A METHODOLOGY TO ESTIMATE THE COST SAVINGS AND BENEFITS OF IMPROVED EFFICIENCY IN INDUSTRIAL CAPITAL MOTOR STOCK

Kevin L. Stamber, Purdue University

INTRODUCTION

Electric utilities expand their generating capacity over time to meet growing demand from the commercial, industrial and residential sectors. Failure to do so would result in electric power shortages. Unneeded expansion would result in excess capacity sitting idle and millions of dollars in excessive expenditure. The State Utility Forecasting Group (SUFG) at Purdue University, West Lafayette, Indiana, provides assistance on this front within the state of Indiana by developing forecasts of electricity demand in each of the sectors mentioned above.

Of particular interest to SUFG is electricity use by motors in the industrial sector. Electric motors consume nearly 70 percent of all electricity used by industry.[1,2] While small motors dominate the actual motor quantity, it is those motors larger than 5 horsepower that consume the majority of electricity used by electric motors.[3] During the life of an electric motor, operating costs far outweigh purchase costs, by a factor of 100 or more in many cases.

PROBLEM

SUFG uses both econometric and end-use models for the residential and commercial forecasts produced, but is limited to an econometric model exclusively in forecasting industrial electricity usage. This restriction prevents consideration of the possibility of analyzing the effects of new technology, governmental regulation or deregulation on the electric motor market, as econometric models are exclusively dependent upon the past in forecasting the future. Development of an accurate end-use model of industrial motor stock, such that SUFG can more accurately forecast industrial electricity usage, is therefore important.

PREVIOUS APPROACHES

Creation of a new motor model begins with an examination of existing methodologies. In this case, three software packages were examined: The motor model in INFORM (McMenamin and Monforte, Regional Economic Research, San Diego CA for Electric Power Research Institute, Palo Alto CA, 1992), MotorMaster (Washington State Energy Office, Olympia WA, 1992) and ITEMS (Jaccard and Nyboer, Simon Fraser University, Vancouver BC, 1992). Each has aspects of interest for development of a new motor model.

INFORM Motor Model

The INFORM motor model serves a series of purposes, as outlined in the INFORM user's manual:

- to define motor segmentation,
- to define motor efficiency options and technology data,
- to define base-year energy costs and market profiles, and
- to develop motor energy sales forecasts.[4]

Important to the INFORM motor model and its performance are the market segmentation and the component for motor purchase decisions. The market segmentation defines the characteristics of a given motor, and the component for motor purchase decisions allows new motors to enter the model as they would in real life. Segmentation within the INFORM motor model is based upon sectors of industry represented by the respective Standard Industrial Classifications (or SICs). Segmentations are designed around the use (pumps, fans and compressors; materials handling; materials processing), size (small -- less than 1 to 20 hp; medium -- 20.1 to 125 hp; large -- greater than 125 hp), load type (constant; variable) and efficiency design (standard or high efficiency AC motors with or without adjustable speed drives, or ASDs; DC motors) of the motors in each respective SIC. The motor purchases made by the model during the course of a year are based on two types of decisions: replacement of motors at the time of physical decay and purchase of new motors at times of expansion or construction of new facilities.[5]

MotorMaster

MotorMaster would be best categorized as a database-selection model. Given user input on a motor's horsepower, speed, enclosure and voltage, MotorMaster returns a list of all corresponding motors from among the 14 motor manufacturers listed in the database. MotorMaster also permits three different types of comparisons, as outlined in the *MotorMaster User's Reference Guide*:

- *Comparing New Motors*, which compares the purchase and operating costs of two new motors
- *Rewind vs. New*, which compares the cost of rewinding a failed motor with the higher cost of purchasing a new, more efficient motor. Efficiency loss as a result of rewinding the motor can be taken into consideration
- *Replace Working Motor*, which indicates whether it is cost effective to replace an operating motor with a new, more efficient model.[6]

MotorMaster also permits the user to introduce to the problem potential rebates that a utility might offer.

ITEMS

ITEMS is a Windows-based end-use demand simulation model. It uses a spreadsheet interface to edit the primary data and modeling structure of each problem. The modeling program is written in the APL programming language. Users can change the format of the simulation model through alteration of the data, rather than altering the APL code. This is an important feature, as it permits the user to alter the structure of the simulation without knowledge of the underlying code or language.

ITEMS disaggregates each sector of industry into a process flow model with three types of nodes:

- *Primary Output Groups*, nodes which define each of the requirements for output in the given sector;
- *Intermediate Nodes*, used to translate group demands into energy requirements; and
- *Competition Nodes*, at which different technologies compete to meet the energy requirements of a group.[7]

In the ITEMS modeling structure, machine drive could be seen as a primary output group and various size classifications as competition nodes. Motors with different efficiency designs would therefore compete for shares of machine drive of a given size. The structure outlined by Jaccard and Nyboer for machine drive is general and can be expanded through an increase in the number of primary groups which focus on machine drive or through the introduction of intermediate nodes to better detail machine drive use. Retirement of base stocks are based on a logistic function. Stocks which have not been retired can be tested for potential retrofit or change in technology.[8]

Shortcomings

Within the INFORM motor model, usage breakdown is simplified by gathering pumps, fans and compressors into a single group. A motor operating at 60 percent of full load will require different percentages of full-load input power depending upon whether the motor is attached to a fan or a pump. While the existing segmentations are satisfactory for a technical examination of replacement decisions, they are inadequate for defining the differences in business practices, knowledge and expectations among the establishments within a specific SIC.

The component for motor purchase decisions in INFORM also presents some difficulties. As replacement of a motor can only take place at the time of physical decay, early retirement, retrofit and rewind of failed motors are ignored. Most important among these is motor rewind; A.D. Little 1980 estimated that 70 percent of motors greater than 5 hp in size were rewound and returned to service rather than replaced with new motors, as INFORM assumes.[9] Rewound motors will typically have lower efficiency than a newly purchased motor; as a result, INFORM will underestimate energy requirements of the motor population.

MotorMaster does permit consideration of rewind of failed motors and early retirement of working motors, but the program structure was designed for single motor examinations only. Examining a population of motors for a long period of time using MotorMaster would be difficult, if not impossible.

ITEMS follows INFORM in that it fails to consider motor rewind. The structure of ITEMS also restricts competition to technology at a given competition node, defined in the example above as a size group. This prohibits consideration of examination of oversizing of motors, as an oversized motor cannot be replaced by a motor from a different size group.

PROPOSED APPROACH

The approach proposed incorporates the best points of the INFORM motor model, MotorMaster and ITEMS. The technological segmentation established within INFORM is refined; pumps, fans and compressors are distinguished, and a new technological segmentation based on the duty cycle of a motor is established. In addition, a series of establishment segmentations are added to address the differences in corporate decisionmakers (and their resultant motor purchases). The approach also considers motor rewind as a potential alternative for the replacement of a failed motor, adding another dimension of reality to the model. The primary goal of the final programming structure will be similar to that of ITEMS, placing the data within the reach of the user, leaving the that which must be coded in a high-level programming language out of the hands of the user.

The motivation for these changes is simple. Incorporating such changes adds to the reality of the model, and should improve the resulting electricity demand forecast, reducing the risk of a forecast erring short.

MODELING FRAMEWORK

Four principal ideas play an important role in development of the model. It is important to understand each of them. They are the central energy equation, high-efficiency motors, adjustable speed drives, and motor rewind.

The Central Energy Equation

The Central Energy Equation defines the electricity used by a motor (in kilowatt-hours) for a given period (a year, for example) as

$$kWh = \frac{(0.746hp)}{EFF}\left(\sum_i (\%IP_i)(HOURS_i)\right)$$

where hp ≡ motor size (in horsepower),

EFF ≡ efficiency of the motor,

$\%IP_i$ ≡ percentage of full-flow input power required for the i^{th} segment of the motor's duty cycle, and

$HOURS_i$ ≡ hours spent at the i^{th} segment of the motor's duty cycle in the given period.

In order to perform a given process, a specific motor's hp will be required. Depending upon the demand for the process, specific values of each of the $HOURS_i$ will be required. These two values cannot be changed readily. At the time a motor is purchased, decisions can be made which can alter the EFF and $\%IP_i$ -- purchase of a high-efficiency motor or an ASD, respectively -- and, as a result, change the kWh required by the motor to perform the same amount of work. These two terms are the true dynamics of the central energy equation.

High-Efficiency Motors

As the cost of electric power has increased over the past 20 years, demand for electric motors with improved efficiency has increased as well. McCoy et al. 1992 estimated that high-efficiency motors carry a 15 to 30 percent premium over their standard efficiency counterparts.[10] This cost carries benefits. Increased efficiency (estimated by ACEEE as ranging between 1 and 9 percent depending on motor size) reduces the kWh required by a motor and subsequently, the energy cost.[11] In addition, high-efficiency motors often are of better quality and will live longer than standard efficiency motors -- as much as 50 to 100 percent longer under identical operating conditions, according to COMPETITEK.[12]

Adjustable Speed Drives

Resource Dynamics Corporation 1993 contains a description of ASD operation:

> ASDs are devices used to provide a continuous range of speed control for motor application. ASDs are typically housed in an electrical cabinet, and are made up of electrical circuits and components. ASDs are a means for varying the frequency supplied to the motor. This is usually done by converting 60 Hz power provided by the electric service to direct current with a rectifier, then using an inverter to produce AC power at the desired output frequency and voltage for the motor driven system.[13]

ASDs are significantly more expensive than the motors that they control. For example, in 1991, a 5 hp AC motor could be purchased for $277 to $387,[14] while the corresponding ASD would cost approximately $2,700 installed,[15] about 10 times the cost of the motor. Energy savings helps to justify this added cost.

Note from the above discussion on the central energy equation that the kWh used annually -- and subsequently, the operating expense of a motor system -- increases as the percentage of full-flow input power required to satisfy a load increases. By using an ASD under appropriate conditions, energy savings can be considerable. For example, consider the range of full-flow input power required for an Inlet Vane Fan both with and without an ASD, as displayed in Table 1.[16] Energy costs will be halved by using an ASD on a motor operating at 60 percent of full load. Because electric motors in industry typically consume 10 to 20 times their own capital cost in electricity every year,[17] purchasing an ASD can pay back the capital cost expended on the ASD rapidly, depending upon the percent of full load at which the motor operates.

Operating cost savings are not the only benefits of the technology. Others include soft-starting, or ramping up to full power, and soft-stop, or ramping down from full power, both of which prolong motor life. The technology is not without drawbacks. Some of them include: low-loading, or running a motor at a small fraction of rated speed, which can damage the motor; space required for installation of the ASD; and harmonics caused by ASDs, which can cause interference with other electronic equipment.

Motor Rewind

When a motor fails, one of the possible options is to send the motor to a repair shop, where a rewind takes place. Three issues make understanding of motor rewinds an important part of the modeling framework.

First among these, as mentioned previously, is the frequency of rewinds among motors 5 hp and greater in size. A second issue is the variability of the efficiency of the rewound motor. In most cases, motor efficiency will degrade as a result of the rewind process itself. In order to remove the old windings from a failed motor, burnoff is frequently used. In burnoff, the motor core is placed inside a furnace and baked for a period of time specified for that operation. Rewind shops which use burnoff will often conduct the burnoff at a temperature that is unsafe to the integrity of the motor core. This speeds the process, but causes a decrease in motor efficiency. Resource Dynamics Corporation 1992 used the rule of thumb that rewound motors suffer 4 to 9 percent efficiency loss.[18] Recent studies have significantly decreased this number,[19] increasing the economic appeal of motor rewind.

A third issue when considering rewind is the existing variability of rewind pricing. Causes of variance in cost include the treatment technique, the quality and gauge of wire used in the rewind, the quality of insulation materials, and the amount of damage done to the motor during failure. For example, one rewind shop might perform burnout at a temperature which causes damage to the motor core (and therefore reduces efficiency), use high quality copper wires and H-type insulators (the highest quality insulators on a scale from A to H). Another shop might perform burnout at a temperature reasonably safe to the motor core (causing negligible or no efficiency loss), but use a lower grade copper wire and common F-type insulators. Each failure presents new questions and different costs.

Table 1. Percentage of Full-Flow Input Power for Inlet Vane Fans with and without ASDs.

% of Load	% IP no ASD	% IP with ASD
100	109	105
95	100	86
90	93	73
85	86	64
80	82	57
75	78	50
70	75	44
65	72	38
60	69	32
55	66	26
50	65	21
45	64	17
40	63	14
35	62	11
30	60	8
25	56	6
20	51	5

Source: Pacific Gas & Electric, 1989.

The Potential for Electricity Savings

The reasoning behind technology measures such as high efficiency motors and ASDs is simple. Energy savings can be significant. ACEEE estimates that conservation measures such as these have a savings potential between 18 and 49 percent. ACEEE cites that the average savings over a series of five studies ranges from 30 to 48 percent. End use models can be used to express the validity of these numbers.[20]

SEGMENTATION

There are two groups of segmentation within the model. Technological segmentations help to define the differences in physical characteristics of motors and of their operation. Establishment segmentations help to define variations in the business practices, expectations and knowledge of decisionmakers, who replace the motors of a specific establishment when appropriate.

Technological Segmentations

Many of the technological segmentations in the new model are similar to those in the INFORM motor model. There are changes, which this section will emphasize. The segmentations always begin by examining the sectors of industry, as represented by the SIC. The levels of segmentation include:

- *Motor Use.* The share of motors with a specific use vary from one SIC to the next. Use and efficiency design play an important role in determining the kWh required by a motor. Differentiating between one SIC and the next is therefore important. The different uses considered by this model include pumps, fans, compressors, materials handling and materials processing.
- *Motor Size.* Motor size is an important factor used in the presentation and analysis of data on motors. Annual government reports that tally the quantity of motors purchased each year are classified according to size. Reports such as A.D. Little 1980 present significant information on motor population, again differentiated by the horsepower of the motor. The model uses the following size ranges: less than 1 hp; 1 to 5 hp; 5.1 to 20 hp; 20.1 to 50 hp; 50.1 to 125 hp; greater than 125 hp.
- *Load Type of Motor.* Here the new model retains the format of the INFORM motor model, using two load types: Constant load, where a motor spends 100 percent of its operating time at some fixed percentage of full load; and Variable load, where a motor spends various percentages of its operating time at various percentages of full load.
- *Efficiency Design of Motor.* Again, the classifications used by the INFORM motor model are used in the new model: Standard-efficiency AC motor without ASD control; Standard-efficiency AC motor with ASD control; High-efficiency AC motor without ASD control; High efficiency motor with ASD control; and DC motor.
- *Duty Cycle of Motor.* In order to make a valid comparison of replacement and repair alternatives, the cost of energy used to power a motor must be taken into consideration. The duty cycle of a motor is the sequence of loads a motor must proceed through to finish its assigned work. As duty cycles change, energy costs -- and subsequently, economic best choices for motor replacement -- change as well. A.D. Little 1980 gives an average load for a motor of a given size. This, combined with knowledge about the type of load the motor carries presents a clear picture around which can be built a series of potential duty cycles that can be altered to the user's needs. Each will be unique to the given SIC and use.

Establishment Segmentations

The establishment segmentations are distinct to the new model. Each is independent of the other and is examined for each SIC. They include:

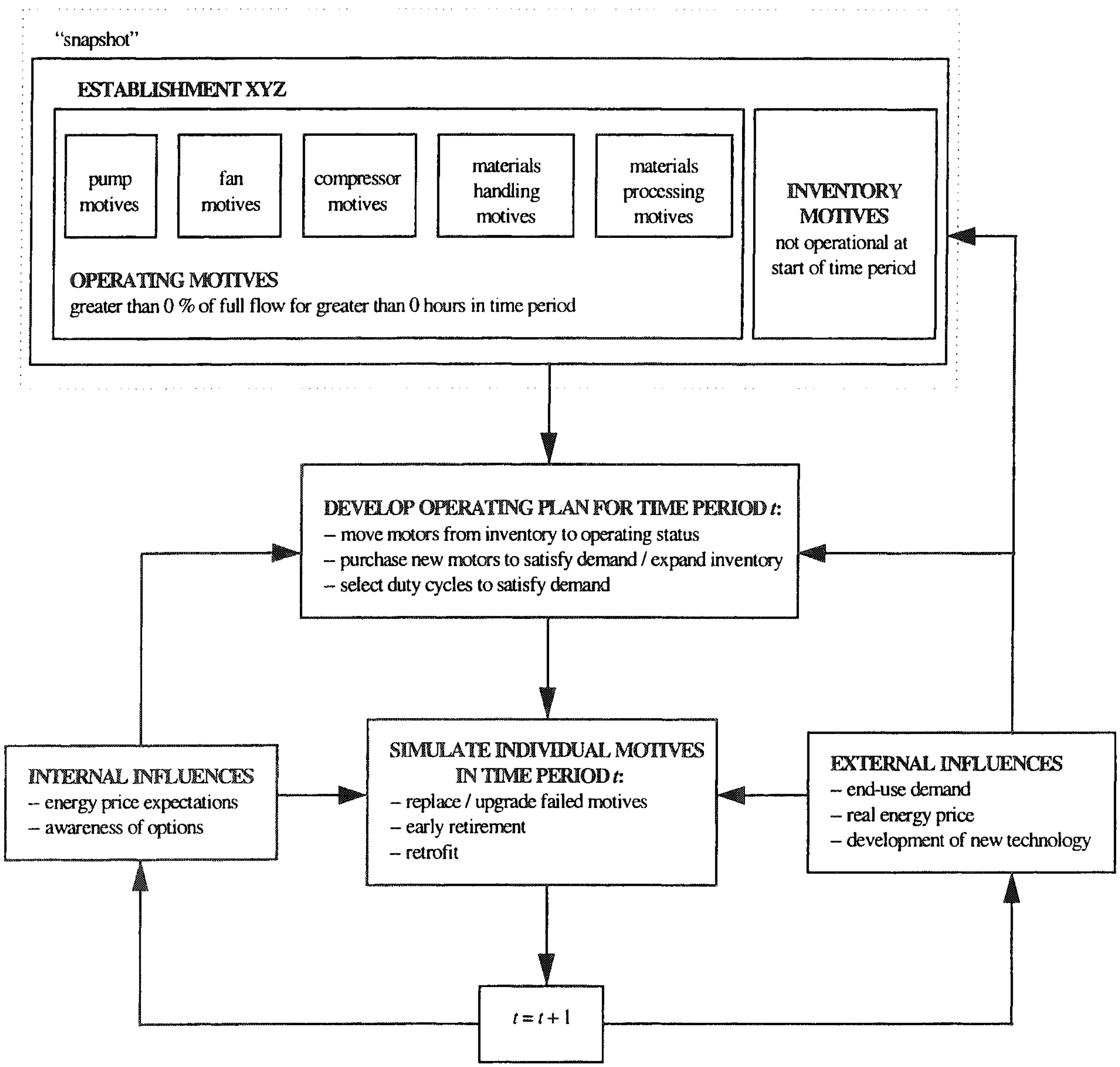
- *Rate of Return.* Each business entity has different requirements for capital investments. In the case of a necessary motor replacement, a company would consider the purchase cost and annual energy costs considering the establishment's minimum acceptable rate of return, or MARR, minimizing their total cost over that period. The company could select a motor purely on the basis of the minimum initial cost.
- *Expectation of Energy Costs.* Different decisionmakers also have different expectations about the future for energy costs. One decisionmaker may project to pay more than the current rate , while another might expect costs to decline. This segmentation permits variance in expectations.
- *Awareness of Options.* Decisionmakers also have different knowledge about products and options. For example, one decisionmaker might be aware of motor rewinds but not of ASDs. Another might be aware of high-efficiency motors and ASDs but not aware of rebates offered by electric utilities. This segmentation attempts to take into account the differences in knowledge between one decisionmaker and the next, differences that can affect the choice made at time of replacement.

A unique combination of SIC, use, size, load type, efficiency design, duty cycle, rate of return, expectation of energy cost and awareness will be referred to as a *cell*. Each cell has the potential to produce different values in the simulation.

MOTOR MODEL SIMULATION

The general procedure of the simulation model, much like that of the general segmentation outlined in the previous section, is tiered with two central areas of focus. Simulation takes place at the level of the establishment and the motor systems operated by those establishments in working towards a more accurate representation of electricity usage in the industrial sector. Influences on the model are outlined as well. Figure 1 is a flow chart representing the model's general procedure (detailed in the following sections).

Figure 1. General Procedure of the Simulation Model



Establishment Monte Carlo Simulation

It would be useful to begin by defining what is meant by an establishment in this paper, as the term likely conjures different concepts for each individual. An establishment is an industrial facility, such as a building or complex of buildings, that uses motive power in one form or another for the production of an output that can be clearly represented as belonging to a particular SIC.

Establishment simulation begins in all cases with the examination of an industrial establishment in a given SIC. This is performed at the level of the 3-digit SIC. Small, medium and large establishments are examined in the given sector of industry, and the results scaled to estimate electricity use in the SIC in question. Each establishment selected has a required output, which points to the various end-use demands of that establishment. The shares of the varied end-use demands differ based on the SIC that is being examined. Each establishment has a defined motor population existent at the base point of the simulation (the base point being defined in the model structure as some fixed time that is identical for all establishments), defined to satisfy the end-use demand. This defined motor population provides a "snapshot" of motor allocation at the base point: Motors are assumed to be operating under one of the defined end uses. Otherwise, a motor is defined as inventory and is capable of being implemented by any of the end uses as needed.

The primary purpose of the establishment simulation is to develop an operating plan for each period in the time horizon under which the establishment that is being simulated operates. From the initial motor allocation at the base point of the simulation, the establishment operating plan begins by examining end-use demand, assigning from the existing motor stock to meet the demand where possible; this includes the possibility of shifting motor stock between operating and inventory status. If demand cannot be met with the existing stock, the establishment can then purchase new motors to satisfy the demand. At this point, it is also possible that new motors will be purchased to expand the establishment inventory if the decisionmakers believe that expansion or creation of inventory will be more cost effective than purchasing for need in the future. In all cases, motor duty cycles are selected to aid in satisfying demand for the respective end uses.

It is important to note that the establishment simulation only addresses motor assignment and acquisition at the establishment level. It is left to the motive simulation to address the actual use of the motors and motor systems in the establishment. Their failures and replacement are addressed at this finer level of detail.

Motive Monte Carlo Simulation

The motive simulation examines individually selected motors operated by the simulated establishment, performing much as a sub-simulation of the establishment simulation. Each randomly selected motor lies in an appropriate cell, with technological values such as end use, size, and existing load type, efficiency design and duty cycle at the base point determined through random selection.

A value of significant interest for the motive simulation is the time until the motor next fails. Personal contact with a motor rewind shop helped bring to light the cause of motor failure. The shop estimated that better than 95 percent of the motors they received had failed due to one form or another of insulation failure. The remaining failures were characterized by the shop as mechanical, bearing failure being a prime example of this. These values are significantly different from those in Andreas, as shown in Table 2.[21] Andreas points out that insulation life can be determined using the Arrhenius model, which relates insulation life to the operating temperature of a motor.

The essence of the Arrhenius model is that insulation life is an exponential process. This is an important point from the standpoint of the simulation in that if we take insulation to be a common cause of failure, the model can approximate the time between failures as an exponential function. The exponential function is characteristic of a memoryless process, that is, a process in which the probability of failure in a given segment of time is independent of how many equivalent time segments in which failure has not taken place prior to the current segment of time. This is helpful because the model can therefore treat all motors existing in the base year as if they were new. An exponential function requires a mean value; in this case the model can consider the mean motor life. A.D. Little 1980 presents two values of interest, the mean motor life in years and the mean annual operating hours. Taking the product of these two values will result in determining the mean motor life in hours, which is the value the model will use for each motor simulated.

Table 2. Probabilities of Motor Failure Causes.

Failure Cause	Pr (Failure Cause)
Overload (overheating)	0.25
Normal Insulation Deterioration (old age)	0.05
Single Phasing	0.10
Bearing Failures	0.12
Contamination	0.43
Miscellaneous	0.03

Note: Probabilities do not add to 1.0 because of rounding error.

Source: Andreas, 1992.

In all replacement, rewind and retrofit situations, a series of options are analyzed by the simulation and the option that is optimal subject to the business practices of the decisionmaker is made. Each simulated motor is examined to determine if the motor has failed during the current time period. If this is the case, then an analysis is conducted with two possible alternatives

- the motor is rewound, or
- the motor is replaced with another motor.

The second option allows for changes in the cell characteristics of the simulated motor. Oversized motors can be replaced with smaller motors, and standard efficiency motors can be replaced with high efficiency models and/or fitted with an ASD. When a motor does not fail in the given time period, there are still a series of options that must be considered. They include

- retrofit of a motor with an ASD,
- early retirement of a working motor, or
- to do nothing

Since the 'do nothing' option does exist in the working motor case, downtime costs for installation have to be factored into the total replacement cost for the first two options which makes them unlikely (as they are to one extent or another in the real world) but potential nonetheless.

In examining a sufficient quantity of motors to represent the establishment's motor stock, the simulation is able to update stock characteristics, which the simulator can use later to examine the effectiveness and impact of projects such as rebates and legislation. This is where the true power of end-use modeling lies.

Influences on the Model

In addressing the operating plan, there are a series of influences both internal and external to the individual establishment that must be considered and discussed. The internal influences are those influences that, to one extent or another, are controlled by the actions of the establishment. The list of internal influences is representative of the establishment segmentations previously discussed: an establishment's decisionmakers control their expectations for energy price and through their own investigation (or lack thereof), control their knowledge of available technology options and rebates. These actions affect the operating plan chosen by the establishment and the results of decisions on individual motives.

Other influences are outside the direct control of the establishment. These influences include the end-use demand in a given period of the time horizon of the simulation; the real energy price charged in a given period by an electric utility; and the development of new technologies, such as super-high-efficiency motors, written pole motors[22], and fuzzy logic controlled ASDs.[23] External influences have impacts on all phases of the simulation process of a given establishment.

EXECUTION OF THE SIMULATION

Initial attempts at implementation of the simulation are to be performed subsequent to the writing of this paper. The initial implementation will be primarily spreadsheet based. Results of this work will be presented in conjunction with this paper.

REFERENCES

1. Institute for Interdisciplinary Engineering Studies, Purdue University, and University of Texas at Austin, 1994. Notes from the short course *Industrial Electrification: Technology & Economics,* held May 17-20, West Lafayette IN. v. 1, p. 50.

2. Energy Information Administration, 1994. *Manufacturing Consumption of Energy 1991.* DOE/EIA - 0512(91). United States Department of Energy, Washington DC.

3. Resource Dynamics Corporation, 1992. *Electric Motors: Markets, Trends, and Applications.* Electric Power Research Institute, Palo Alto CA (Project Manager Ben Banerjee). pp. 9-10.

4. McMenamin, J. Stuart and Frank J. Monforte. *User's Guide for INFORM-PC 1.0.* Regional Economic Research, Inc., San Diego CA for Electronic Power Research Institute, Palo Alto CA (Project Manager Phil Hummel). 1992. ch. 5, p. 1.

5. McMenamin and Monforte, ch. 5, pp. 1-23.

6. Washington State Energy Office, 1992. *MotorMaster Electric Motor Selection Software Version 1 User's Reference Guide.* Olympia WA. p. 8.

7. Jaccard, Mark and John Nyboer, 1992. *ISTUM-PC User Guide.* School of Resource and Environmental Management, Simon Fraser University, Vancouver BC. v. 1, pp. 4-5.

8. Jaccard and Nyboer, v. 1, pp. 20-21.

9. Arthur D. Little, Inc., 1980. *Classification and Evaluation of Electric Motors and Pumps.* United States Department of Energy, Washington DC. ch. 3, pp. 47, 49.

10. McCoy, Gilbert A., Todd Litman, and John G. Douglass. *Energy-Efficient Electric Motor Selection Handbook.* Washington State Energy Office, Olympia WA for Bonneville Power Authority, Portland OR and United States Department of Energy, Washington DC. Revision 2, 1992. p. v.

11. Elliott, R. Neal, 1994. *Electricity Consumption and the Potential for Electric Energy Savings in the Manufacturing Sector,* American Council for an Energy-Efficient Economy, Washington DC. p. 29.

12. Lovins, Amory B., Joel Neymark, Ted Flanigan, Patrick B. Kiernan, PE, Brady Bancroft and Michael Shepard. *The State of the Art: Drivepower.* COMPETITEK, an information service of Rocky Mountain Institute, Snowmass CO. April 1989. p. 103.

13. Resource Dynamics Corporation, 1993. *Electric Motor Systems Sourcebook.* Electric Power Research Institute (Project Manager Ben Banerjee), United States Department of Energy, Washington DC (Project Manager Paul Scheihing) and Bonneville Power Authority, Portland OR (Project Manager Craig Wohlgemuth). 1993. ch. 2, p. 7.

14. *BALDOR Motors & Drives Stock Products Catalog 501.* Baldor Electric Company, Fort Smith AR. 1992.

15. Nadel, Steven, Michael Shepard, Steve Greenberg, Gail Katz and Anibal T. de Almeida. *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities.* American Council for an Energy-Efficient Economy, Washington DC. 1992. p. 121.

16. Pacific Gas & Electric, 1989. *Adjustable Speed Drives: What's in it for You?* (brochure).

17. Lovins, Amory B., et al., p. 236.

18. Resource Dynamics Corporation, 1992. p. C-1.

19. Douglass, John G. *Electric Motor System Repair and Rewind.* From the unpublished Proceedings of the Motor Challenge Tools and Protocols Workshop, September 22-23, 1994. United States Department of Energy, Washington DC.

20. Elliott, R. Neal, pp. 36-38.

21. Andreas, John C. *Energy-Efficient Electric Motors: Selection and Application.* Marcel Dekker, Inc., New York. 1992. p. 244.

22. Morash, Richard T., Ronnie J. Barber and John F. Roesel, Jr., Precise Power. *"Written Pole" Motor - A New AC Motor Technology.* EPRI Advance Motor Drive News, v. 2, no. 2, Winter 1995. Electric Power Research Institute, Palo Alto CA. p. 4.

23. Spiegel, Ronald J. and Paul J. Chappell, 1993. *Fuzzy Logic Integrated Control Method and Apparatus to Improve Motor Efficiency.* U.S. Patent 5,272,428. United States Patent and Trademark Office, Crystal City VA. 1993.