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MANAGING RISK AND UNCERTAINTY IN MACHINE REPLACEMENT DECISIONS USING REAL OPTIONS ANALYSIS AND MONTE CARLO SIMULATION

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Abstract:
The present research discusses the application of risk management tools and Real Option Analysis (ROA) to assess and quantify managerial flexibility in machine replacement decisions under uncertain conditions. Different management configurations are used for the real options approach: options to execute, options to delay, and options to cancel. This reflects the uncertainty inherent to each stage of planning. Uncertainties such as future demand and life-cycle costs are implemented in the model as probability distributions. Monte Carlo simulation is employed to deal with such uncertainties and to facilitate experimental trials. The net present value is used as a decision criterion to determine the best replacement option under different replacement and real option scenarios. Herein, a case study to evaluate different replacement alternatives was conducted for the garment industry. Results of the stochastic net present value, mean-standard-deviation scatter plot, and stochastic dominance showed that the best option was to rent and then buy a new machine of reduced size but greater technological advancement. Finally, tornado diagrams and perfect control methods were used to analyze uncertain factors in order to improve the model and further minimize uncertainty effects.

Key words: *machine replacement, Monte Carlo simulation, Real Option Analysis, risk management*

INTRODUCTION

Asset management refers to the coordinated activities of identifying, developing, maintaining, acquiring, reviewing, and disposing of assets in order to achieve a specific level of service in the most effective manner [1, 2, 3]. Asset management is usually used to maximize asset efficiency while minimizing risk and life-cycle costs [4, 5, 6, 7]. Among the primary goals of applying asset management is to help managers decide when it is suitable to maintain or replace an asset in order to enhance work performance and productivity [8]. Using the same equipment for a long period time is often not feasible due to reduced machine availability, increased operating and maintenance costs, and increased risk of accidents. Adopting new machine at appropriate time can therefore reduce these barriers and increase organizational productivity, efficiency and, ultimately, financial returns [9, 10]. In spite of these benefits, machine replacement decisions are often constrained by requirements and uncertainties, including expected future demand, investment costs, lifecycle operating and maintenance costs, technology, salvage value, and useful life. Successful replacement decisions require an understanding of these requirements and uncertainties, their relative importance, associated risks, and how potential alternatives may be evaluated in order to assure the best choice [4, 7, 11, 12, 13].

This paper aims to model different machine replacement scenarios and analyze potential sources of risk and uncertainty by applying Real Option Analysis (ROA) aided by Monte Carlo simulation (MCS). ROA has been proposed as a useful uncertainty management technique that enables decision makers to assure satisfactory investment decisions in real situations. ROA adds a variable time into the analysis using different options, such as the decision to invest, defer or wait, expand, or abandon. These options can be applied at any stage during the lifetime of a project [14]. Determining the most appropriate machine replacement scenario is undertaken using financial indicators. Risk and uncertainty management methods are used to minimize risk and yield higher returns.

LITERATURE REVIEW

Machines are replaced for many reasons, including deterioration, obsolescence, inadequacy, and safety. Machine deterioration refers to a decline in the performance of a machine due to wear and tear. Common signs of machine deterioration include an increase in maintenance and labor costs, degradation in productivity and quality, and an increase in the duration and frequency of breakdowns.

Obsolescence means that the machine has become outdated due to technology advancements. Inadequacy means that the expected demand has not been met by the machine [15].

Previous research has investigated asset management and asset replacement decisions in numerous sectors. For example, Zambujal-Oliveira and Duque [16] studied the optimal moment for the replacement of assets by developing a two-factor model including operation and maintenance costs and salvage value. Brownian processing was used to model uncertainty. Mardin and Arai [17] evaluated replacement and overhaul policies on capital assets subject to technological changes. They concluded that the best action to extend the useful life of an asset is to combine overhaul actions with the adoption of improved technology. Rishardson et al. [12] studied the optimal order placement strategy in the mining industry for equipment with long and uncertain delivery lead times. Managing these uncertainties in terms of real options including the optimum replacement over an infinite time horizon used cost–rate evolution based on Brownian methods. Abdi and Taghipour [18] developed a repair/replacement decision model based on economic and environmental factors; this involved the development of an initial deterministic model which was then mapped on to a probabilistic Bayesian structure. Reindorp & Fu [19] used real option analysis and capital renewal to balance future profitability and uncertainty for obsolete subsystems with a complex infrastructure.

A dynamic theoretical model using numerical analysis was developed by Stutzman, Weiland, Preckel, and Wetzstein [20] for the optimal renewal and/or replacement of an asset under real option analysis. Soleimani, Alizadeh, and Moallem [21] studied the replacement of old and low-efficiency induction motors under different economic scenarios using the payback period method. Yazdandoost et al. [7] used an asset management approach to optimize life cycle cost (LCC) and determine the impact of water meter failure risks on utility' revenues and, thereby, to estimate their remaining useful lifetimes. Abbaspour and Maghaminik [22] used decision tree algorithms based on expected benefits (productivity of equipment) and costs (repair and maintenance of equipment) in the context of mining applications as a means to decide whether to replace or keep using equipment through their lifespan. Shah [23] aimed to increase earnings from lathe machines by determining the minimum average cost of their operation. The optimal replacement policy is defined by balancing the cost of operating and maintaining old machines. A combination of traditional LCC and MCS was developed by Macián, Tormos, and Riechi [24] to identify the appropriate replacement time of transportation fleets. A cost analysis model depending on age, mileage driven, and unit cost per mile was developed for each vehicle as a means to assess their useful life. Xu and Cao [25] developed an optimal replacement time model for cutting tools in order to define a balance amongst product quality loss, production capacity loss, and tool replacement cost. Replacement decisions have been also studied in many other fields, including transport management, the oil and gas industry, and urban infrastructure [26, 27, 28, 29]. Although extensive and valuable research has been carried out regarding the machine replacement problem, a holistic decision support model to manage risk and uncertainty is still lacking. In this study, risk and uncertainty management tools are used in a structured approach to complement stochastic economic analysis to define new and improved potential replacement solutions.

RISK AND UNCERTAINTY MANAGEMENT

Uncertainty refers to the lack of exact knowledge about present or future conditions and events, whereas risk is a measurable outcome of uncertainty in which the chances of occurrence and impact can be predicted and measured [30]. Risk and uncertainty management involves the identification and assessment of sources of risk and uncertainty, followed by the definition of appropriate actions to manage such risks, using approaches such as avoidance, mitigation, transfer, or acceptance [31, 32]. Different methods and tools are used to manage risk and uncertainty, such as brainstorming, root cause analysis, decision trees, ROA, MCS, and scenario planning, as well as sensitivity analysis tools such as tornado diagrams [33]. These methods can be used to complement decision analysis such that new potential solutions emerge. Two methods are used in the present research, ROA and MCS. These are described in the following paragraphs.

ROA has been proposed as a useful uncertainty management technique aiding decision makers to assess investment in real situations, such as healthcare, energy, maintenance, supply chain, and machine replacement [34, 35, 36, 37]. Traditional methods to evaluate investments, such as net present value (NPV), endorse an investment project if its expected returns exceed the cost of its capital. However, traditional approaches do not promote inclusive investment decisions when projects are burdened with degrees of uncertainty that demand financial flexibility. Real options enable managers to enumerate the rewards and risks of multiple strategies under uncertain conditions, thereby taking appropriate action. Managers may immediately exercise the option to execute and undertake investment, or may elect to delay their investment by allowing postponement. During this time, managers collect more data and clarify their assessment of future markets, demand, and prices [38], relying on overtime shifts or subcontractors to meet increased demand during the interim period. They may also exercise options to allow management to withdraw at any point during the investment, retaining the current production capacity if expenditures become excessive or demand falters [38]. In addition, they may exercise options to abandon and end a project even if it is already underway, there by preserving its salvage value if returns fall dramatically beneath targets.

MCS is a computer simulation technique that constructs probability distributions of possible outcomes by using a computer to generate a chance process, running this process many times, and then observing the results.

Probability distributions of outcomes allow decision-makers to quantitatively assess the level of risk accompanying a particular decision and, as a result, to select the decision that provides the best balance of benefit against risk [39]. MCS is used to study the impact of different risks and uncertainty factors on project cost, maintenance, forecasting and replacement [40, 41]. MCS is widely used in diverse fields, such as manufacturing [42], materials science [43], material handling [44], renewable energy [45], mining [46], safety [47], travel [48], and vehicle routing problems [49], among others.

PROPOSED METHODOLOGY

The proposed methodology to manage risk and uncertainty in machine replacement decisions consists of five steps. The first step involves forecasting future probabilistic demands that incorporate potential uncertainties. The second step generates machine replacement alternatives using the ROA model, thereby introducing more flexibility for evaluating realistic replacement scenarios. The third step estimates cash flows and financial indicators. The fourth step evaluates machine replacement alternatives, taking anticipated uncertainties into consideration. Probabilistic NPV decision criteria, cash flow analysis, and MCS are used in this step. Finally, uncertainty management tools are used to identify and evaluate improvement opportunities.

Step One: Forecast Future Demand

Demand forecasting is the first step in any capital investment project. Reliable forecasting of demand allows for more efficient and responsive business planning and decision-making. In machine replacement decisions, expected probabilistic demand is modeled as a probability distribution that best fits the demand profile and associated uncertainties, and results in a comprehensive predictive value. Probabilistic forecasting can differentiate changes in variability over time and enable a proper assessment of the shape and size of uncertainties around the forecast. Demand forecasting follows four steps:

1. Setting the objective:

In this step, the objective of the forecasting and the factors that may influence the process are clearly specified. This takes into consideration the types of products produced by the machine, its level of competition and technology, the time period of the forecast, and expected future prices.

2. Selecting the appropriate method of forecasting:

According to the forecasting purpose, as well as the type and availability of data required, the expected type and amount of uncertainty, and the timeframe, an appropriate forecasting method is selected. Several methods exist for demand forecasting. These can be classified into two categories: i) judgmental forecasting, which depends on managers' and experts' opinions and customer surveys, and ii) statistical methods, such as regression and time series approaches. Selecting the appropriate method is necessary in order to reduce cost and time and to achieve adequate levels of accuracy. These methods are used primarily as the basis of discussion, and then to communicate uncertainties when baseline forecasts are revised to determine the probability distribution.

3. Collecting and adjusting data:

In this step, required data, such as past sales and demand, seasonality, promotions, and market forces are collected through examining past records, questionnaires, interviews, observations, and sales trend analyses. These collected data may need to be manipulated and adjusted in order to assure consistency with the required data format.

4. Estimating the results:

After the forecasting method is finalized and the required data are collected, the final step in this phase involves estimating the incremental stochastic demand over a predefined forecasting period. This demand probability distribution represents a projection of future processes and can be used as an input to estimate both expected cash flow and the financial implications of various machine replacement scenarios.

Step Two: Generate Machine Replacement Alternatives

In this step, a range of potential machine replacement alternatives is generated. Decision makers should identify all feasible alternative choices before beginning to conduct their analysis and evaluation. The identified alternatives constitute the basis for subsequent analysis and evaluation, and ultimately the decision itself. Possible replacement alternatives are illustrated in the tree diagram shown in Figure 1. This diagram branches out from a starting point, with each branch representing a different replacement option, followed by ROA to address uncertainties and to evaluate real investment scenarios.

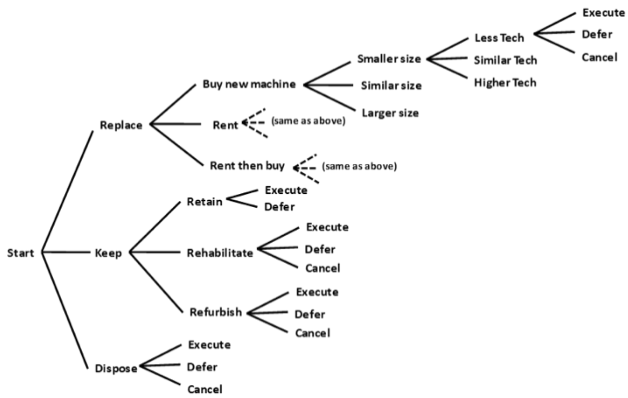

Fig. 1 Tree diagram for machine replacement lternatives and real options

There are essentially three options. The first is to directly replace the machine. This can be achieved either by purchasing a new machine, renting a substitute machine, or renting a substitute machine for some period of time before buying a new one. All of these options can be employed either with similar, higher, or lesser capacity and technology. Generally, machines are considered for replacement due to a number of reasons, including deterioration, obsolescence, safety, or an inability to meet production requirements. The second option is to keep the machine with three possible actions: (1) retain the machine during the planning horizon and continue with a scheduled maintenance program, (2) rehabilitate the machine by replacing damaged and worn parts, aligning machine components, and identifying and correcting machine faults, thereby restoring the machine to an acceptable or normal operational condition, or (3) refurbish the machine by replacing and modernizing its main components so as to restore it to its original manufactured state, or by upgrading the machine with new technology. Refurbishment typically addresses every component of the machine and is usually accomplished *via* downtime. Keep options will extend the production life of the machine with less capital investment compared with replacement options, but its maintenance and rebuild costs will increase. The third option is to dispose of the machine. A machine is generally considered for disposal without replacement when it no longer supports current needs, or when product sales are declining over an extended period of time and a significant downturn in revenue occurs. Such situations can arise due to a number of reasons, such as market saturation, customers switching to a different type of product, or a downturn in product demand. The disposal option gives the opportunity for the organization to cut investments if market conditions deteriorate.

Herein, ROA is applied to the machine replacement decision in order to investigate and evaluate a wide spectrum of replacement opportunities and to actively manage uncertainties and reduce risks. ROA introduces a more realistic capital budgeting method that estimates a flexibility value when making future choices; traditional net present value methods do not take this flexibility into account. When making machine replacement decision, real options include the decision to execute, defer, or abandon a replacement scenario. The option to execute examines the probabilistic uncertain environment *via* immediate execution of a replacement alternative. It is valid for each generated replacement alternative until the end of a predetermined planning period. The option to defer incorporates a delay of one year or more before the execution of a replacement alternative. The keep and retain alternative is executed and continues until the delay time has passed, at which time the deferred alternative is executed immediately. This option is used to postpone the initiation of an investment or replacement decision, allowing further details about the machine condition and performance to be collected; this potentially enables an improved comprehension of future market situations [38] and the identification of a greater number of uncertainties. The option to cancel allows the management to cancel any step of the alternative and adopt a state of keep and retain. This enables management to hold the investment for any planning period. However, since this option considers lost revenues due to alternative approaches opportunity costs can be considered when evaluating the expected NPV for each alternative.

Step Three: Estimate Cash Flows and Financial Indicators

In this step, financial indicators and cash flows are estimated for each replacement alternative. Financial indicators include revenue, investment cost, direct material cost, operational cost, and NPV. Such indicators are necessary for evaluating replacement alternatives and promoting the best scenario. Only future incremental cash flows are considered during machine replacement decisions. Past expenditures, such as the initial cost of the machine are irrelevant.

Estimate the incremental revenue

Incremental revenue denotes the expected future revenue generated by an existing or new machine. It is calculated by multiplying the selling price by the minimum value between an uncertain demand and production capacity and considers that such estimations are conducted at the end of each year (t) during the planning horizon [50]. Equation (1) calculates the incremental revenue (R_t) generated from expected product sales:

$$R_t = \sum_{n=1}^{N} \left(min \left(D_{t,n}, PC_{t,n} \right) \cdot p_{t,n} \right) \tag{1}$$

where:

R_t – the annual revenue generated in year t from all products;

$D_{t,n}$ and $PC_{t,n}$ – demand and production capacity during year t for product n;

$P_{t,n}$ – sale price of product n during year t.

Estimate investment cost

Investment cost is defined as the initial expenditure related to the amount of money that must be invested in acquiring new machines for replacement, rebuilding existing machines for rehabilitation, and refurbishment options. This includes the purchase price of new machines or spare and main parts for existing machines, as well as administration and engineering, installation and set-up, and training. Investment cost (IC_t) at year t can be calculated using equation (2) [50]:

$$IC_t = AC_t + LP_t \tag{2}$$

where:

AC_t – machinery acquisition or rebuild costs for year t;

LP_t – lost profit for year t.

Investment cost is irreversible and differs between replacement alternatives. If sold, the machine would not return the same value.

Estimate direct material cost

Material cost depends on production, which is affected by uncertainties in demand. It represents the cost of raw materials and parts used to create the product, which can be determined from production schedules. It includes all transportation and delivery costs [50,51]. Equation (3) describes the direct material cost (DMC_t) for all products produced by a machine during year t:

$$DMC_t = \sum_{n=1}^{N} \left(min \left(D_{t,n}, PC_{t,n} \right) \cdot W_n \cdot MP_{t,n} \right) \tag{3}$$

where:

$D_{t,n}$ and $PC_{t,n}$ – demand and production capacity during year t for product n;

W_n – weight per unit of product n;

$MP_{t,n}$ – material price per unit weight of product n during year t.

Material costs depend on the minimum amount between demand $D_{n,i}$ and production capacity $PC_{n,i}$ Consequently, if demand exceeds production capacity, it cannot be met. On the other hand, if a larger quantity of a product can be produced relative to its demand, the cost of idle capacity will increase, since only the demand is capable of generating revenues.

Estimate annual operating costs

Operating costs include all expenses associated with operating and maintaining an existing or new machine. They include labor costs, energy costs, deprecation, poor quality costs, lost production, and repair and maintenance costs, as detailed in the following.

1. Annual labor cost

Annual labor costs depend on the number of workers required to operate the machine. Equation (4) indicates the calculation of labor cost (LC_t) during year t [50]:

$$LC_t = WN_t \cdot WS_t \cdot (1 + IN_t) \quad (4)$$

where:

WN_t – number of workers required for a new machine in year t;

WS_t – annual salary (including benefits) for workers operating machine n;

IN_t – annual salary increase (percentage).

Note that labor cost is affected by the percentage of annual salary fixed increase rate (IN_t).

2. Annual energy cost

The annual energy cost for each machine type is calculated by multiplying its expected annual production by the unit standard time, energy consumption rate, and projected energy prices. Equation (5) is used to calculate the total annual energy costs (EC_t) of an existing or new machine [50]:

$$EC_t = \sum_{n=1}^{N}(min\left(D_{t,n}, PC_{t,n}\right) \cdot S_{t,n} \cdot ECO_{t,n} \cdot EP_t) \quad (5)$$

where:

$D_{t,n}$, $PC_{t,n}$ – as defined above;

$S_{t,n}$ – standard time per unit of product n produced during year t (hr);

$ECO_{t,n}$ – energy consumed per machining hour of product n during year t (kW/h);

EP_t – price of energy per kilowatt consumed during year t ($/kW).

3. Annual repair & maintenance costs

Repair and maintenance costs refer to the expenses incurred to keep an existing or new machine in good working condition and to extend its service life. Repair and maintenance costs depend on the type and scale of operations, processing conditions, and the type of equipment used, and always increases with time as the machine ages. Such costs include the cost of materials used in maintenance tasks, such as lubricants, regular spare parts, labor/repairman costs, and costs arising from unscheduled breakdowns and downtime [51, 52]. These costs should be estimated carefully for each year during the planning horizon of each replacement alternative. Numerous sources can be used to obtain fairly accurate estimates, such as historical maintenance data, condition monitoring records, operations and maintenance manual, maintenance instructions, standard maintenance procedures, best practices, and handbooks.

4. Annual depreciation cost

Depreciation cost denotes the amount removed from the purchase price of a fixed asset over its useful life. It reflects the fact that assets lose their value over time, and reduces the amount of tax. If depreciation is spread over fewer years, the depreciation amount is increased and tax reduced [51]. Equation (6) is used to calculate the annual depreciation cost (DEP_t) for a replacement alternative:

$$DEP_t = (IV - SV)/LS \quad (6)$$

where:

IV – investment value of the existing machine ($);

SV – salvage value of the existing machine ($);

LS – lifespan of the existing machine (years).

Note that for a rental option, no depreciation cost is applied because the company does not own the machine.

Estimate machine terminal value

Machine terminal value (salvage value) includes the value of the machine at the end of the planning horizon or at the moment of its replacement. It is represented as a cash inflow and can be expressed as a specific amount or percentage of the original price. Operations and purchasing departments can estimate this value from experience, trade publications, "blue-book"-type references, or used equipment brokers [53].

Estimate net cash flow

NPV indicates the discounted difference between incremental cash inflow and outflow over the project planning horizon. NPV summarizes all investment cash flows as a single value. Future cash flows must be discounted because money in the present is worth more than the same amount in the future due to inflation and earnings from alternative investments that could be made during the intervening time period. The discounted cash flow formula is given in equation (7). MCS is used to generate stochastic NPV based on a large number of simulated values from the probability distributions of uncertain inputs [50].

$$NPV = \sum_{t=1}^{T}((R_t + TV_t - IC_t - DMC_t - OC_t) \cdot (1 + Tax_t) + DEP_t)/(1+r)^t \quad (7)$$

where:

t – year index;

R_t, IC_t, DMC_t, DEP_t – as defined above;

TV_t – machine terminal value at year t;

OC_t – operating costs, including labor, energy, maintenance, and overheads at year t;

Tax_t – predefined tax on net cash flow at year t.

r – risk neutral discount rate.

Step Four: Evaluation of Machine Replacement Alternative

During this phase, stochastic NPV is used as a decision criterion to evaluate and rank competing machine replacement alternatives. Replacement options are generally associated with higher investment costs but lower maintenance, operating, poor quality, and downtime costs. On the other hand, keep options are generally associated with lower investment costs but higher maintenance and operating costs. Therefore, it is necessary to select the optimum solution that maximizes NPV and minimizes risk and uncertainties. The spread of probability distributions is often used to measure risk associated with a given investment option. In this regard, mean-standard deviation scatter plots are initially used to screen out inferior alternatives. Therefore, the stochastic dominance approach compares and promotes preferred machine replacement alternatives amongst superior alternatives.

Step Five: Use Uncertainty Management Tools to Identify and Evaluate Improvement Opportunities

This step includes the investigation of options to reduce uncertainty and associated risks and the opportunities to improve prefered machine replacement alternatives are investigated as a means to guide the decision making process and enhance both the financial return and firm value. This step can be subdivided into the following substeps [54, 55]:

1. Identify sources of uncertainty

In this substep, input factors that may contribute to uncertainty infinancial returns and NPVs are investigated and identified. Sources of uncertainty may include volatile demand, sale price, operating and maintenance costs, rebuild costs, raw material costs, and salvage values.

2. Estimate the effect of perfect control

This substep exmines the resulting changes in terms of the probability distribution of stochastic NPVs for the preferred alternative due to fully controlling input factors that are assumed to be uncertain. This can be achieved by changing each uncertain quantity to its most favorable value while assuming that other quantities remain uncertain, after which the degree to which this change would improve the NPV is evaluated. The results of this step provide helpful information regarding critical input factors that should direct research efforts toward improved probability distributions and reduced uncertainty.

3. Identify and evaluate improvement opportunities

Based on the results of the previous substep, possible actions and opportunities to reduce the extent of risk and improve the prefered alternative are investigated and evaluated. Data collection and analysis tools, such as creative thinking and brainstorming, are used to explore and generate improvement ideas. The probability distributions for costs and revenues are re-estimated in the light of these feasible changes and a new model is simulated using the revised inputs and results in order to promote the preferred replacement alternative. Additionally, suggestions and ideas to reduce risk and improve returns are considered.

CASE STUDY

This section demonstrates the application of the proposed methodology at a garment industry company located in north Jordan. The company name is concealed to protect the confidentiality of their financial data; we instead use “The Alpha company” in place of their real name.

Step One: Forecasting Future Demand

Historical data were used to forecast future demand over the next ten years, taking into consideration expected trends, seasonality, and promotions that can influence the forecasting method, as well as judgment modifications to account for uncertainties. Different time series forecasting methods were evaluated using measures of forecast error. The most appropriate forecast method was found to be trend-adjusted exponential smoothing using smoothing parameters of $\alpha = 0.9$ and $\beta = 0.9$. This forecasting model was used to forecast the most likely demand trajectory over the planning horizon. To account for uncertainties, interviews were conducted with the company manager and salesperson as a means of collecting data about expected trends, seasonality, and promotions, as well as other types of uncertainties. Based on these findings, uncertain future demands over the planning period were represented by a triangular probability density function. This distribution is simple to construct because it requires the determination of only three parameters: minimum, most likely, and maximum.

Step Two: Generating Potential Machine Replacement Alternatives

During this step, feasible machine replacement alternatives are investigated and generated as shown in Figure 1. Each of these alternatives has a direct effect on machine ownership costs, namely fixed, variable, direct, and indirect costs. Some replacement alternatives were not available in this specific case, for example buying or renting a machine with higher capacity and buying a new machine with less advanced technology. Three real options were examined: execute, defer, and cancel. Options to execute were applied to assess the immediate execution of machine replacement alternatives under an uncertain environment. Options to defer were applied to postpone the replacement alternatives for two, four, six, or eight years. Options to cancel were used to keep and retain the machine without replacing or rebuilding.

Step Three: Financial Indicators and Cash Flow Estimations

Future incremental revenues, investment costs, direct and indirect operational costs, and net cash flows for each replacement alternative were calculated using the equations outlined before. The annual revenues for each product along the planning horizon were calculated by multiplying the minimum value between demand and production capacity by the selling price, which is assumed to have an annual increase rate of two percent. The investment costs for replacement options with different capacity, technology, and real options were calculated using equation (2). The machine purchase price was fixed for each executing action and decreased for each year when applying deferment actions. No investment cost was applied for rental options, and the training costs required for more technologically advanced machine were set at higher values than those of lesser and similarly technologically developed machines.

Direct material costs depend on two uncertain factors: production volume and raw material prices. The raw materials processed by the case study machine are sewing thread and embroidery papers with initial purchase prices of $0.33, and $0.267 per meter respectively. Raw material prices are estimated to increase annually by one percent.

Annual operating costs include labor, maintenance, energy, administrative, and depreciation costs. Labor costs depend on the machinery installed. The existing knitting machine requires two workers, whereas a smaller machine requires only one and a larger machine needs three workers. Annual salaries were assumed to increase by five percent. Energy costs depend on uncertain demands and production volumes and both the expected energy consumed per hour, which is expected to increase by nineteen percent annually, and the price of energy per unit consumed, which is expected to increase by seven percent annually. Maintenance and repair costs were estimated for each replacement alternative separately based on expected needs for preventive and breakdown maintenance.

Finally, with the aid of MCS, the stochastic estimates of cash inflows and outflows were combined with a discount rate of ten percent in order to calculate the NPV for each replacement alternative. MCS was carried out over 10,000 runs using Model-Risk software. Tables 1 and 2 show the mean and standard deviations of the NPV for different machine replacement alternatives.

Table 1
Expected NPVs for different replacement alternatives

Replacement options	Size	Technology	Real Options	NPV ($)	
				Mean	SD
Buy	Larger	Same	Execute	13,802,426	206,364
			Defer (2)	13,821,068	202,319
			Defer (4)	13,834,393	207,178
			Defer (6)	13,845,477	207,468
			Defer (8)	13,813,117	211,941
	Same	Higher	Execute	13,858,966	205,026
			Defer (2)	13,866,103	196,020
			Defer (4)	13,864,036	207,653
			Defer (6)	13,876,153	208,450
			Defer (8)	13,820,464	209,512
	Same	Same	Execute	13,874,620	211,299
			Defer (2)	13,885,925	209,573
			Defer (4)	13,869,076	211,602
			Defer (6)	13,865,658	204,815
			Defer (8)	13,796,790	203,827
	Smaller	Higher	Execute	13,848,268	209,107
			Defer (2)	13,851,085	203,235
			Defer (4)	13,848,501	206,493
			Defer (6)	13,847,469	208,361
			Defer (8)	13,850,086	204,811
	Smaller	Same	Execute	13,805,333	211,559
			Defer (2)	13,814,947	209,332
			Defer (4)	13,805,195	213,200
			Defer (6)	13,811,791	205,744
			Defer (8)	13,812,263	205,160
Rent	Same	Higher	Execute	13,964,180	202,629
			Defer (2)	13,949,326	209,388
			Defer (4)	13,952,648	200,471
			Defer (6)	13,944,268	206,183
			Defer (8)	13,799,695	197,875
	Same	Lower	Execute	13,958,698	203,136
			Defer (2)	13,952,593	209,309
			Defer (4)	13,962,325	206,354
			Defer (6)	13,930,535	201,918
			Defer (8)	13,796,800	206,627
	Same	Same	Execute	13,959,125	202,975
			Defer (2)	13,949,380	203,747
			Defer (4)	13,964,055	209,028
			Defer (6)	13,953,117	215,765
			Defer (8)	13,950,136	207,539
	Smaller	Higher	Execute	13,967,863	210,542
			Defer (2)	13,975,592	215,903

			Defer (4)	13,961,310	212,360
			Defer (6)	13,949,196	210,923
			Defer (8)	13,959,397	217,206
	Smaller	Lower	Execute	13,967,729	204,668
			Defer (2)	13,967,232	212,066
			Defer (4)	13,964,838	207,832
			Defer (6)	13,958,722	205,320
			Defer (8)	13,945,715	202,081
	Smaller	Same	Execute	13,973,922	212,450
			Defer (2)	13,958,181	202,490
			Defer (4)	13,951,150	200,837
			Defer (6)	13,957,800	210,434
			Defer (8)	13,791,216	208,283
Rent Then Buy	Same	Higher	Execute	13,948,616	207,790
			Defer (2)	13,955,902	206,447
			Defer (4)	13,948,744	206,941
			Defer (6)	13,948,658	211,252
			Defer (8)	13,796,486	209,357
	Same	Same	Execute	13,940,489	208,827
			Defer (2)	13,953,970	209,508
			Defer (4)	13,949,017	210,489
			Defer (6)	13,945,255	210,817
			Defer (8)	13,946,150	210,103
	Smaller	Lower	Execute	13,949,512	207,521
			Defer (2)	13,962,010	204,465
			Defer (4)	13,950,697	207,332
			Defer (6)	13,954,843	205,287
			Defer (8)	13,954,957	199,325
	Smaller	Same	Execute	13,949,713	214,093
			Defer (2)	13,959,326	203,278
			Defer (4)	13,954,372	208,389
			Defer (6)	13,948,378	208,070
			Defer (8)	13,790,249	203,950
	Smaller	Higher	Execute	13,953,483	197,958
			Defer (2)	13,946,468	203,813
			Defer (4)	13,951,914	212,203
			Defer (6)	13,947,590	214,050
			Defer (8)	13,954,356	215,259

Table 2

Expected NPVs for different keep or dispose alternatives

Keep/Dispose Options	Real Options	NPV ($)	
		Mean	SD
Retain	Execute	13,337,114	219,773
	Defer (2)	13,210,650	202,187
	Defer (4)	13,367,266	197,482
	Defer (6)	13,298,493	212,037
	Defer (8)	13,126,306	207,572
Rehabilitate	Execute	13,231,185	207,314
	Defer (2)	13,351,649	209,738
	Defer (4)	13,366,588	206,248
	Defer (6)	13,385,270	204,765
	Defer (8)	13,291,027	198,483
Refurbish	Execute	13,955,009	206,665
	Defer (2)	13,349,502	213,991
	Defer (4)	13,353,386	210,758
	Defer (6)	13,360,141	208,175
	Defer (8)	13,354,200	206,775
Dispose	Execute	0	0
	Defer (2)	214,914	669
	Defer (4)	216,875	584
	Defer (6)	219,792	329
	Defer (8)	223,103	2,058

Step Four: Evaluating Machine Replacement Alternatives

NPVs are represented by probability distributions; therefore, stochastic methods to evaluate and compare alternatives were employed at this stage. Mean-standard deviation scatter plots were used to determine the options with the highest expected monetary value (mean) and lowest expected risk (standard deviation). The stochastic dominance approach was used to evaluate the monetary value of different investment scenarios under uncertain environments by plotting the cumulative probability distribution functions (CDF) of stochastic NPVs. The option with the rightward-most CDF is assumed to be stochastically dominant or superior over the other options because it gives the highest NPV at any cumulative probability value. The results were then divided among three machine replacement options: replace, keep, or dispose.

Replacement options

Figure 2 shows the mean-standard deviation scatter plot for replacement options. Points positioned furthest to the lower right corner represent the best candidate alternatives with the highest NPV means and lowest standard deviations.

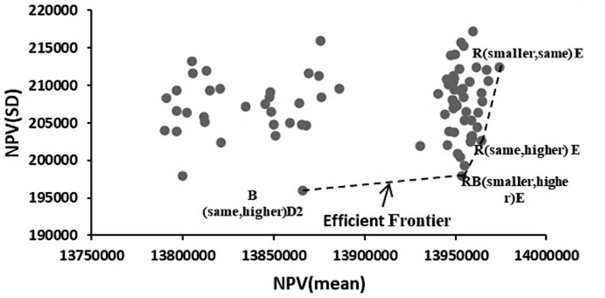

Fig. 2 NPV mean-standard deviation scatter plot for replacement alternatives

The efficient frontier options are i) a two-year deferral before buying a new machine of the same size but higher technology, ii) the execution option involving renting then buying a new machine with a smaller size but higher technology, iii) the execution option of renting a machine with the same size but higher technology, and iv) the execution option of renting a machine with a smaller size and higher technology.

These four efficient frontier alternatives were further evaluated using a stochastic dominance approach as shown in Figure 3.

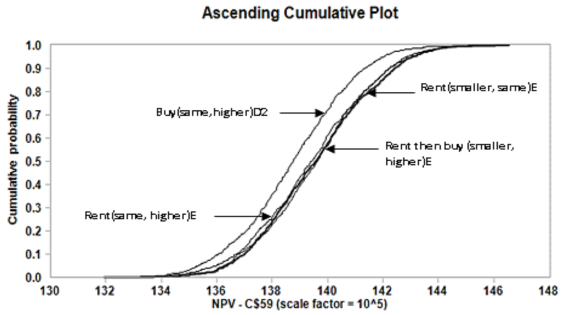

Fig. 3 Stochastic dominance for replacement alternatives

Although the three alternatives showed comparable results, the execution option of renting then buying a new machine with a smaller size and higher technology was found to slightly outperform the other options.

Keeping options

Figure 4 shows the mean-standard deviation scatter plot for keeping options.

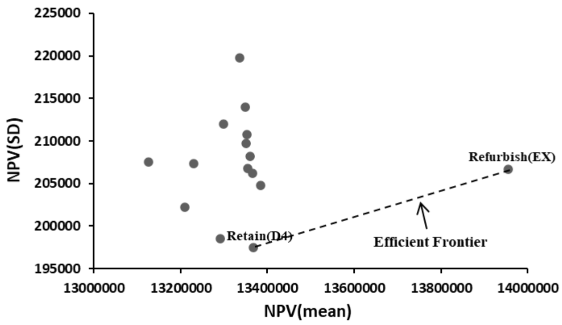

Fig. 4 NPV mean-standard deviation scatter plot for keeping alternatives

The efficient frontier options are i) a four-year deferral during which the existing machine is retained, and ii) the execution option of refurbishing the machine. Refurbishment has higher mean than retention, but this option is also characterized by a higher standard deviation.

Therefore, to determine the better option, stochastic dominance was used as shown in Figure 5, clearly showing that the refurbishment option exhibits stochastic dominance over the retention option.

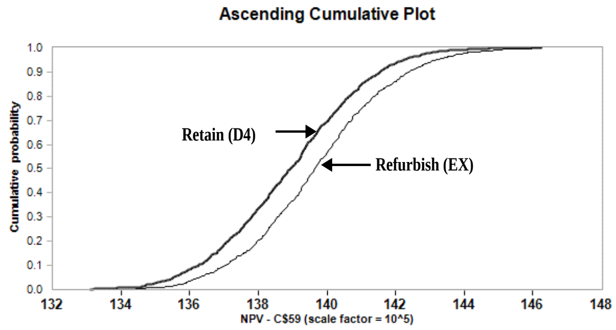

Fig. 5 The stochastic dominance results for keeping alternatives

Disposing options

Figure 6 shows the mean-standard deviation scatter plot for disposal options. It is clear that a six-year deferment option before disposing the existing machine without replacement has the highest mean and least standard deviation.

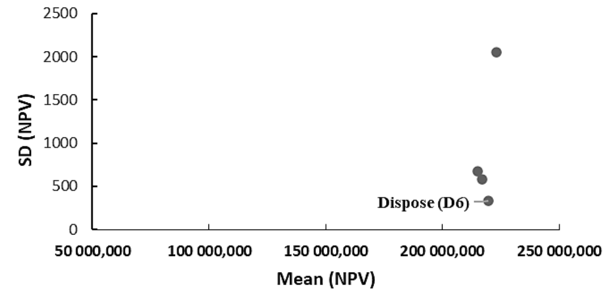

Fig. 6 NPV mean-standard deviation scatter plot for disposing alternatives

There is no need in this case to apply the stochastic dominance approach.

Comparing the results of all replacement options

Figure 7 shows the mean-standard deviation scatter plot for the pre-chosen options from all replacement scenarios.

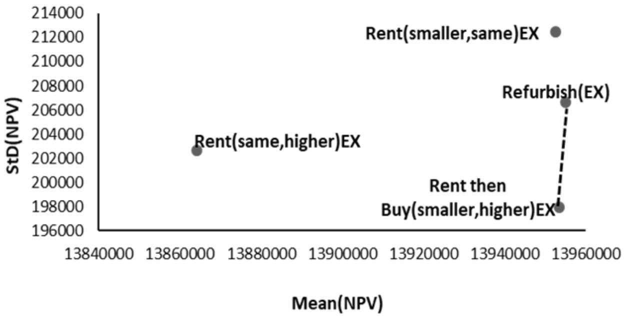

Fig. 7 NPV mean-standard deviation scatter plot for the candidate alternatives

The best alternative is the execution option of renting then buying a new machine of smaller size but higher technology followed by the execution option of refurbishing the machine. The disposal option was excluded because it provided insignificant NPV results relative to other options.

Step Five: Using Uncertainty Management Tools to Identify and Evaluate Improvements Opportinities

Risk and uncertianty management tools were employed to identify and evaluate areas in whichrisk associated with the preferred alternative might be reduced and financial return enhanced. The following subsections elaborate the details of this process.

1. Calculate the effect of perfect contol

In this step, a tornado diagram was used to identify the most critical input factors that should be addressed in order to reduce risk and uncertainty. Input factors were varied between their lowest and highest possible values, whereas all other factors were held at their most likely values. A tornado diagram for the rent then buy option with immediate execution is shown in Figure 8.

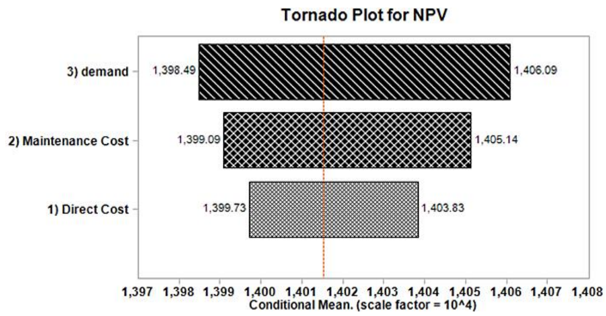

Fig. 8 Tornado diagram for rent then buy (execute) option

Note that only the most influential uncertain values are shown on the diagram. In this case, variations in demand areassociated with major variations in NPV followed by maintenance cost. Direct cost appears to be less important.

2. Use ideas generating techniques to create actions to improve the preferred options

Brainstorming sessions were held to create and evaluate actions that would potentially reduce risks and identify opportunities. Table 3 shows the initial list of feasible ideas. These ideas were investigated and evaluated in order to establish whether they are realistic and to estimate their expected benefits and costs.

The following portfolio of actions was chosen by management for further evaluation in terms of effects on risk reduction and the improvement of expected returns: enhance the demand forecasting methods, reduce the percentage of defective components, choose a qualified outsourced maintenance company, and train machine operators on minor repairs and adjustments. Consequently, the probability distributions of input factors were re-estimated taking into consideration the application of the suggested portfolio of improvements, and a new model was simulated. These simulation results revealed an increase of $66,237 over current expected NPV, and an increase in the lowest possible NPV from $13,480,000 to $13,560,000 during the planning horizon. Figure 9 shows the new and old cumulative probability distributions of NPV for the preferred alternative, i.e., the execution option of renting then buying a new machine of smaller size but higher technology.

Table 3

Ideas for risk and uncertainty management to improve the best alternative

Uncertain Factor	Ideas for Uncertainty Management	Reference
Demand	Enhance the demand forecasting methods by collecting more information at points of sale and conducting market research	The Author
	Use buffering and dampening techniques (safety stock and safety lead time)	[56]
	Integrate and collaborate with suppliers and customers to improve demand chain management	[57]
	Collect data about competitors	The Author
	Reduce percentage of defective components	[54]
Maintenance Costs	Use computerized maintenance management systems to schedule preventive maintenance	The Author
	Apply inventory control systems on the spare parts inventory	The Author
	Choose a qualified outsourced maintenance company	The Author
	Train machine operators in performing minor repairs and adjustments	[58]
	Choose a supplier with warranties and an insurance period	[58]
Direct Cost	Control material cost by reducing waste and packaging material	[54]
	Choose alternative suppliers for raw materials	
	Control labor costs by tracking productivity	
	Train operators on new equipment	
	Create efficient work spaces and processes	
	Construct standard times for each process in order to specify the real time needed for each	

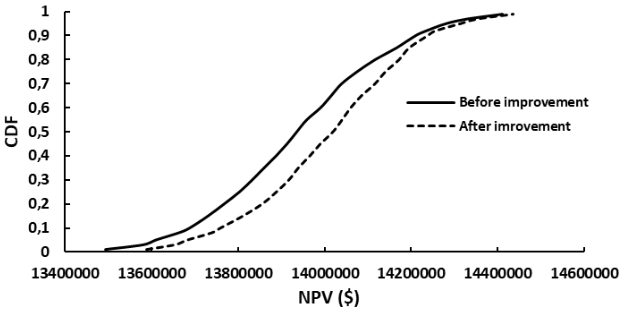

Fig. 9 The effectiveness of risk management actions for the immediate execution of the rent then buy option

It can be seen that the effect of applying risk management is to push the bulk of the distribution to the right. This means that any given NPV after applying these actions has a higher probability of being achieved. These results indicate the benefit of applying risk management strategies as described herein.

CONCLUSIONS

This research outlines and demonstrates a structured approach for managing risk and uncertainty in machine replacement decisions using ROA and MCS. Our conclusions are as follows:

- The ROA model provides more managerial flexibility than traditional capital budgeting methods in terms of evaluating realistic machine replacement alternatives. Enabling managers to enumerate the rewards, costs, and risks of multiple investment scenarios under uncertainty leads to actionable insights and a deeper understanding of the available options, which in turn reduces the associated risk and improves the quality of the final solution.
- When managers have cause to consider replacement, equipment needs to be evaluated in order to determine whether its replacement is economically viable. Economic analysis is required to determine the point at which replacement is justified. To help the manager make a decision, stochastic NPV is used as a decision criterion. MCS assists in introducing the expected uncertainties into the system as a probability distribution. Mean-standard deviation and stochastic dominance were also used to examine the superiority of one distribution over another in order to promote the best choice.
- Perfect control and tornado diagram methods were used to provide guidance on whether it was worth devoting effort to improve the probabilities of uncertain factors and to help indicate where the best opportunities for uncertainty management were likely to be.
- In a case study of garment production, the preferable replacement alternatives offer attractive results in reducing risks and enhancing financial returns, regardless of the uncertainties considered.

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