A Technique for Predicting Compressor Replacement Rates in a System

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A technique for predicting compressor replacement rates in a system

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ABSTRACT

A method for predicting failure rates is presented using a series of constants assigned by a regression analysis technique applied to a simple equation. A basic failure rate is multiplied by constants representing the effects of compressor design details and each system component. Other factors can be added representing manufacturing quality, installation and service skill level, etc.

BACKGROUND

With the maturing of the central air conditioning and heat pump business has come the desirability of predicting the reliability of the motor-compressor used in any given system. The scheme for accomplishing this prediction should be tied to a definition of the motor-compressor itself along with all proposed system components and a definition of the system. Further use can be made of a definition of manufactured quality (of the compressor and system), the degree of competence of installation and quality of service.

To begin, a reliability history of a line of compressors in total is necessary, along with a history of the reliability of a number of unitary equipment models using these compressors in sufficient quantity to be statistically significant. Originally two production years (1975 and 1976) were chosen. Five year replacement rates had been predicted to a fairly high degree of confidence. For these years, 74 cooling unit models and 44 heat pump models were used. In later stages of the program when the computer was being used, a smaller number of the higher volume models was used in order to reduce the number of models handled.

RELIABILITY EQUATION

An equation for the five year failure rate \( R_{5} \) is written as follows:

\[
R_{5} = R_{C} \times C_{S} \times C_{PR} \times C_{CHG} \times C_{FC} \times C_{SH} \times C_{...}
\]

For a listing of factors considered, along with early values used, see Figure 1. Originally values were assumed based on discussions with individuals with experience in compressor design, unit design, reliability studies, and product service. Values were adjusted by strictly empirical observation and comparison to predicted replacement rates by model.

Compressor basic rates \( R_{C} \) were assumed for each basic family in the model line. The more significant items first tried were stroke factor \( C_{S} \), product \( C_{PR} \) (cooling or heat pump), charge \( C_{CHG} \), flow control \( C_{FC} \), crankcase heat \( C_{SH} \), operating range \( C_{OR} \), power supply \( C_{PS} \) and packaged or split \( C_{SP} \). The stroke factor is basically the length of stroke squared. The product factor was taken as 1 for cooling units and 1.5 for heat pumps. The charge factor is based on results of flooding tests which determined the amount of refrigerant that each compressor family could tolerate. Thus:

\[
C_{CHG} = \left( \frac{\text{unit charge}}{\text{tolerance}} \right)^2
\]

Five year replacement rates were then calculated for each unit model in the product line by using the above equation.

After tracking rates of the 1975 and 1976 production years, it was recognized that values should be assigned to other factors to improve the overall results. Results were so promising that calculated failure rates were used to project total costs of
a product line while still in the design stage. Further accuracy of the various factors could be improved by a regression routine on a computer.

REGRESSION ANALYSIS

The equation form $R_{05} = R_c X C_1 X C_2 X C_3 X \ldots X C_N$ is not in a standard form for common regression routines. It should also be noted at this time that general regression of this equation does not provide a unique solution. To show this point, consider the following: Suppose you do have the best solution, with $C_1$ being assigned the values $c_{1A}$ and $c_{1B}$ depending on two mutually exclusive attributes, $C_2$ being assigned the values $c_{2A}$ and $c_{2B}$ depending on two more mutually exclusive attributes, and so on down to $C_{NA}$ and $C_{NB}$. A solution just as good as this best solution can be obtained by multiplying $C_{1A}$ and $C_{1B}$ by a constant $K$ and dividing $C_{2A}$ and $C_{2B}$ by $K$. Another solution is obtained by multiplying $C_{1A}$ and $C_{1B}$ by $K$ and dividing $C_{NA}$ and $C_{NB}$ by $K$. The same overall solution is obtained by multiplying any $C_i$ set of constants by a given number and dividing another $C_j$ set of constants by the same number.

When given known replacement rates and the attributes of a complete system, there are several methods to determine the coefficient $R_c$ and $c_{1A} - c_{N}$. A simple method is trial and error; this is very wasteful of resources, whether done by hand or computer. A more useful method is obtained by taking the logarithm of the equation.

$$\ln(R_{05}) = \ln(R_c X C_1 X C_2 X \ldots X C_N) \quad \text{(1)}$$

or

$$\ln R_{05} = \ln R_c X \ln C_1 + \ln C_2 + \ldots + \ln C_N \quad \text{(2)}$$

To demonstrate the advantage of this transform, consider a very simple case. There are 7 known replacement rates $R_1, R_2, \ldots, R_7$ for 7 systems. We desire to determine coefficients for $R_c$, which has three mutually exclusive coefficients $R_{CA}, R_{CB}$ and $R_{CC}$, and for $C$, which has two mutually exclusive coefficients $C_{1A}$ and $C_{1B}$. System 1 has attributes $R_{CA}$ and $C_{1A}$. The replacement rate equation can then be written

$$\ln R_1 = \ln R_{CB} + \ln C_{1A} \quad \text{(3)}$$

Let $r_1 = \ln R_1$, $r_{CB} = \ln R_{CB}$, and $c_{1A}$; and the equation becomes

$$r_1 = r_{CB} + c_{1A} \quad \text{(4)}$$

The equations for all 7 in this hypothetical case are:

$$r_1 = r_{CB} + c_{1A}$$
$$r_2 = r_{CA} + c_{1A}$$
$$r_3 = r_{CC} + c_{1A}$$
$$r_4 = r_{CB} + c_{1B}$$
$$r_5 = r_{CA} + c_{1B}$$
$$r_6 = r_{CB} + c_{1B}$$
$$r_7 = r_{CB} + c_{1A}$$

These can be rewritten as:

$$r_1 = (0)r_{CA} + (1)r_{CB} + (0)r_{CC} + (1)c_{1A} + (0)c_{1B}$$
$$r_2 = (1)r_{CA} + (0)r_{CB} + (0)r_{CC} + (1)c_{1A} + (0)c_{1B}$$
$$r_3 = (0)r_{CA} + (0)r_{CB} + (1)r_{CC} + (1)c_{1A} + (0)c_{1B}$$
$$r_4 = (0)r_{CA} + (1)r_{CB} + (0)r_{CC} + (0)c_{1A} + (1)c_{1B}$$
$$r_5 = (1)r_{CA} + (0)r_{CB} + (0)r_{CC} + (0)c_{1A} + (1)c_{1B}$$
$$r_6 = (0)r_{CA} + (0)r_{CB} + (1)r_{CC} + (0)c_{1A} + (1)c_{1B}$$
$$r_7 = (0)r_{CA} + (1)r_{CB} + (0)r_{CC} + (1)c_{1A} + (0)c_{1B}$$

Although these are now in the form for multiple linear regression, standard regression routines will not handle the problem. Even though there are 7 equations and 5 unknowns, only 4 of the equations are independent. Increasing the number of equations will not change this situation. This is consistent with the statement above that a unique best solution does not exist.
(6) can be written as:

\[
\begin{bmatrix}
  r_1 \\
r_2 \\
r_3 \\
r_4 \\
r_5 \\
r_6 \\
r_7
\end{bmatrix}
= 
\begin{bmatrix}
  0 & 1 & 0 & 1 & 0 & 0 & 1 \\
  1 & 0 & 0 & 1 & 0 & 0 & 1 \\
  0 & 0 & 1 & 1 & 0 & 0 & 1 \\
  0 & 1 & 0 & 0 & 1 & 0 & 1 \\
  1 & 0 & 0 & 0 & 1 & 0 & 1 \\
  0 & 0 & 1 & 0 & 1 & 0 & 1 \\
  0 & 1 & 0 & 1 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  r_{CA} \\
r_{CB} \\
r_{CC} \\
r_{IA} \\
r_{IB} \\
\end{bmatrix}
\]

(7)

By setting \( r \) equal to the vector of known failure rates, \( X \) equal to the matrix of ones and zeroes, and \( c \) equal to the vector of desired constants we obtain:

\[
r = Xc
\]

(8)

c cannot be found by \( c = X^{-1}r \) (where \( X^{-1} \) is the matrix inverse of \( X \)) because \( X^{-1} \) cannot be found. However, by use of \( X^T \), matrix transformation, the following equation can be obtained.

\[
X^T r = X^T X c
\]

or

\[
c = (X^T X)^{-1} X^T r
\]

(9)

This form will provide a least squares solution to (6) provided that a generalized matrix inversion routine is available to find \((X^T X)^{-1}\).

The solution vector \( c \) will include 5 constants, one of which is zero. This is due to the fact there are only 4 independent equations. The original coefficients are then obtained by exponentiating each constant in \( c \). Thus \( R_{CA} = e^{r_{CA}} \) and so forth. Since \( e^0 = 1 \), one of the coefficients will be 1.

This example can easily be expanded to include other attributes. The solution vector \( C \) for equation (1) will contain \( N \) zeroes, one for each of the general attribute \( C_1 \) - \( C_N \).

Although (10) is a least squares fit it is minimizing the sum of \((\ln R_{R5})^2\) rather than \((R_{R5})^2\). One method to bias the regression is to multiply both sides of line 1 in equation (6) by \( R_1 \), both sides of line 2 by \( R_2 \), and so on. This transformation forces the regression to minimize the sum of \((\ln R_{R5} R_{R5})^2\). For the range of numbers used, this transformation is somewhat approximate to \((R_{R5})^2\) and works very well.

The above technique is shown for mutually exclusive attributes, such as a factor \( C_1 \) for heat pump or cooling use. That is, the system is one or the other, but not both. This forms the matrix of zeroes and ones in (7). Certain factors, such as stroke and change factors, are not of this type. These factors are continuous functions. If the factor function is known (such as \( C_S = 5^2 \)), then each known replacement rate \( R_{R5} \) can be divided by \( C_S \) for that system. The equations thus appear as in (7) except that \( r_1 - r_N \) are now modified. Another approach is to set up another column of numbers in the large matrix (7). For example, if a column of compressor strokes is included in (7) a new coefficient \( c_L \) is obtained. The resulting regression now gives a function for the stroke, \( C_S = e^{c_L} \). Transforms can again be used to alter the form of this function.

**CONCLUSION**

An example using the most recently used coefficients can now be explored. A proposed 2½ ton split heat pump will be considered. This is defined as a 230 volt, single phase unit with a 10.4 pound R-22 charge, a thermostatic expansion valve with a 15% bleed port outdoors, and a capillary tube indoors. The compressor is a two cylinder permanent split-capacitor machine with a 0.866 inch stroke. Off cycle crankcase heat is by "Trickle Circuit." It has been determined that the charge tolerance (For \( C_{CHG} = 1 \)) is 9 pounds. For purposes of this example, the basic compressor rate \( (R_C) \) is 1.2. Factors and their values are:

\[
\begin{align*}
R_C &= 1.2 \\
C_S &= (0.866)^2 = 0.75 \\
C_{PR} &= 1.6 \quad \text{(Heat Pump)} \\
C_{S/P} &= 1.3 \quad \text{(Split)} \\
C_{CHG} &= (10.4 \div 9)^2 = 1.335 \\
C_{FC} &= 1.8 \\
C_{PS} &= 1 \\
C_{SH} &= 1 \\
C_{OR} &= 1
\end{align*}
\]

Thus:

\[
R_{R5} = R_C \times C_S \times C_{PR} \times C_{S/P} \times C_{CHG} \times C_{FC} \times C_{PS} \times C_{SH} \times C_{OR}
\]

152
Becomes:

\[ R_{5} = 1.2 \times 0.75 \times 1.6 \times 1.3 \times 1.335 \times 1.8 \times 1 \times 1 \times 1 \]

Or:

5 YEAR REPLACEMENT RATE \( R_{5} \) = 4.5%

If a decision were made to change the indoor capillary tube to a thermostatic expansion valve with a 15% bleed port, \( C_{PC} \) would change from 1.8 to 1.4. The resulting calculated failure rate would change from 4.5% to 3.5%. Other system design considerations can be similarly applied.

Figure 2 is a comparison of calculated replacement rates with projected (actual) rates for the unit models considered in the 1974 and 1976 production years. Cumulative percent of units considered is plotted against a ratio of actual to calculated or calculated to actual (whichever is unity or greater). Curves for both the original empirical study as well as the latest work are included to show the improvement between the two methods. For example, 90% of the calculated failure rates were within a 2.7 ratio of the actual rate with the empirical study. When the regression was used, 90% of the calculated values were down to a 1.5 ratio. On this plot, it is obvious that if this technique were perfect, the ratio would be unity for all units under study. Results have shown that this technique can be an extremely useful tool in making timely, economical design decisions.

Author's Note: The above example is hypothetical. No actual failure information is given.
<table>
<thead>
<tr>
<th>FACTOR</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_c$</td>
<td>Basic Compressor Rate (%)</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Stroke Factor</td>
</tr>
<tr>
<td>$C_{PR}$</td>
<td>Product</td>
</tr>
<tr>
<td>$C_{CHG}$</td>
<td>Charge</td>
</tr>
<tr>
<td>$C_{FC}$</td>
<td>Flow Control</td>
</tr>
<tr>
<td>$C_{S/P}$</td>
<td>Type (Split or Packaged)</td>
</tr>
<tr>
<td>$C_{SH}$</td>
<td>Sump Heat</td>
</tr>
<tr>
<td>$C_{AMB}$</td>
<td>Compr. Ambient</td>
</tr>
<tr>
<td>$C_{OR}$</td>
<td>Operating Range</td>
</tr>
<tr>
<td>$C_{IOL}$</td>
<td>IOL Rating</td>
</tr>
<tr>
<td>$C_{LC}$</td>
<td>Limit Controls</td>
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<tr>
<td>$C_{CMA}$</td>
<td>Charge Measurements &amp; Adjustment</td>
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<tr>
<td>$C_{HSV}$</td>
<td>Hi Side Volume</td>
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<td>$C_{PS}$</td>
<td>Power Supply</td>
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<tr>
<td>$C_{NMI}$</td>
<td>New Model Introduction</td>
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<tr>
<td>$C_{DS}$</td>
<td>Diagnosis &amp; Serviceability</td>
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<tr>
<td>$C_{QC}$</td>
<td>Quality Control</td>
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<tr>
<td>$C_{PST}$</td>
<td>Production Stability &amp; Operator Experience</td>
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<tr>
<td>$C_{WPPP}$</td>
<td>Warranty Policy &amp; Policing Practice</td>
</tr>
<tr>
<td>$C_{FSIP}$</td>
<td>Field Service Instruction Policies</td>
</tr>
<tr>
<td>$C_{LST}$</td>
<td>Local Service Training &amp; Practices</td>
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<tr>
<td>$C_{DIC}$</td>
<td>Distr-Independent or Company Owned</td>
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<tr>
<td>$C_{BCP}$</td>
<td>Branch Circuit Protection</td>
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<tr>
<td>$C_{LT}$</td>
<td>Lightning &amp; Surge Suppression</td>
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<tr>
<td>$C_{V, REG}$</td>
<td>Voltage Regulation</td>
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<tr>
<td>$C_{CLI}$</td>
<td>Installation Climate</td>
</tr>
<tr>
<td>$C_{DF}$</td>
<td>Defrost: Timed or Demand</td>
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</table>

<table>
<thead>
<tr>
<th>VALUE OF COEFFICIENTS</th>
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<tbody>
<tr>
<td>Omitted</td>
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<tr>
<td>(Stroke-inches)$^2$</td>
</tr>
<tr>
<td>Cooling-1 Heat Pump-1.5</td>
</tr>
<tr>
<td>Unit Charge \ 2 Tolerance</td>
</tr>
<tr>
<td>Cap Tube Cooling - 2</td>
</tr>
<tr>
<td>Cap Tube Heating &amp; Cooling-3</td>
</tr>
<tr>
<td>Shutoff TXV Cooling-1</td>
</tr>
<tr>
<td>10% Bleed TXV Cooling-1.5</td>
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<tr>
<td>Etc.</td>
</tr>
<tr>
<td>Packaged-1 Split-1.5</td>
</tr>
<tr>
<td>Cartridge-1, Trickle-.9, None-2</td>
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<tr>
<td>?</td>
</tr>
<tr>
<td>% Beyond 90%-110% Voltage</td>
</tr>
<tr>
<td>(L.Ramps/IOL Rating)$^2$</td>
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<td>?</td>
</tr>
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<tr>
<td>?</td>
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<tr>
<td>1 for 230V, 3Ø</td>
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<tr>
<td>.85 for 230V, 1Ø KCP</td>
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<td>1.1 for 460V, 3Ø</td>
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<tr>
<td>1.2 for 230V, 1Ø KC</td>
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<td>1.2 for 230/200V, 3Ø</td>
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FIGURE I
FIGURE 2 - $R_{S5,ACT/CALC OR CALC/ACT}$