A Real Options Analysis of Automatic Milking Systems

Phoebe D. Engel and Jeffrey Hyde

Automatic, or robotic, milking systems have the potential to significantly change the way milk is produced on U.S. dairy farms. However, there is a high degree of uncertainty associated with adoption of this new technology. A real options approach is used to analyze the decision to replace an operational milking system with an automatic milking system. The most important source of uncertainty is shown to be the length of the technology's useful life. Under our assumptions, the automatic system is always an optimal investment if it is certain that it will last longer than the operational system being replaced.

Key Words: automatic milking system, capital budgeting, net present value, real options, robotic milking system

The technology of milking dairy cows has changed a great deal over time, from hand milking (still used in many less-developed regions) to highly automated milking parlors. In the 1980s, Dutch researchers began work to develop a milking system that would require no human assistance to prep a cow (clean and stimulate her teats and udder) and milk her (Lind et al., 2000). These systems have become known as robotic, or automatic, milking systems (AMSs).

The first AMS unit was installed on a commercial dairy farm in the Netherlands in 1992 (van der Vorst and Hogeveen, 2000). The technology has subsequently been adopted in Europe, Japan, Canada, and some other countries. AMS adoption has been slow in the United States, however. As of March 2002, only five commercial U.S. farms and one university farm had installed an AMS (Reinemann, 2002). These have been installed on a provisional basis while the United States works to specify milk quality-related regulations, as current regulations do not apply directly to the AMS (Dersam and Price, 2003).

The most obvious benefit of using an AMS is that it reduces the amount of labor required to milk the cows. For some farmers, this may mean they hire less labor after installing an AMS. For others, it may mean the farm manager now has additional time to devote to other farm enterprises and to management tasks. These are important considerations, particularly for small-scale operators. Other important costs and benefits include increased capital investment, increased milk production and feed cost, and possibly a shorter useful life relative to a traditional milking system (denoted TMS).[1]

Some previous work has been conducted to analyze the decision of whether or not to invest in an AMS or a TMS. These earlier studies implicitly assume the farmer must choose one or the other at the time the decision is made. To date, no analysis has examined the issue of replacing an operational milking system with an AMS. The objective of this research is to estimate the effect of uncertainty and irreversibility on the decision to replace an existing TMS with an AMS. A real options approach is employed to examine this issue.

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[1] Throughout this analysis, we compare the AMS to possible alternative milking systems, such as milking parlors and stanchion (or "tie-stall") systems, collectively referred to as traditional milking systems (TMSs). Thus, we assume the costs and benefits of the AMS are equal relative to all of these systems. While one could argue this assumption is incorrect, we address potential changes related to milk production, purchase price of the TMS, or labor costs with a TMS in the sensitivity analyses. Therefore, this assumption is necessary for the analysis to be tractable and widely applicable.

AMS Literature Review

A review of existing literature related to economic analysis of AMS adoption reveals relatively little work has been done to investigate investment in this technology. The work that has been published draws primarily on traditional capital budgeting methods of analyzing investments, such as net present value (NPV) analysis. This section highlights the most closely related AMS investment research. The following section discusses real options valuation and briefly addresses how real options approaches have been utilized in empirical applications.

Parsons (1988) used a discrete simulation cost-benefit approach to assess the potential impact an AMS would have on traditional British dairy farms. By the author's own admission, the results of his research are not currently relevant because the technology has advanced considerably since the study was published. However, the model described in Parsons' paper was later used to examine the timing and frequency of milking in an AMS to compare farm costs and income to production in a conventional parlor system (Cooper and Parsons, 1999). In the later study, findings show profitability with an AMS increases as the amount of time the system is in use approaches 24 hours a day (i.e., as it nears full capacity). Also, the AMS is found to be economically competitive with a milking parlor when there is no grazing and when milk quota prices are low. The existence of a milk quota system is shown to significantly alter the results from what they would be under a market-based milk pricing system because the producer must pay for the right to produce additional milk in the AMS.

Armstrong et al. (1992) showed that large-scale adoption of AMS units (e.g., up to 1,500 milking cows) is not economically viable when compared to an efficient milk parlor system. Like Parsons (1988), however, the assumptions made in that analysis do not necessarily hold relative to current AMS units. For example, Armstrong et al. assume that one unit could accommodate 20 milking cows, compared to a figure of 60 cows reported by Cooper and Parsons (1999). Armstrong et al. also used an NPV approach in their analysis.

A slightly more rigorous economic analysis of AMS investment compares an AMS to a milking parlor on farms with 125 cows (Dijkhuizen et al., 1997). A capital budgeting framework is employed to analyze the choice of whether to purchase an AMS or a milking parlor. The authors calculate the NPV of a parlor system, convert the NPV to an annuity equivalent, and then solve for the AMS purchase price which will result in an annuity equivalent equal to that of the parlor. The resulting purchase price is referred to as the breakeven value.

Under the assumptions of Dijkhuizen et al., a farmer in the United States could afford to spend up to \$175,000 on an AMS. If the AMS cost is less than this amount, then the farmer should purchase an AMS rather than a milking parlor. To place this result in perspective, the current price for two AMS units (the appropriate number for 125 cows) is approximately \$250,000. Thus, the authors' results would indicate that the breakeven AMS investment cost is less than the purchase price, and therefore the farmer should purchase a parlor or other milking system to milk 125 cows.

A later study by Hyde and Engel (2002) used a similar analytical framework with the incorporation of Monte Carlo simulation to estimate distributions of breakeven values given alternative specifications of distributions associated with some of the input variables (e.g., useful life of the parlor and AMS, and change in production with AMS adoption). Based on their findings, the mean breakeven cost for a U.S. dairy farmer was slightly greater than the cost of investing in the equipment. However, the variability of breakeven values was quite high.

Both Dijkhuizen et al. (1997) and Hyde and Engel (2002) look at the decision to invest in a parlor versus an AMS at a given point in time. The decision to replace an existing parlor with an AMS is not considered. These earlier studies also do not directly take into account the effect that the variability of returns (uncertainty) and sunk costs (irreversibility) associated with investment may have on the decision.

Real Options Analysis

Real options exist only under three conditions associated with a given decision: (*a*) the decision maker must be able to postpone the choice for some period of time, (*b*) the outcome of the decision must be uncertain, and (*c*) there must be sunk costs. Thus, a real option exists when a decision maker is able to wait until some uncertainty is resolved before making a decision which will result in the permanent loss of capital. If one or more of these characteristics are not present, then the decision maker does not hold a real option and the decision cannot be analyzed within a real options framework.

As with an option on a financial asset, the holder of a real option has the right, but not the obligation, to buy or sell the capital asset at some point in the future. In the present context, the decision maker has the right, but not the obligation, to purchase an AMS in the future if he or she decides to forego investment in the current period. In the AMS case, the option holder observes new information about the technology, such as how long it may last or what impacts it might have on production, labor costs, or other factors affecting investment returns. Based on the addition of information, the farmer can make a decision at a later time.

Real options approaches have been widely used to analyze a number of different types of options. Both Trigeorgis (1996) and Brach (2003) note there are many different types of options that may exist for businesses. Some examples include options to defer investment in a project or to abandon a project (notions based on early work by McDonald and Siegel, 1986), to switch or change the firm's mode of operation, to expand or to contract production, or to make incremental investments.

Lander and Pinches (1998) offer a review of the empirical literature on real options analyses. Real options approaches have also been applied to various facets of agricultural production, including investment in free-stall dairy barns (Purvis et al., 1995), investment in hog production (Balmann and Mu§hoff, 2002), precision technology adoption (Isik, 2001), adoption of conservation tillage (Kurkalova, Kling, and Zhao, 2001), agribusiness entry-exit decisions and capacity choice (Isik et al., 2002), investment in new generation cooperatives (Sporleder and Bailey, 2001), and biotechnology research and development (Lavoie and Sheldon, 2000).

If the decision maker does, in fact, hold a real option, then there is a value of waiting to make a decision and a value to making the decision now. The relationship between the value of investing now and the value of waiting to invest is illustrated graphically in figure 1. The horizontal axis represents the annualized returns from investing (R) when the investment is assumed to be renewed at the same cost into perpetuity.[2] The vertical axis represents the value of the decision (V), whether the decision is to invest now or to wait to invest.

The straight diagonal line $i_1 i_2$, whose mathematical representation is (R/ρ) !K, represents the value of investing now. Its vertical intercept is !K, where K is the initial sunk cost of the investment, and its slope is $1/\rho$, where ρ is the discount rate. When the investment generates no annualized returns (i.e., $R = 0$), the investor loses K. This line crosses the horizontal axis at $R = M$, where M is the level of R that drives the investment's NPV to zero. Thus, if returns are greater than M, investment is attractive under an NPV rule. (M is referred to as the "Marshallian trigger.")

The curve $w_1 w_2$ in figure 1 represents the value of waiting to invest. The mathematical representation of this curve is BR^{β}, where B is a constant and β is a function of the discount rate and the variability of investment returns, as described below. [The interested reader is encouraged to see Dixit (1992) for a discussion of B.] The convex shape of $w_1 w_2$ indicates that the value of waiting increases with R at an increasing rate.

Two points in figure 1 are of particular interest. First, point H, the optimal investment trigger value when accounting for irreversibility and uncertainty, occurs at a tangency between $i_1 i_2$ and $w_1 w_2$. Referred to as the "smooth pasting" condition (Dixit and Pindyck, 1994), this ensures investment is optimal when the marginal value of waiting equals the marginal value of investing. Dixit (1992) argues there is no value in waiting to invest when R is greater than H, and thus points along $w_1 w_2$ to the right of H represent a "speculative bubble." The value of investing and waiting to invest at point H is denoted as h.

It should also be noted that $w_1 w_2$ passes through the origin, indicating the option value associated with this investment is equal to zero when R is zero. For any R greater than zero, the value of waiting to invest is positive. Specifically, there is always value to waiting because a later decision, which may incorporate new information, may be a better one.

Traditional capital budgeting approaches cannot objectively account for irreversibility and uncertainty associated with investment. Barry et al. (2000) point out that risk can be incorporated into a capital budgeting framework in one of three ways: (*a*) by adding a "risk premium" to the discount rate, (*b*) by using a risk-free discount rate and adjusting the cash flows under a certainty equivalent approach, or (*c*) by "probability analysis" in which the decision maker uses a risk-free discount rate to obtain a

[2] The notion of perpetually renewing the investment, which has implications for incorporating inflation, for example, is an artifact of Dixit's (1992) model. In the method used here, we are only truly concerned with the current price and what it may be one year from now. Where we have a solid basis for including inflation or a price trend (e.g., labor and feed cost), we do so. In the case of K, the AMS purchase price, it is possible it will move up or down within the year. Because we have no basis for assuming one or the other, or for specifying a distribution of changes in the price of K, we assume it to be constant over the year.

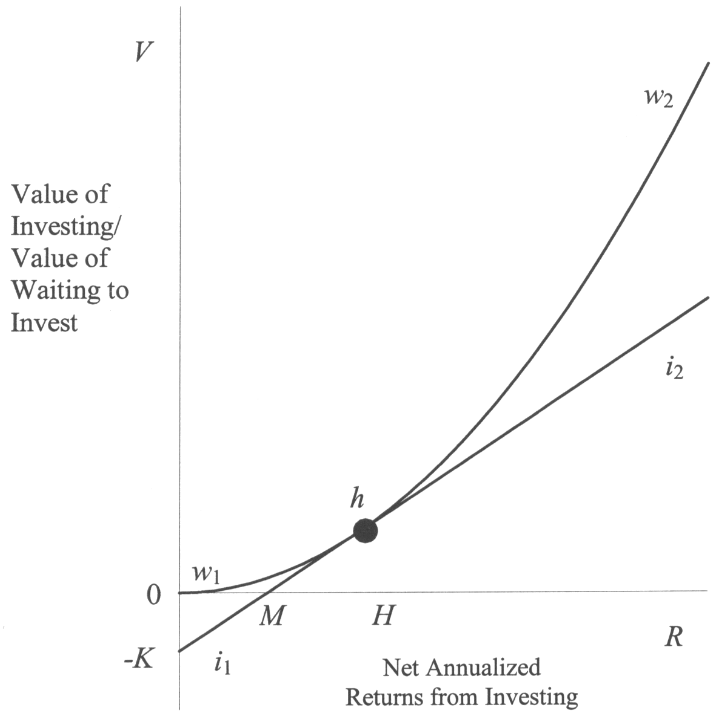

Figure 1. Graphical representation of real options analysis

distribution of possible outcomes, then basing the decision on the moments of the distribution.

The first two approaches are rather subjective methods of incorporating risk, based on the perceptions of the decision maker. Probability analysis may be used, but requires some method of obtaining the distribution of outcomes. This approach may be either sensitivity analysis or Monte Carlo simulation. Using this approach, the decision is still based on the subjective risk preferences of the decision maker as he or she trades off expected returns against the variability of those returns. Thus, an investment analysis approach which incorporates risk in an objective fashion would be superior to the approaches described by Barry et al. (2000). The real options approach employed here is one such method.

A real options approach allows the analyst to simulate the cash flows associated with AMS investment and then use the variability of discounted net cash flows to develop a modified discount rate and an associated modified hurdle rate, *H*. If the simulated annualized net cash flow exceeds *H*, then the real options decision rule suggests investment is warranted.

Methodology

Dixit (1992) shows that β, the exponent in the equation representing the value of waiting, can be described mathematically as follows:

$$(1) \qquad \beta = \frac{1}{2}\left[1 + \sqrt{1 + \frac{8\rho}{\sigma^2}}\right],$$

where ρ is the discount rate and σ^2 is the variance of returns. Recall that the Marshallian investment trigger ($M = \rho K$) is not the appropriate investment return trigger level under conditions of irreversibility and uncertainty. Thus, Dixit proposes a modified investment return trigger level, *H*, which is equal to $\rho' K$, where ρ' is defined as:

$$(2) \qquad \rho' = \left(\frac{\beta}{\beta - 1}\right)\rho.$$

The empirical method used here is designed to provide an estimate of σ^2, which can then be used to find the modified investment trigger level of returns, *H*. By comparing the expected value of the investment returns (also obtained through Monte Carlo simulation) to M and H, we are able to determine whether investment should proceed under either an NPV or a real options criterion.

Under the assumption that investment returns follow geometric Brownian motion,[3] Purvis et al. (1995) show the variability of returns can be approximated by using the variance of $\Delta\ln(V_n) = \ln(V_n) - \ln(V_{n-1})$, where V_n is defined as follows:

$$(3) \qquad V_n = \frac{\left[\dfrac{\rho}{1 - \left(\dfrac{1}{(1+\rho)^T} \right)} PV_n \right]}{\rho}.$$

Here, V_n is a perpetuity, which assumes the decision maker can reinvest in the project at the end of its useful life at the same cost, K. PV_n represents the present value of the project if investment occurs at time n, where n indexes the age of the TMS. This present value does not include K and considers only the useful life span of the investment, indexed by $t = 1$ to T. The numerator of equation (3) represents the annuity equivalent of PV_n, while dividing by the discount rate yields the value of the project into perpetuity.

The cash flows, or net benefit, in each period of the investment's life are defined in equation (4):

$$(4) \qquad NB_t = Benefits_{AMS,t} - Costs_{AMS,t} + Costs_{TMS,t} - Benefits_{TMS,t}.$$

Because the problem involves the replacement of the current milking system, the net benefit in period t of the AMS' life is a function of the lost benefits from the TMS (representing an opportunity cost of AMS investment) and the avoided costs associated with the TMS' operation. Therefore, this represents a partial budgeting model. We will show that the benefit of avoiding reinvestment in the TMS over the life of the AMS is important in an AMS adoption decision.

The method used here can be summarized as follows.

1. One partial capital budget is developed for each potential age of the existing TMS. Each of these provides a measure of PV_n given that investment in the AMS occurs and the TMS is n years old.
2. We use @Risk, a Monte Carlo simulation add-in to Microsoft Excel, to simulate 5,000 potential realizations of PV_n, and thus V_n.
3. We calculate $\Delta\ln(V_n)$ in each of the 5,000 Monte Carlo iterations and then measure the variance of $\Delta\ln(V_n)$ over the simulated outcomes.
4. Once the variance of $\Delta\ln(V_n)$ is calculated, we are able to calculate β, ρ', and H, as shown above.
5. The decision of whether to adopt now or wait to decide is made by comparing the expected investment returns (i.e., the mean of the distribution of PV_n) to M under an NPV criterion, or H under a real options criterion.

This method is primarily designed to provide a measure of the current uncertainty associated with AMS adoption. The model does not incorporate a means by which uncertainty is resolved. However, the results do point out the important factors underlying the uncertainty of investment returns. These are the critical factors farmers should analyze over time if waiting to make the decision to invest in an AMS.

Data

The simulation model requires many variables and parameters to be specified. Tables 1 and 2 provide a description of the stochastic input variable distributions and parameters used in the model. Here, we discuss how these were incorporated into the simulation model. It is important to note that we analyze a 60-cow herd, requiring one AMS unit, in the base case.

- *Production.* Production in the AMS relative to the TMS is based upon the assumption that the farmer milks twice daily (2X) in the TMS and up to 3X in the AMS. Erdman and Varner (1995) showed that increasing from 2X to 3X results in an increase in production of about seven to eight pounds per cow per day. Therefore, eight pounds represents the maximum value. Because some farmers have seen no increase in production in the AMS, despite increased milking frequency, we set the lower bound to no change (Rodenburg, 2001–2002). We specify a uniform distribution

[3] The assumption that V follows geometric Brownian motion is consistent with both Dixit (1992) and Purvis et al. (1995). This imposes several attractive properties on V (Dixit and Pindyck, 1994). First, the current value is known and future values are lognormally distributed—i.e., they follow a continuous-time random walk. Second, as long as the initial value of V is positive, future values will always be positive. Third, the variance of the forecast of V grows linearly as one expands the time horizon associated with the forecast. As we model the change in V from the current period to one year hence, it must follow a geometric Brownian motion.

Table 1. Base Case Variable Distributions

Variable	Unit	Distribution[a]	Notes/Data Sources
Production in AMS relative to TMS	lbs./cow/day	Uniform (0, 8)	Observation is multiplied by 305 days milking and by number of cows; one observation drawn per iteration (Erdman and Varner, 1995)
TMS milk price	$/cwt	*N* (base milk price, $1.15)	One observation drawn each year per iteration (USDA/NASS, 2001b)
AMS milk price	$/cwt	TMS milk price *T* ($0.99, $1.00, $1.01)	Distribution values based on percentages of milk price; one observation drawn per iteration (Dijkhuizen et al., 1997; van der Vorst and de Koning, 2002; van der Vorst and Hogeveen, 2000)
AMS labor cost	$/year	TMS labor cost *T* ($0.31, $0.67, $0.90)	Distribution values based on percentages of TMS labor; one observation drawn per iteration (Dijkhuizen et al., 1997; Arts, 2001; Grant, 2002)
Labor inflation	%	*T* (3.88%, 4.95%, 5.57%)	One observation drawn each year per iteration (USDA/NASS, 2001a)
Feed cost change	$/cwt	*N* ($0.16, $0.54)	One observation drawn each year per iteration (USDA/ERS, 2001)
Useful life of AMS	years	*T* (9, 12, 15)	One observation drawn per iteration (Kamps, 2001; Geleynse, 2001–2002)

Source: Adapted from Engel (2002).

[a] *T* denotes a triangular distribution (minimum, mode, maximum); *N* denotes a normal distribution (mean, standard deviation).

Table 2. Base Case Parameters

Parameter	Unit	Value	Notes/Data Sources
Base milk price	$/cwt	$14.94	Based on all milk PA monthly data for 1996–2001 (USDA/NASS, 2001b)
TMS labor cost	$/year	$10,000	Approximately equal to $9.70/hour (Rogers, 2001) times 3 hours/day (Stup, 2001) times 365 days
Base feed cost	$/cwt	$7.38	Based on cost of production data for PA, NY, and VT dairy farms from 1980–2000 (USDA/ERS, 2001)
Useful life of TMS	years	15	Based on broad interaction with equipment industry personnel
TMS purchase cost	$	$90,000	Based on double-4 herringbone parlor at $10,000 to $12,000/stall (McFarland, 2001)
AMS purchase cost	$/unit	$150,000	(Kamps, 2002; Geleynse, 2001–2002)
Herd size	cows	60	Assumed capacity of a single-stall AMS unit (Hyde and Engel, 2002)
Total TMS maintenance cost	% of purchase cost	45%	Based on 3% per year over a 15-year life (Dijkhuizen et al., 1997)
Base annual TMS maintenance cost	$ in year one	$337.50	Grows linearly such that total cost over 15 years equals 45% of purchase cost
AMS maintenance cost	$/year	$1,800	Based on least expensive warranty plan offered by Lely Industries (Kamps, 2002)
Salvage value	% of purchase cost	2.5%	(Dijkhuizen et al., 1997)
Depreciation period	years	7	Standard depreciation period for farm machinery (Barry et al., 2000)
Discount rate	%	8%	(Dijkhuizen et al., 1997)
Milk price inflation	%	0.2%	Based on yearly all milk PA data (USDA/NASS, 2001b)
Average tax rate	%	30.5%	(Canning and Tsigas, 2000)

Source: Adapted from Engel (2002).

because we lack data to specify a potentially more accurate one. A 2% increase in milk production per cow per year in both the AMS and the TMS is also included (Hyde and Dunn, 2002).

- *Milk Price.* The price received for milk produced in a TMS is normally distributed with a mean equal to the base milk price ($14.94 in year zero of the investment and inflated by 0.2% per year thereafter) and standard deviation of $1.15, which represents the average deviation from the price trend between 1996 and 2001 [U.S. Department of Agriculture/National Agricultural Statistics Service (USDA/NASS), 2001b]. In each iteration, the price for milk produced in the AMS ranges from a minimum of 99% of the TMS-produced milk price to a maximum of 101%, with the most likely value of 100%. This reflects small potential increases or decreases in milk price due to changes in milk quality with the AMS.

- *Labor Costs.* The assumed cost of labor to milk 60 cows is $10,000 per year (Rogers, 2001; Stup, 2001). We specify a triangular distribution for labor cost inflation with minimum, mode, and maximum of 3.88%, 4.95%, and 5.57% per year (USDA/NASS, 2001a). The reduced labor demand in the AMS is highly variable. We specify a triangular distribution (31%, 67%, and 90%) for the percentage of TMS labor remaining employed after AMS adoption (Dijkhuizen et al., 1997; Arts, 2001; Grant, 2002).

- *Feed Costs.* The base feed cost is $7.38 per hundredweight (cwt) of milk produced (USDA/ Economic Research Service, 2001). Therefore, the increase in feed costs associated with AMS adoption is a function of the increased milk production resulting from the new technology. To determine the change in feed costs from year to year, we fit a trend line to the time series of prices used. The slope of that trend line is $0.16, and the average deviation from the trend line is $0.54. Subsequently, we specify a normal distribution with mean of $0.16 and standard deviation of $0.54 to reflect the change in feed costs.

- *Maintenance Costs.* Following Dijkhuizen et al. (1997), we specify the total maintenance expenses for the TMS to be equal to 45% of its purchase price. Maintenance costs grow linearly such that year one's cost is $337.50, year two's is $675, and so on. (This is based upon a TMS purchase price of $90,000.) For the AMS, a maintenance contract is assumed such that annual expenses are $1,800 (Kamps, 2002).

- *Miscellaneous.* The respective purchase prices for the TMS and AMS are $90,000 and $150,000 (McFarland, 2001; Kamps, 2002; Geleynse, 2001–2002). We assume the TMS has a 15-year useful life and the AMS has an uncertain length of useful life, distributed triangular (9, 12, and 15 years). The salvage value for each system is 2.5% of its purchase price (Dijkhuizen et al., 1997), and each system is depreciated over seven years (Barry et al., 2000). Furthermore, the average tax rate is assumed to be 30.5% (Canning and Tsigas, 2000). An average tax rate is used here because we do not make assumptions about income from other sources (e.g., off-farm income, sale of cull cows, and sale of bull calves) that would be necessary to use a marginal rate.

For the base case analysis, an 8% discount rate is assumed. This discount rate was chosen because it is consistent with previous analyses (Dijkhuizen et al., 1997; Hyde and Engel, 2002). Also note that this represents a risk-free discount rate, consistent with real options analysis (Brach, 2003). [In fact, this type of analysis is generally similar to the "probability analysis" described by Barry et al. (2000).] As a risk-free rate, some may argue 8% is relatively high. Thus, sensitivity analysis is performed on the discount rate to determine how our results would change as the discount rate is increased or decreased.

Empirical Results

When reviewing these results, it is important they be interpreted correctly. Specifically, the reader should be aware that the analysis is based upon the current understanding of AMS technology. Thus, the decision is one being faced currently by the dairy farmer. Where alternative TMS ages are discussed, reference is being made to current TMS ages and should not be interpreted as meaning the farmer should wait until the TMS reaches a given age before replacing it with an AMS. Indeed, the assumptions incorporated here may well prove to be inaccurate over time as more is learned about production with an AMS.

The decision to replace the TMS was analyzed in each year of the TMS' 15-year useful life. In year zero, the decision is similar to that analyzed by Dijkhuizen et al. (1997) and Hyde and Engel (2002);

Table 3. Base Case Results by Age of TMS at Time of AMS Investment Decision

TMS Age (years)	ρ' Discount Rate (%)	$E(R)$ Expected Annualized Returns from Investing ($)	H Investment Return Trigger Level ($)
0	10.02	20,455 ‡	15,036
1	11.50	9,114	17,245
2	12.62	10,566	18,930
3	13.04	12,468 †	19,567
4	12.29	14,489 †	18,431
5	10.54	16,036 ‡	15,810
6	8.20	17,021 ‡	12,300
7	8.16	17,714 ‡	12,242
8	8.17	17,925 ‡	12,253
9	8.16	18,144 ‡	12,247
10	8.20	18,395 ‡	12,305
11	8.19	18,705 ‡	12,292
12	8.17	19,084 ‡	12,255
13	8.15	19,514 ‡	12,229
14	8.15	19,971 ‡	12,227

Notes: † indicates that investment is accepted under the NPV rule [$E(R) > M$]; ‡ indicates that investment is accepted under the real options rule [$E(R) > H$].

i.e., the old milking equipment is completely inoperable and the farmer must purchase a system to maintain operations. Therefore, the decision is whether to purchase a new TMS or an AMS. In all other periods, however, the decision is whether to continue milking with the current operational TMS or to replace it with an AMS.

We first present results from the base case analysis, which is based upon the data previously discussed. Next, we present the results of our sensitivity analyses, in which we assess how certain key variables may affect the AMS investment decision.

Base Case Analysis

The base case results (table 3) show that, under an NPV rule [i.e., $E(R) > M$], replacing a TMS with an AMS is attractive at all TMS ages except one and two. This includes period zero in which the farmer must purchase an operational system to continue milking the herd. In the base case, M is $12,000, or 8% ($\rho$) of $150,000. However, the real options rule [i.e., $E(R) > H$] indicates investment should not occur if the TMS is between one and four years old. Thus, when not accounting for uncertainty and irreversibility, investment might occur if the TMS is three or four years old.

Looking at the variability of returns, as signified by higher values of ρ', uncertainty is clearly greatest if the TMS is zero to five years old. At other ages, ρ' is just higher than ρ, indicating the variability of returns is quite low at those TMS ages. Variability is shown to be greatest if the TMS is three years old.

This pattern of the variability of returns, first increasing and then decreasing with TMS age, is consistent throughout the analysis. It is a function of two factors: our specification of the distribution of the AMS' useful life, and the benefit associated with avoiding reinvestment in the TMS. Recall that costs associated with the TMS are benefits to the AMS because they are avoided with AMS adoption. Therefore, if the AMS lasts long enough for the farmer to realize this benefit, then the AMS is a more attractive investment. If the TMS is between six and fourteen years old, for example, the farmer knows with certainty that the AMS will outlast the current TMS because the AMS has a minimum useful life of nine years.

However, in year five of the TMS' life, it is possible the AMS will not outlast the TMS. Therefore, it becomes less certain that the farmer will experience the $90,000 TMS reinvestment benefit. The uncertainty is greatest if the TMS is three years old, in which ρ' is 63% greater than ρ. At ages one and two, it is more likely that the benefit will not be realized. Therefore, ρ' is lower at those ages. Thus, the pattern of return variability closely follows our specification of the triangular distribution of the useful life of the AMS.

The results at a TMS age of zero do not represent a decision to replace an operational TMS. Rather, the farmer is in a position in which inoperable equipment must be replaced with a new TMS or an AMS. Therefore, the analysis is similar to that performed by Dijkhuizen et al. (1997) and Hyde and Engel (2002). These results are consistent with Hyde and Engel's earlier research findings showing the AMS is attractive when choosing between it and a TMS.

Sensitivity Analyses

Several sensitivity analyses were performed to determine how the base case results might be affected by our specification of input distributions or parameters. We present qualitative results here (table 4). (The numerical results are available from the authors upon request.) The qualitative results allow us to more directly draw conclusions about how results change in the sensitivity analyses. Note that AMS investment is optimal in year zero of the TMS' life in all scenarios. Therefore, we do not discuss it further.

The first group of sensitivity analyses is related to 3X milking in the TMS. Although most farmers milk at a frequency of 2X in a TMS, many milk more frequently. In this case, we assume production does not change from the TMS to the AMS. That is, the producer is already milking at about the same average frequency as is achieved in the AMS. Therefore, the change in net benefits is a result of a change in avoided labor costs associated with increased labor use in 3X versus 2X milking in the TMS. Three alternative annual labor costs are analyzed: \$10,000, \$15,000, and \$20,000.

At a \$10,000 annual labor cost for milking in the TMS, the results are slightly different from the base case. The real options rule $[E(R) > H]$ indicates investment is optimal if the TMS is 6–14 years old, compared to 5–14 years in the base case. Under the NPV rule $[E(R) > M]$, investment is not optimal at TMS ages of 1–4, as compared to 1–2 years old in the base case. Therefore, the AMS is slightly less attractive for some farmers if the benefit of increased production is zero. With a \$15,000 annual labor cost, the results are qualitatively identical to the base case. Finally, when labor costs are \$20,000 per year in the TMS, the real options rule suggests investment is optimal at all TMS ages except age one.

Next, we considered herd sizes of 120 and 240 cows, requiring two and four AMS units, respectively. These analyses require modified TMS purchase costs and labor costs. For the 120-cow farm, these costs are \$125,000 (McFarland, 2001) and \$21,000 per year, and for the 240-cow dairy, the corresponding costs are \$252,000 (McFarland, 2001) and \$35,000 per year. The results are not significantly different from the base case. The real options rule suggests investment is optimal if the TMS is at least six years old, compared to five years in the base case. Because results are not very different from the base case, we continued our analysis assuming a 60-cow farm.

Choice of risk-free discount rate was shown to be an important factor affecting the AMS investment decision. At lower discount rates, investment is attractive with relatively new TMSs under the real options rule. When $\rho = 3\%$, investment is optimal if the TMS is at least three years old. Investment is optimal if the TMS is at least four years old at $\rho = 5\%$. Finally, when $\rho = 10\%$, investment is optimal if the TMS is at least six years old.

Annual labor costs are also expected to be important in determining the value of AMS investment. Indeed, one reason posited for increased adoption in Europe and Canada is that labor costs are typically higher in those countries (Hyde, 2002). Furthermore, results presented earlier suggest annual labor costs may be important when comparing an AMS to a TMS with a milking frequency of 3X. As seen from the results in table 4, higher annual labor costs are associated with optimal investment at lower TMS ages. When annual labor costs are \$7,500 per year, investment is optimal under the real options criterion if the TMS is at least six years old. At a labor cost of \$15,000 per year, the AMS is attractive if the TMS is at least five years old. The results change more significantly if one applies an NPV rule to investment. At a cost of \$7,500 per year, investment is optimal under an NPV rule if the TMS is at least four years old. This decreases to two years when the annual labor cost is \$15,000.

Next, we analyzed the effects a nonstochastic production increase may have on the investment decision. Specifically, if one knows with certainty that production will increase by a given number of pounds per cow per day, it may impact the decision. If this increase is five pounds per cow per day, the real options results are the same as under the base

Table 4. Qualitative Results of Base Case and Sensitivity Analyses

	Age of TMS at Which the Following Results Occurred:		
Scenario Analyzed	$E(R) < M$	$H > E(R) > M$	$E(R) > H$
Base Case	1–2	3–4	0, 5–14
3X TMS milking, $10,000 labor cost	1–4	5	0, 6–14
3X TMS milking, $15,000 labor cost	1–2	3–4	0, 5–14
3X TMS milking, $20,000 labor cost	none	1	0, 2–14
Herd size of 120 cows	1–3	4–5	0, 6–14
Herd size of 240 cows	1–3	4–5	0, 6–14
Discount rate, 3%	none	1–2	0, 3–14
Discount rate, 5%	none	1–3	0, 4–14
Discount rate, 10%	1–4	5	0, 6–14
Labor cost, $7,500	1–3	4–5	0, 6–14
Labor cost, $12,500	1–2	3–4	0, 5–14
Labor cost, $15,000	1	2–4	0, 5–14
AMS production increase, 5 lbs./cow/day	1	2–4	0, 5–14
AMS production increase, 8 lbs./cow/day	none	1–3	0, 4–14
Feed cost, $6.50 per cwt	1–2	3–4	0, 5–14
Feed cost, $7 per cwt	1–2	3–4	0, 5–14
Feed cost, $8 per cwt	1–2	3–5	0, 6–14
TMS cost, $67,500	1–3	4–5	0, 6–14
TMS cost, $112,500	1–2	3–4	0, 5–14
TMS cost, $135,000	1–2	3–4	0, 5–14
Milk price, $13 per cwt	1–3	4–5	0, 6–14
Milk price, $14 per cwt	1–3	4–5	0, 6–14
Milk price, $16 per cwt	1–2	3–4	0, 5–14
Total TMS maintenance cost, 30% of price	1–3	4–5	0, 6–14
Total TMS maintenance cost, 50% of price	1–2	3–4	0, 5–14
Total TMS maintenance cost, 60% of price	1–2	3–4	0, 5–14

case. At an increase of eight pounds per cow per day, investment becomes optimal with a four-year-old TMS. Note that the NPV rule shows investment is optimal at all TMS ages at a production increase of eight pounds.

Feed costs could be an important factor affecting the AMS investment decision because these costs increase with higher production. Therefore, the higher the per cwt feed cost, the greater the cost increase associated with AMS adoption. Over a reasonable range, however, the effects of feed costs are minimal. Results for feed costs of $6.50 and $7 per cwt are qualitatively identical to the base case. At a cost of $8 per cwt, investment is optimal with a six-year-old or older TMS, as compared to five years or older in the base case. Thus, higher feed costs may affect the decision to some extent.

Some argue that a proper analysis compares the AMS to a TMS having approximately the same technological capabilities. Our $90,000 figure used in the base case is intended to reflect this level of technology with the TMS. However, the farm manager may not be able to take full advantage of the technology. Therefore, this manager might reasonably compare the AMS to a less sophisticated TMS. On the other hand, the total cost of construction to shift from a stanchion barn to an AMS, for example, may exceed the $90,000 base case TMS purchase price. Consequently, we analyze three different TMS costs, $67,500, 25% less than the base case, and $112,500 and $135,000, 25% and 50% above the base case.

Based on findings of the analysis, higher TMS costs do not change the qualitative results compared to the base case. The real options rule suggests adoption is optimal if the TMS is at least five years old. At a reduced TMS cost, adoption is optimal if the TMS is six or more years old. Therefore, the cost of the TMS is shown to have a relatively small impact on the farmer's decision to replace an existing system with an AMS.

Expected milk prices may also affect the AMS investment decision. This is potentially crucial because milk prices can differ significantly across regions in the United States. Three different milk prices were analyzed—$13, $14, and $16 per cwt—removing the stochastic specification. Compared to the base case mean price of $14.98, lower milk prices result in investment being optimal in a TMS which is one year older. That is, investment is optimal if the TMS is at least six years old, compared to the base case of five years. The $16 milk price results in optimal investment with a TMS that is five years old or older.

Finally, we considered the effect of the TMS maintenance cost on the AMS investment decision. Because the producer signs a maintenance contract agreement with the AMS manufacturer, the maintenance costs for the AMS are fixed. However, TMS maintenance costs may be higher or lower than was assumed in the base case, 45% of the TMS' purchase price over its useful life. Three alternative percentage levels are therefore considered: 30%, 50%, and 60%.

At percentages greater than 45%, results are qualitatively identical to the base case. With a 30% maintenance cost, the optimal TMS age to initiate investment is six, as compared to five in the base case. Therefore, costs to maintain the TMS have a relatively insignificant effect on the AMS investment decision over reasonable ranges.

Conclusions

We have used a real options analytical framework to investigate the decision to replace an existing traditional milking system (TMS) with an automatic milking system (AMS) given the uncertainty and irreversibility inherent in the decision. This work differs from previous economic analyses in two distinct ways. First, the choice to replace an operational TMS with an AMS was analyzed, where previous work has focused on the choice of AMS versus TMS when the farmer is choosing to install one or the other. Second, our adoption of a real options approach lends itself to a more thorough assessment, relative to a traditional capital budgeting approach, of uncertainty and irreversibility associated with the adoption decision.

Our base case results indicate that farmers whose milking systems are five years old or older would be economically justified in replacing their operational systems with an AMS under a real options criterion. Under an NPV criterion, replacement is optimal if the TMS is three years old or older. Therefore, the real options criterion does lead to different decisions in some cases where the value of waiting is shown to exceed the value of investing.

Base case results also suggest that the most critical source of uncertainty is the useful life of the AMS. If the TMS is of an age at which the farmer is certain to reap the benefit of avoiding reinvestment to replace a worn-out system over the life of the AMS, then our findings indicate the TMS should be replaced. This result is consistent throughout the sensitivity analyses.

Our sensitivity analyses revealed that the minimum optimal age of AMS adoption changes little when assumptions are changed. In only two analyses did the minimum optimal TMS age change by more than one year. With 3X milking in the TMS and an annual labor cost of $20,000 per year, the minimum optimal TMS age is two. With a 3% discount rate, the minimum optimal TMS age is three. Results did not change by more than one year when analyzing herd size, labor costs, AMS production increase, feed costs, TMS purchase cost, milk price, or TMS maintenance costs.

Based on our findings, many U.S. dairy farmers would benefit by replacing an operational milking system with an AMS. The major source of uncertainty, as evidenced by the results, is associated with the useful life of the AMS technology. Consequently, farmers with newer milking systems may have to wait several years before the technology proves itself to be long-lasting. However, the results suggest that those farmers with older milking systems, perhaps those which are fully depreciated, may benefit by switching despite this uncertainty.

The AMS may be viewed by some as another step in the development of the global agricultural industry. It certainly continues the trend of replacing labor with capital in production agriculture. Also, it could help the smaller-scale operation to remain competitive with larger-scale operations. To the extent that the 60-cow farm milking with an AMS can increase production, lower labor costs, and increase the time spent in managerial tasks, then that farm enhances its competitive position. Although these issues are beyond the scope of the current analysis, these are important considerations worthy of future investigation.

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