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ESTIMATING THE LIFE EXPECTANCY OF FACILITIES

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Champaign, Illinois

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This technical report presents a model which predicts the expected remaining life of a building. Procedures for use of the model are described.

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FOREWORD

This work was performed by the Construction Engineering Research Laboratory (CERL) for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4DM728012AOK1, "Engineering Criteria for Design and Construction," Task 02, "Applications Engineering," Work Unit 101, "Life Expectancy of Facilities." The applicable requirement code is QCR 1.01.005. Mr. Frank Beck is the OCE Technical Monitor.

The study was conducted under the general supervision of Dr. E. L. Murphree, Chief, Facilities Operations and Maintenance Division. COL M. D. Remus is Commander and Director of CERL and Dr. L. R. Shaffer is Deputy Director.

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ESTIMATING THE LIFE EXPECTANCY OF FACILITIES

1 INTRODUCTION

Objective

The objective of this investigation is to provide the facility engineer with a simple and reasonably accurate procedure for estimating the life expectancy of new and existing facilities.

Definition of Life Expectancy

Several criteria may be used to define the life expectancy of facilities (LEF).

Physical Life

This is the time period after which a facility can no longer perform its function because increasing physical deterioration has rendered it useless.[1] If there are no cost constraints, maintenance and repair activities can indefinitely extend the physical life of a facility.

Functional Life

This is the length of time until the need for the facility no longer exists or until the facility cannot effectively fulfill its original function.[2] The physical life of a facility often exceeds its functional life by many years.

Economic Life

Economic life is exhausted when a financial evaluation indicates that replacement is more economical than retention.[3] With most facilities physical life exceeds economic life.

Since the physical life of a facility normally exceeds both functional and economic life, the actual life-span of the building is normally limited by functional or economic considerations. This investigation is principally concerned with forecasting the economic life of a facility. Other CERL studies are concerned with investigating the functional life of a facility.

Background

The U.S. Army maintains buildings worth approximately $1 billion. Roughly $387 million was expended during Fiscal Year 1972 to maintain this 858 million sq ft.[4] Despite this high funding level, the Backlog of Essential Maintenance and Repair (BEMAR) has increased substantially. In 1967 the total BEMAR was $84 million; by 1972 it had increased to $253 million.[5] The efficient allocation of this large amount of funds is a necessity since maintenance requirements are never fully funded. The effective use of maintenance funds requires the replacement of buildings that have exceeded their economic life-spans

Current procedures for predicting building life-spans can be classified as extremely rough estimates. One estimation technique is based on the type of construction (temporary, 0-5 yr; semi-permanent 5-25 yr; and permanent, over 25 yr).[6] Other methods require estimation of the life-span of the building from tables of expected lives of buildings or from charts showing life-spans of building components of various material types.[7] Field personnel normally use one of these techniques or an educated guess to estimate the expected life of a building. The field-developed LEF figure is then recorded in the Building Information Schedule (BIS-DA Form 2368-R), which is used to predict future building requirements. Thus, an improvement in LEF estimating procedures can produce an improvement in the master planning process.

Both the initial cost and the maintenance costs incurred over the life-span of a building are included in an analysis of total life cycle cost (LCC). In an

[1] Jeffrey G. Kirby, *Life Expectancy of Facilities*, Preliminary Report A-14/AD760489 (Construction Engineering Research Laboratory [CERL], 1973), p 1.

[2] Kirby, *Life Expectancy of Facilities*, p 1.

[3] Kirby, *Life Expectancy of Facilities*, p 1.

[4] *Facilities Engineering Annual Summary of Operations Fiscal Year 1972* (Department of the Army [DA]), pp 4-5.

[5] *Facilities Engineering Annual Summary of Operations Fiscal Year 1972*, p 27.

[6] *Engineering Economic Studies Life Cycle Costing Instructions* (DA, 1972), p 9.

[7] *Instructions for Preparation of DA Forms 3640 and 3641* (DA, 1966), p 15.

LCC analysis, future expenditures are considered more desirable than present expenditures, since they allow the present use of funds and produce either interest payments for an individual or a social return for the government. A common method of comparing costs incurred at different times is through present worth conversions. All costs are compared at the same point in time by discounting them to their present value, as expressed in Eq 1:

$$PV_n = x \frac{1}{(1+i)^n} \quad \text{(Eq 1)}$$

where PV_n = present worth of expenditure x at the end of year n
i = interest rate.

The LCC of a building is expressed by Eq 2:

$$PV_n = C + \sum_{j=1}^{n} \left[\frac{1}{(1+i)^j}(O_j + M_j)\right] - \frac{1}{(1+i)^n} S_n \quad \text{(Eq 2)}$$

where PV_n = present value of cost associated with a building over a time period n
C = initial cost
O_j = operating expense in yr j
M_j = maintenance expense in yr j
S_n = salvage value in n yr
i = discount rate
n = expected remaining life of the building (in yr).

To determine life expectancy of the building, the period of time during which the facility will be required, m, is established (m can be greater than n). The total cost of keeping the original building k yr and its replacement m minus k yr is then calculated. The value of k, for which the total cost over time period m is minimum, is the building's life expectancy n, as expressed in Eq 3:

$$n = \min_k \left(PV_I\Big|_o^k + PV_R\Big|_k^m\right) \quad \text{(Eq 3)}$$

where I = initial structure
R = replacement structure.

The LCC analysis of a building can be used to determine the most economical choice of construction materials either initially or during replacement. Over a fixed period of time, the LCC of building materials can be compared. The materials that produce the minimum LCC would be the most economical. Obviously, an improvement in the life expectancy estimates of materials will result in increased accuracy of LCC calculations.

Original LEF Model

An accurate determination of the economic life of buildings requires substantial information on maintenance frequencies and expenditures for building materials. This data must be used in an iterative solution to Eq 3 to determine the optimum time (the time at which cost is a minimum) to replace the building. The goal of this study has been to develop a shortcut procedure by which the facility engineer can effectively evaluate the life expectancies of the hundreds of permanent buildings on an installation without having to apply Eq 3. The LEF is the point in time when the facility should either be replaced or extensively modernized. A review of the estimating procedure initially presented in a previous report[8] is outlined below.

A life expectancy estimate based on economic considerations requires a forecast of the anticipated maintenance costs. In this report maintenance costs include routine operations expected to occur yearly and less frequent periodic replacements. As a building ages, its routine maintenance costs can be expected to increase. Economic justification for replacement of a building normally occurs when routine maintenance costs are substantially higher than those required for a new building, and several major components of the building need replacement (or will need replacement shortly). The replacement costs of major components are substantially higher than routine maintenance costs. Thus, the major factor that justifies replacement of a building is the necessity of the replacement of major building components.

The replacement costs of building components vary. When a building component with a small replacement cost deteriorates, it is replaced without considering the alternative of replacing the entire building. However, when one or more of the major components needs replacement, the feasibility of

[8]Kirby, *Life Expectancy of Facilities*, Preliminary Report A-14/AD760489 (CERL, 1973), pp 4-7.

either replacing the entire building or performing an extensive modernization should be determined.

Techniques for estimating replacement costs of building components are not readily available; however, data on average initial in-place costs of building components is accessible. A reasonable assumption is that initial costs and replacement costs are related; i.e., building components with high initial costs tend to have high replacement costs.

The Naval Civil Engineering Laboratory (NCEL) examined the initial cost distribution of a sample of 65 buildings selected from the 15 construction category codes with the largest planned new construction during the Fiscal Year 1971-75 Military Construction (MILCON) budget.[9] The number of buildings selected from each category code was approximately proportional to the amount budgeted for that category code. Construction cost information on the sample buildings was obtained from Naval Facilities Engineering Command (NAVFAC) Form 83, "Schedule of Prices." The costs were divided into 17 standard building components.[10] Average percent costs were calculated for each component along with 95 percent confidence intervals (assuming normal distributions). Analysis of the confidence intervals indicated that the distribution of initial in-place costs of building components was independent of category code. Listed in Table 1 are the sample average percent costs of those components that amount to 6.0 percent or more of the in-place cost of the building.

A life expectancy estimation model was developed that used the concept of a weighted average. The application of the technique requires that the estimated remaining lives of the six principal components listed in Table 1 be weighted in proportion to their relative initial costs. The sum of these weighted life-spans is the LEF estimate. Effective application of the approach is based on the following assumptions:

a. Expected remaining lives and replacement costs of building components are the only variables which significantly affect the expected remaining life of a building.

Table 1

Distribution of Initial In-Place Costs

Component	% of Total Cost	Adjusted to 100
Mechanical	14.2	25.0
Foundation	12.8	22.5
Support*	10.8	
Electrical	8.9	15.6
Structural Frame	7.9	13.9
Exterior Walls	7.1	12.5
Plumbing	6.0	10.5
	67.7	100.0

*Refers to site improvements outside the building line

b. Expected remaining lives of building components can be estimated with reasonable accuracy.
c. Building components with small replacement costs have no effect in determining when a building should be replaced.
d. Replacement costs of building components are proportional to their initial costs.
e. The relative distribution of initial costs of building components remains constant over time.
f. The effect that a building component has in determining when a building should be replaced increases linearly with the cost to replace that component.

Using the adjusted weights listed in Table 1, the LEF model* is expressed by Eq 4:

$$EL = .250M + .225F + .156E + .139S + .125W + .105P \quad \text{(Eq 4)}$$

where EL = expected remaining life of the building
M = expected remaining life of the component Mechanical
F = expected remaining life of the component Foundation
E = expected remaining life of the component Electrical
S = expected remaining life of the component Structural Frame
W = expected remaining life of the component Exterior Walls
P = expected remaining life of the component Plumbing.

[9] J. A. South, *Life-Cycle Costing of Naval Facilities* (Naval Civil Engineering Laboratory, 1972), Appendix A.

[10] *Uniform System for Construction Specification, Data Filing and Cost Accounting* (American Institute of Architects, 1966).

*A nomograph and computer program were also developed.

All expected remaining lives are expressed in years.

The use of the LEF model involves two steps:

a. The inspection of the building and estimation of the remaining lives of the six principal building components

b. The substitution of the estimated remaining lives of the six components into Eq 4.

Table 2 illustrates this procedure for a fictitious building.

Table 2

Calculation of Expected Remaining Life

Component	Weight	Est. Life*	Life Contribution
Mechanical	.250	10	2.50
Foundation	.225	40	9.00
Electrical	.156	20	3.12
Structural Frame	.139	30	4.17
Exterior Walls	.125	30	3.75
Plumbing	.105	20	2.10
			24.64

*Expected remaining life [illegible] obtained from an actual [illegible] inspection of components and application of Eq 4.

A test implementation of the LEF model was performed at Fort Leonard Wood, Missouri (FLW). Nine permanent construction buildings were selected for inspection and their expected remaining lives were estimated (Table 3). These buildings were selected from the CERL sample buildings at this location on which maintenance data is currently being collected. The buildings were selected to yield the largest possible variety in Facility Classes and Construction Category Codes (F4C), year built, foundation, exterior walls, and roof surface.

Appendix A contains an illustration of a work sheet which was developed for evaluating the condition of building components.[11] Using this work sheet as a guide, the principal building components were rated in one of five conditions: excellent, above average, average, below average, or poor. The following general expected lives were assumed for each component: Mechanical, 50 yr; Foundation, 75 yr; Electrical, 40 yr; Structural Frame, 75 yr; Exterior Walls 50 yr; and Plumbing, 50 yr. The range of the general expected life of each component was divided into five equal sections, each corresponding to a verbal condition rating. For example, for Exterior Walls, excellent condition was assigned from 50 to 40 yr of expected remaining life; above average, 40 to 30 yr; average, 30 to 20 yr; below average, 20 to 10 yr; and poor, 10 to 0 yr. The midpoint of each division, e.g., 35 yr for above average exterior walls, was the actual figure used in the calculations. The expected lives obtained using the LEF model were consistently longer than the figures recorded in the local Building Information Schedule (BIS), as illustrated in Table 4. The differences ranged from 11 to 31 yr.

Table 3

Sample Buildings at Fort Leonard Wood (First Inspection)

Bldg. No.	Category Code	Area (sq ft)	Year Built	Foundation	Exterior Walls	Roof Surface
[illegible]	17120	840	1963	Reinf Conc	Masonry	Shingle
[illegible]	21410	4,786	1964	Reinf Conc	Masonry	Galv Steel
[illegible]	21410	4,786	1977	Reinf Conc	Masonry	Built up
[illegible]	61050	[illegible]	1965	Reinf Conc	Masonry	Built up
[illegible]	72111	40,640	1964	Reinf Conc	Brick	Rolled
[illegible]	72111	40,640	1971	Reinf Conc	Masonry	Built up
410	72410	18,000	1965	Reinf Conc	Brick	Built up
[illegible]	74050	[illegible]	1963	Reinf Conc	Masonry	Built up
[illegible]	74050	1,880	1967	Reinf Conc	Brick	Galv Steel

FLW recently revised the LEF estimates on their BIS by using OCE's guidance on life spans of principal building materials. Since FLW was not designated as a permanent installation until the late 1950's, all permanent buildings were constructed after that time. Consequently, FLW has no permanent buildings over 15 yr old. An examination of the BIS at FLW (Table 4) indicates that the master planning personnel tend to be conservative in their LEF estimation. Thus, the initial CERL model, which uniformly predicts a longer LEF, can be expected to be more accurate at this location.

Application of the initial model requires an inspection process—which is clearly not desirable on a post-wide basis. Revision of the trial model and a review of the available data sources was initiated.

2 REVISION OF INITIAL LEF MODEL TO USE IFS CONDITION RATINGS

Army-wide implementation of the Integrated Facilities System (IFS) will require local inspection of the condition of all post building components and creation of a file to store that information. The

[11]Sidney M. Johnson, *Deterioration, Maintenance, and Repair of Structures* (McGraw-Hill, 1965), pp 20-290.

Table 4

Expected Remaining Life—Original Model

Bldg. No.	Condition Rating M	F	E	S	W	P	Expected Remaining Life (Yr)*	Comments
2300	2	2	1	3	4	1	38	Boiler moderately corroded, pipe ducts good; heavy spalling, cracking of walls, mortar running out; wood rafters have considerable rot
4100	3	2	1	1	1	1	43 (28)	Hot water heater moderately corroded; pipes leaking; several cracks, chips in foundation
900	1	1	1	1	1	1	52 (38)	
672	1	2	1	1	2	1	47 (16)	Walls have some cracks; mortar running out; foundation has some cracks
628	3	3	1	1	1	1	47 (28)	Furnaces somewhat corroded; pipes heavily corroded, leaking
835	1	1	1	1	1	1	[illegible]	
[illegible]	1	1	1	3	2	1	46 (25)	Walls have some cracks, mortar running out; roof support has considerable cracking
1015	2	1	1	1	1	1	49 (38)	Heating units have much wear, some corrosion
639	1	1	1	1	1	1	52 (26)	

KEY

Components		Condition Rating	
M	Mechanical	1	Excellent
F	Foundation	2	Above Average
E	Electrical	3	Average
S	Structural	4	Below Average
W	Exterior Walls	5	Poor
P	Plumbing		

*Second column, in parentheses — local BIS.

building components will be rated in one of three conditions. Condition C1 indicates that the component is in good condition and requires only minor, routine maintenance. Condition C2 indicates that the component needs major maintenance and requires an individual job order (IJO). Current requirements for an IJO are minimums of 16 labor hr and $350 total cost. Condition C3 indicates that the component requires major repair or replacement, since it impairs the function of the facility. A detailed description of condition ratings appears in Appendix B.

IFS will provide a detailed data source of the component condition ratings for all the facilities at a post. It is highly desirable to use this data source for LFF estimation since it will reduce both the effort involved and the expense necessary to update the life expectancy estimates in local BIS's.

Expansion of the Model

The IFS inspectors at Fort Bliss, Texas, the test implementation site for a portion of IFS, have performed a complete inspection of all building components. Their opinions as to how long material types remain in given condition ratings were obtained. The results of these interviews are described in Table 5.

Table 5

Expected Remaining Lives of Components in Three Condition Ratings

Component	Material Type	Expected Remaining Life (Yr) In C1	In C2	In C3
Mechanical	Boilers	30-6	5-1	0
Foundation	All types	75-26	25-1	0
Electrical	RH wiring	30-6	5-1	0
	THWN wiring	50-6	5-1	
Structural Frame	Steel	75-26	25-1	0
	Wood	30-2	1	0
Exterior Walls	Brick	75-26	25-1	0
	Concrete	75-26	25-1	0
	Metal	75-26	25-1	0
	Rock	75-26	25-1	0
	Wood	20-6	5-1	0
Plumbing	Copper	75-6	5-1	0
	Galvanized iron	50-6	5-1	0

The following procedure was developed to assist in using condition ratings to estimate the expected remaining life of a building:

a. Determine the material type of each of the six components: Mechanical, Foundation, Electrical, Structural Frame, Exterior Walls, and Plumbing. Information is available from local Real Property cards (DA Form 2877).

b. Inspect the building and assign the appropriate condition rating to each of the six components.

c. Determine the expected remaining life of each component from the following equation.

$$T = \text{Max}\,(U - A, L) \qquad \text{(Eq 5)}$$

where T = expected remaining life of the component
U = upper limit of the range of values of expected remaining lives for the appropriate material type of the component in the given condition rating
L = lower limit of the range of values of expected remaining lives for the appropriate material type of the component in the given condition rating
A = number of years the component has been in its present condition rating.

All values are expressed in years. If A is unknown and the component has been given a C1 rating, A is assumed to be the age of the building. If A is unknown and the component has been assigned a C2 rating, A is assumed to be zero. A C3 rating always results in an expected remaining life of zero years.

d. Substitute the values calculated in Eq 5 for the appropriate variables in Eq 4 and solve for the expected remaining life of the building.

The above procedure is illustrated in Table 6 for a fictitious building that is 32 yr old. The component Mechanical has been in its present condition, C1, for the past 8 yr. In this case, 8 is subtracted from 30, the upper limit for a C1 rating for the Mechanical component. Since the resulting figure (22 yr) is greater than the lower limit for a C1 rating of the Mechanical component (6 yr), 22 is selected to be multiplied by the weighting factor. The expected remaining life contributions of the other five components are similarly computed. These six values are then summed to yield the expected remaining life of the building.

Testing IFS Revised Model

Eight buildings at Fort Bliss were selected to test the IFS revised LEF model. The buildings were selected to represent as wide a variety of components as possible within a small sample. The buildings are described in Table 7.

The expected remaining lives predicted by the second version of the LEF model closely correspond to the BIS estimates at Fort Bliss. In six of the eight buildings inspected, the difference between the two estimates was 5 yr or less. For one building, the LEF model's estimate of the remaining life was 18 yr longer than the BIS estimate. A portion of the difference can be identified since the building was rewired 8 yr ago and this information was noted in the CERL model. For the other building, the LEF model's estimate of the remaining life was 19 yr shorter than the BIS estimate. This discrepancy was attributed to two factors. First, a change in building use might have accelerated the rate of deterioration of the building components. The building was originally designed as a post exchange containing a barber shop and a launderette. The building is now used as a tavern but no major alteration accompanied its change in use.

Table 6

Estimating the Expected Remaining Life of a Building

Component	Material Type	Yrs. in Condition	Condition	Expected Remaining Life	Weight	Life Contribution
Mechanical	Boilers	8	C1	30 - 8 = 22	250	5.500
Struc Frame	Steel	6	C2	25 - 6 = 19	.225	4.275
Electrical	RH wiring	Unknown	C2	5	156	0.780
Foundation	Concrete	32	C1	[illegible] - 32 = 43	139	5.977
Ext Walls	Brick	1	C3	0	125	0
Plumbing	Copper	Unknown	C1	75 - 32 = 43	105	4.515
						21.047*

*Expected remaining life is 21 yr

Table 7

Sample Buildings at Fort Bliss

Bldg. No.	Category Code	Area (sq ft)	Year Built	Foundation	Exterior Walls	Roof Surface
762	17120	14,218	1939	Concrete	Adobe	Composition
2529	21410	13,200	1949	Concrete	SFASB*	Asbestos
2527	44220	65,935	1963	Concrete	RCFMU*	Composition
2010	61050	1,607	1908	Rock	Rock	Composition
2020	61050	765	1919	Concrete	Rock	ASBSH*
500	72111	59,327	1934	Concrete	HTS*	Spanish Tile
223	72410	3,390	1893	Rock	Brick	Asphalt
2408	74050	4,035	1956	Concrete	Masonry	Composition

*Abbreviations: ASBSH: asbestos shingles; HTS: hollow-tile stuccoed; RCFMU: reinforced concrete frame and masonry units; SFASB: steel frame asbestos.

Second, the heating system was poorly designed. The heaters are virtually inaccessible in an attic room too small for a repairman. To perform maintenance on the heaters, a man must stand on a ladder outside the building. Although the heaters may have been in excellent condition, their inaccessibility resulted in a C2 rating which reduced the model life expectancy estimate.

The implication of the field test at Fort Bliss is that its local BIS seems to agree remarkably well with those values derived from the CERL model. One reason may be that since Fort Bliss has had experience with evaluating building components, its LEF estimates based on principal building materials may have taken into account the existing physical condition of the building components.

3 REVISION OF MODEL

During the first two field applications of the LEF model it became apparent that it would be extremely difficult to obtain one accurate approach to LEF estimation that would be applicable for all facility types. In view of this discovery, the initial formulation of the model was reviewed. Four areas were re-examined: component selection, component lives, relative component costs, and applicability of the model to a variety of building types.

Component Selections

Since practical considerations require that IFS condition ratings be used in the LEF model, it became necessary to adjust the LEF building components to be compatible with IFS building components (listed in Table 8). The IFS component Structure includes the three LEF components—Foundation, Structural Frame, and Exterior Walls—plus other minor subcomponents. The IFS inspector gives one rating to the component structure; he does not rate each subcomponent. Compatibility requires that the three LEF components of Foundation, Structural Frame, and Exterior Walls be combined into one component—Structure. Application of the LEF model is simplified since there is a reduction of the number of independent variables from six to four.

Table 8

IFS Facility Components

Component Number	Component Name
01	Roofing
02	Structure
03	Floor Covering
04	Exterior Painting
05	Interior Painting
06	Heating
07	Air Conditioning
08	Plumbing
09	Electrical
10	Equipment
11	Utility Plant Equipment
12	Systems
13	Pavements
14	Trackage
15	Ties
16	Drainage
17	Appurtenances
18	Ground Cover
19	Forest Land
20	Fish and Wildlife Habitats

The IFS inspectors give separate condition ratings to the Heating and the Air Conditioning components. In the LEF model, these two components were considered as both being in the component Mechanical. An analysis of the initial cost distribution of building components indicated that air conditioning would not be a significant component (that is, amount to 6 percent or more of the initial cost of the building). A high percentage of buildings have no air conditioning, while in other buildings the air conditioning is considered part of the IFS component Heating. It was determined that the best procedure would be to leave the LEF component Mechanical unchanged (including both air conditioning and heating). The IFS condition rating for the component Heating would apply to the LEF component Mechanical.

Component Life-Spans

Appendix C presents a table of estimated lives for building components of various material types. Where the year of estimate is 1973, the estimated life is an opinion expressed by the appropriate IFS inspector at Fort Bliss. The other estimates are from data or opinions expressed in 19 of the publications listed under Uncited References at the end of this report. An examination of the data in Appendix C and the information in Table 5 combines to give the information presented in Table 9.

Table 9

Range of Expected Remaining Lives of Components

Component	Material Type	Expected Remaining Life (Yr) In C1	In C2	In C3
Structure	Wood or shingle exterior walls	20-6	5-1	0
	Other exterior walls	75-26	25-1	0
Mechanical	All types	20-6*	5-1	0
Electrical	All types	20-6*	5-1	0
Plumbing	Galvanized iron pipes	50-6	5-1	0
	Other pipes	75-6	5-1	0

*According to numerous sources the electrical and mechanical components, although not worn out, would be functionally obsolete at the end of 20 years.

Relative Component Costs

Every 3 months, *Engineering News-Record* (ENR) publishes cost data on buildings. The relative percent costs of the various building components are supplied by building contractors throughout the continental United States (CONUS). These costs were collected for a sample of 103 buildings to check the previously examined cost distributions obtained from NCEL.[12]

The average percent costs of components obtained from the NCEL data, using IFS classification, were compared with the costs obtained from the ENR data. A visual comparison of the average percent costs indicated that the two data sources did not seem to exhibit any significant differences (Table 10). Since the NCEL report supplied only the average costs, statistical comparisons were difficult; however, reasonable assumptions could be made. The first step in performing statistical analyses is to determine distribution of the data. Evidence suggests that the percent costs should be normally distributed. This premise was tested graphically and analytically.

Table 10

Comparison of Relative Component Costs Between NCEL and ENR Data

Component	NCEL % Cost	ENR % Cost	Difference (%)
Structure	27.8	29.62	−1.8
Mechanical	14.2	12.55	1.6
Electrical	8.9	10.56	−1.7
Plumbing	6.0	5.18	0.8
	56.9	57.91	

In performing a statistical comparison of two averages, the distribution of the populations must be either known or assumed. The normal distribution is one that fits many physical phenomena. To test the applicability of this distribution, it was assumed that the distribution of initial costs of each component was normal and independent of building type. The normality assumption could not be directly checked on the NCEL data since only the average costs of

[12] "Quarterly Cost Roundup," *Engineering News-Record* (McGraw-Hill), Vol 177, No. 24 (1966), pp 129-130; Vol 178, No. 12 (1967), pp 128-131; Vol 180, No. 25 (1968), pp 138-140; Vol 181, No. 25 (1968), pp 111-112; Vol 182, No. 12 (1969), pp 100-101; Vol 182, No. 25 (1969), p 120; Vol 183, No. 12 (1969), pp 148-149; Vol 184, No. 12 (1970), p 96; Vol 185, No. 12 (1970), p 137; Vol 185, No. 25 (1970), p 58; Vol 186, No. 24 (1971), pp 130-131; Vol 187, No. 12 (1971), pp 132-133; Vol 187, No. 25 (1971), p 73; Vol 188, No. 12 (1972), pp 65-66; Vol 188, No. 25 (1972), p 126; and Vol 189, No. 12 (1972), pp 132-133.

each component were provided, not the actual data. However, NCEL did use the normal distribution to calculate confidence intervals.

Plots of the cumulative distribution functions for the ENR cost data on the components Structure, Mechanical, Electrical, and Plumbing were made on normal probability paper. A straight line obtained on this type of paper indicates a normal distribution. The resulting plots were very close to straight lines for the components Structure and Electrical. However, the data points for Mechanical and Plumbing did not approximate straight lines. In particular, the curve of plumbing costs appeared to be a graph of two normal distributions.

To analytically check for possible deviations from normal distributions, Chi-Square Goodness-of-Fit Tests* were performed using a 95 percent level of significance. This level relates to a 5 percent chance of concluding that the distribution is abnormal when it is, in fact, normal. At the 95 percent level of significance, the hypothesis of a normal distribution of costs was rejected only for the component Plumbing.

Differences Due to Building Type

One reason that the original assumption used to test the applicability of the normal cost distributions was found to be unjustified might be that the building type had a significant effect on costs of building components. Thus, if building F4C was in fact a significant variable, it might still be possible that component cost distributions are normal for certain building F4C's. To examine these revised hypotheses, the ENR sample buildings were divided into six categories: offices, factories, storage, medical, housing, and others. Kolmogorov-Smirnov Goodness-of-Fit Tests** were performed to test the normality of the distributions of each of the four components in each of the six building categories. At the 95 percent level of significance, the hypotheses of normal cost distributions were accepted for all 24 of the distributions. Thus, the assumption of normal distribution governing the percent costs of the components was shown to be valid for each of the six building categories.

*Appendix D explains the statistical analyses used.

**These tests were required since some of the categories had small sample sizes.

The first step to check the feasibility of decreasing the number of building categories was to compare the variances of each of the category distributions for each of the four components. Ratios of the variances of each pair of building categories (F ratios) were computed for each of the four components (a total of 60 comparisons). At a 95 percent level of significance, seven comparisons were rejected. This is sufficient to reject the hypothesis that the variances are equal.

The observation of unequal variances requires the use of t tests to compare the average component costs between building categories. At a 95 percent level of significance, the hypothesis of equal average percent costs was not rejected for any of the four components in comparing offices with factories, factories with others, and offices with others. These results indicate that there are no significant differences in the cost distributions of these three building types. For this reason, they were combined into one building category (Others).

Storage was found to be a separate category since there were many significant cost differences between it and the other building categories. The hypotheses of equal averages for the percent cost of the component Structure were rejected for comparisons between storage and offices, storage and medical, storage and housing, and storage and the original category Others. For the Mechanical component, the hypotheses of equal averages were rejected for comparisons between storage and offices, storage and medical, storage and the original category Others. For the component Plumbing, the average costs of storage and medical and of storage and housing differed significantly.

The categories Medical and Housing differed only slightly in the average distribution of costs for each component. The only hypothesis of equal averages rejected at a 95 percent level of significance between these two building types was the component Mechanical, and that hypothesis was very close to being accepted. The hypothesis of equal averages for the component Mechanical would have been accepted at a 98 percent level of significance. Since simplicity of application of a proposed LEF model would require a minimum number of building categories and the component Mechanical was close to being accepted, it was assumed that the distribution of mechanical cost was equal for medical and housing.

Kolmogorov-Smirnov Goodness-of-Fit Tests were performed on the newly formed composite building categories of Medical and Housing, and Others. All four of the building components were found to have normal cost distributions in both building categories.

Tests for equal average component costs between the three building categories were performed. In all cases the hypotheses of equal average costs were rejected. Calculations indicated that a further reduction of the number of building categories could not be made.

Classification of Buildings

The Army has a facility classification scheme based on building use. Each facility is assigned a 5-digit code, the F4C.[13] Appendix E contains the assignment of each F4C to one of the three CERL building categories, Storage, Medical and Housing, and Others. Each F4C was examined to determine which building category its cost distributions most nearly resembled. Some of the CERL classifications were contrary to F4C designation. For example, greenhouses were grouped under storage, since it is felt that they have low percent costs for the components Mechanical, Electrical, and Plumbing, and high percent costs for Structure. Cold storage facilities are expected to have much higher percent costs for Mechanical and lower percent costs for Structure than the facilities normally grouped under Storage. For this reason, cold storage facilities are included in the CERL category Others.

Derivation of Revised LEF Models

Using the same weighted average procedure as was used to determine the original model, component costs were adjusted to 100 percent (Tables 11, 12, and 13), and an equation was developed for each of the three building categories (Eq 6, 7, and 8).

For Storage:

$$EL = .739S + .057M + .162E + .042P \quad \text{(Eq 6)}$$

For Medical and Housing:

$$EL = .512S + .175M + .167E + .146P \quad \text{(Eq 7)}$$

For Others:

$$EL = .500S + .233M + .188E + .079P \quad \text{(Eq 8)}$$

where EL = expected remaining life of the building
S = expected remaining life of the component Structure
M = expected remaining life of the component Mechanical
E = expected remaining life of the component Electrical
P = expected remaining life of the component Plumbing.

All values are expressed in years.

Table 11

Distribution of Initial In-Place Costs of Storage Facilities

Component	% Total Cost	Components Adjusted to 100%
Structure	42.04	73.9
Mechanical	3.25	5.7
Electrical	9.18	16.2
Plumbing	2.40	4.2
	56.87	100.0

Table 12

Distribution of Initial In-Place Costs of Medical and Housing Facilities

Component	% Total Cost	Components Adjusted to 100%
Structure	28.11	51.2
Mechanical	9.59	17.5
Electrical	9.17	16.7
Plumbing	8.01	14.6
	54.88	100.0

Table 13

Distribution of Initial In-Place Costs of Other Facilities

Component	% Total Cost	Components Adjusted to 100%
Structure	29.25	50.0
Mechanical	13.59	23.3
Electrical	10.99	18.8
Plumbing	4.63	7.9
	58.46	100.0

[13] *Department of the Army Facility Classes and Construction Categories*, AR 415-28 (DA, 1973), pp 3-38.

In meeting the objective of establishing a simple procedure for estimating the LEF, facilities were combined into the smallest possible number of building groups. This philosophy produced an LEF model composed of only three equations. The inclusion of other factors, although increasing the accuracy of the model, would also have increased its complexity.

The distribution of initial costs of a building was assumed to remain constant over time. Thus the proposed model would be applicable to old as well as new buildings.

Geographical location does have some effect on the expected lives of building components. The period of time a component remains in various condition ratings (Table 9) was developed from a wide range of information sources and therefore should represent an average value. These values should, therefore, be applicable to a variety of geographical locations. A periodic reapplication of the model (e.g., every 20 yr) will correct the prior estimate for variances in the environment on maintenance policy.

After some experience has been gained with the component condition code transition time frames in various climates, specific transition estimates can be developed for each geographical location.

Use of Model

Two techniques have been developed for use of the revised LEF models.

Analytical Procedure

The use of the LEF model entails four basic steps:

a. Inspection of the building to determine condition ratings of the components Structure, Mechanical, Electrical, and Plumbing (in lieu of an inspection, an IFS file could be used).
b. Use of the condition ratings to estimate the expected remaining lives of the four components (Eq 5).
c. Determination of the appropriate LEF equation (from Appendix E).
d. Substitution of the values obtained in Eq 5 for the appropriate variables determined in (c) and solving for the expected remaining life of the building.

Application of the revised LEF model is identical to the procedure used in the initial version of the model, except for the determination of which equation should be used. Table 14 illustrates application of the LEF model on a fictitious building. This general-purpose warehouse (F4C = 44220) was assumed to have been built in 1964. The building has brick exterior walls and copper pipes.

Graphical Procedure

For quick application to the LEF process on a limited number of buildings, a nomograph was developed for each of the three groupings of facilities (Figures 1, 2, and 3). The procedure is identical for all three nomographs and involves the following six steps:

a. Determining which graph is applicable from Appendix E.
b. Obtaining condition ratings of the components Structure, Mechanical, Electrical, and Plumbing.
c. Using condition ratings to estimate expected remaining lives of the four components.

Table 14

Final Version of the LEF Model

Component	Condition Rating	Yr in Condition	Estimated Remaining Life	Weight	Life Contribution
Structure	C1	10	65	.739	48.035
Mechanical	C2	Unknown	5	.057	0.285
Electrical	C2	3	2	.162	0.324
Plumbing	C1	Unknown	65	.042	2.730
					51.374*

*Estimated remaining life is 51 yr.

$$EL = 0.739\,S + 0.057\,M + 0.102\,E + 0.042\,P$$

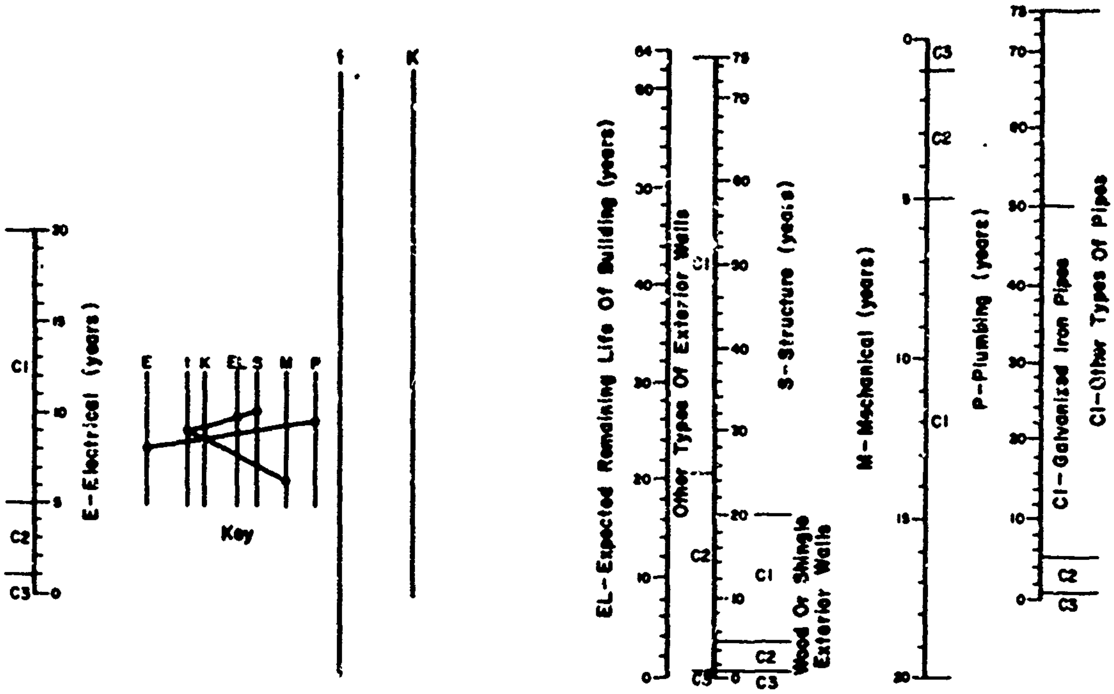

Figure 1. Expected remaining life of storage facilities.

$$EL = 0.500\,S + 0.233\,M + 0.188\,E + 0.079\,P$$

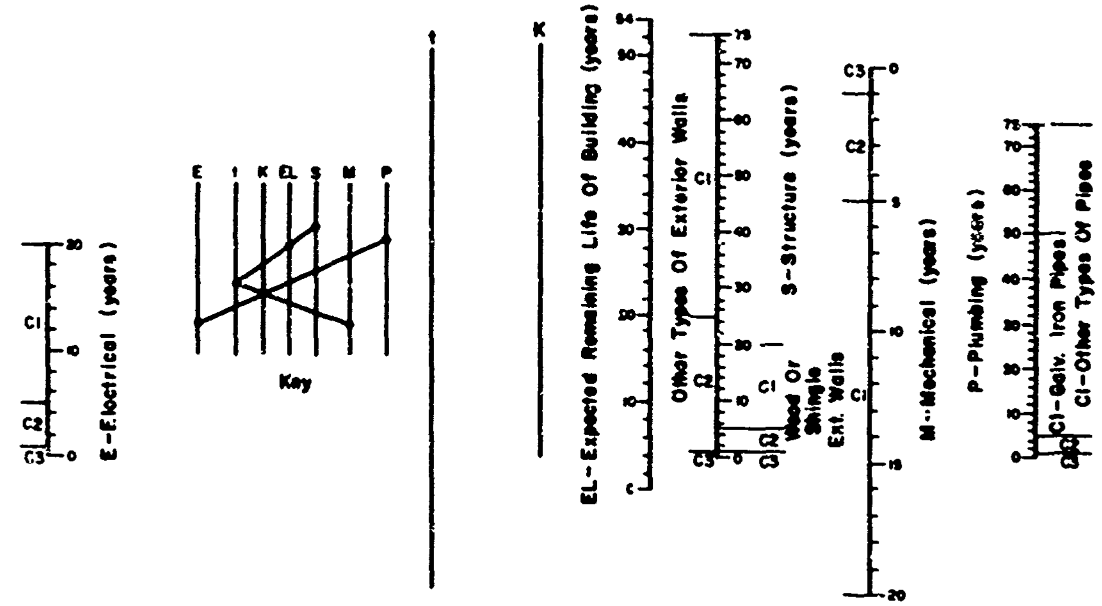

Figure 2. Expected remaining life of medical and housing facilities.

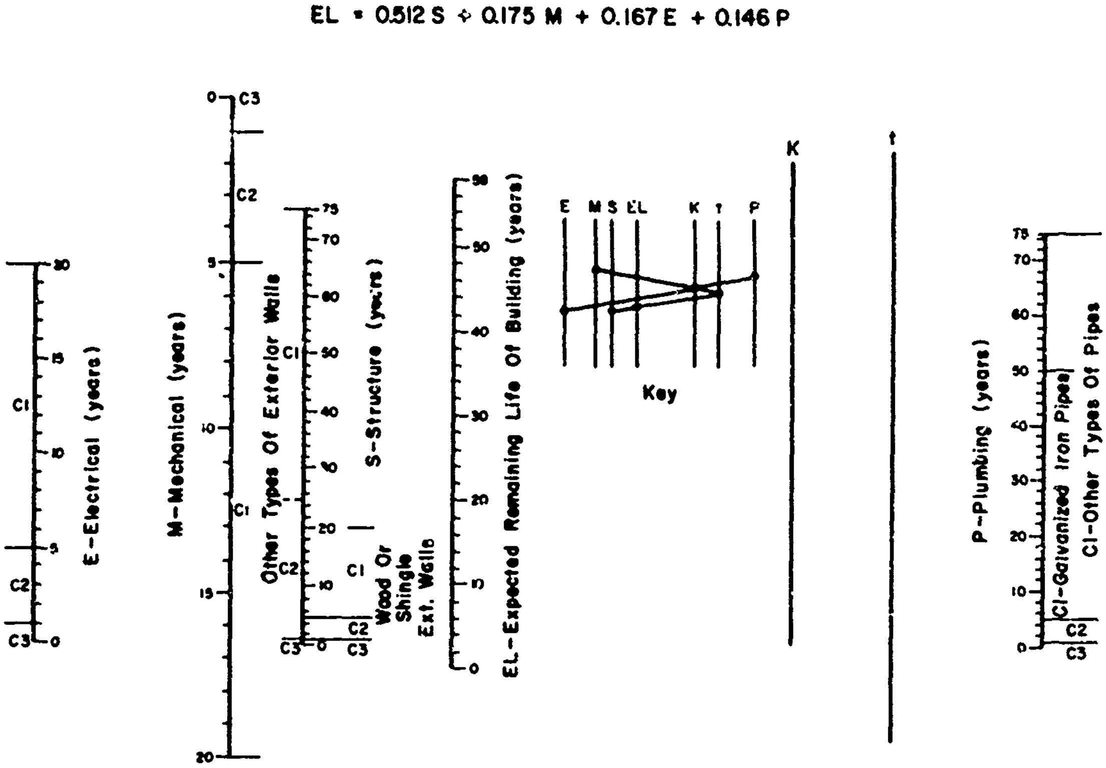

Figure 3. Expected remaining life of other facilities.

d. Drawing a straight line from the expected remaining life of the component Electrical on the E-scale to the expected remaining life of the component Plumbing on the P-scale, intersecting the K-scale at X.

e. Drawing a straight line from the expected remaining life of the component Mechanical on the M-scale through point X on the K-scale, intersecting the t-scale at point Y.

f. Drawing a straight line from point Y on the t-scale to the expected remaining life of the component Structure on the S-scale, intersecting the EL-scale at point Z. Z is the expected remaining life of the building.

The nomographs indicate maximum lives of 64 years for storage facilities, 58 years for medical and housing facilities, and 54 years for other facilities. These figures are the initial estimates and are not the absolute limits on the lives of the facilities. The estimates are based upon the assumption that none of the major components is replaced. The replacement of components clearly extends the life of a facility and reapplication of the model at the replacement time would reflect this fact. Assume, for example, that a storage facility is initially assigned a life of 64 years. After 34 years, the estimated remaining life is 30 years. If the exterior walls were extensively repaired or replaced at this time, reapplication of the I EF model would increase the remaining life to over 50 years.

Applicability of Model as Determined by Inspections

Inspections of buildings at FLW and at Fort Bliss have determined that there are some buildings for which the model is ambiguous. One example is a building which is composed of more than one facility. Should the building be assigned one expected remaining life or should each facility be assigned an expected remaining life? At FLW, one building consisted of facilities 2348, 2349, A2347, and A2348. Facility A2348 was built in 1954; the others were built in 1941. Facility 2349 has wood exterior walls; the others have concrete exterior walls. Since different facilities have different exterior walls and different ages, it would be impossible to assign one expected remaining life to the building. For consistency in application procedures, each facility (though all are portions of one building) must be individually evaluated and the LEF determined for each one.

A second problem area is those buildings that are missing one or more of the four components used in the model. For example, a warehouse may not have Plumbing or Mechanical components. LEF estimates for several buildings with missing components were made by a simplified weighted average (only those applicable components normalized to 100 percent) and also by substituting a notional value for the missing component (maximum expected life of component minus age of building—if negative substitute zero). In most cases the two approaches produced LEF estimates within 3 yr of each other. The results obtained from the notional approach for evaluating facilities with missing components were considered accurate. A benefit of this finding was that additional equations (for missing components) did not have to be developed for each of the three facility groupings.

The BIS estimates of the LEF at Fort Bliss are significantly longer than the estimates of FLW. An examination of the BIS for Fort Bliss showed that 28 percent of the buildings were temporary, 10 percent were semi-permanent, and 62 percent were permanent.[14] The average expected life of the temporary buildings in existence at Fort Bliss (as of 31 March 1970) was 32 yr; of the semi-permanent buildings, 36 yr; and of the permanent buildings, 58 yr. Less than 2 percent of the buildings are expected to be extended beyond the replacement date listed in the BIS. The Ft. Bliss engineers seem to make a serious attempt to estimate the actual replacement date and most buildings are maintained in reasonably good condition until this date. These findings are presented in Table 15.

Examination of the BIS for FLW showed that 49 percent of the buildings were temporary, 6 percent were semi-permanent, and 45 percent were permanent.[15] As of 31 December 1969, the average expected life of the existing temporary buildings was 31 yr; of the semi-permanent buildings, 26 yr; and of the permanent buildings, 39 yr. Most of the temporary buildings were constructed from 1941 to 1944 and are still being used. The replacement dates of these buildings have been extended several times. The option to extend life was applied to over 63 percent of the buildings. The engineers at FLW tend to give conservative estimates of replacement dates and reserve the option to extend the dates—a policy that has created conservative BIS estimates of LEF.

The final version of the LEF model was reapplied to the buildings previously inspected at Fort Bliss. For six of the eight buildings inspected, the LEF estimate of the remaining life was within 5 yr of the BIS estimate. Figure 4 shows the results of application of the LEF model to one of these buildings. In one building, the LEF estimate of the remaining life exceeded the BIS estimate by 12 yr. This building had a small BIS estimate of its remaining life, despite the fact that the Electrical component had recently been replaced. On the building which had been converted from a PX to a tavern, the BIS estimate of the remaining life exceeded the LEF estimate by 24 yr.

The final version of the LEF model was applied to the buildings previously inspected at FLW, plus an

[14]*Building Information Schedule—Fort Bliss*, DA Form 2368-R (DA, 1970), pp 1-157.

[15]*Building Information Schedule—Fort Leonard Wood*, DA Form 2368-R (DA, 1969), pp 1-114.

Table 15

Distribution of Buildings by Type of Construction and Corresponding Expected Lives

	Fort Bliss*			Fort Leonard Wood**		
	Temp.	Semi-perm	Perm	Temp.	Semi-perm	Perm
% Total Bldgs.	28	10	62	49	6	45
Average EL	32	36	58	31	26	39

*Two percent extended beyond replacement date.
**Sixty-three percent extended beyond replacement date.

Installation Name:	Ft. Bliss, Texas
Facility Number:	500
F4C:	72111
Facility Description:	Enlisted Men's Barracks Without Mess
Comments on Facility:	Hollow tile stuccoed exterior walls, currently being used as an administration building
Year Built:	1934
Date of Estimate:	25 March 1974
Estimated Remaining Life (BIS):	30 yrs
Estimated Remaining Life (LEF):	28 yrs

Component Name	Year Installed	Condition Rating	Comments on Condition of Components
Structure	1934	C1	
Mechanical	1934	C1	hot water heater, boiler leak
Electrical	1973	C1	
Plumbing	1934	C1	

Figure 4. Life expectancy—final model.

additional 16 buildings. This list is shown in Table 16. In 22 of the 24 buildings, the LEF estimates of the remaining lives of the buildings were longer than the BIS estimates. The BIS estimate was 2 yr longer for one building and 8 yr longer for another. In 15 of the 24 buildings, the LEF estimates were more than 10 yr longer than the BIS estimates. Table 17 summarizes these results.

4 SUMMARY

Results

a. The initial formulation of a single-weighted average model to predict life expectancy was shown to be inapplicable to a wide range of facility category codes.

b. It was found that if most buildings were divided into three groups, there was no statistical difference within each group between the initial component cost distributions (normal).

c. A weighted averaged model to predict the LEF was formulated for each group.

d. The revised model was field tested and met with acceptance when there was an available data source.

Conclusions

A more methodical procedure than is currently used to estimate LEF is necessary if consistent estimates are to be obtained. Observations at two field locations indicated that a wide discrepancy exists in LEF estimation even if the same guidance is followed. Both the FLW and Ft. Bliss master planning functions had recently revised the expected lives on their BIS by using OCE's principal material guidance. Table 15 confirms the previously mentioned observation that FLW is conservative in its LEF estimation. Permanent construction at Ft. Bliss, on the average, has a listed expected life that is 49 percent greater than that of FLW. Clearly, this is not caused by any geographical influence but is due to different evaluation philosophies. One inconsistency was noted at FLW—the average expected life of semipermanent facilities is shorter than that of temporary facilities. Thus, an LEF evaluation procedure that can provide an estimate that has minimum personal bias is necessary if any Army-wide improvement of expected life evaluation is desired.

The CERL approach minimizes personal bias by forcing evaluators to examine the principal components of all facilities. Structure is relatively easy to evaluate since it is visible; however other components are important and should also be evaluated. The CERL model forces the evaluator to look at the entire facility—not just his area of interest.

The CERL model also meets two important requirements stated in the original plan of study.

a. The model should be easy to comprehend and use.

b. It should be reasonably accurate.

Criterion b cannot be vigorously tested in a short period of time. However, it is safe to assume that this procedure is substantially better than any of the existing methods.

Use of the model requires a more detailed level of information on a "per-facility" basis than currently exists. Were it not for the IFS, the cost of obtaining this information would be prohibitive. Increment 1 of IFS is scheduled to begin implementation in Fiscal Year 1975. The Assets Accounting Module of Increment 1 will contain a file of the current condition of each component of each facility at an installation. An interim solution of how to translate IFS condition codes into component life expectancies has

Table 16

Sample Buildings at Fort Leonard Wood (Final Model)

Bldg. No.	Category Code	Area (sq ft)	Year Built	Foundation	Exterior Walls	Roof Surface
1606	17120	840	1963	Reinf Conc	Masonry	Composition
672	21410	4,786	1964	Reinf Conc	Masonry	Galv Steel
673	21410	4,786	1964	Reinf Conc	Masonry	Galv Steel
990	21410	4,786	1970	Reinf Conc	Masonry	Built-up
991	21410	4,786	1970	Reinf Conc	Masonry	Built-up
A2347	43210	6,510	1941	Reinf Conc	Wood	Built-up
2349	43210	6,726	1941	Reinf Conc	Wood	Built-up
1977	44220	10,726	1941	Reinf Conc	Wood	Composition
2310	44220	9,267	1941	Reinf Conc	Wood	Composition
2311	44220	9,267	1941	Reinf Conc	Wood	Composition
5432	44221	304	1968	Reinf Conc	Masonry	Built-up
2428	44222	2,432	1961	Reinf Conc	Wood	Galv Steel
2390	44285	6,048	1964	Reinf Conc	Steel	Galv Steel
85	51010	3,812	1941	Reinf Conc	Wood	Composition
2399	61050	2,126	1965	Reinf Conc	Masonry	Built-up
628	72111	40,640	1964	Reinf Conc	Brick	Rolled
1015	72111	40,640	1971	Reinf Conc	Masonry	Built-up
1028	72111	40,640	1971	Reinf Conc	Masonry	Built-up
1482	72111	4,720	1957	Reinf Conc	Wood	Composition
4100	72410	18,690	1965	Reinf Conc	Brick	Built-up
4102	72410	22,003	1966	Reinf Conc	Brick	Built-up
639	74050	3,973	1964	Reinf Conc	Masonry	Built-up
744	74050	4,800	1966	Reinf Conc	Brick	Galv Steel
835	74050	4,800	1967	Reinf Conc	Brick	Galv Steel
280	74076	11,669	1941	Reinf Conc	Wood	Composition

Table 17

Comparison of LEF Estimates with BIS Estimates

Difference (Yr) LEF-BIS	Number of Buildings			
	Fort Bliss		Fort Leonard Wood	
	Initial LEF	Revised LEF	Initial LEF	Revised LEF
− 25 to − 16	1	1	0	0
− 15 to − 6	0	0	0	1
− 5 to + 5	6	6	0	3
+ 6 to + 15	0	1	3	9
+ 16 to + 25	1	0	3	8
+ 26 to + 55	0	0	2	3
Total	8	8	8	24

been presented. After some widespread experience with IFS, the transitional probabilities between condition ratings and the effect of component condition on facility function will be established.*

The availability of IFS will provide the data source necessary to automatically produce updated LCF estimates each time facility component condition ratings change. This automated feature will remove a tedious manual burden from the Directorate of Facilities Engineering (DFAE) master planning section. (Incidentally, master planning normally assigns BIS maintenance a very low priority.)

*Appendix F gives a proposed experimental plan to determine these factors.

Recommendations

a. Required interfaces between the CERL LEF Model and IFS Assets Accounting should be developed after implementation of IFS Increment 1.

b. An experimental design, such as outlined in Appendix F, should be implemented to determine the IFS condition rating transition time frames.

APPENDIX A: INSPECTION OF FACILITIES

I. Foundation

A. Concrete
1. Cracks
2. Spalling
3. Decay
4. Settling

B. Timber
1. Cracks
2. Decay
3. Insect attack
4. Deterioration of hardware
5. Excessive deflection
6. Settling

II. Structure

A. Floor Joists
1. Cracks
2. Deterioration
3. Excessive deflection
4. Insect and fungus infestation

B. Roof Rafters and Purlines
1. Cracks
2. Deterioration

C. Wood Trusses
1. Cracks
2. Slippage
3. Deterioration

D. Steel Trusses
1. Corrosion
2. Abrasion
3. Loose connections
4. Fatigue (small fractures perpendicular to line of stress)

III. Exterior Walls

A. Concrete
1. Cracks
2. Spalling
3. Decay
4. Settling

B. Masonry
1. Structural cracks
2. Efflorescence (change to powder)

C. Corrugated Sheet Steel
1. Rust

D. Siding and Shingles
1. Loose
2. Broken
3. Cracked
4. Warped

IV. Mechanical

A. Radiators
1. Broken parts
2. Leaking valves and connections

B. Pipes
1. Corrosion
2. Scale

C. Stoker—Coal Burner
1. Wear

V. Plumbing

A. Bath Fixtures
1. Improper functioning
2. Sluggish drains
3. Broken

B. Pipes
1. Leaks
2. Broken or loose supports

VI. Electrical

A. Wire Insulation
1. Frayed

B. Protective Devices
1. Damaged

C. Conductor or Conductor-Enclosure Supports
1. Damaged

D. Fittings
1. Loose or separated

E. Connections
1. Loose or partly contacting
2. Broken

APPENDIX B: FACILITIES CONDITION RATING INDICATORS

The following building component condition ratings have been defined for IFS:[16]

1 STRUCTURE

The structure component includes, but is not limited to, foundations, exterior and interior walls, chimneys, porches, columns, beams, exterior and interior doors, jambs, trusses, platforms, exterior and interior stairs, partitions, floor joists, subfloors, floor slabs, hung ceilings, windows, antennas, flagpoles, interior building utility ducts, etc.

C1 Rating

The structure is sound. All subcomponents are in good structural or operating condition. Requirements include inspection, cleaning, removal of safety and fire hazards, the application of preventive entomology, and any adjustments to doors, windows, locks, and hinges.

C2 Rating

The structure is sound but a number of subcomponents are damaged, show pronounced signs of wear, and perform improperly. A structure in this condition will have a number of load-bearing members, closures, and fixtures that are broken, damaged, fitted improperly, cracked, split, insecurely fastened, rusted or have missing parts. Siding is loose, warped, and cracked. Window glass is broken or held by loose putty. Requirements include the replacement of some of the defective subcomponents and the adjustment and reworking of the remainder.

C3 Rating

There are indications that the structure may be unsound. Furthermore, wear and deterioration have progressed to the point that activities conducted within the structure are seriously hampered. Several load-bearing members, closures, and fixtures of the structure show the defects mentioned under rating C2 plus decayed and rotted members that are beyond repair, have settled excessively, and are questionable in their ability to support loads (as evidenced by excessive deflections). Combustible materials are continuously exposed to sources of ignition, portions of the structure are in an out-of-plumb condition, and there is termite infestation, broken siding, and dangerously sagging ceilings and floors. Requirements include major restoration of unsatisfactory subcomponents and replacement of those that are beyond restoration, or replacement of the complete structure.

2 HEATING

Heating within buildings applies to all heating plants under 0.75 million Btu/hr capacity with heat sources such as boilers or furnaces. These heating plants include heat exchangers, combustion chambers, fuel storage, fuel-firing and handling equipment, controls and meters, pumps, fans, piping, insulation, flues, and stacks. Heating within buildings also applies to heat distribution except duct work and emission equipment and includes direct-fired space heaters and unit heaters, piping, insulation, radiators, convectors, heating coils, fan coil units, grilles, dampers, and all other related equipment.

C1 Rating

The system components are in excellent to good condition and require only routine maintenance and repair.

C2 Rating

Major restoration is required on some system components that cannot be maintained economically by routine maintenance, such as radiator valves and steam traps. Usually, heating service is inadequate.

C3 Rating

Breakdown is imminent for some of the system components, such as the furnace heat exchanger or condensate return lines. They are beyond economical restoration and usually require complete replacement. Curtailment of service will result if replacement is not accomplished. Extensive deterioration, major wear, or severe leakage probably exists.

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[16] *Assets Accounting, Real Property Maintenance Activities, Facilities Engineering Management Information System*, GOV R-1209, Vol 17 (DA, 1972).

3 ELECTRICAL

The facility electrical system begins at the point of attachment to or entry into the facility. It includes the main disconnect device, substation and substation components if within the building, cables, wires, raceways, ducts, distribution transformers, capacitors, regulators, grounding equipment, wall switches, contractors, receptacles, lighting fixtures, ballasts, dimmers, lamps, and all the parts and accessories necessary to distribute electricity to the utilization equipment.

C1 Rating

The system components are in excellent to good condition and require only routine maintenance and repair.

C2 Rating

Major restoration is required on some system components that cannot be maintained economically by routine maintenance such as wall switches, receptacles, and lighting fixtures. The condition is such that inconvenient or inefficient service is being provided.

C3 Rating

Major system components, such as transformers, switchgears, wiring, and insulation, are in imminent danger of failure such that the resulting curtailment of service would seriously affect the mission of the facility. The system or components are beyond economical restoration and require major replacements. The major components fail to operate properly as revealed by tests; e.g., a circuit breaker fails to operate within tolerances when a simulated load is applied to it and it cannot be adjusted or repaired to meet requirements, or an inspection reveals brittle wiring or overheated insulation.

4 PLUMBING

Plumbing within buildings includes valves, traps, hot and cold water piping, drains, wastes, vents, faucets, lavatories, water closets, urinals, other plumbing fixtures, water heaters, hot water generators, piping, and sump pumps.

C1 Rating

System components are in excellent to good condition, requiring nothing more than routine recurring maintenance and repair.

C2 Rating

Major restoration is required on some system components, such as worn-out faucets or shower valves and heads, that cannot be maintained economically by routine maintenance. Usually, service is inadequate.

C3 Rating

Breakdown is imminent on some of the system components, such as water lines or sanitary waste lines. They are beyond economical restoration and usually require complete replacement. Curtailment of service will result if replacement is not accomplished. Extensive deterioration, major wear, or severe leakage exists.

APPENDIX C:
LIVES OF BUILDING COMPONENTS

Component	Sub-Component	Material Type	Estimated Life	Year of Estimate
Structure	Foundation	General	75 yr	1973
		Wood piles	Indefinite	1951
		Concrete	Indefinite	1951
		Steel piles	Indefinite	1963
	Structural frame	Wood	30 yr	1973
			Almost indefinite	1951
			75 yr	1951
			66 yr	1951
			50 yr	1951
			40 yr	1951
		Wood floor joists	40 yr	1951
			30 yr	1951
			25 yr	1951
		Concrete	Indefinite	1951
		Steel	75 yr	1973
			Indefinite	1971
			(40-50)+ yr	1970
			30+ yr	1951
	Exterior walls	Wood (untreated)	1-10 yr	1951
		Wood (Creosote)	20 yr	1973
			15-20 yr	1951
		Brick	75 yr	1973
			75 yr	1951
			66 yr	1951
		Concrete	75 yr	1973
			40+ yr	1967
			Indefinite	1951
		Terra cotta	120+ yr	1929
			100+ yr	1929
			60+ yr	1929
			50+ yr	1929
		Rock	75 yr	1973
		Metal	75 yr	1973
		Shingles	16 yr	1951
Mechanical	Heating	Boilers	30 yr	1973
			20 yr	1948
		Stokers and burners	20 yr	1948
		Furnaces	15 yr	1973
		Concealed radiation	25 yr	1948
		Direct radiation	25 yr	1948
		Pipes, general	20 yr	1973
		Pipes, copper	Life of Bldg.	1948
		Pipes, iron	20 yr	1948
	Air conditioning	Units	10 yr	1948
		Refrigeration units	7 yr	1973
		Centrifugal refrigeration	20 yr	1948

Component	Sub-Component	Material Type	Estimated Life	Year of Estimate
		Reciprocating refrigeration	20 yr	1948
		Evaporative coolers (small)	5-8 yr	1973
		Evaporative coolers (large)	12-20 yr	1973
		Pipes, copper	20 yr	1948
		Pipes, steel	20 yr	1948
	Ventilation	Ductwork	Indefinite	1973
			Indefinite	1948
Electrical	Wiring	General	20 yr	1948
		Sheathed	20 yr	1968
		THWN	50 yr	1973
		RH	30 yr	1973
	Conduit	Rigid	Indefinite	1972
	Cables	Plastic vinyl clad	Indefinite	1968
Plumbing	Pipes	General	50 yr	1964
			40+ yr	1957
		Brass	Indefinite	1950
			Indefinite	1948
		Copper	Indefinite	1973
			Indefinite	1948
		Iron (cold water)	25 yr	1948
		Iron (hot water)	20 yr	1948
		Cast iron (sewer)	Indefinite	1948
		Galvanized iron	50 yr	1973
		Vitrified clay (sewer)	Indefinite	1948
		Plastics	Almost indefinite	1970
		Steel	14+ yr	1957
		Asbestos cement	Indefinite	1955

APPENDIX D:
STATISTICAL ANALYSES

1 CHI-SQUARE GOODNESS-OF-FIT TEST

With a fairly large sample size, the Chi-Square Goodness-of-Fit Test is a valid method of testing whether a distribution is normal. The procedure involves the steps listed below:[17]

a. Calculate the mean and the standard deviation of the sample.

b. Divide the range of the distribution into many intervals of equal size.

c. Record the number of data points that fall into each interval (observed frequency).

d. Form cells. Each interval that contains less than five data points should be combined with the next higher or lower interval until each cell contains at least five data points.

e. Calculate the number of standard deviations the low end of each cell is from the mean by use of Eq D-1.

$$N = \frac{x - \bar{x}}{s} \qquad \text{(Eq D-1)}$$

where N = number of standard deviations the low end of the cell is from the mean
x = low end of the cell
$\bar{x}$ = mean of the sample
s = standard deviation of the sample.

f. Determine the theoretical frequency of each cell by use of Eq D-2.

$$F_i = (Z_u - Z_L)n \qquad \text{(Eq D-2)}$$

where F_i = theoretical frequency of the cell i
Z_u = value of Z distribution at upper end of cell (determined from Standard Normal Distribution Table[18])
Z_L = value of Z distribution at lower end of cell
n = sample size.

g. Calculate the observed value of chi-square by use of Eq D-3.

$$X^2_{OBS} = \sum_{i=1}^{K} \frac{(f_i - F_i)^2}{F_i} \qquad \text{(Eq D-3)}$$

where X^2_{OBS} = observed value of chi-square
i = cell number
K = number of cells
f_i = observed frequency of cell i
F_i = theoretical frequency of cell i.

h. Determine the table value of chi-square $(1 - a)$ percent confidence and $(K - 3)$ degrees of freedom.[19]

i. If the observed value of chi-square is less than the table value of chi-square, accept the hypothesis of a normal distribution.

Table D-1 is an example of the use of the Chi-Square Goodness-of-Fit Test for determining the normality of the distribution of mechanical costs. Since X^2_{OBS} is less than $X^2_{.95}(3)$, the normal distribution is a good approximation. Reject hypothesis at $a = .10$.

2 KOLMOGOROV-SMIRNOV GOODNESS-OF-FIT TEST

The Chi-Square Goodness-of-Fit Test is not valid for small samples. The Kolmogorov-Smirnov Goodness-of-Fit Test, described below, is used to test for the type of distribution when only small samples are available.[20]

a. Calculate the mean and the standard deviation of the sample.

b. Order the observations by magnitude.

c. Calculate the sample distribution function:

$$F_n(X) = \frac{1}{n}(i) \qquad \text{(Eq D-4)}$$

where X = value of the observation
$F_n(X)$ = sample distribution function at X
n = sample size
i = number of observation less than or equal to X.

d. The theoretical cumulative distribution is determined from Eq D-5:

$$F_0(X) = Z_N \qquad \text{(Eq D-5)}$$

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[17] Wilfred J. Dixon and Frank J. Massey, Jr., *Introduction to Statistical Analysis* (McGraw-Hill, 1969), pp 243-244.

[18] B.W. Lindgren and G.W McElrath, *Introduction to Probability and Statistics* (MacMillan, 1966), pp 254-255.

[19] Dixon and Massey, *Introduction to Statistical Analysis*, p 465.

[20] Lindgren and McElrath, *Introduction to Probability and Statistics*.

Table D-1

X^2 Goodness-of-Fit Test*

Interval	Observed Freq.	Midpoint	$\frac{x-\bar{x}}{s}$ at Low End	Theoretical Freq.	$\frac{(\text{Obs.}-\text{Theo.})^2}{\text{Theo.}}$
0-3	2 } 12	3.0		17.9	1.95
3-6	10 }				
6-9	6	7.5	−1.28	11.2	2.42
9-12	15	10.5	−0.692	16.6	0.154
12-15	23	13.5	−0.107	17.6	1.66
15-18	11	16.5	0.478	13.4	0.430
18-21	6 }				
21-24	4 } 11	22.5	1.06	11.3	0.00796
over 24	1 }				
Totals	78			78.0	6.62196

*$\bar{x}$ = 12.55, s = 5.13, X^2_{OBS} = 6.62196, $X^2_{.95}(3)$ = 7.81

where $F_0(X)$ = theoretical value of the cumulative distributive function at X

N = value obtained from Eq D-1

Z = value of Z distribution at X.

e. The following statistic is calculated:

$$D_n = \max |F_n(X) - F_0(X)|. \quad \text{(Eq D-6)}$$

f. If the value of D_n is less than the table value of D, the hypothesis of a normal distribution with a mean of X and a standard deviation of s is accepted.[21]

The following example illustrates use of the technique to test the distribution of plumbing costs in the building category Others.

OTHERS (171, 310, 730, 740)

PLUMBING:

H: normal distribution, $\mu = 4.99$, $\sigma = 2.38$

n = 20

a = .05

D_n = .1699

D = .294.

Since $D_n < D$, the normal distribution with a mean of 4.99 and a standard deviation of 2.38 is a good approximation of the data.

[21]B.W. Lindgren and B.W. McElrath, *Introduction to Probability and Statistics* (MacMillan, 1966), pp 262.

3 TEST FOR EQUAL VARIANCES

The F ratio is used to test for equality of variances between two normal populations.[22] The F ratio is expressed by Eq D-7:

$$F = \frac{S_1^2}{S_2^2} \quad \text{(Eq D-7)}$$

where F = F ratio

S_1^2 = variance of sample 1

S_2^2 = variance of sample 2.

The F ratio is compared with table values of $F_{1-a/2}(n_1-1, n_2-1)$ and $F_{a/2}(n_1-1, n_2-1)$ where a is the probability of rejecting a true hypothesis, n_1 is the size of sample 1, and n_2 is the size of sample 2.[23] The hypothesis of equal variances is accepted when the F ratio lies between the two table values of F. This technique is illustrated for the component Plumbing in the example below. The test is for equality of the variances of the NCEL costs, sample 1, and the ENR costs, sample 2, at a 95 percent level of significance.

[22]W.J. Dixon and F.J. Massey, Jr., *Introduction to Statistical Analysis* (McGraw-Hill, 1969), pp 109-112.

[23]Dixon and Massey, *Introduction to Statistical Analysis*, pp 472-485.

PLUMBING:

$n_1 = 65$
$n_2 = 77$
$F = \frac{16.32}{6.25} = 2.611$
$F_{.025}(64,76) = 0.613$
$F_{.975}(64,76) = 1.62$
Since $F > F_{.975}(64,76)$, the hypothesis that the variances are equal is rejected.

4 TEST FOR EQUAL MEANS

The t-test is used to test for equality of means between two normal populations whose standard deviations are unknown and assumed to be unequal.[24] The value of the t statistic is expressed by Eq D-8:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad \text{(Eq D-8)}$$

where $\bar{X}_1$ = mean of sample 1
S_1^2 = variance of sample 1
n_1 = size of sample 1.
The number of degrees of freedom is:

$$df = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(\frac{S_1^2}{n_1}\right)^2}{n_1} + \frac{\left(\frac{S_2^2}{n_2}\right)^2}{n_2}} \quad \text{(Eq D-9)}$$

where df = number of degrees of freedom for the t distribution

a = probability of rejecting a true hypothesis.

The hypothesis of equal means is accepted if the calculated t statistic lies between the table values $t_{a/2}(df)$ and $t_{1-a/2}(df)$.[25]

The following examples illustrate use of this technique to compare the means between the NCEL costs, sample 1, and the ENR costs, sample 2. The first example compares electrical costs. The second example compares plumbing costs.

ELECTRICAL:

$\bar{X}_1 = 8.9$ $\bar{X}_2 = 10.56$
$S_1^2 = 10.30$ $S_2^2 = 8.82$
$n_1 = 65$ $n_2 = 98$
$t = -3.330$
$df = 131.64$
$t_{.025}(131) = -1.980$
$t_{.975}(131) = 1.980$
Since $t < t_{.025}(131)$, the hypothesis that the means are equal is rejected. Accept hypothesis at $a < .01$.

PLUMBING:

$\bar{X}_1 = 6.0$ $\bar{X}_2 = 5.18$
$S_1^2 = 16.32$ $S_2^2 = 6.25$
$n_1 = 65$ $n_2 = 77$
$t = 1.423$
$df = 104.59$
$t_{.025}(105) = -1.985$
$t_{.975}(105) = 1.985$
Since $t_{.025}(105) < t < t_{.975}(105)$, the hypothesis that the means are equal is accepted. Reject hypothesis at $a = .20$.

[24] W. J. Dixon and F. J. Massey, *Introduction to Statistical Analysis* (McGraw-Hill, 1969), p 119.

[25] Dixon and Massey, *Introduction to Statistical Analysis*, p 464.

APPENDIX E:
CLASSIFICATION OF BUILDINGS

BUILDING TYPES INCLUDED IN STORAGE:

121XX: All buildings which have an F4C beginning with 121.

F4C	DESCRIPTION
121XX	Aircraft Dispensing
122XX	Marine Dispensing
12310	Gasoline Station with Building
12320	Diesel Fuel Station with Building
12390	Land Vehicle Dispensing—Other
12530	Pump Station Aboveground
12590	POL Pipeline—Other
14121	Missile Launching and Storage Shelters
14130	Signal Photographic Laboratory Film Library and Equipment Exchange
14132	Ready Building
14133	Shipping and Receiving Building
14140	Care and Preservation Shop
14150	Box and Crate Shop
14160	Blocking and Banding Facility
14170	Transfer Depot Explosives Building
14180	Scale House
14220	Helium Storage Facility
21870	Storehouse Spare Parts
421XX	Ammunition Storage—Depot and Arsenal
422XX	Ammunition Storage—Installation and Ready Issue
423XX	Ammunition Storage—Liquid Propellant
44110	General Purpose Warehouse
44150	Inflammable Material Storehouse
44160	Radioactive Storage Warehouse
44180	Open Warehouse Facility
44181	Vehicle Storage Facility
44190	Storage—Covered—Depot and Arsenal—Other
44210	Aircraft Parts Storage Building
44211	Aircraft Accountable Parts Supply Building
44212	Aircraft Parts and TOE Consolidated Storage Building
44220	General Purpose Warehouse
44221	Target Storage
44222	Storage Shed
44223	Arms Building
44240	Flammable Material Storehouse
44245	Aircraft Flammable Storage Building
44260	Transit Shed
44261	Lumber and Pipe Shed, Facilities Engineer
44262	Vehicle Storage
44270	General Storehouse
44271	General Storage, Family Housing
44275	Facilities Engineer Storehouse
44276	Storage Materials Handling Equipment
44280	Open Warehouse

F4C	DESCRIPTION
44285	Salvage and Surplus Property Facilities
44286	Division Breakdown Building
44290	Storage—Covered—Installation and Organizational—Other
71410	Detached Garages, Family Housing
71420	Detached Storage Buildings, Family Housing
72335	Battalion Storage Building
72350	Detached Garages
73011	Fire Hose House
73070	Bicycle Shed
74029	Greenhouse
74031	Golf Course Maintenance Building
74055	Exchange Warehouse
74081	Self-Service Supply Center
76XXX	Museums and Memorials

BUILDING TYPES INCLUDED IN MEDICAL AND HOUSING:

F4C	DESCRIPTION
5XXXX	Hospital and Medical Facilities
711XX	Family Housing—Dwellings
71441	Detached Servants Quarters, Family Housing
721XX	Bachelor Housing—Enlisted Men's Barracks
724XX	Bachelor Housing—Officers Quarters
73015	Confinement Facility (Stockade)
74032	Guest House

BUILDING TYPES INCLUDED IN OTHERS:

F4C	DESCRIPTION
131XX	Communications Buildings
133XX	Navigation and Traffic Aids Buildings
14110	Airfield Operations Building
14111	Airfield Fire and Rescue Station
14112	Aviation Unit Operations Building
14115	Representative Weather Observation Station
14120	Missile Warheading Building
14131	Operations Building General Purpose
14181	Safety Shelter
14182	Regimental Headquarters Building
14183	Battalion Headquarters Building
14184	Group Headquarters Building
14185	Company Headquarters Building
14186	Regimental Brigade Headquarters Building
14190	Operational—Buildings—Other
14210	Helium Processing Plant
171XX	Training Buildings

F4C	DESCRIPTION
211XX	Maintenance Aircraft
212XX	Maintenance Guided Missile
21330	Ship Repair Shop
21390	Maintenance Ships, Spares—Other
21410	Motor Repair Shops
21412	Oil House
21414	Dispatch Office
21420	Tank Repair Shops
21422	Oil House Tank
21424	Dispatch Office Tank
21430	Ordnance Field Maintenance Shop
21490	Maintenance Tank, Automotive—Other
215XX	Maintenance Weapons, Spares
216XX	Maintenance Ammunition, Explosives, Toxics
217XX	Maintenance—Electronics and Communication Equipment
21810	Parachute Packing and Drying Facility
21815	Non-TOE Support Maintenance Shop
21820	Engineer Field Maintenance Shop
21830	Drum Reconditioning Plant
21840	Railroad Equipment Maintenance Shop
21850	Battery Shop
21860	Railroad Engine Shop
21880	Chemical Field Maintenance Shop
21881	Airborne Equipment Repair Shop
21882	Quartermaster Repair Shop
21883	Metal and Woodworking Shop
21884	Air Delivery Equipment Field Maintenance Shop
21885	Maintenance Shop General Purpose
21890	Maintenance—Facilities for Miscellaneous Procured Items and Equipment—Other
219XX	Maintenance—Installation, Repair, and Operation
22XXX	Production
31XXX	Research and Development, and Test Buildings
424XX	Weapon—Related Battery Storage Refrigerated Storehouses
43XXX	Cold Storage
44130	Controlled Humidity Warehouse
44230	Controlled Humidity Warehouse
61XXX	Administrative Buildings
71320	Trailer Park Service Buildings
71430	Detached Laundry Building, Family Housing
71490	Family Housing—Detached Facilities—Other
722XX	Bachelor Housing—Mess Facilities
72320	Detached Lavatory Building
72321	Detached Latrine Building
72323	Detached Shower Building
72330	Administration and Supply Building
72360	Detached Day Rooms
72390	Bachelor Housing—Detached Facilities—Other
73010	Fire Station
73016	Police Station
73020	Garrison Bread Bakery

FAC	DESCRIPTION
3025	Central Pastry Kitchen
73030	Fixed Laundry
73031	Fixed Drycleaning Plant
73045	Dependent Nursery School
73046	Dependent Kindergarten School
73047	Dependent Grade School
73048	Dependent High School
73050	Air Raid Shelter
73052	Fallout Shelter
73055	Waiting Shelter
73060	Decontamination Facility
73075	Public Toilet
73090	Community Facilities—Personnel—Other
74010	Auditorium General Purpose
74011	Bank
74012	Bowling Center
74013	Bath House
74014	Bus Station
74015	Civilian Club Facility
74016	Post Chapel
74017	Religious Educational Facilities
74018	Unit Chapel
74019	Chapel Center Facilities
74020	Clothing Sales Store
74021	Commissary
74022	Skill Development Center
74023	Credit Union
74024	Automotive Self-Help Garage
74025	General Educational Development Facility
74026	Entertainment Workshop
74028	Physical Fitness Center
74030	Golf Club House
74033	Community Center
74034	Gymnasium
74040	Library Branch
74041	Library Main
74043	Child Care Center
74047	Open Mess NCO (Formerly NCO Club)
74048	Open Mess Officers (Formerly Officers Club)
74050	Exchange Branch
74051	Exchange Cafeteria
74052	Exchange Automotive Service Station
74053	Exchange Main Retail Store
74054	Exchange Maintenance Shop
74056	Exchange Service Outlets
74057	Exchange Special Support Facilities
74058	Post Office Branch
74059	Post Office Main
74060	Lunch Room
74061	Billiards Facility

F4C	DESCRIPTION
74062	Snack Bar
74063	Cafeteria
74064	Post (Installation) Restaurant
74065	Special Service Office
74066	Youth Center
74067	Rod-Gun Club
74068	Enlisted Men Service Club
74069	Recreation Building
74070	Skating Rink
74071	Red Cross Building
74072	Indoor Swimming Pool
74073	Indoor Firing Range, Recreational
74074	Boy Scout Building
74075	Girl Scout Building
74076	Theater with Stage
74077	Theater without Stage
74078	Thrift Shop
74080	Boathouse
74083	Telephone Center
74090	Community Facilities—Morale, Welfare, and Recreational—Interior—Other
811XX	Electric Power—Source
821XX	Heat—Source
82310	Gas Generating Plant
82390	Heat, Gas—Source—Other
826XX	Refrigeration (Air Conditioning)—Source
83110	Sewage Treatment Plant
83130	Industrial Waste Treatment
83190	Sewage and Industrial Waste—Treatment and Disposal—Other
83230	Sewage Pumping Station
83290	Sewage and Industrial Waste—Collection—Other
833XX	Refuse and Garbage
84110	Water Treatment Plant
84131	Water Well with Pumping Station
84141	Pumping Station
84150	Chlorinator Building
84190	Water—Supply, Treatment, and Storage—Potable—Other
84220	Water Pumping Station Potable
84520	Water Pumping Station Nonpotable
87230	Sentry Station
87240	Kennel
87290	Ground Fencing, Gates, and Guard Towers—Other
89010	Acetylene Plant
89020	Compressed Air Plant
89030	Oxygen Plant
89045	Combined Air Conditioning and Heating Plant
89050	Ice Plant
89090	Miscellaneous—Other

APPENDIX F: FACILITIES SYSTEMS EFFECTIVENESS MODEL*

1 INTRODUCTION

Central to the concept of the life-cycle model and the reporting of facility data under the IFS is the problem of quantifying the condition of the facilities found in the typical Army installation. Both IFS and life-cycle studies attempt to provide relevant decision-making information for facility engineer funding in the former, and for construction replacement policy formulation in the latter. A major problem with both efforts has been the quantification of the facility condition in terms that are common to all facilities and are easily convertible to dollar costs or some other unit of measure which is needed for policy formulation.

In general, the IFS scheme has divided the facility into various components, and it has then attempted to describe each component as falling into one of several condition categories. These condition ratings, though literally equal, did not permit direct comparison of components of different size, design, or environmental conditions. Condition was reported in terms of dollars required to return the component to its best condition.

The facilities were broken into "functional groups" or "control groups" in an effort to reduce the detail provided by the existing Army F4C. The functional and component groupings have been changed frequently to better fit the reporting requirements of the system.

LCC studies have gathered a large amount of data on facility performance and maintenance history and have applied traditional statistical comparisons to the data to arrive at predictive equations which reduce the variables describing the facility to some common denominator, such as dollar cost.

In the course of the work leading to this model, it became apparent that facilities could not easily fit into traditional models of failure such as the exponential chance-failure model or the wearout failure model. In particular, a deterioration phenomenon seemed to be common to most facility component wearout in which there was seldom a point where a complete failure of a given component or facility could be identified; but rather the characteristics of the component which describe its performance changed gradually over time, making a failure difficult to define. The deterioration phenomenon, or parameter drift, is more difficult to deal with when applied to complex systems; the model is not easily applied to situations where data gathering is automated and large amounts of data are encountered. A discrete state Markov model has been formulated to help supply data in support of this model. It uses existing data formats and is compatible with the general scheme of IFS reporting.

2 NOMENCLATURE

$p_{ij}(k)$	One-step transition probability, the conditional probability that component k will go from state i to j.
$P(k)$	One-step transition matrix for component k.
$\pi_j(k)$	Steady-state probability that component k will be in state j in the long run.
$[\pi_j(k)]$	Steady-state probability vector for component k.
$\mu_j(k)$	Average recurrence time for component k to return to state j.
$X_{hij}(k)$	Occurrence of a transition of component k from state i to state j, for the *hth* facility observed.
$[o(k)]_i$	Matrix of observations of transitions at data point i for component k.
T_i	Transition data matrix at data point i.
$\hat{P}(k)$	Theoretical transition matrix.
β_i	Least squares estimate of parameter of polynomial equation.
V_i	*ith* variable describing a component.
$d_{ij}(k)$	Extent that the *kth* component in the *ith* state degrades the *jth* mission of a facility, expressed as a decimal fraction.
$D(k)$	Mission effects matrix for component k.
$D_j(k)$	Column vector of mission effects for mission j, component k.
$F(k)$	Ineffectiveness vector for component k.
$f_j(k)$	Ineffectiveness of component k on facility mission j, expressed as a decimal fraction.
$e_j(k)$	Effectiveness of component k on facility mission j, expressed as a decimal fraction.

*This appendix was prepared by P. V. Kaufhold, R. E. DeVor and M. J. Kraitsik of the University of Illinois at Urbana-Champaign Department of Mechanical and Industrial Engineering, under contract DACA 88-73-A-0004.

Q	Matrix portion for absorbing Markov chain which does not contain absorption probabilities.
I	Identity matrix.
N	$(I-Q)^{-1}$, or fundamental matrix of absorbing chain.
R	Absorption state vector portion of absorbing state transition matrix.
$\underline{1}$	Column vector of all 1's.
NR	Vector of mean absorption probabilities from any state.
M	Mean number of steps for absorption from any state.
$\hat{P}_{ij}(k)$	Theoretical transition probabilities calculated from a polynomial model.
b_i	Least squares estimate of parameter of polynomial equation.

3 MARKOV MODELS

The Markov chain is a model of a stochastic process—a set of random events which are measurable in some terms—which will be found in one of a set of mutually exclusive states, s_t, $t = 1, 2, \ldots, M$. The Markovian property, which gives the name to the model, requires that the state of the system at the $(n+1)th$ observation be independent of all previous states except the *nth* state, that state immediately preceding the next state, or:

$$\Pr\{S_{t+1} = s | S_1 = s_1, S_2 = s_2, \ldots, S_t = s_t\}$$

$$= \Pr\{S_{t+1} = s | S_t = s_t\} \qquad \text{[Eq F-1]}$$

This property must hold for any and all sequences which led to S_t. In practice, this property is often difficult to prove and is usually assumed.

The model is dynamic in the sense that it describes the operation of a system over time; however, it requires that the transition probabilities (that the system will go from state i to state j, given that the system was in state i) be stationary over time. Each system must have a finite initial probability.

In summary, a system may be described with a Markov chain model if it has:

a. a finite number of discrete states, which are exhaustive and mutually exclusive
b. the Markovian property of independence
c. stationary state transition probabilities
d. finite initial probabilities for each state.

The model generally takes the form of an n-step transition matrix which gives the probabilities of arriving in a state after n-steps or transitions, given an initial state at time $t = 0$:

$$S_i = \begin{array}{c|cccc} & s_1 & s_2 & \cdots & s_m \\ \hline s_1 & p_{11} & p_{12} & \cdots & p_{1m} \\ s_2 & p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & & & & \\ s_m & p_{m1} & p_{m2} & \cdots & p_{mm} \end{array} \quad (S_j =) \qquad \text{[Eq F-2]}$$

1-Step Transition Matrix

In order to find the transition probabilities after the first n-steps, it is necessary to take the 1-step transition matrix to the *nth* power. By the Chapman-Kolmogorov equations:[28]

$$p_{ij}^{(n)} = \sum_{k=1}^{M} p_{ik}^{(v)} p_{kj}^{(n-v)} \quad \text{for all } i, j, n, 0 \le v \le n \qquad \text{[Eq F-3]}$$

where p_{ij} = probability that the system will go from state i to state j, given that the system was in state i.

In matrix notation:

$$P^{(n)} = P^n = P^{n-1} \cdot P \qquad \text{[Eq F-4]}$$

If the matrix is multiplied through a sufficient number of steps, the transition probabilities will reach a steady-state condition in the limit:

$$\lim_{n \to \infty} p_{ij}^{(n)} = \pi_j \qquad \text{[Eq F-5]}$$

where π_j = steady-state probability that the system will be in state j in the long run, regardless of the initial state of the system.

The system states of the Markov model may be further characterized by their recurrence time and

[28] F.S. Hiller and G.J. Lieberman, *Introduction to Operations Research*, Section 13.3 (Holden-Day, Inc., 1967).

first-passage time. The first-passage time is a random variable, having the density function $f_{ij}^{(n)}$, giving the probability that the system will go from state i to state j in exactly n-transition steps. Recurrence time is a special case where the probability that the system will return to a given state once it has entered that state should be determined. Where

$$\sum_{n=1}^{\infty} f_{ii}^{(n)} = 1.0 \qquad \text{[Eq F-6]}$$

then s_i is said to be a recurrent state since once the system has entered s_i it will always return to that state. Where

$$\sum_{n=1}^{\infty} f_{ii}^{(n)} < 1.0 \qquad \text{[Eq F-7]}$$

then s_i is said to be a transient state in that there is a positive probability that the system will not return to that state. Where

$$p_{ii} = 1.0 \qquad \text{[Eq F-8]}$$

s_i is said to be an absorbing state, a special case of the recurrent state in which once the system enters s_i, it will remain in that state forever.

The average recurrence time, in step units, may be easily calculated from the steady-state probabilities as:

$$\pi_j = \frac{1}{\mu_j} \qquad \text{[Eq F-9]}$$

where μ_j = average number of steps required for the system to return to state j once the system has been in state j.

4 ABSORBING STATE MODEL

As stated previously, a special case of a recurrent state is an absorbing state. If, in a transition matrix, any $p_{ij} = 0$, the transition does not occur. Conversely, if any $p_{ij} = 1$, every element in state S_i moves to state S_j in the next period. Also, if any $p_{ii} = 1$, i.e., if any transition probability on the main diagonal (from northwest to southeast) of the matrix is equal to 1, or the row of transition probabilities can be moved to where $p_{ii} = 1$ (by simply renumbering the states), that state, s_i, is an absorbing state: that is, it is not possible to leave the state. Finally, if a transition matrix has at least one absorbing state, and if it is possible to reach an absorbing state from every other non-absorbing state, then the Markov chain is an absorbing Markov chain.

It has been pointed out that a state k is called an absorbing state if $p_{kk} = 1$ so that once the chain visits k, it remains there forever. If k is an absorbing state, the first passage probability from i to k is called the probability of absorption into k having started in i.

The transition matrix can be partitioned by:

r → absorbing state

s → non-absorbing states

so that the matrix becomes one of the following form:

$$P = \begin{array}{c c} & \begin{array}{cc} r & s \end{array} \\ \begin{array}{c} r \\ s \end{array} & \left[\begin{array}{c|c} I & 0 \\ \hline R & Q \end{array}\right] \end{array}$$

Let b_{ij} ≡ probability the chain is absorbed in j given that it started in i.

$$b_{ij} = p_{ij} + \sum_k p_{ik} b_{kj}$$

$$B = [b_{ij}]$$

$$B = R + QB \qquad \text{[Eq F-10]}$$

$$B - QB = R$$

$$(I - Q)B = R$$

$$B = (I - Q)^{-1} R = NR \text{ where } N = (I - Q)^{-1}$$

It is desirable to find the mean absorption time (or number of steps it takes to reach the absorbing state). It is usually more convenient to obtain the mean absorption times $\{M_j, j \in T\}$ where T represents the set of non-recurrent states in the chain of linear equations:

$$M_j = 1 + \sum_{K \varepsilon T} p_{jk} M_k, j \varepsilon T. \quad \text{[Eq F-11]}$$

But this system of linear equations can be solved using a matrix formulation. Let Q be the matrix:

$$Q = \{p_{jk} : j, K \varepsilon T\} \quad \text{[Eq F-12]}$$

of transition probabilities of states j into states in T. Let $\underline{M}$ be a column vector whose components are M_j, $j \varepsilon T$. The system of equations:

$$M_j = 1 + \sum_{K \varepsilon T} p_{jk} M_k \quad \text{[Eq F-13]}$$

can then be written in matrix form

$$I\underline{M} = \underline{1} + Q\underline{M}$$

where $\underline{1}$ is the column vector each of whose components are 1, and I is the identity matrix. The above can be rewritten as:

$$(I - Q)\underline{M} = \underline{1}$$

: N be the inverse matrix of $(I - Q)$

$$N = (I - Q)^{-1} \quad \text{[Eq F-14]}$$

It may be verified that $I - Q$ possesses an inverse. In fact

$$(I - Q)^{-1} = I + Q + Q^2 + \ldots + Q^n + \ldots . \quad \text{[Eq F-15]}$$

To prove this, prove that the matrix defined as an infinite series converges, and prove that it has the property that when multiplied by $(I - Q)$ the product is I. The vector $\underline{M}$ of mean absorption times in terms of N can be written as:

$$\underline{M} = N\underline{1}$$

5 APPLICATION OF THE MARKOV MODEL

The typical facility as a system exhibits a continuous process of deterioration over time, a complex process in which a large number of interrelated performance characteristics change to produce overall reduced system effectiveness. The relatively complex nature of the facility system does not lend itself to the discrete failure model in which there are only two possible states, "failed" and "not failed."

Chance failure and wearout failure are treated primarily as discrete, attribute events; the process is one of counting rather than measuring. Failure rates, the parameter of the chance failure models, are defined as failures per unit time or percent failures per unit time. Wearout failure parameters are the mean wearout time and variance of the wearout time.

Deterioration, or degradation, is a different phenomenon in that the performance parameter of a component is measured over time, with the change in the parameter representing deterioration of the component. Presumably, measurement of the parameter contributes to the component's ability to perform. If the parameter value falls outside some design limit, a deterioration failure occurs. In a deterioration failure model, the rate at which the parameter changes over time is a measure of component reliability.

A stochastic deterioration model would define the performance characteristics of the system as random variables, where the parameters of the distributions of the performance characteristics are functions of time; for example, let q equal the component performance measure and let q have a normal distribution at any given time with mean μ_q and variance σ_q^2. Let these parameters be a function of time:

$$\mu_q(t) = f(t) \quad \text{[Eq F-16]}$$

$$\sigma_q^2(t) = s(t). \quad \text{[Eq F-17]}$$

Let q_0 equal the design limit of the component. The hazard function for the component would take the form:

$$g(q) = \frac{1}{2\sqrt{s(t)}} e^{\frac{-[q - f(t)]^2}{2\sqrt{s(t)}}}. \quad \text{[Eq F-18]}$$

By integration, the failure time distribution function would be:

$$F(t) = \int_{\partial=0}^{t} \frac{1}{2\sqrt{s(\partial)}} \int_{q=0}^{q_0} e^{\frac{-[q-f(\partial)]^2}{2\sqrt{s(\partial)}}} \, dq \, d\partial. \qquad \text{[Eq F-19]}$$

The deterioration model is more descriptive of the deterioration in a facility system, but it does not simplify definition of the failed condition of the component. The deterioration model still permits only two distinct states and makes it difficult to adequately include the intermediate steps in the deterioration process, which are also of interest in arriving at policy decisions.

The Markov model falls somewhere between the chance failure model and the continuous deterioration model by providing for any number of discrete states into which the system may fall during deterioration. The Markov model, unlike either of the others, looks at the *change* in state of the system and is in this sense a more dynamic model. This approach is particularly suited to the facility situation in providing relevant management information in a useful form.

Use of the discrete state model for the deterioration phenomenon requires that the component performance continuum be divided into a number of mutually exclusive, but all-inclusive states. For practical purposes, it is desirable that these states be minimum in number, while adequately representing the range of deterioration, and in sufficient detail to avoid ambiguity in definition. It is assumed that this approximation to the continuous nature of the deterioration model will not seriously affect results obtained with the model.

No attempt is made here to define all components and corresponding states. General guidelines for component definitions are suggested as follows:

a. Component breakdown should be on a functional basis, rather than according to shop responsibilities, size, capacity, etc. The general function for the defined component should be the same for *all* facilities.
b. All components should be defined with the same level of detail; in this respect, a hierarchical or tree structure can be helpful.
c. Components should be primarily divided as building components and non-building components. The number of components which can be applied to both categories will probably be small.
d. Components should be mutually exclusive.

The definition of the component states is similar to the condition rating scheme used in the early versions of IFS.[27] This scheme defined four states into which the condition of all components would fall. Benchmarks for the evaluation of components related their condition classifications with the effectiveness of the facility as a whole and did not differentiate component conditions from the relative effect of any particular component on a particular facility mission.

The definition of component states suggested for the Markov model is performed independently of consideration of the effect that a component condition may have on a facility as a whole. It represents a significant improvement on the present condition rating scheme—with the greatest improvement being that each component condition is given in terms of that component only. Guidelines for definition of the component states are suggested as follows:

a. Component states should be clearly defined in terms of measurable quantities, such as capacity, or in clearly defined attribute terms.
b. Each state should be defined in terms of the particular component without regard to other components or facility functions.
c. States should be defined in sufficient detail to avoid ambiguity; unnecessary detail should be avoided to minimize complexity of the resulting state model.

It may be reasonably assumed that the state transition probabilities at any given time will depend on a set of variables which determine how the system will behave. Added dynamic dimension is achieved in the model by formulating the transition probabilities as functions of this set of variables, as

$$p_{ij} = f(\{V\}, \{\beta\}) \qquad \text{[Eq F-20]}$$

where $\{V\}$ = set of variables

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[27] R.J. Colver, *Facilities Engineer Management and Evaluation System: A Data Base Maintenance Strategy*, Preliminary Report A-5 (CERL, 1972).

{β} = set of parameters of a polynomial model.

The polynomial model allows the inclusion of all relevant and significant factors which, logically, will have an impact on deterioration of a facility.

It should be noted that variables are defined for the facility as a whole, and the set of values of the variables will be roughly the same for all components; in practice, the values of variables can differ for components within the same facility, from facility to facility, or from installation to installation. In all cases the set of variables will be the same for all installations, all facilities, and all components. Therefore, it is through definitions of components, component states, and significant variables that the model achieves its generality; through the application of the particular values of the variables and mission analysis (covered later) the model is applied to specific circumstances.

Estimates of the parameters of the polynomial model are obtained by the method of least squares from the observation of samples of facilities over a "transition step," normally a change from 1 year to the next.

6 APPLICATION OF ABSORBING STATE MODEL TO FACILITIES

The absorbing state model has a different development. Although the basic states are the same as those listed above, there is one more state that must be added. This state, the absorbing state, represents the point in time where the component of the facility has degraded to such a degree that it is disposed.

It should be noted that a particular component's disposal may or may not mean that the facility itself is disposed. For example, a gas heating system can be replaced by an electrical heating system with no effect to the facility. However, if a roof is disposed, the building itself will also be disposed, unless the roof is only being replaced; in this case, the component returns to the best condition.

Probabilities for the absorbing chain are computed in the same way as probabilities for the regular chain, with the exception that for the *kth* absorbing state, $p_{kk} = 1$ and p_{k}. for all j is 0.

7 EXPERIMENTAL DESIGN

Experience with facility data has suggested that the variables which can determine the change in state of components can be divided into three broad categories with corresponding important variables in each category as follows:

Design Variables

These are variables whose values are determined at the time the component is designed and constructed. They remain unchanged throughout the life of the component, such as:

a. Type of construction—permanent or temporary, masonry or wood, etc.
b. Size or capacity—sq ft, Btu/hr, persons, etc.
c. Year constructed—age of the component.

Environmental Variables

These describe the actual conditions under which the component is operated, such as:

a. Component loading—actual load being placed on the component as compared with designed capacity.
b. Climatic conditions—heating degree-days, annual rainfall, etc.

Policy Variables

These describe policies of the organization responsible for the operation or maintenance of the component, such as:

a. Dollars spent on preventive maintenance of the component
b. Dollars spent on corrective maintenance of the component

This list of variables, though reasonably complete without the benefit of extensive data analysis, should not be considered exhaustive. As many variables as possible should be included in the data gathering process so that sources of variation can be accounted for. The larger the list, the more data points will be required to arrive at independent estimates of the least squares parameters; for this reason the variables included in the analysis should be chosen with care.

Data for the analysis should be collected according to a two-level factorial design scheme; in the case of the seven variables listed, a 2^{7-3} fractional factorial design could be used, and by confounding the main effects of three of the variables with third-order and fourth-order interactions, it is possible to gain independent estimates of main effects and all second-order interactions. An assumption required for the model is that all third- and higher-order interactions will be statistically insignificant, a reasonable assumption under the circumstances. The design matrix is shown in Table F-1. High and low levels of the variables should be chosen so that they lie at or near the extreme values to be reasonably encountered in practice.

The fractional factorial design will permit independent estimates of the least squares parameters of first- and second-order terms; use of the factorial also permits the inclusion of attribute-valued variables which have two levels in the model.[28]

The response to be observed is whether the component changed state from one condition evaluation to the next. Obviously, this requires that the same set of facilities and components be observed under the same or nearly the same conditions for 2 years consecutively. The observed data would be recorded as a matrix as:

$$[o(k)]_i = \begin{array}{c} \\ s_1 \\ s_2 \\ \vdots \\ s_m \end{array} \begin{array}{c} \begin{array}{cccc} s_1 & s_2 & \cdots & s_m \end{array} \\ \left[\begin{array}{cccc} \sum_{h=1}^{n} X_{h11}{}^{(k)} & \sum_{h=1}^{n} X_{h12}{}^{(k)} & \cdots & \sum_{h=1}^{n} X_{h1m}{}^{(k)} \\ \sum_{h=1}^{n} X_{h21}{}^{(k)} & \sum_{h=1}^{n} X_{h22}{}^{(k)} & \cdots & \sum_{h=1}^{n} X_{h2m}{}^{(k)} \\ \vdots & & & \\ \sum_{h=1}^{n} X_{hm1}{}^{(k)} & \sum_{h=1}^{n} X_{hm2}{}^{(k)} & \cdots & \sum_{h=1}^{n} X_{hmm}{}^{(k)} \end{array}\right] \end{array}$$

where n is the size of the total sample taken at data point i

$$X_{hij} = \begin{cases} 1 \text{ if component goes from state i to state j} \\ 0 \text{ otherwise} \end{cases}.$$

It should be noted that, in effect, there will be three samples taken at each data point. The transition matrix which results from the observation matrix is a series of conditional probabilities, and thus, each row of the transition matrix must add to 1.0.

[28] O.L. Davies, *Design and Analysis of Industrial Experiments*, Chapter 10 (Hafner Publishing Co., 1956).

Table F-1

Design Matrix—2^{7-3} Fractional Factorial Design

Test	1	2	3	4	12	13	14	23	24	34	123	124	7= 234	6= 134	5= 1234
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
2	—	+	+	+	—	—	—	+	+	+	—	—	+	—	—
3	+	—	+	+	—	+	+	—	—	+	—	—	—	+	—
4	—	—	+	+	+	—	—	—	—	+	+	+	—	—	+
5	+	+	—	+	+	—	+	—	+	—	—	+	—	—	—
6	—	+	—	+	—	+	—	—	+	—	+	—	—	+	+
7	+	—	—	+	—	—	+	+	—	—	+	—	+	—	+
8	—	—	—	+	+	+	—	+	—	—	—	+	+	+	—
9	+	+	+	—	+	+	—	+	—	—	+	—	—	—	—
10	—	+	+	—	—	—	+	+	—	—	—	+	—	+	+
11	+	—	+	—	—	+	—	—	+	—	—	+	+	—	+
12	—	—	+	—	+	—	+	—	+	—	+	—	+	+	—
13	+	+	—	—	+	—	—	—	—	+	—	—	+	+	+
14	—	+	—	—	—	+	+	—	—	+	+	+	+	—	—
15	+	—	—	—	—	—	—	+	+	+	+	+	—	+	—
16	—	—	—	—	+	+	+	+	+	+	—	—	—	—	+

From the observation matrix, taken at each data point of the factorial design, a transition matrix is calculated:

$$p_{ij}(k) = \frac{\sum_{h=1}^{n} X_{hij}(k)}{\sum_{j=1}^{m} \sum_{h=1}^{n} X_{hij}(k)} \quad \text{[Eq F-22]}$$

The resulting transition matrix is referred to as the transition data matrix, and there will be a transition data matrix for each data point; in the case of the 2^{7-3} design, there will be 16 such data matrices:

$$[p_{ij}(k)]_i = T_i \quad \text{[Eq F-23]}$$

where T_i = transition data matrix at data point i.

Because the data being collected will be of an attribute nature, a large sample will be required in order to maintain the desired precision of the estimated transition probabilities. The estimate $p_{ih}(k)$ will have a variance

$$p_{ij}(k) = \frac{p(1-p)}{n} \quad \text{[Eq F-24]}$$

where n = the total number of components which were initially in state i. The variance of the estimate p will be a maximum when $p_{ij}(k) = 0.50$; therefore, in order to have a precision of ± 1 percent

$$n \geq \frac{0.50^2}{0.10} \qquad n \geq 25.$$

This is not to suggest that a sample of at least 25 components in state 1, 25 in state 2, etc., be taken; the total sample of components taken at a data point should be as random as possible in order to have some idea of the distribution of the initial states. The samples should be sufficiently large so that there are about 25 components in each of th[illegible]tial states; barring this, the resulting precision of the estimate should be kept in mind.

8 LEAST SQUARES MODEL

The data derived from the observations is used to estimate the parameters of a second-order least squares model as follows:

$$p_{ij}(k) = b_0 + b_1 V_1 + b_2 V_2 + \ldots + b_n V_n + b_{12} V_1 V_2 + \ldots + b_{1n} V_1 V_n + \ldots b_{n-1,n} V_{n-1} V_n + \text{Residual} \quad \text{[Eq F-25]}$$

Estimates of parameters are obtained by the method of least squares in matrix notation:

$$\underline{b(k)} = (V'V)^{-1} Y_{ij}(k) \quad \text{[Eq F-26]}$$

where $\underline{b(k)}$ = vector of parameter estimates
V = design matrix
$Y_{ij}(k)$ = vector of the $p_{ij}(k)$ estimates from all data points, where $y_h(k) = p_{ij}(k)$ at data point h.

Analysis of the data by least squares will result in a set of polynomial models, one for each possible state transition:

N^2 = number of state transitions, and least-squares polynomial models r[illegible]quired, where N = the number of states.

This provides an additional reason for keeping the number of states at the minimum necessary.

With the parameter estimates, it is possible to calculate a transition matrix from a set of values for the independent variables. Because of the lack of fit and residual error inherent in the least-squares process, it may be necessary to adjust the derived transition probabilities so that

$$\sum_{j=1}^{m} p_{ij}(k) = 1.0 \quad \text{[Eq F-27]}$$

To do this, a "dummy" term is introduced so that:

$$\sum_{j=1}^{m} p_{ij}(k) - C = 1.0 \quad \text{[Eq F-28]}$$

$$\sum_{j=1}^{m} p_{ij}(k) = 1.0 + C \quad \text{[Eq F-29]}$$

$$\frac{\sum_{j=1}^{m} p_{ij}(k)}{1+C} \quad \frac{1+C}{1+C} = 1.0.$$

[Eq F-30]

Thus, dividing each element in a row of the derived transition matrix by the sum of the probabilities in that row will result in a corrected row of transition probabilities whose sum will be equal to 1.0.

9 MISSION ANALYSIS

Each component of a facility can be expected to affect the mission of the facility. The states of the component can be expected to have different impacts on the various facility missions. As an independent part of the analysis, and as a part of the generalized aspect of the model, it is necessary to quantitatively assess impacts that the component states will have on the various missions. This multiple mission concept will mainly apply to the components which relate to buildings rather than to non-building facilities. Non-building facilities will more likely have a single mission or function.

The process for estimating these effects is, for the most part, subjective; the accuracy and reliability of the effectiveness measure will largely be a function of the skill and experience of the person or persons making the estimates. The procedure and resulting mission effects matrix is easily understood and lends itself to easy correction and arrival at a consensus where there may be differences of opinion. In many cases, degradation of the facility mission will be closely correlated with effectiveness of the facility as a whole (e.g., the electrical power distribution component in a missile launch facility), while in other cases there may not be a clear-cut relationship (e.g., with the roof component of a warehouse facility). It is hoped that a maximum of objective and reliable mission effectiveness estimates will result by making the mission analysis independent of the condition of the component.

At the onset, all facility missions should be listed to include all types of facilities which may contain the component in question. Next, these facility missions should be grouped according to any commonality of the specific function that the component is to perform (see numerical example). This will better relate the component to the mission of the facility and reduce the complexity of the estimating process.

When all missions of the facility have been listed, a fraction is assigned to each state of the component for each facility mission that may be encountered. The fraction indicates the degree to which the facility mission is degraded when the component is in a particular state, the resulting mission effects matrix D(k) will appear:

$$\begin{array}{c} \\ \\ s_1 \\ s_2 \\ s_j = . \\ . \\ . \\ s_m \end{array} \begin{array}{c} \text{mission } j = \\ \begin{array}{cccc} 1 & 2 & \dots & a \end{array} \\ \begin{bmatrix} d_{11}(k) & d_{12}(k) & \dots & d_{1a}(k) \\ d_{21}(k) & d_{22}(k) & \dots & d_{2a}(k) \\ . & & & \\ . & & & \\ . & & & \\ d_{m1}(k) & d_{m2}(k) & \dots & d_{ma}(k) \end{bmatrix} \end{array}$$

[Eq F-31]

The estimates $d_{ij}(k)$ are required to be in the range:

$$0 \leq d_{ij}(k) \leq 1.0.$$

10 TOTAL COMPONENT EFFECTIVENESS

The effectiveness of a component can be computed from two determining inputs: the set of design, environmental, and policy variables which describe the component, and the mission of the facility or facilities which contain the component by way of the mission effects matrix.

The variable values are applied to the polynomial equations to arrive at a theoretical one-step transition matrix. After any necessary adjustments, the matrix $\hat{P}(k)$ is taken to a power, usually 5 or 6, sufficient to arrive at steady-state probabilities $[\pi(k)]$. These represent the long-run probabilities that the component, under conditions as set by values of the input variables, will be in a given state.

Multiplying the steady-state probability vector by the mission effects matrix results in an ineffectiveness vector, showing the long-run degradation of the component on the missions of facilities containing

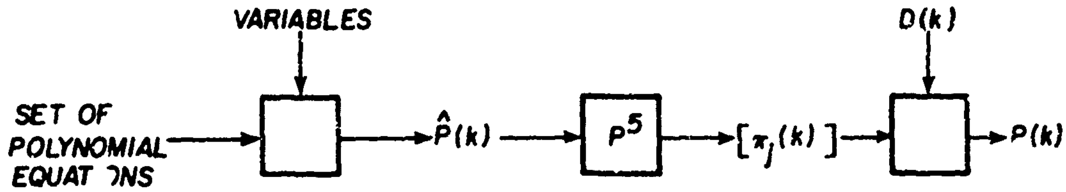

Figure F1. Component effectiveness model.

the component, as:

$$[\pi(k)] \cdot D(k) = F(k). \quad \text{[Eq F-32]}$$

The component ineffectiveness is expressed as a decimal fraction. Multiplying the steady-state probability vector by a single column vector from D(k) will result in the element from the ineffectiveness vector for a particular mission in question:

$$[\pi(k)] \cdot D_j(k) = f_j(k) \text{ for the } j\text{th mission.} \quad \text{[Eq F-33]}$$

The effectiveness of the component (Figure F-1) as applied to a facility with mission j, is:

$$e_j(k) = 1.0 - f_j(k) \quad \text{[Eq F-34]}$$

$$0 \leq e_j(k) \leq 1.0.$$

11 NUMERICAL EXAMPLE

It is desirable to evaluate the effectiveness of a particular type of central air conditioning system installed in a number of different facilities.

Three states are defined for the component:

State 1: Excellent operating condition; operating at 95 to 100 percent reliability with no downtime for corrective maintenance. Requires only routine periodic cleaning and lubrication.

State 2: Operating at 80 to 95 percent reliability; system is down for corrective maintenance on minor components, with failed parts showing wearout node.

State 3: System marginally operational, at less than 80 percent reliability. Major replacement of parts required due to wearout. Total failure imminent.

The important variables* which determine the performance of the system are:

V_1 = system age, yr
V_2 = percent capacity utilized (Btu demand/Btu rated) × 100
V_3 = preventive maintenance policy (average $ spent per unit per yr).

These variables are related to the Markov transition probabilities by the following first-order equation:

$$p_{ij} = \beta_0 + \beta_1 V_1 + \beta_2 V_2 + \beta_3 V_3. \quad \text{[Eq F-35]}$$

Estimates of the parameters of the equations are to be made by the method of least squares. In order to obtain independent estimates of the parameters, a 2^3 factorial design will be used which will result in a total of eight test points:

Table F-2

Design Matrix*

Test Point	V_1	V_2	V_3
1	+1	+1	+1
2	−1	+1	+1
3	+1	−1	+1
4	−1	−1	+1
5	+1	+1	−1
6	−1	+1	−1
7	+1	−1	−1
8	−1	−1	−1

*Interaction terms, though not included, would automatically be available for estimation of parameters.

*Use of these three variables is for illustration only; the model is kept small for clarity.

Table F-2 (cont'd)

Variable	Units	Levels	
		Low (−1)	High (+1)
V_1 system age	yr	2	11
V_2 percent capacity utilized	%	50	95
V_3 maintenance policy	$/unit/yr	50	150

At each data point, for the combination of levels for the variables, a sample of components having these conditions is randomly identified and the present state of each component is recorded. After a passage of 1-yr, these components are again evaluated. From these evaluations, the change in state is determined in the form of the observation matrix:

V_1 = 11 yr
V_2 = 95 percent capacity
V_3 = $150 per unit per yr

Data Point 1

$$\begin{array}{c} \quad S_1 \quad S_2 \quad S_3 \\ S_1 = s_2 \begin{bmatrix} 6 & 10 & 4 \\ 22 & 11 & 2 \\ 10 & 10 & 5 \end{bmatrix} \end{array} \qquad \text{[Eq F-36]}$$

Complete example data appear in Table F-3.

Next, use the elements of the transition data matrix, from Eq. F-22:

$$p_{11} = \frac{6}{20} = 0.300$$

$$p_{12} = \frac{10}{20} = 0.500$$

$$p_{33} = \frac{6}{30} = 0.200$$

$$T_1 = \begin{bmatrix} 0.300 & 0.500 & 0.200 \\ 0.380 & 0.380 & 0.240 \\ 0.400 & 0.400 & 0.200 \end{bmatrix} \qquad \text{[Eq F-37]}$$

Similar data are gathered and calculations are made to give a set of eight transition data matrices.

Table F-3

Example Data

Data Point 1

$$\begin{bmatrix} .300 & .500 & .200 \\ 6 & 10 & 4 \\ .380 & .380 & .240 \\ 19 & 19 & 12 \\ .400 & .400 & .200 \\ 12 & 12 & 6 \end{bmatrix} \begin{matrix} \\ 20 \\ \\ 50 \\ \\ 30 \end{matrix}$$

Data Point 2

$$\begin{bmatrix} .629 & .314 & .057 \\ 22 & 11 & 2 \\ .527 & .382 & .091 \\ 29 & 21 & 5 \\ .467 & .400 & .133 \\ 7 & 6 & 2 \end{bmatrix} \begin{matrix} \\ 35 \\ \\ 55 \\ \\ 15 \end{matrix}$$

Data Point 3

$$\begin{bmatrix} .400 & .400 & .200 \\ 10 & 10 & 5 \\ .383 & .383 & .234 \\ 23 & 23 & 14 \\ .467 & .400 & .133 \\ 7 & 6 & 2 \end{bmatrix} \begin{matrix} \\ 25 \\ \\ 60 \\ \\ 15 \end{matrix}$$

Data Point 4

$$\begin{bmatrix} .757 & .186 & .057 \\ 53 & 13 & 4 \\ .560 & .360 & .080 \\ 14 & 9 & 2 \\ .600 & .400 & .000 \\ 3 & 2 & 0 \end{bmatrix} \begin{matrix} \\ 70 \\ \\ 25 \\ \\ 5 \end{matrix}$$

Data Point 5

$$\begin{bmatrix} .267 & .533 & .200 \\ 4 & 8 & 3 \\ .267 & .444 & .289 \\ 12 & 20 & 13 \\ .225 & .350 & .425 \\ 9 & 14 & 17 \end{bmatrix} \begin{matrix} \\ 15 \\ \\ 45 \\ \\ 40 \end{matrix}$$

Data Point 6

$$\begin{bmatrix} .600 & .333 & .067 \\ 18 & 10 & 2 \\ .417 & .450 & .133 \\ 25 & 27 & 8 \\ .400 & .300 & .300 \\ 4 & 3 & 3 \end{bmatrix} \begin{matrix} \\ 30 \\ \\ 60 \\ \\ 10 \end{matrix}$$

Data Point 7

$$\begin{bmatrix} .400 & .400 & .200 \\ 6 & 6 & 3 \\ .267 & .450 & .283 \\ 16 & 27 & 17 \\ .320 & .320 & .360 \\ 8 & 8 & 9 \end{bmatrix} \begin{matrix} \\ 15 \\ \\ 60 \\ \\ 25 \end{matrix}$$

Data Point 8

$$\begin{bmatrix} .725 & .200 & .075 \\ 29 & 8 & 3 \\ 420 & .440 & .140 \\ 21 & 22 & 7 \\ .500 & .300 & .200 \\ 5 & 3 & 2 \end{bmatrix} \begin{matrix} \\ 40 \\ \\ 50 \\ \\ 10 \end{matrix}$$

By least squares, parameters of nine polynomial equations are then estimated:

Model: $p_{11} = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 +$ residual

In matrix notation, Eq. F-26:

$$\underline{b} = (V'V)^{-1} V' Y_{11}$$

$$Y_{11} = \begin{bmatrix} 0.300 \\ 0.629 \\ 0.400 \\ 0.757 \\ 0.267 \\ 0.600 \\ 0.400 \\ 0.725 \end{bmatrix}$$

$$
V = \begin{bmatrix} +1 & +1 & +1 \\ -1 & +1 & +1 \\ +1 & -1 & +1 \\ -1 & -1 & +1 \\ +1 & +1 & -1 \\ -1 & +1 & -1 \\ +1 & -1 & -1 \\ -1 & -1 & -1 \end{bmatrix}
$$

$$
(V'V)^{-1} V' Y_{11} = \begin{bmatrix} \frac{1}{8} & 0 & 0 \\ 0 & \frac{1}{8} & 0 \\ 0 & 0 & \frac{1}{8} \end{bmatrix} \begin{bmatrix} +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 & +1 & +1 & -1 & -1 \\ +1 & +1 & +1 & +1 & -1 & -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} 0.300 \\ 0.629 \\ 0.400 \\ 0.757 \\ 0.267 \\ 0.600 \\ 0.400 \\ 0.725 \end{bmatrix}
$$

[Eq F-38]

$$\underline{b_n} = [-0.168 - 0.059 + 0.0118]$$

$$\overline{Y}_{11} = 0.510$$

By analysis of variance (ANOVA, Table F-4), the significant equation parameters are determined.

Table F-4

ANOVA: Data Point 1

Source	Sum of Squares	D.F.	Mean Square	F
Total	[illegible] 336	8	—	
Mean b_0	[illegible]79	1		
Regression: b_1	0.2[illegible]5	1	0.225	225.0
b_2	0.027	1	0.027	27.0
b_3	0.001	1	0.001	1.0
Regression total	0.253	3	0.084	84.3
Residual (by subtraction)	0.004	4	0.001	

$$F_{0.95}(1,3) = 10.1$$

$$F_{0.95}(3,4) = 6.59$$

(b_3 is not significant.) The equation now becomes

$$\hat{p}_{11} = 0.510 - 0.168\,V_1 - 0.059\,V_2 \quad \text{[Eq F-39]}$$

The least-squares analysis for all of the transition probabilities resulted in the following set of equations:

$$p_{11} = 0.510 - 0.168\,V_1 - 0.061\,V_2 + .012\,V_3 \quad \text{[Eq F-40]}$$

$$p_{12} = 0.358 + 0.10\,V_1 + .062\,V_2 \quad \text{[Eq F-41]}$$

$$p_{13} = 0.132 + 0.068\,V_1 \quad \text{[Eq F-42]}$$

$$p_{21} = 0.403 - 0.078\,V_1 \qquad + 0.060\,V_3 \quad \text{[Eq F-43]}$$

$$p_{22} = 0.411 \qquad - 0.035\,V_3 \quad \text{[Eq F-44]}$$

$$p_{23} = 0.186 + 0.075\,V_1 \qquad - 0.025\,V_3 \quad \text{[Eq F-45]}$$

$$p_{31} = 0.422 - 0.069\,V_1 - 0.49\,V_2 + 0.061\,V_3 \quad \text{[Eq F-46]}$$

$$p_{32} = 0.359 + 0.041\,V_3 \quad \text{[Eq F-47]}$$

$$p_{33} = 0.219 \qquad - 0.102\,V_3 \quad \text{[Eq F-48]}$$

Missions for facilities which may contain this component, a building type component, can be listed with the corresponding specific component function, as shown in Table F-5.

Table F-5

Mission Analysis

Mission No.	Facility Mission	Component Function
1	Troop housing	Comfort, habitability
2	Family housing	Comfort, habitability
3	Community building	Comfort, habitability
4	Operational-electronics	Equipment cooling
5	Operational-other	Personnel efficiency
6	Training	Personnel efficiency
7	Administraion	Personnel efficiency
8	Production	Personnel efficiency
9	Medical	Enhanced medical efficiency

The mission analysis proceeds with an assessment (Table F-6) of the effect that the previously defined component states have on the above missions.

This mission analysis necessarily refers to conditions at a particular installation; in this case, the

Table F-6

Assessment of Component States

Facility Mission No.

$$S = \begin{bmatrix} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ S_1 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ S_2 & 0.20 & 0.25 & 0.10 & 0.50 & 0.25 & 0.30 & 0.25 & 0.05 & 0.45 \\ S_3 & 0.30 & 0.35 & 0.20 & 1.00 & 0.35 & 0.40 & 0.30 & 0.10 & 0.65 \end{bmatrix}$$

climate is one where hot weather is frequently encountered. In a different climate, the mission effects for a component (in this case, air conditioning) would be different. In this way, the conditions under which the mission occurs enter the model.

For the air conditioning system installed in family housing (mission No. 2) and in a radar transmitter building (mission No. 4), the important variables are as follows:

$V_1 = 1.7$ yr old	-1.07
$V_2 = 30$ percent capacity	-1.89
$V_3 = \$75$ per unit per yr	$-.50$

The theoretical transition matrix, derived from the equations, results in:

$$\hat{P} = \begin{bmatrix} 0.799 & 0.134 & 0.059 \\ 0.456 & 0.429 & 0.118 \\ 0.558 & 0.339 & 0.270 \end{bmatrix} \quad \text{[Eq F-49]}$$

Taking this to the fourth power results in the steady-state probabilities:

$$[\pi] = [0.762 \quad 0.239 \quad 0.100].$$

Applying these to the mission effects matrix:

$$F = [\pi] \cdot D = [0.078 \quad 0.095 \quad 0.044 \quad 0.220 \quad 0.095 \quad 0.112 \quad 0.090 \quad 0.022 \quad 0.173].$$

The mission effectiveness due to the component in family housing (mission No. 2) is:

$$e_2 = 1 - 0.095 = 0.905.$$

However, the effectiveness when used for cooling radar equipment is:

$$e_4 = 1 - 0.220 = 0.780.$$

12 NUMERICAL EXAMPLE FOR ABSORBING STATE

The following is an example wherein a component may be in any of four states. Only the names of the states are given; descriptions can be determined at time of application. Assume that the p_{ij}'s have been calculated by the method described before and the following is obtained:

	Good	Average	Poor	Disposal
Good	0.4	0.4	0.2	0.0
Average	0.2	0.5	0.2	0.1
Poor	0.0	0.2	0.4	0.4
Disposal	0.0	0.0	0.0	1.0

The matrix is partitioned into:

r = 1 absorbing state

s = 3 non-absorbing states.

The following form is used:

$$P = \begin{matrix} r \\ s \end{matrix} \begin{bmatrix} I & 0 \\ R & Q \end{bmatrix} \quad \text{[Eq F-50]}$$

The matrix then becomes:

	Disposal	Good	Average	Poor
Disposal	1.0	0.0	0.0	0.0
Good	0.0	0.4	0.4	0.2
Average	0.1	0.2	0.5	0.2
Poor	0.4	0.0	0.2	0.4

$$Q = \begin{bmatrix} 0.4 & 0.4 & 0.2 \\ 0.2 & 0.5 & 0.2 \\ 0.0 & 0.2 & 0.4 \end{bmatrix}$$

$$(I-Q) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0.4 & 0.4 & 0.2 \\ 0.2 & 0.5 & 0.2 \\ 0.0 & 0.2 & 0.4 \end{bmatrix}$$

$$(I-Q) = \begin{bmatrix} 0.6 & -0.4 & -0.2 \\ -0.2 & -0.5 & -0.2 \\ 0.0 & -0.2 & 0.6 \end{bmatrix}$$

$$(I-Q)^{-1} = \begin{bmatrix} 2.48 & 2.42 & 1.08 \\ 1.04 & 3.10 & 0.67 \\ 0.346 & 1.03 & 1.89 \end{bmatrix} = N$$

$$NR = \begin{bmatrix} 2.48 & 2.42 & 1.08 \\ 1.04 & 3.10 & 0.67 \\ 0.346 & 1.03 & 1.89 \end{bmatrix} \begin{bmatrix} 0.0 \\ 0.1 \\ 0.4 \end{bmatrix} - \overset{\text{Disposal}}{\begin{bmatrix} 0.674 \\ 0.578 \\ 0.859 \end{bmatrix}} \begin{matrix} \text{good} \\ \text{average} \\ \text{poor} \end{matrix}$$

[Eq F-51]

From the above, the probability of being disposed given an initial good condition is 0.674. The probability of being disposed given an initial average condition is 0.578. The probability of being disposed given an initial poor condition is 0.859.

To arrive at the mean number of steps it takes to absorb from a given state:

$$M = N\underline{1} = \begin{bmatrix} 2.48 & 2.42 & 1.08 \\ 1.04 & 3.10 & 0.67 \\ 0.346 & 1.03 & 1.89 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 5.98 \\ 4.81 \\ 3.27 \end{bmatrix}$$

[Eq F-52]

From the above, given an initial good state, it takes 5.98 steps to dispose of the component; given an initial average state it takes 4.81 steps; and given an initial poor state, it takes 3.27 steps.

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LIST OF ABBREVIATIONS

LEF	life expectancy of facilities
DA	Department of the Army
BEMAR	backlog of essential maintenance and repair
LCC	life-cycle cost
BIS	Building Information Schedule
NCEL	Naval Civil Engineering Laboratory

MILCON military construction

NAVFAC Naval Facilities Engineering Command

FLW Fort Leonard Wood, Missouri

F4C facility classes and construction category codes

IFS Integrated Facilities System

IJO individual job order

ENR *Engineering News-Record*

CONUS continental United States

DFAE Directorate of Facilities Engineering

ANOVA analysis of variance