A Real Options Approach to Investment Analysis of Automatic Milking Systems

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Introduction

The technology of milking dairy cows has changed a great deal over time, from hand milking 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 (AMS). The first unit was installed on a commercial dairy farm in the Netherlands in 1992 (van der Vorst and Hogeveen, 2000). Since, the technology has been heavily adopted in Europe, Japan, Canada, and some other countries (Reinemann, 2002). AMS adoption has been slow in the U.S., where existing milk quality-related regulations have not yet been modified to apply directly to the AMS.

There are important tradeoffs associated with adoption of an AMS relative to a milking parlor. The most important differences are increased capital investment, decreased labor requirement, increased milk production and feed cost, and possibly a shorter useful life. The purchase price for a single-stall AMS unit[1] capable of milking about 60 cows is approximately $150,000. Hyde and Engel (2002) use a figure of $90,000 for a comparably-sized parlor with similar technological capabilities[2].

Increased production may result from increased milking frequency in the AMS relative to a parlor. Many Canadian farmers are realizing an average milking frequency

[1] There are two different general types of robotic systems. Single-stall systems have one robotic arm serving one milking stall. Multi-stall systems have two or more stall serviced by one robotic arm.
[2] The AMS units are able to collect detailed data on each cow. These data include production levels, milking frequency, milk quality, etc.

of 2.7-3.0 times per cow per day (Rodenburg, 2001-2002). By contrast, many commercial dairy farms milk twice daily. With increased milk production comes increased feed intake to support that higher level. Dijkhuisen, *et al*. (1997) used a 10% increase in feed cost with an AMS. Finally, the technology's relative novelty means that there is no clear consensus on how long an AMS will remain in operation. Dijkhuisen, *et al*. (1997) use a figure of seven years while Hyde and Engel (2002) specify a range of seven to twelve years for the AMS's useful life. Both studies may underestimate the true length of the AMS's useful life according to some experts (Rodenburg, 2001-2002). There are other less significant tradeoffs, described later.

Several studies have analyzed the farm-level question of whether or not to invest in an AMS. Dijkhuisen, *et al*. (1997) employ a capital budgeting framework to analyze the choice of whether to purchase an AMS or a milking parlor. They calculate the net present value (NPV) of a parlor system, convert that to an annuity equivalent, and then solve for the AMS purchase price that will result in an annuity equivalent equal to that of the parlor. The resulting purchase price was referred to as the breakeven value.

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 increase in production with AMS adoption). They showed that the mean breakeven cost was slightly greater than the cost of investing in the equipment. However, the variability of breakeven values was quite high. As stated, both of these papers look at the decision to invest in a parlor versus an AMS at a given point in time. That is, the decision to replace an existing parlor with an

AMS is not considered. They also do not take into account the effect that the variability of returns (uncertainty) and sunk costs (irreversibility) associated with investment may have on the decision.

The objective of this research is to estimate the effect of uncertainty and irreversibility on the decision to replace an existing milking parlor with an AMS. We employ an *ex ante* real options approach to analyze this issue.

Method and Data

Traditional capital budgeting analyses do not account for irreversibility and uncertainty associated with investment. One might adjust the discount rate in an NPV analysis (or the hurdle rate in an internal rate of return (IRR) framework) as a method of incorporating uncertainty (Barry, *et al*., 2000). However, these are rather subjective methods of incorporating risk based on the perceptions of the decision maker.

Investment analysis using an *ex ante* real options approach allows us to simulate the cash flows associated with AMS investment and then use the variability of discounted net cash flows to develop a modified hurdle rate and an associated perpetuity. As seen below, this perpetuity becomes an important factor in the decision criterion. If the simulated annualized net cash flow exceeds the perpetuity, then the real options decision rule indicates that investment is warranted. In this section, we provide a brief review of real options, a description of the *ex ante* simulation model, and details about the data used in the analysis.

Review of Real Options Analysis

Given an investment decision that can be postponed for some period of time (i.e., the choice is not "now or never"), a real options (RO) approach can be employed. Basically, RO analyses apply the fundamentals of financial option pricing methods to problems of investment in capital assets. Here, we present a basic overview. Interested readers should consult Black and Scholes (1973) and Dixit and Pindyck (1994) for a thorough review of RO methodologies.

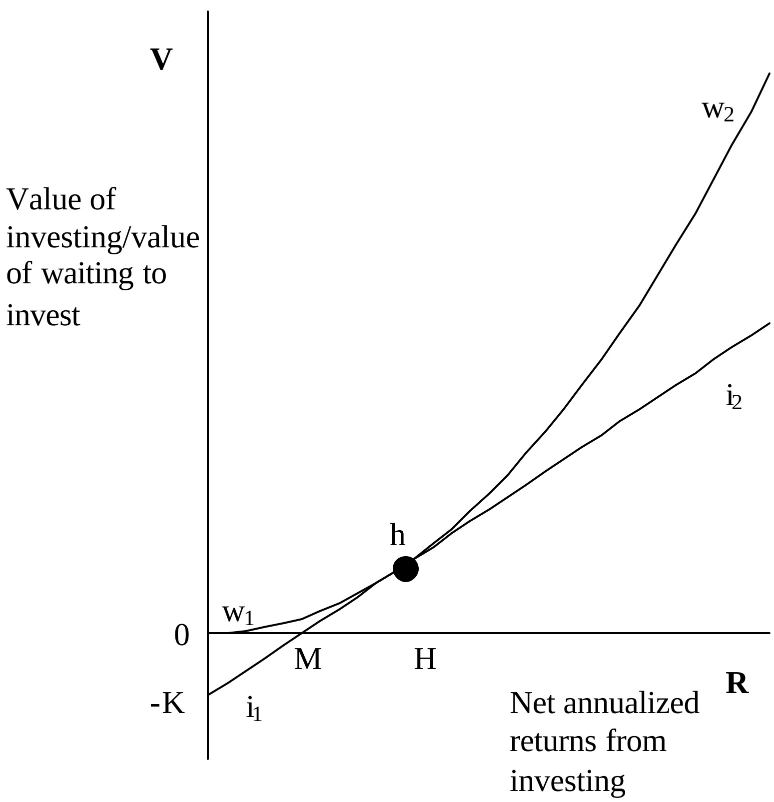

Figure 1. Graphical Representation of Real Options Analysis

The relationship between the value of investing now and the value of waiting to invest can be described graphically (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. The vertical axis represents the value of the decision (V), whether the decision is to invest now or to wait to invest.

The straight line $i_1 i_2$ represents the value of investing now. Its vertical intercept is –K, where K is the initial sunk cost of the investment. Therefore, when the investment generates no annualized returns, 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" by Dixit and Pindyck (1994).) It can be shown via the "value matching condition" that the slope of $i_1 i_2$ is $1/r$, where r is the discount rate.

The curve w_1w_2 represents the value of waiting to invest. Its convex shape indicates that the value of waiting increases with R at an increasing rate. Two points 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_1w_2. Referred to as the "smooth pasting" condition (Dixit and Pindyck, 1994)), this ensures that investment is optimal when the marginal value of waiting equals the marginal value of investing. Dixit (1992) points out that there is no value of waiting to invest when R is greater than H, thus points along w_1w_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_1w_2 passes through the origin. This indicates that 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. That is, there is always value to waiting as a later decision, which may incorporate new information, may be a better one.

Ex Ante Simulation Model

Because AMS units are in the very early adoption stages in the U.S., there is a considerable level of uncertainty associated with investment returns. Therefore, we employ an *ex ante* approach to RO analysis that was used by Purvis, *et al*. (1995) to analyze adoption of free-stall barns on Texas dairy farms. Description of this method begins with a mathematical representation of the value of investing and the value of waiting to invest (Equation 1).

$$V(R) = \begin{Bmatrix} BR^{b} \rightarrow if \quad R \leq H \\ R/r - K \rightarrow if \quad R \geq H \end{Bmatrix} \tag{1}$$

The value of waiting to invest (w_1w_2 in Figure 1) is BR^{b}, where B is a constant and b (Equation 2) is a function of the discount rate, r, and the variance of expected investment returns, s^{2}, defined below.

$$b = \frac{1}{2}\left[1 + \sqrt{1 + \frac{8r}{s^{2}}}\right] \tag{2}$$

The Marshallian investment trigger, M, is equal to rK. The modified investment trigger, H, is equal to $r'K$, where r' is defined as

$$r' = \left(\frac{b}{b-1}\right)r . \tag{3}$$

Thus, given a value for s^2 from the simulation and the chosen discount rate, H can be found easily.

We assume that V follows a geometric Brownian motion[3]. Therefore, the following is true.

$$\frac{dV}{V} = mdt + sdz \qquad (4)$$

where m represents the mean of V over time (often called a drift parameter), dt is an infinitesimally small increment of time, s is a measure of the variability of V (often called a diffusion parameter), and dz is an increment of the geometric Brownian motion process, $z(t)$.

Taylor-series expansion can be used to show that

$$\frac{dV}{V} = \frac{\Delta V/\Delta t}{V} = \frac{1}{V}\times\frac{\Delta V}{\Delta t} = \frac{\Delta(\ln V)}{\Delta t} = \ln V_n - \ln V_{n-1}. \qquad (5)$$

Thus, we can use the difference in the log of V from one period to the next (i.e., period n-1 to n, where n indexes the year in the parlor's usable life) as a discrete approximation of dV/V. We refer to this difference as $\Delta(\ln V_n)$. It is the variance of $\Delta(\ln V_n)$ that provides our estimate of s^2, which is used in Equation 2 to calculate b.

To calculate $\Delta(\ln V_n)$, we must first calculate V_n (Equation 6).

$$V_n = \frac{\left[\dfrac{r}{1-\left(\dfrac{1}{(1+r)^{T-n}}\right)} PV_n\right]}{r} \qquad (6)$$

[3] It is common to assume that the underlying asset value follows a GBM. See Dixit and Pindyck for details about this assumption.

Here, V_n is a perpetuity, which assumes that 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. 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 6 represents the annuity equivalent of PV_n, while dividing by the discount rate yields the value of the project into perpetuity.

The net benefit in each period of the AMS's life (indexed by t) is described in Equation 7.

$$NB_t = benefits_{AMS,t} - costs_{AMS,t} + costs_{parlor,t} - benefits_{parlor,t} \tag{7}$$

Because the problem involves the replacement of the current parlor, the net benefit in period t of the AMS's life is a function of the lost benefits from the parlor (representing an opportunity cost of AMS investment) and the avoided costs associated with the parlor's operation. We will show that the benefit of avoiding reinvestment in the parlor over the life of the AMS is important.

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 in the base case. Therefore, only one AMS unit is needed.

Table 1. Base Case Variable Distributions

Variable	Units	Distribution	Notes/sources
Production in AMS relative to parlor	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)
Parlor milk Price	$/cwt	N(Base milk price, $1.15)	One observation drawn each year per iteration. (USDA/NASS, 2001b)
AMS milk price	$/cwt	Parlor milk price T(0.99, 1.00, 1.01)	Distribution values based on percentages of milk price. One observation drawn per iteration. (Dijkhuisen, *et al*., 1997; van der Vorst and de Koning, 2002; van der Vorst and Hogeveen, 2000)
AMS labor cost	$/year	Parlor labor cost T(0.31, 0.67, 0.90)	Distribution values based on percentages of parlor labor. One observation drawn per iteration. (Dijkhuisen *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(9.0, 12.0, 15.0)	One observation drawn per iteration. (Kamps, 2001; Geleynse, 2001-2002)

Note: T denotes a triangular distribution (minimum, mode, maximum). N denotes a normal distribution (mean, standard deviation).

Table 2. Base Case Parameters

Parameter	Units	Value	Notes/sources
Base Milk Price	$/cwt	14.94	Based on all milk PA monthly data for 1996-2001. (USDA/NASS, 2001b)
Parlor labor cost	$/year	10,000	Approximately equal to $9.70/hr (Rogers) times 3 hrs. per day (Stup) 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)
Useful life of parlor	years	15.0	Broad interaction with equipment industry personnel.
Parlor purchase cost	$	90,000	Based on double-4 herringbone parlor at $10-12,000/stall. (McFarland).
AMS purchase cost	$/unit	150,000	(Kamps; Geleynse)
Herd size	cows	60.0	Assumed capacity of a single-stall AMS unit (Hyde and Engel)
Total parlor maintenance cost	% of purchase cost	45.0	Based on 3% per year over a 15 year life (Dijkhuisen, *et al.*)
Base annual parlor 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)
Salvage value	%of purchase cost	2.5	(Dijkhuisen, *et al*.).
Depreciation period	years	7.0	Standard deprec. period for farm machinery. (Barry, *et al.*)
Discount rate	%	8.0	(Dijkhuisen *et al*.)
Milk price inflation	%	0.2	Based on yearly all milk PA data. (USDA/NASS, 2001b)
Average Tax Rate	%	30.5	(Canning and Tsigas)

Production - Production in the AMS relative to the parlor is based upon the assumption that the farmer milks twice daily (2X) in the parlor 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, despite increased milking frequency in the AMS, we set the lower bound to no change (Rodenburg, 2001-2002). We specify a uniform distribution because we lack data to specify a potentially more accurate one.

Milk price - The price received for milk produced in a parlor is normally distributed with a mean equal to the base milk price ($14.94 in year zero 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 (USDA/NASS, 2001b). In each iteration, the price for milk produced in the AMS ranges from a minimum of 99% of the parlor price to a maximum of 101%, with the most likely value of 100%. This reflects small potential increases or decreases 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 parlor labor remaining employed after AMS adoption (Dijkhuisen, *et al.*, 1997; Arts, 2001; Grant, 2002).

Feed costs - The base feed cost is $7.38 per hundredweight (cwt) of milk produced (USDA/ERS, 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 from USDA/ERS, 2001. The slope of that trend line is $0.16 and the average deviation from the trend line is $0.54. Thus, 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 Dijkhuisen, *et al*. (1997), we specify the total maintenance expenses for the parlor 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 $675.00, and so on. (This is based upon a parlor purchase price of $90,000.) For the AMS, a maintenance contract is assumed such that annual expenses are $1,800 (Kamps, 2002).

Miscellaneous - The purchase prices for the parlor and AMS are $90,000 and $150,000 (McFarland, 2001; Kamps, 2002; Geleynse, 2001-2002). We assume that the parlor has a 15 year useful life and the AMS has an uncertain length of useful life, distributed triangular (9, 12, 15). The salvage value for each system is 2.5% of its purchase price (Dijkhuisen, *et al*., 1997). Each system is depreciated over seven years (Barry, *et al*., 2000). Furthermore, we assume an 8% discount rate for the base case analysis (Dijkhuisen, *et al*., 1997; Hyde and Engel, 2002). Finally, we assume that the average tax rate is 30.5% (Canning and Tsigas, 2000). We use an average tax rate 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.

Empirical Results

The decision to replace the parlor was analyzed in each year of the parlor's 15-year useful life. In year zero, the decision is similar to that analyzed by Dijkhuisen, *et al*. (1997) and Hyde and Engel (2002). That is, the farmer must purchase a system to maintain operations. In all other periods, however, the decision is whether or not to replace the current milking parlor. We first present results from the base case analysis, which is based upon the data previously discussed. Following that, we present the results of our sensitivity analyses, in which we analyze how certain key variables may affect the AMS investment decision.

Base Case Analysis

The base case results show that, under an NPV rule (E(R) > M), replacing a parlor with an AMS is attractive in all years of the parlor's life except years one and two (Table 3). In this case, M is $12,000, eight percent (?) of $150,000. However, the real options rule indicates that investment should not occur in years one through four. Thus, when not accounting for uncertainty and irreversibility, investment might occur in years three and four of the parlor's life.

Looking at the variability of returns, as signified by higher value of ?´, it is obvious that uncertainty is greatest in years zero through five. In other years, ?´ is just higher than ?. This indicates that the variability of returns is quite low in those years. Variability is shown to be greatest when the parlor is three years old.

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

Parlor Age	?´	E(R)	H
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

* indicates that investment is accepted under NPV rule (E(R)>M)
** indicates that investment is accepted under real options rule (E(R)>H)

This pattern of the variability of returns, first increasing then decreasing, is consistent throughout this analysis. It is a function of two things; our specification of the distribution of the AMS's useful life and the benefit associated with avoiding reinvestment in the parlor. Recall that costs associated with the parlor 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 it is a more attractive investment. In years six through fourteen, for example, the farmer knows with certainty that the AMS will outlast the current parlor because the AMS has a minimum useful life of nine years.

However, in year 5 of the parlor's life, it is possible that the AMS will not outlast the parlor. Therefore, it becomes less certain that the farmer will experience the $90,000 parlor reinvestment benefit. The uncertainty grows until year three, in which ?´ is 63% greater than ?. In years one and two, it becomes more likely that the benefit will not be realized. Therefore, ?´ falls in those years. Thus, the pattern of uncertainty closely follows our specification of the distribution of the useful life of the AMS.

The year zero results do not represent a decision to replace an operational parlor. Rather, the farmer is in a position in which he must replace old equipment. Therefore, the analysis is similar to that performed by Dijkhusen, *et al.* (1997) and Hyde and Engel (2002). These results are consistent with the earlier research findings that showed that the AMS is attractive when choosing between it and a parlor.

Sensitivity Analyses

We performed several sensitivity analyses to determine how the base case results might be affected by our specification of input distributions or parameters (Table 4). We analyzed ten different variables, as discussed below. We present qualitative results here. (The numerical results are available from the authors.) These 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 parlor's life in all scenarios. Therefore, we do not discuss it further below.

The first group of sensitivity analyses is related to 3X milking in the parlor. Although most farmers milk at a frequency of 2X, many milk more frequently. In this case, we assume that production does not change from the parlor to the AMS. That is, the producer is already milking them 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 parlor. We analyze three alternative labor costs: $10,000, $15,000, and $20,000.

Table 4. Qualitative results of base case and sensitivity analyses

	Years of parlor life in which 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 parlor milking, $10,000 labor cost	1-4	5	0, 6-14
3X parlor milking, $15,000 labor cost	1-2	3-4	0, 5-14
3X parlor 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 - $7.00 per cwt	1-2	3-4	0, 5-14
Feed cost - $8.00 per cwt	1-2	3-5	0, 6-14
Parlor cost - $67,500	1-3	4-5	0, 6-14
Parlor cost - $112,500	1-2	3-4	0, 5-14
Parlor cost - $135,000	1-2	3-4	0, 5-14
Milk price - $13.00 per cwt	1-3	4-5	0, 6-14
Milk price - $14.00 per cwt	1-3	4-5	0, 6-14
Milk price - $16.00 per cwt	1-2	3-4	0, 5-14
Total parlor maintenance cost - 30% of price	1-3	4-5	0, 6-14
Total parlor maintenance cost - 50% of price	1-2	3-4	0, 5-14
Total parlor maintenance cost - 60% of price	1-2	3-4	0, 5-14

At a $10,000 labor cost for milking in the parlor, the results are slightly different from the base case. The RO rule indicates that investment is optimal when the parlor is six to fourteen years old. The NPV rule indicates that investment is not optimal in years one through four. Therefore, the AMS is less attractive when the benefit of increased production is zero. With a $15,000 labor cost, the results are qualitatively identical to the base case. Finally, when labor costs are $20,000 per year in the parlor, the RO rule indicates that investment is optimal in all but year one of the parlor's life.

Next, we looked at herd sizes of 120 and 240 cows, requiring two and four AMS units, respectively. There is no reason to believe, *a priori*, that the adoption of this technology is sensitive to production scale[4]. The results confirm this as they are not significantly different from the base case. The real options rule suggests that investment is optimal when the parlor 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 decided to continue our analysis based on a 60-cow farm.

Choice of discount rate was shown to be an important factor affecting the AMS investment decision. At lower discount rates, investment becomes attractive earlier in the parlor's life under the real options rule. When ? = 3%, investment is optimal when the parlor is at least three years old. Investment is optimal when the parlor is at least four years old at ? = 5%. Finally, when ? = 10%, investment is optimal when the parlor is at least six years old.

[4] To date, farmers adopting more than one AMS unit have established a 60 cow (approximate) herd that is milked by each one. Therefore, these farms are comprised of two or more roughly identical units. Thus, scaling is an issue only to the extent that the farmer might be able to negotiate a lower price for multiple units. However, some larger farms have recently begun to explore the possibility of having more than one unit available to the same group of cows such that a single cow may choose which unit to attend for milking. There may be issues associated with scaling in these cases. However, these are beyond the scope of this paper.

Labor costs are also expected to be important in determining the value of AMS investment. One reason posited for increased adoption in Europe and Canada is that labor costs are typically higher in those countries (Hyde, 2002). Results show that higher labor costs indicate that investment is optimal with a newer parlor. When labor costs are $7,500 per year, investment is optimal when the parlor is at least six years old. At a cost of $15,000 per year, the AMS is attractive when the parlor 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, investment is optimal under an NPV rule when the parlor is at least four years old. This decreases to two years when the labor cost is $15,000.

Next, we analyzed the effects that a non-stochastic production increase may have on the investment decision. That is, if one knows with certainty that production will increase by a given number of pounds per cow per day, it may impact the decision. When this increase is five pounds per cow per day, the RO results are the same as the base case. At an increase of eight pounds per cow per day, investment becomes optimal with a four year old parlor. Also, the NPV rule indicates that investment is always optimal at an increase of eight pounds.

Feed costs could be an important factor because these increase with increased production. Therefore, the higher the per-hundredweight 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 $6.50 and $7.00 per hundredweight are qualitatively identical to the base case. At a cost of $8.00 per hundredweight, investment becomes optimal in year six, as compared to year five in the base case. Thus, higher feed costs may affect the decision to some extent.

Some suggest that a proper analysis compares the AMS to a parlor that has approximately the same technological capabilities. Our $90,000 figure used in the base case is intended to reflect this level of technology with the parlor. However, the farm manager may not be able to utilize all of the technological “bells and whistles.” Therefore, this manager might reasonably compare the AMS to a less advanced parlor. We analyze three different parlor costs, $67,500, 25% less than base case, and $112,500 and $135,000, 25% and 50% above the base case. Higher parlor costs may indicate that additional costs associated with bulk tanks, milk lines, or other complementary equipment is needed.

Results indicate that higher parlor costs do no change the qualitative results compared to the base case. The RO rule suggests that adoption is optimal when the parlor is at least five years old. At a reduced parlor cost, adoption is optimal when the parlor is six or more years old. Therefore, the cost of the parlor is shown to have a relatively small impact on the farmer’s decision to replace an existing parlor with an AMS.

Expected milk prices may also affect the decision. This is potentially crucial because milk prices can differ significantly across regions in the U.S. We analyzed three different milk prices, removing the stochastic specification. These prices are $13.00, $14.00, and $16.00 per hundredweight. Compared to the base case, lower milk prices result in investment being optimal one period later. That is, investment is optimal when the parlor is at least six years old, compared to the base case of five years. The $16.00 price results in optimal investment beginning with a five year old parlor.

Finally, we considered the effect that parlor maintenance cost may have on the decision. Because the producer signs a maintenance contract agreement with the AMS manufacturer, the costs for the AMS are fixed. However, parlor costs may be higher or lower than was assumed in the base case, 45% of the parlor's purchase price over its useful life. We analyze three percentage levels; 30, 50, and 60%.

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

Conclusion

We have used an *ex ante* real options approach to analyze investment in an automatic milking system in the United States. Conditions in this country differ somewhat from other countries. The most relevant differences are milk prices (due to differences in use of market versus quota systems) and labor costs. Milk prices were shown to have little impact on the decision to adopt the AMS. However, labor costs are shown to be a more important factor in determining the optimal timing of AMS investment. Where labor costs are relatively high, *ceteris paribus*, adoption is more attractive.

In general, the results of the sensitivity analyses are not significantly different from the base case. Herd size, labor costs, AMS production increase, feed cost, parlor cost, milk price, and parlor maintenance cost alternatives did not change the initial replacement period by more than one year, compared to the base case. Increased milking frequency did significantly decrease the minimum parlor age for replacement to two years (compared to five in the base case). However, this only occurs when labor costs are twice that of the base case. Therefore, the change is more a function of labor costs than it is of milking frequency. Choice of discount rate is also shown to be a factor that may change the minimum parlor age by more than one year.

In all cases, the AMS is the optimal choice in year zero. That is, when the farmer is in a position in which he must replace his current milking equipment, then the optimal choice is an AMS. Again, this is consistent with earlier analyses (Dijkhusen, *et al.*, 1997; Hyde and Engel, 2002). Also, results show that replacing the parlor is optimal once it becomes certain that the AMS will last longer than the current parlor, in year six of the analysis.

It is very important to note that we do not account for issues related to financing the AMS investment. In fact, we maintain the assumption that the milking systems, whether parlor or AMS, are financed solely out of farm equity in this research. This is consistent with the work of Purvis, *et al.* (1995), who used a similar approach to analyzing adoption of free-stall dairy barns. Using a mix of debt and equity financing is probably more typical for this type of large investment. However, analyzing the effects of alternative financing strategies is beyond the scope of the current analysis, but would be an appropriate topic for further research. The literature has little to say about how choices, in a real options framework, are affected by financing.

It is difficult to predict how widely the AMS will be adopted in the United States. These results, like those of other papers cited here, suggest that adoption may be profitable for many farmers, at least under certain conditions. Conditions in the U.S. are different from much of the world for at least four reasons (Hyde, 2002).

First, we have already mentioned that the U.S. has a market based pricing system, as opposed to the quota systems used in most of the rest of the world. Therefore, U.S. dairy farm milk prices are more highly variable. Second, labor costs also tend to be lower in the U.S. compared to Europe and Canada. Third, producing milk with an AMS does not meet current guidelines for acceptable milking practices. Milk sanitarians must develop standardized guidelines that are flexible enough for producing with robots. Finally, producers are often very risk averse, particularly when a major change in production practices are being considered. Many will likely take a wait and see approach to AMS adoption. This makes sense when the farmer places his business on the line. Although the rate of AMS adoption is difficult to predict, this research adds to earlier results suggesting that some farmers may benefit from changing milking systems from a parlor to an AMS.

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