Taguchi loss function and AHP methodology are used by Nukala and Gupta [65] to address the supplier selection problem in a closed-loop supply chain network. However, these techniques have not been used for technology selection problems. In the present study, the aforementioned techniques are integrated to solve the technology selection problems.

In the current research, the quality loss functions are used to quantify the impact of the benefits and risks of adopting a new technology. However, the target values are different for the benefit and risk categories. One hundred percent possibility of receiving a benefit category from adoption of a new technology is the target value. On the other hand, the target value for the risk categories is zero. The loss function for each benefit and risk categories can be determined by calculating the loss coefficient k, where k is the consumer's loss/functional tolerance. Functional tolerance is defined as the maximum permissible deviation from the target value. Consumer's loss is the loss generated when the value of the quality characteristic exceeds the functional tolerance.

The decision maker sets the specification limit to indicate the allowable deviation from the target value for each risk and benefit category. The loss coefficient k can then be determined for the benefit and risk categories based on these specification limits. Thus, the appropriate loss functions for all the benefit and risk categories are determined. The technology's loss scores are then calculated using these loss functions and the deviation of the actual performance from the target value. As a result, each technology alternative will end up with several

Table 2 Sample utility calibration procedure of the benefits of technology adoption (please indicate which of the following benefits of technology adoption is useful in achieving your firm's objectives)

Benefits	Useful for consideration?
Improved delivery reliability	No
Reduced defect rate	Yes
Decreased safety hazards	Yes
Increased product variety	No
Reduced scrap and rework	Yes
Reduced lead time	Yes
Improved quality of life	No
Reduction in cycle time	Yes
Increased customer satisfaction	No
Increased market share	Yes
Increased number of achieved goals	No
Faster response to changing market demands	No
Increased speed for new product introduction	No

Table 3 Sample utility calibration procedure of the risks of technology adoption (following is a list of possible risk factors associated with technology adoption. Please indicate which of these factors are pertinent to your firm)

Risk factor	Applicable to your firm?
Incompatibility with current operation	Yes
Obsolescence due to poor timing of adoption	Yes
Reduction in versatility of personnel skills	No
Lower employee performance due to resistance to change	No
Not completing the implementation	Yes
Increase in labor contract costs	No

separate loss scores for the pertinent benefit and risk categories. However, a single value is desirable to allow the comparison of the performance of the technology alternatives. To achieve this, for each technology a weighted loss score for all the benefit categories is calculated. The weights used in the calculation are the relative importance of each benefit category that has already been determined through AHP methodology. A weighted loss score for all the risk categories is also calculated using the relative importance of these risks from the AHP methodology.

To select the appropriate technology, technology candidates need to be ranked based on their composite loss scores that combine the weighted loss scores for the benefit and risk categories. The calculation of the composite loss scores and ranking of the technology alternatives are performed in the final stage of the model as detailed in the following section.

3.5 Determining the rankings of the technology alternatives

At this point, each technology alternative has received a weighted loss score for all pertinent benefit categories as well as a weighted loss score for all relevant risk categories. However, to be able to compare performances of the technology alternatives, a single loss score for each technology alternative is desirable. To accomplish this task, the composite loss score for each technology is determined by calculating the average of the weighted loss scores for benefit and cost categories. The technology alternatives are then ranked based on their composite loss scores.

In this study, a final unified loss score is obtained by using the average of the loss scores for benefits and risks. Of course, the calculation of the composite loss score can vary by the company and/or the decision maker. Some decision makers might feel that different weights should be assigned to the loss scores for benefit and risk categories. Some prefer to assign equal weights to these loss scores. Others may prefer to use a ratio of benefits to risks or any other economic analysis quantity. The proposed model can be used to consider various factors for ranking of the technology alternatives.

4 An illustrative example

Following hypothetical case is presented here to illustrate the application of the proposed model. The president of a small manufacturing company in Iowa recently cited the dilemma he was facing.

> As the president I am facing with a difficult decision. The company is having difficulty meeting customers' demands and delivering products on time. After some discussions with the managers and several long brain storming sessions we reached the conclusion that adoption of an advanced manufacturing technology is necessary to make our operations more efficient. Furthermore, we were able to narrow down the list of the potential technologies to three; Flexible Manufacturing Cell (FMC), Automated Material Handling system (AMHS), and Automated Storage & Retrieval (AS/AR). All three technologies meet our company's operational requirements.
> In addition, one of my managers performed financial analysis to test the economic feasibility of investing in each of these technologies. The results of the economic evaluation were very close and we could not identify one to be the 'best' alternative based on financial results alone. Thus, we thought maybe other factors that were not quantifiable to be included in the economic evaluation can help us with the rankings of these three

Table 4 Pair-wise comparison matrix for the benefit categories

Benefits	RDR	DSH	RSR	RCT	RLT	IMS	Priorities
RDR	1	3	5	2	1/3	1/3	0.1941
DSH	1/3	1	1/2	3	5	3	0.2476
RSR	1/5	2	1	7	1/3	1/3	0.1468
RCT	1/2	1/3	1/7	1	1/2	1/3	0.0486
RLT	3	1/5	3	2	1	1/2	0.1586
IMS	3	1/3	3	3	2	1	0.2044
CR = 0.05							

RDR reduced defect rate, *DSH* decreased safety hazards, *RSR* reduced scrap and rework, *RCT* reduced cycle time, *RLT* reduced lead time, *IMS* increased market share

Table 5 Pair-wise comparison matrix for the risk category

Risks	ICO	OBS	NCI	Priorities
ICO	1	1/5	1/3	0.1069
OBS	5	1	3	0.6383
NCI	3	1/3	1	0.2548
CR=0.0026				

ICO incompatibility with current operation, *OBS* obsolescence due to poor timing, *NCI* not completing implementation

technologies. For example, our customers have already communicated with us that the company's image can be improved tremendously if we can offer a reliable delivery process. This in turn will retain the current customers and attract new customers, the number of complaints will go down and thus the level of customer satisfaction would increase.

Our employees also have indicated that they believe their quality of work life can be improved by having the opportunity to use the advanced technologies. The new technology could result in reduction of the safety hazards and increase in the morale/satisfaction from learning new skills to operate this technology. Actually in a recent meeting of the general managers I was informed that most of the employees were not pleased with working with the obsolete machines and some of them even threaten to quit. As it is, we already have problem attracting qualified employees because of our location and our benefit package and we cannot afford to lose any of our employees. At the same time several employees expressed their concern about the time and efforts they have to put in to learn the required skills for operating the new technology. Others have shown their reluctance to contribute to the implementation process by stating their concern regarding their job security since automation often could result in reduction in the labor force.

At this point I know that not investing in a new technology is not an option, since inaction will result in losing our market share to the competitors. Thus, to make the right decision I need to be able to analyze the impact of the potential benefits as well as the risks associated with the implementation of each of the three technology candidates. Such an analysis along with the result of the economic evaluation that has already been performed will help me make the right decision.

Now that the decision maker's problem is stated, the proposed model is applied to solve the president's dilemma. Application of the proposed methodology is illustrated through the following steps:

1. Identification of the risk and benefit categories

This step is accomplished through an elicitation and calibration procedure. A master list of the benefit and risk categories associated with technology adoption is presented to the decision maker (president of the company). The purpose is to make this decision maker aware of the potential benefits and risks associated with his decision of implementing a new technology. The decision maker is then instructed to review the list of the risk and benefit categories and identify the categories that he feels are pertinent to the situation at hand. Using the input from the decision maker, the list is narrowed down to include only the benefits/risks that are considered relevant. A sample calibration procedure for the benefit category is illustrated in Table 2. Table 3 illustrates such process for the risk category.

2. Determination of the relative importance of cost and benefit categories

This step is accomplished through an elicitation procedure. A pair-wise comparison matrix is developed for the benefit categories considered to be relevant by the decision maker. The decision maker is asked to state the importance of each criterion relative to other criteria. For example, if the decision maker believes benefit "reduced defect rate" is three times more important than benefit "decreased safety hazard," then 3 is entered in the first row (reduced defect rate) and second column (decreased safety hazard) of the matrix in Table 4. The rest of the entries are determined in a similar fashion. Table 4 illustrates the complete pair-wise comparison matrix for all the pertinent benefit categories.

Table 6 Decision maker's perception of technologies' performance with respect to benefit categories

Technology	Benefit category					
	Reduced defect rate (%)	Decreased safety hazards (%)	Reduced scrap and rework (%)	Reduced cycle time (%)	Reduced lead time (%)	Increased market share (%)
FMC	90	65	94	65	75	92
AMHS	85	72	96	70	80	90
AS/AR	92	70	90	65	75	94

Table 7 Decision maker's perception of technologies' performance with respect to risk categories

Technology	Risk category		
	Incompatibility with current operations (%)	Obsolescence due to poor timing of implementation (%)	Not completing the implementation (%)
FMC	4	8	4
AMHS	2	6	7
AS/AR	4	7	8

The priorities listed in Table 4 represent the relative importance of each benefit category to the decision maker. These priorities are calculated using the procedure suggested by Saaty [57]:

$$w_j = \frac{\sum_{j=1}^{j}\left(\frac{a_{jk}}{\sum_{k=1}^{k} a_{jk}}\right)}{k}$$

where w_j is the weight of element j, k is index number of columns, and j is index number of rows.

Of course, the consistency of judgments used in pair-wise comparisons is very important. Decisions should not be based on judgments with such low consistency that they appear to be random. The AHP measures the overall consistency of judgments by means of consistency ratio (CR). The value of the consistency ratio should be 10 % or less (5 % for a 3×3 matrix, 9 % for a 4×4 matrix, and 10 % for a larger matrix). If the value is larger than 10 %, the judgments may be somewhat random and must be revised [57]. The CR is calculated as CR=CI/RI, where CI is the consistency index and RI is the average random consistency index.

$CI=(\lambda_{max}-n)/n-1$ where λ_{max} is the maximum eigenvalue of the matrix and n is the size of the matrix. RI is obtained from the experience data provided by Saaty [57]. The values for various matrix sizes (n) are shown below:

n	1	2	3	4	5	6	7	8	9	10
RI	0.0	0.0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

For the matrix illustrated in Table 4, the consistency ratio is calculated as follows:

$$CI = (6.03 - 6) / 5 = 0.006$$
$$RI = 1.25$$

Thus, CR=CI/RI=0.006/1.25=0.05 which is less than 10 % indicating the consistency of the judgments.

To determine the relative importance of the risk categories, a pair-wise comparison matrix is developed and local priorities and consistency ratio are calculated in a similar manner. Table 5 illustrates the completed matrix along with the priorities and consistency ratio.

3. Determining performance of technology alternatives with respect to risk and benefit categories

This step is accomplished by eliciting decision maker's perception of technologies' performances. The decision maker is asked to state his perception of the delivery of the benefits/risks by each of the three technology alternatives. The decision maker bases such judgments on the historical data, reputation of the technology brand, and the specifics of the situation at hand. For instance, the decision maker might believe that possibility of reaping the benefit "decreased safety hazards" by implementing FMC technology is 65 % while this possibility is 70 % for AS/AR technology. The decision maker's perceptions of performance of the three technologies with respect to all the benefit and risk categories are elicited. The results are summarized in Tables 6 and 7.

4. Development of a mechanism to quantitatively measure technologies' performances with respect to the risk and benefit categories

Table 8 Taguchi parameters for the pertinent benefit categories

Benefit category	Target value (%)	Range (%)	Specification limit for the deviation (%)	Loss coefficient (k)	Taguchi loss function
Reduced defect rate	100	100–80	20	2,500	$L(X)$=2,500 $(X-T)^2$
Decreased safety hazards	100	100–50	50	400	$L(X)$=400 $(X-T)^2$
Reduced scrap and rework	100	100–90	10	10,000	$L(X)$=10,000 $(X-T)^2$
Reduced cycle time	100	100–60	40	625	$L(X)$=625 $(X-T)^2$
Reduced lead time	100	100–70	30	1,111.11	$L(X)$=1,111.11$(X-T)^2$
Increased market share	100	100–90	10	10,000	$L(X)$=10,000 $(X-T)^2$

Table 9 Taguchi parameters for the pertinent risk categories

Risk category	Target value (%)	Range (%)	Deviation specification limit (%)	Loss coefficient (k)	Taguchi loss function
Incompatibility with current operations	0	0–5	5	40,000	$L(Y)=40,000\ (Y-T)^2$
Obsolescence due to poor timing of implementation	0	0–10	10	10,000	$L(Y)=10,000\ (Y-T)^2$
Not completing the implementation	0	0–8	8	15,625	$L(Y)=15,625\ (Y-T)^2$

This step is accomplished by calculating Taguchi parameters for the benefit and cost categories. For each benefit and cost category, the decision maker identifies the target values and specification limits for the acceptable deviation from the target. The loss coefficients (k) are calculated based on these values, and the loss functions are formed accordingly. For example, 100 % possibility of receiving the benefit "reduced defect rate" as a result of technology implementation is the target value. The decision maker sets the minimum acceptable performance level at 80 % which means the maximum allowable deviation from the target is 20 %. The loss coefficient k for this benefit category is calculated as $k=100/(0.20)^2=2,500$. The loss coefficients for the rest of the benefit categories are calculated in the same manner.

The loss coefficient for each risk category can also be calculated based on the target value and the specification limit for that category. For example, zero percent possibility of "obsolescence due to poor timing" is the target value for this risk category. The decision maker sets the maximum acceptable level at 10 %. The loss coefficient k for this risk category is calculated as $k=100/(0.10)^2=10,000$. The loss coefficients for the rest of the risk categories are calculated in the same manner. The target values, specification limits, loss coefficients, and loss functions for the benefit categories are illustrated in Table 8. Table 9 summarizes these parameters and the loss functions for the risk categories.

5. Determining the rankings of the technology alternatives

This step is completed by calculating individual loss scores and composite loss scores for the technology alternatives. Individual loss scores for each technology are calculated using the loss functions from previous step and the performance levels from step 3. For example, the loss function for benefit category "reduced defect rate" is $L(X)=2,500(X-T)^2$ as indicated in Table 8. FMC technology's performance level with respect to "reduced defect rate" is 90 % as indicated in Table 6. Thus, FMC's loss score for this benefit category is calculated as $2,500\times(0.10)^2=25$. The loss scores for the rest of the benefit categories for FMC are calculated in the same manner. The weights (relative importance) of the benefit categories obtained in step 2 are then used to determine the weighted loss score for FMC. The weighted loss scores for the other two technologies are calculated using the same procedure. The technologies' individual and weighted loss scores for the risk categories are determined in the same manner by applying the loss functions for the risk categories. The individual loss scores, weights, and the weighted loss scores for the three technologies are shown in Table 10 for the benefit categories. Table 11 illustrates this information for the risk categories.

Calculation of the composite loss scores and rankings of the technology alternatives To allow the ranking of the three technology alternatives, one composite loss score is needed for each technology. The average of the weighted scores for the benefit and cost categories is used to determine the single composite loss score for each technology. The technologies are then ranked according to these composite loss sores. The technology with the smallest loss score is assigned the highest priority and is selected for implementation. The weighted loss scores, the composite loss scores, and technologies' rankings are summarized in Table 12.

Table 10 Individual and weighted loss scores for the benefit categories

Technology	Benefit category												
	Reduced defect rate		Decreased safety hazards		Reduced scrap and rework		Reduced cycle time		Reduced lead time		Increased market share		Weighted score
	Weight	Loss	Weight	Loss	Weight	Loss	Weight	Loss	Weight	Loss	Weight	Loss	
FMC	0.1941	25	0.2476	49	0.1468	36	0.0486	76.56	0.1586	69.44	0.2044	64	50.0853
AMHS	0.1941	56.25	0.2476	31.36	0.1468	16	0.0486	56.25	0.1586	44.44	0.2044	100	51.2536
AS/AR	0.1941	.16	0.2476	36	0.1468	100	0.0486	76.56	0.1586	69.44	0.2044	36	48.7916

Table 11 Individual and weighted loss scores for the risk categories

Technology	Risk category						
	Incompatibility with current operations		Obsolescence due to poor timing of implementation		Not completing the implementation		Weighted score
	Weight	Loss	Weight	Loss	Weight	Loss	
FMC	0.1069	64	0.6383	64	0.2548	25	54.0628
AMHS	0.1069	16	0.6383	36	0.2548	76.56	44.1967
AS/AR	0.1069	64	0.6383	49	0.2548	100	63.5983

As can be seen from Table 12, AMHS has received the highest ranking (minimum average weighted loss score) and thus will be selected for adoption. The decision maker believes that AMHS is the best technology when considering the impacts of all benefit and cost categories that are important to him.

5 Conclusions and suggestions for future research

A decision model is developed to help decision makers evaluate and select the appropriate technology for adoption. Although investing in a new technology provides certain benefits for the company, it carries with it several risks as well. The proposed decision model is an attempt to consider all aspects of such investment in the evaluation process. To accomplish this task, first all the benefit and risk categories associated with technology adoption are identified. The importance of each category along with the decision maker's perception of each technology's performance with respect to these categories is elicited. AHP methodology is used to determine the relative importance of each category while Taguchi loss function is applied in order to quantitatively measure the technology's performance. The individual loss scores for each benefit/cost category are calculated. The weighted and composite loss scores are then determined and used for rankings of the technology alternatives. The technology with the lowest composite loss score is selected for adoption.

The strength of the model is twofold: First, it provides a comprehensive list of various risks and benefits associated with a technology adoption. In addition, it provides a systematic approach for quantifying the intangible risks and benefits. The use of the proposed model improves the quality of the evaluation process. The managers no longer have to guess the potential risks and benefits of investing in a new technology and/or come up with a list of their own each time a decision needs to be made. These managers can consult the comprehensive list of the risk/benefit categories provided in the model and customize the list to fit their specific situation. The model also has the capability of quantifying the intangible risks and benefits of technology adoption. As a result, all factors are objectively considered in the evaluation process which adds to the validity of the decision. In addition, since the model provides a systematic approach for quantitative measurement of the intangible factors, the mangers are relieved from haphazardly determining the values of the intangibles. These unique features of the model provide the managers with a powerful tool for making appropriate decisions regarding their investment in advanced technologies.

Table 12 Technologies' composite loss scores and rankings

Technology	Weighted loss score (benefit categories)	Weighted loss score (risk categories)	Average weighted loss score	Technology ranking
FMC	50.0853	54.0628	52.074	2
AMHS	51.2536	44.1967	47.725	1
AS/AR	48.7916	63.5983	56.195	3

However, the proposed model is not without limitations. The pair-wise comparisons of the criteria require decision maker's knowledge of the company, its operations, and internal structure. Even so, the bias of the decision maker toward particular criteria can influence the result of the decision. To avoid this, group decisions are recommended for pair-wise comparisons. For situations with large number of decision factors, clusters, and alternatives, the task of conducting all necessary pair-wise comparisons is quite demanding. In addition, the model is heavily dependent on the weightings provided by the decision maker. As a result, the accuracy of the judgments provided by the decision maker is very crucial. However, consistency checks can be conducted to increase the decision quality.

Several opportunities for future research are identified. First, it is recommended that the proposed model be implemented into a software or Internet-based tool. This will allow the calculation of loss scores for the technology alternatives to be done internally with minimum input from the user of the tool. Also the application of AHP methodology for determining the relative importance of the risk and benefit categories can be done more efficiently. In addition, such an implementation allows the tool to be easily accessible to the decision makers who wish to use the tool.

Second, the list of benefits and risk categories used in the development of the model can be enriched by seeking feedback from experts in the field. The list used in this study is based on the currently available literature. It is recommended to enhance this list by designing and sending out appropriate surveys to the experts in the field. Those involved in the technology investment decisions on a regular basis definitely can add their real-world experiences to the academic findings. This would provide additional support for the validity of inclusion of the benefit and risk categories in the analysis. The software mentioned above could be made so that it can be easily modified for changes in the benefit and risk categories.

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