A Longitudinal Study of Non-Residential DSM Measure Retention

Donald R. Dohrmann, ADM Associates, Inc., Sacramento, CA
Marian V. Brown, Southern California Edison Company, Rosemead, CA
Martin H. Morse, ADM Associates, Inc., Rochester, NY

ABSTRACT

This paper reports on the results of a four-year longitudinal study of the retention rates and effective useful lives of demand-side management (DSM) measures installed by customers of Southern California Edison (SCE) in 1993 and 1994 under SCE's Commercial, Industrial, and Agricultural (C/I/A) Energy Efficiency Incentives Programs.

Study Scope

The objectives of this non-residential measure retention study were as follows:

- Locate energy conservation measures installed by 1993 or 1994 participants in SCE's commercial, industrial, and agricultural energy efficiency incentive programs
- Establish baseline conditions by determining fraction of measures that were installed and operational
- Determine rates of early removal and disconnects and reasons why
- Determine what has replaced removed measures
- Identify changes in usage patterns over time and in circumstances of use (e.g., location of measure, end-use service provided, use of space in the area surrounding the measure, etc.) over time
- Establish measures' effective useful lives

The measures studied were as follows:

- Commercial sector measures:
- Electronic ballasts
- CFBs (modular)
- T8 lamps
- Delamping/Reflectors
- HVAC EMS systems
- High-Efficiency Chiller Systems
- Adjustable Speed Drives

- Industrial/Agricultural Measures:
- Adjustable Speed Drives
- Pumps
- Pump System (hardware) improvements
- Ballasts
- T8 Lamps
- Lighting EMS
- Injection molding
- Process cooling
- Insulation on process equipment
- Air compressors
- High efficiency chillers (for processes)

Survey Design

Data on measure retention were collected for a sample of facilities chosen from among SCE customers who participated in SCE's Energy Management Hardware Rebate Program (EMHRP) in 1993 and 1994. The sample of facilities was chosen through measure-based sampling. The goal in preparing the sample design was to permit the useful life of a measure to be estimated with a relative precision of ±20 percentage points at the 80 percent confidence level. A sample that combined sample points from the EMHRP for 1993 and 1994 was used to satisfy these precision/confidence requirements. At the same time, the sample design incorporated features to lower the data collection costs.

The analytical framework for the development of the sample design for the study was provided by survival analysis techniques. Survival analysis pertains to the analysis of data that correspond to the time from a well-defined time origin until the occurrence of some particular event or end-point. For this study, the time origin was defined by the installation of a measure under the EMHR program, while the end-point was defined by the removal or failure of the measure or the discontinuance of its use.

The measure survival data were expected to have several features that warranted special treatment in preparing the sample design.

- The measure survival data would probably not be symmetrically distributed and could not be reasonably represented by a normal distribution.
- The survival data would be right-censored in that the removal, failure, or discontinuance end-points would not be observable for some of the installed measures.
- The survival data for some types of measures (e.g., lighting measures) would likely be affected by clustering. That is, a single customer might have multiple occurrences of a particular type of measure (e.g., T8 lamps). For a single customer, there could be expected to be some homogeneity in the lifetimes for the particular type of measure, since they were all installed at the same time and were subject to similar operational conditions. Because of this homogeneity, a sample of clustered measure occurrences would provide less information than a similar sample that did not show such homogeneity.

A sample design for addressing these and other features of the data was developed through the following steps.

- First, the number of removals/failures required to meet the precision/confidence specifications for each type of measure was determined.
- Second, the probability of removal/failure for each type of measure over the period of the study was determined and applied to the required number of removals/failures to determine the number of points required in the sample.
- Third, the required sample size was adjusted to account for the effects of clustering.
- Fourth, sample points for a measure were allocated among facilities.

To arrive at quantitative estimates of the required sample sizes for the various types of measures, it was necessary to use a parametric representation for the measure survival data. For the purposes of sample design, it was assumed that the survivor function for a measure's life data could be represented with the exponential distribution. With an exponential survivor function, the standard error for the estimated mean from a sample depends on the number of removals/failures that are observed. In particular, 41 removals/failures would be required to estimate mean measure life for a particular measure at a relative precision of ±20 percent at the 80 percent confidence level.

Not all of the occurrences of a measure would be observed until their life end-point, giving rise to right-censoring in the sample. Accordingly, the number of measure occurrences brought into the sample had to be greater to accommodate this right censoring phenomenon. The sample size needed to provide the required number of removals was determined as follows:

$$\text{Sample Size} = \frac{\text{Number of required removals / failures}}{\text{Probability of removal / failure}}$$

The probability of removal/failure with an assumed survivor function could be calculated as a function of (1) specified values for the survivor function, (2) the study accrual time (i.e., the period when measure occurrences take place) and (3) the study follow-up time (i.e., the period when occurrences are tracked to see whether they are removed or fail). For this study, the accrual period was 24 months (the years 1993 and 1994 for the EMHR Program), and the follow-up period was 48 months (the four years 1995-1998 when on-site and telephone data collection occur). Mean values of measure life for calculating the parameters of the assumed exponential survivor functions for the various types of measures were taken from a report on *DSM Measure Life Project: Master Tables of Measure Life Estimates and Final Report*, prepared by Energy Management Services for the California DSM Measurement Advisory Committee (CADMAC).

Given that the length of the study was fixed, the probability of removal/failure was determined primarily by the expected mean life of a measure. The shorter the mean life of a measure, the higher the probability of removal or failure. For example, the probability of removal/failure is 0.593 for a measure with a mean life of 5 years and 0.368 for a measure with a mean life of 10 years. With the required number of removals/failures for either type of measure being 41, the respective sample sizes are 69 and 112.

For measures where there were expected to be multiple occurrences at a site (e.g., for lighting measures), an additional step in the sample design was to adjust for the intra-site correlation among useful lives for the different occurrences at a site. A sample drawn from clusters with some degree of homogeneity carries less information than a random sample of the same size which is heterogeneous. On the other hand, using a cluster sampling approach would lower the number of sites that needed to be visited, thereby reducing costs.

A two-stage sampling procedure was used, with sites were designated as primary sampling units and measure occurrences as secondary sampling units. A sample of sites was chosen first and then a sample of measure occurrences was chosen within each selected site. Whether information was collected for all or for a sample of measure occurrences at a site depended on the type of measure.

- For lighting measures, a sampling of occurrences was used. For each type of lighting measure, 10 occurrences of the measure were inspected at a sample site. Fixture groups were defined that had equivalent physical design and approximately similar operating hours (based on lighting system operating controls). Detailed information was recorded on ballast, reflector, lens, bulb, controls, task use, and other features as installed under the program and as noted on program records.

- For HVAC measures and process measures, a census approach was used, since there were generally only one or two occurrences of a measure at a site.

For each type of measure, EMHRP participants in each year were stratified according to program year, business sector and size.

- The number of sample points required for any particular measure was divided equally between 1993 and 1994 participants.
- With the business sector stratification, participants were separated into a commercial customer class and an industrial/agricultural customer class.
- Within each measure/sector grouping, customers were further stratified according to size using a program category variable developed by SCE program staff. Commercial and industrial customers were assigned to categories according to their kW demand.

In practice, customers who had been surveyed within the past year for another SCE study were not included in the sample. Where possible, the data collected on such customers for the other studies were used. For example, data for sites with chillers that had been visited as part of an impact evaluation of the EMHR Program were included in the sample for the retention study.

The final sample of sites that resulted after sample design and recruitment is shown in Table 1. There was a total of 937 sites included in the final sample, distributed across sectors and program years as shown in Table 1. Also shown in Table 1 are the numbers of sites having the measures of interest for the study. The number of occurrences for some of the measures was higher than the number of sites because of multiple occurrences of a measure at a site. For example, there generally were multiple occurrences of lighting measures at a site.

Table 1. Final Sample of Sites for Retention Study

	1993 Commercial	*1993 Industrial/ Agricultural*	*1994 Commercial*	*1994 Industrial/ Agricultural*	*All Sites*
Total Number of Sites	356	179	253	149	937
Numbers of Sites with Specified Measures					
ASDs	78	49	64	42	233
T8 Lamps	145	59	114	41	359
Electronic Ballasts	98	52	114	41	305
Compact Fluorescent Bulbs	79		50		129
Delamping/Reflectors	72		28		100
Chillers	17		21		38
HVAC Energy Management Systems	94		84		178
Pump Improvements		26		31	57
Pump Replacements		48		50	98
Lighting EMS				11	11
Injection molding machines				24	24
Plastic extrusion equipment				6	6
Process cooling				7	7
Process equipment insulation				9	9
High efficiency chillers				7	7
Air compressors				18	18

Data Collection Instruments And Procedures

Data for the measure retention study were collected both through on-site visits and telephone interviews over the four-year period of the study. Each sampled site was visited on-site twice, once for baseline data collection and once for follow-up. To keep track of events that were relevant to measure retention but which occurred between on-site surveys, two telephone follow-up interviews were conducted for each sampled site as well.

Baseline and follow-up data on the measures studied were collected through the on-site data collection visits. Data were collected that could be used to estimate effective measure lives and to analyze the effects on service lives of such factors as operational hours, maintenance practices, etc. The on-site data collection forms were designed for collecting the following types of information:

- Was the program-installed measure still in place and properly installed as specified by program requirements?
- If the measure was not in place and/or properly installed:
  - Was it removed, disconnected, broken, or damaged?
  - Why?
  - When was it removed/disconnected?
  - Was its removal part of a larger change? What?
  - What, if anything, replaced the measure?
- Was the measure in a good state of repair?

- Was there a specific maintenance schedule for each measure?
- Has the use of space surrounding the measure changed since installation? How?
- Was the equipment used differently than it was originally? Less? More? Had it been modified?
- Had there been business turnover and/or occupant changes?
- What were the customer and building characteristics?

Program data that SCE had collected were used to establish the baseline information on equipment and measures that were installed in the buildings under the EMHR Programs. Changes from these data were indicative of building changes and component changeouts. Information extracted from the program records was provided to the field staff so that they could know what "was" to compare with what "is" at the site and thereby note or query any apparent changes.

Discrepancies between baseline, interview, and visual inspection results were resolved by field personnel prior to leaving a facility. The field staff prepared facility layouts that showed the locations of the measures inspected. They also placed stickers on the measure devices to identify them as being included in this study; the stickers included a telephone number to be called if the devices were removed.

For the follow-up on-site data collection, the baseline data collection form was carried back to the site, and changes in any of the original conditions at the site were noted on the form.

For the telephone interviews, information was collected to determine the following:

- Whether the facility identified in the baseline survey was still occupied
- Whether the owner/tenant had changed
- Whether the business conducted on the site had changed
- Whether remodels or renovations had occurred or were planned
- Whether the building occupant was satisfied with the measure

Retention Rates For Measures

The data collected were used to establish baseline conditions by determining the fraction of measures that had been installed and were operational and to determine the rates of early removal and disconnects and the reasons for early removal and disconnects.

The fourth-year retention rates for the various types of measures for each program year are shown in Table 2. The rates of retention for some of the measures were relatively high (e.g., energy management systems, chillers).

Table 2. Retention Rates for Measures

Type of Measure	*Number of Measures Installed in Sample*	*Number of Measures Removed, Failed or Replaced in Four Years after Installation*	*Percentage of All Measures Removed, Failed or Replaced in Four Years after Installation*	*Percentage of Measures Retained after Four Years*
Commercial Sector Measures: 1993 and 1994 Program Years Combined				
T8 lighting fixtures	2,613	244	9.3%	90.7%
T8 lamps	6,667	2,209	33.1%	66.9%
Electronic ballasts	2,749	161	5.9%	94.1%
CF fixtures (modular)	1,301	74	5.7%	94.3%
CF lamps	1,586	403	25.4%	74.6%
Delamping/reflectors	1,354	105	7.8%	92.2%
HVAC EMS	178	2	1.1%	98.9%
Chillers	38	-	0.0%	100.0%
Adjustable speed drives	225	6	2.7%	97.3%
Industrial Sector Measures: 1993 and 1994 Program Years Combined				
T8 lighting fixtures	1,005	66	6.6%	93.4%
T8 lamps	2,753	525	19.1%	80.9%
Electronic ballasts	1,073	30	2.8%	97.2%
Adjustable speed drives	139	14	10.1%	89.9%
Lighting EMS	11	1	9.1%	91.9%
Injection molding machines	27	5	18.5%	81.5%
Plastic extrusion equipment	8	3	37.5%	63.5%
Process cooling	6	0	0.0%	100.0%
Process equipment insulation	5	1	20.0%	80.0%
High efficiency chillers	5	0	0.0%	100.0%
Air compressors	18	3	16.7%	83.3%
Agricultural Sector Measures: 1993 and 1994 Program Years Combined				
Pumps/pump system improvements	175	18	10.3%	89.7%
Adjustable speed drives	139	14	10.1%	89.9%

Estimates of Effective Useful Lives

For purposes of this study, the effective useful life of a measure was defined as the median number of years that the measure installed under a program was in place and operable. In effect, the median age is the number of years that pass until 50% of the installed measures are no longer in place and operable. Determining the effective useful life according to this definition required deriving a survival function for a measure, where a survival function shows the fraction of installed measures still in place and operable as time passes.

Because the retention rates for the first four years after installation were relatively high for the measures studied, non-parametric methods of estimating survival functions were not appropriate. Non-parametric methods can give an accurate estimate of median survival time only if more than 50% of the measures are no longer in place and operable.

Parametric methods therefore were used for estimating a median survival time for each measure. One difficulty with using a parametric approach to estimate a survival function directly is that if a measure has a high early retention rate, then there is little information with which to distinguish between different functional forms for the survival function. By definition, 100% of the measures were in place and operable under baseline conditions. As Table 2 showed, estimates of the percentage of measures still in place after three or four years could also be determined from the data collected. However, no actual data on which to base the survival function were available for the particular measures beyond the third or fourth year. Because of the limited time span that the collected data cover, a variety of functions that imply significantly different survival patterns and median lives could be fitted through the data points.

Instead of estimating the survival function directly, a hazard function was first estimated using the available data, and the estimated hazard function was then used to develop an associated survival function. A hazard function defines the probability that an item will fail in the next unit of time, given that it has survived to the present. For the analysis in this study, the hazard rate for any given time period (e.g., a year) represents the proportion of measures that were removed or failed during the time period, given that they had survived to the beginning of the time period Once a hazard function is estimated, a corresponding survival function S(t) can be determined, where S(t) represents the percent surviving at time t.

Two of the distributions commonly used for survival analysis are the exponential distribution and the Weibull distribution. With the exponential distribution, the hazard rate is constant, and the associated survival function is also exponential. However, the exponential distribution does not represent hazards that increase or decrease over time. If the hazard rate does increase or decrease monotonically with age, the Weibull distribution can be used to represent the hazard function and the survival function.

To illustrate the procedure used to estimate measure life, consider T8 lamps in the commercial sector as an example. To estimate a hazard function for T8 lamps, data were taken from the on-site data collection, since dates of removal for individual lamps were identified during the on-site inspections. Data for both 1993 and 1994 program years were combined for the analysis. These data and the calculated hazard rates are reported in Table 3.

Table 3. Data for Calculating Hazard Rates for Commercial T8 Lamps

Years since Installation	*Lamps at Start of Year*	*Lamps Removed/Failed during Year*	*Hazard Rate (Rate of Removal/Failure)*
1	6,667	35	0.52%
2	6,632	166	2.50%
3	6,466	714	11.04%
4	5,752	1,294	22.50%

Inspection of the calculated hazard (removal/failure) rates for commercial T8 lamps for each year since installation showed clearly that the hazard rate increased over time. It therefore was not warranted to assume that the survival function for T8 lamps could be represented using the exponential distribution. A Weibull-based hazard function was therefore used as the functional form for estimating the hazard function for T8 lamps.

A power curve fit to the hazard rate data in Table 3 provided the estimates of the parameters for the Weibull distribution representation of the hazard rate function. The resulting parameterization of the Weibull function for the hazard function was as follows:

Weibull hazard rate function for age t = h(t) = $0.00125*3.7594*Age^{2.7594}$

The associated survival function is given by

Percent surviving at age t = S(t) = $\exp(-0.00125*Age^{3.7594})$

For this survival function calculated for commercial T8 lamps, the median survival time is 5.37 years. By comparison, SCE's ex ante estimate of the effective useful life of a T8 lamp in the commercial sector is 5 years.

A statistical test of whether the ex post estimate of useful life is significantly different from the ex ante estimate can be made by constructing an 80% confidence interval around the ex post estimate and determining whether the ex ante estimate falls within this confidence interval. If the ex ante estimate falls inside the constructed confidence interval, then the hypothesis of no difference between the ex ante and ex post estimates cannot be rejected.

Three sets of parameters for the Weibull hazard rate function were used to construct an 80% confidence interval for the estimated median life of a measure. These sets of parameters were provided by the power curve regression analysis for each measure. One set was the "best" fit parameters, and the other two sets were for the upper and lower bounds of the 80% confidence interval for the estimated "best fit" coefficients.

Figure 1 illustrates this for the case of T8 lamps. Shown there are the "best" fit survival function and the upper and lower bound survival functions associated with the 80% confidence level. The upper and lower bounds on the "best" fit survival function provide the confidence interval bounds for the estimated median useful life. For T8 lamps, the estimated median useful life was 5.37 years. The 80% confidence interval for this estimate is 4.31 years to 6.96 years. Because SCE's ex ante estimate of 5 years for the useful life of T8 lamps falls within this confidence interval, the hypothesis of no difference between the ex ante and ex post estimates could not be rejected.

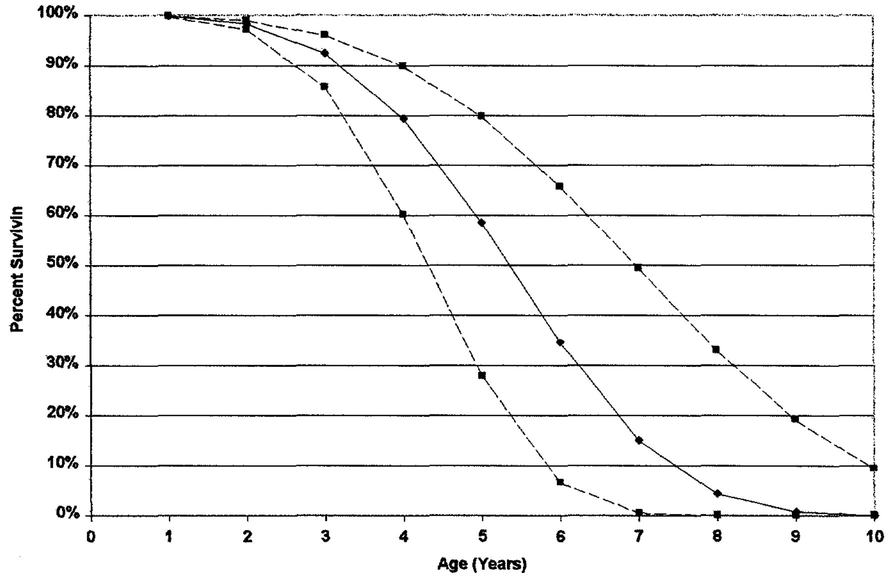

Figure 1. Survival Function Plot for T8 Lamps in Commercial Sector with Upper and Lower Bounds

Similar analyses were performed for other measures where data were sufficient. However, the analysis could not be applied to measures where the numbers of removals or failures were too low to support estimation of a hazard function. Generally, the analysis could be performed for lighting measures and adjustable speed drives, but could not be performed for HVAC and lighting EMS, for high efficiency chillers, and for process measures.

All of the measures for which the data allowed analysis of effective useful lives showed hazard rates that increased with time, so that a Weibull distribution was used to represent the hazard function for each. The resulting estimates of median survival lives are reported in Table 4 and compared to SCE's ex ante estimates of effective useful lives. There was relatively good agreement between SCE's ex ante estimates of effective useful lives and the median survival lives estimated through this study. Only for two measures (i.e., electronic ballasts and compact fluorescent lamps) could the hypothesis of no difference between ex ante and ex post estimates be rejected.

One reason why the median useful life of electronic ballasts as estimated through this study is somewhat lower than SCE's ex ante estimate is that some electronic ballasts manufactured in 1993 and 1994 failed relatively early. To the extent that manufacturing problems with such ballasts carried over, the survival function estimated in this study would show higher percentages of failures in early years, which would lower the estimate of median useful life.

Table 4. Estimated Median Lives Compared to Ex Ante Estimates (Lives in years)

Measure	*SCE Ex Ante EUL Value*	*Estimated Median Life*			*Ex Ante Different from Ex Post?*
		80% Lower bound	*Estimate*	*80% Upper Bound*	
Commercial Measures					
T8 lighting fixtures	11	2.24	9.11	> 100	No
T8 lamps	5	4.31	5.37	6.96	No
Electronic ballasts	10	6.82	7.80	8.78	Yes
CF fixtures (modular)	12	4.38	10.51	78.43	No
CF lamps	2.2	5.48	5.73	5.99	Yes
Delamping/reflectors	10	4.20	18.85	>100	No
Adjustable speed drives	10	**	11.13	**	No
HVAC EMS	15	**	*	**	No
Chillers	20	**	*	**	No
Industrial Measures					
T8 lighting fixtures	11	**	9.18	**	No
T8 lamps	5	3.36	4.32	6.08	No
Electronic ballasts	10	5.97	7.94	11.65	No
Adjustable speed drives	10	**	12.31	**	No
Lighting EMS	15	**	*	**	No
Injection molding machines	15	**	*	**	No
Plastic extrusion equipment	15	**	*	**	No
Process cooling	15	**	*	**	No
Process equipment insulation	15	**	*	**	No
High efficiency chillers	20	**	*	**	No
Air compressors	15	**	*	**	No
Agricultural Measures					
Pumps/pump system improvements	11	2.05	6.72	>100	No
Adjustable speed drives	10	**	12.31	**	No

*Data not sufficient to estimate median life.

**Data not sufficient to estimate confidence interval.

Conclusions

This study represented a major multi-year effort to collect and analyze data pertaining to the lives of demand-side management measures. A sample design was used that would ensure that, where possible, sufficient data would be collected with which to estimate useful lives. Sufficient data were collected with which to develop estimates of useful lives for lighting measures. However, for long-lived measures (e.g., HVAC EMS, chillers), the number of removals or failures that could be observed even over a four-year period was not sufficient to support estimation of useful lives.