Investment Model of Fire Protection Equipment for Office Building

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ABSTRACT

This report presents (1) a canonical correlation analysis that describes the relations between characteristics of a building and cost indices of fire protection equipment, and (2) how to apply the analysis for a standard and a trade-off for investment model of fire protection equipment when designers would decide to invest in fire protection equipment.

The results of the analysis show that the variate pairs between characteristics of a building and cost indices of fire protection equipment are highly related, and also are available for a standard and a trade-off for investment model of fire protection equipment. Based on the canonical loadings, designers evaluate the installation of sprinkler systems against widths within the buildings, and decide to emphasize the installation of dry risers or sprinkler systems by comparison between the width and service cost index of the buildings.

1. INTRODUCTION

There has been a misunderstanding that costs relating to fire protection are usually unduly high in comparison with the entire construction cost of a building. On the other hand, detailed research into the exact cost of fire protection does not seem to have been conducted. There are difficulties involved in conducting such research; estimated data usually are not recorded systematically. Moreover, many fire protection items are not merely installed for the single purpose of fire fighting, but are for multifunctional use. For example, fire walls, staircases, safety zones, and so on.

In my prior reports[1,2,3], the "fire protection costs" included in past estimates from the records of estimation and discussions with a view to determining the facts on their investment are described. Furthermore, taking into account the results of such analyses, the office buildings were chosen for further detailed research.

This report presents a canonical correlation analysis which describes the relations between a set of predictor variables (characteristics of a building) and a set of criterion variables (cost indices of fire protection equipment). And by using the results, also discussed are a standard and a trade-off for investment model of fire protection equipment when designers would decide to invest in fire protection equipment.

2. DATA BASE AND ITEMS TO BE ANALYZED

2.1 Data Base

Shimizu Construction Co Ltd has kept systematic records of estimates on every building construction job it has undertaken. For each building the estimators recorded their estimation results on coding sheets according to an entry manual. A set of coding sheets contains about 2,000 different items, for which 12,350 bytes are computerized as a random-access file. This data base system was, however, suspended for the purpose of reviewing its recording procedures and items. The period of time such estimates cover ranges from March 1970 through December 1983.

2.2 Limitations and Conditions of Analyses

In planning fire safety, there are many fire protection items to be considered. In the data base, most of their quantities are counted in terms of number or area. It is not always possible to pick up the exact cost of each and every item because of certain limitations[1,2,3] in the data base system.

On the other hand, however, it is relatively easy to determine costs relating to fire protection where "electrical and mechanical" works are recorded as separate items under the limitations. In the analysis that follows, the ratio of the costs, and also building construction job, to estimated entire construction cost will be called cost index. The records of 359 office building, with 27 characteristics and 12 cost indices of fire protection equipment of a building, are chosen for the analysis from the system in which are entered 1,592 statistics on buildings.

3. CANONICAL CORRELATION ANALYSIS

The study of relations between a set of predictor variables and a set of criterion variables is know as Canonical Correlation Analysis (CCA). CCA is the most general of the multivariate techniques. In fact, the other procedures - multiple regression, discriminant function analysis, and MANOVA - are all special cases of it. CCA should be used in simultaneously analyzing several predictor variables and criterion variables. It is particularly appropriate when the criterion variables are themselves correlated. The Canonical Correlation Model (CCM), formulated from the CCA, is employed for two reasons: (1) to find a linear combination of the original predictor variables that best explain variation in the criterion variables and (2) to investigate relations between the two sets of variables by duly considering the canonical weights or canonical loadings. The canonical weights express the importance of a variable from one set with regard to the other set in obtaining a maximum correlation between sets. Thus, they are comparable with multiple regression weights.[4] The canonical loading gives the ordinary product-moment correlation of the original variable and its respective canonical variate. Thus, it reflects the degree to which a variable is represented by a canonical variate.[4]

Let "m" be the number of predictors and "p" be the number of criterion variables. The CCM is described as a set of predictor variables-X_m^* (characteristics of buildings) and a set of criterion variables-Y_p^* (fire protection equipment) as shown in Table 1. This can be expressed as --

$$Y_p^* = b_1 X_m^* + b_0 \qquad (1)$$

where b_0 and b_1 are defined as regression coefficients.

X_m^* and Y_p^* of CCA can be defined as the following two-linear combinations of the "m" predictors and the "p" criterion variables:

$$X_m^* = c_1x_1 + c_2x_2 + \ldots\ldots + c_mX_m$$
$$Y_p^* = d_1y_1 + d_2y_2 + \ldots\ldots + d_py_p \tag{2}$$

and

$$d_1y_1 + d_2y_2 + \ldots\ldots + d_py_p = c_1x_1 + c_2x_2 + \ldots\ldots + c_mx_m \tag{3}$$

where d_i (i = 1 ... 27) and c_j (j = 1 ... 12) are defined as canonical weights.

The size or scale of canonical weights is influenced according to those of predictor and criterion variables because the variables under study possess different and arbitrary units and scales. To avoid such an influence, an arbitrary normalization of x_{zi} (i = 1 ... 27) and y_{zj} (j = 1 ... 12) are calculated according to the following:

$$x_{zi} = (x_i - \bar{x}_i) / S_{xi} \quad (i = 1 \ldots 27)$$
$$y_{zj} = (y_j - \bar{y}_j) / S_{yj} \quad (j = 1 \ldots 12) \tag{4}$$

where x_{zi} and y_{zj} are defined as normalized score (Z-score), $\bar{x}_i$ and $\bar{y}_j$ are mean, and S_{xi} and S_{yj} are standard deviation for the predictor and criterion variables. Therefore, X_m^* and Y_p^* have unit variance, that is mean $(X_m^*) = 0$ and similarly mean $(Y_p^*) = 0$; and b_1 in equation (1) is defined as a correlation coefficient between X_m^* and Y_p^*; then $b_0 = 0$.

Following the previous data transformation, the canonical weights do not depend on the original scale of measurement, and are expressed in standardized form, given by --

$$d_1y_1 + d_2y_2 + \ldots\ldots + d_{12}y_{12} = c_1x_1 + c_2x_2 + \ldots\ldots + c_{27}x_{27} \tag{5}$$

4. RESULTS OF CANONICAL CORRELATION ANALYSIS

Table 1 shows the means, standard deviations and Box-and-Whisker plots of 27 characteristic variables, predictor variables, and 12 items of fire protection equipment, criterion variables, of a building. The Box-and-Whisker[5] plot is designed by J W Tukey to summarize the location of the bulk of the data with a box that covers the central 50% of the points, extending from the first to the third quartile. In addition, a "*" in the box points the median, and "whiskers" extend to the extreme points. The box shows the "body" of the data, and the whiskers portray the "tails" with suitably less visual impact.[6]

Table 2 shows that the canonical correlations are large (0.834 and 0.717), which implies that the canonical variate pairs are highly related. Figure 1 might show spuriously high canonical correlation because of the dot "α". Then additional analysis was conducted which eliminated a dot "α" and samples of which buildings were not required to install even one item of fire protection equipment listed in Table 1 according to relevant laws and regulations. The canonical correlations in the above-mentioned analysis are 0.814 and 0.638. Therefore, the canonical weights shown in Table 2 will be employed as a

Table 1. Means, Standard deviations and Box-and-Whisker plots of 39 variables of a building.

variables		means	standard deviations	Box-and-Whisker plots*
x_1 number of stories/basement		0.20	0.476	
x_2 number of stories		3.98	2.378	
x_3 building area	(m^2)	467.22	478.674	
x_4 architectural area	(m^2)	1853.24	3033.737	
x_5 cost index/building work	(%)	26.73	4.860	
x_6 /exterior finishing work	(%)	14.55	6.962	
x_7 /interior finishing work	(%)	15.31	6.472	
x_8 /other work	(%)	1.59	3.486	
x_9 /services	(%)	25.30	7.864	
x_{10} estimation date **		-4.18	2.106	
x_{11} unit cost	(1000Yen/m^2)	120.10	35.710	
x_{12} area index/fire escapes	(%)	0.92	2.155	
x_{13} /balcony	(%)	0.63	1.920	
x_{14} /public	(%)	17.60	8.276	
x_{15} /control	(%)	1.28	4.815	
x_{16} /services	(%)	4.24	4.315	
x_{17} number of spans/ridge direction		4.00	2.106	
x_{18} /bay direction		2.53	1.372	
x_{19} typical span length/ridge direction	(m)	6.56	1.954	
x_{20} /bay direction		8.34	2.693	
x_{21} number of structural bays		9.08	8.681	

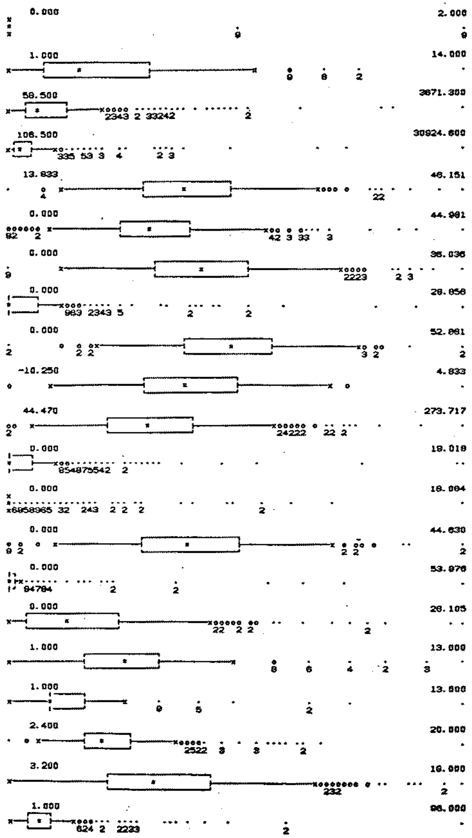
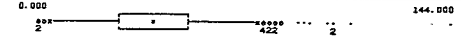
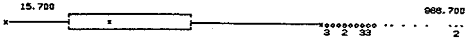
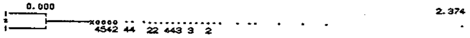
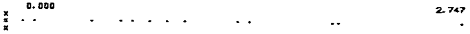
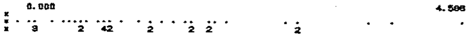
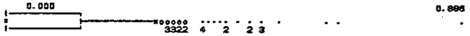
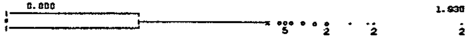
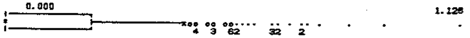
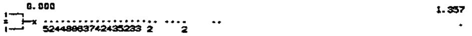
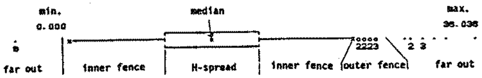


Table 1. (Continued)

variables		means	standard deviations	Box-and-Whisker plots*
x_{22}typical stractural bay spacing	(m^2)	51.46	18.147	
x_{23}number of columns/external		53.42	49.427	
x_{24} /internal		14.04	26.308	
x_{25}total length/external wall	(m)	292.35	198.908	
x_{26} /girders	(m)	809.12	946.430	
x_{27} /beam	(m)	457.52	764.771	
y_1 dry riser		0.17	0.344	
y_2 sprinkler system		0.02	0.109	
y_3 foam extinguishing system		0.06	0.365	
y_4 Halon system		0.04	0.256	
y_5 carbon dioxide extinguishing system		0.00	0.039	
y_6 smoke ventilation system		0.07	0.251	
y_7 independent electric power source		0.16	0.574	
y_8 emergency power source		0.06	0.200	
y_9 fire alarm indicating equipment		0.08	0.139	
y_{10}automatic fire alarm system		0.29	0.406	
y_{11}interlocking device by smoke detector		0.13	0.205	
y_{12}fire detection and alarm warning		0.07	0.149	

** x_{10}=(Year-1977)+(Month-1)/12

* Box-and-Whisker plots



"H-spread"=difference between values of hinges.
"step"=1.5 times H-spread.
"inner fences" are 1 step outside hinges.
"outer fences" are 2 step outside hinges.(and thus 1 step outside of inner fences)
values beyond outer fences are "far out".

Figure 1. Scatter plot between the first canonical score X* (characteristics of a building) and Y* (cost indices of fire protection equipment).

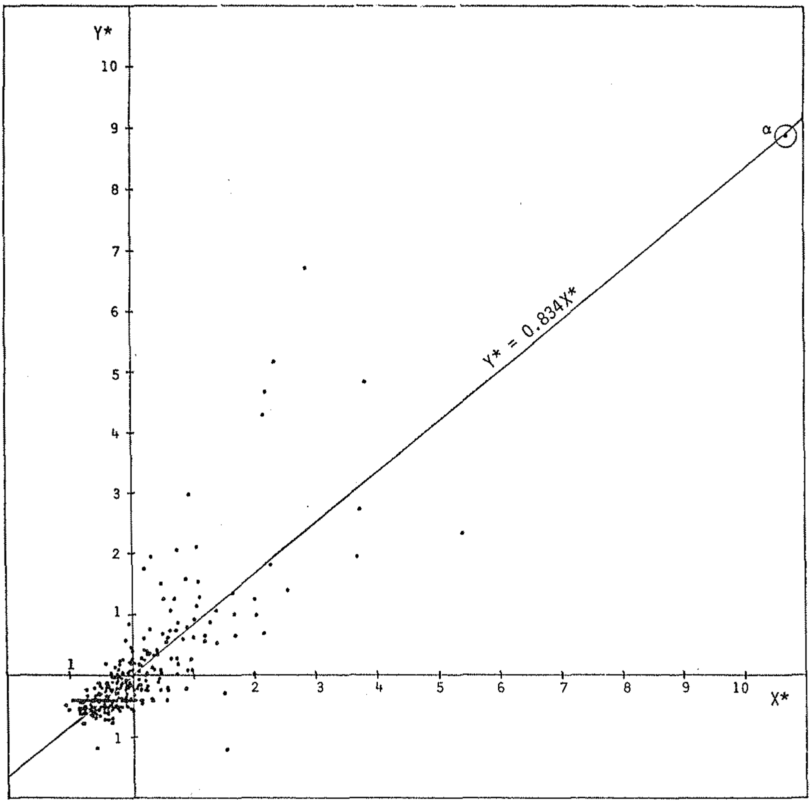


Table 2. Canonical correlation analysis of relations between characteristics of a building and fire protection equipment.

Variables	Variate 1		Variate 2	
	Canonical loadings	Canonical weights	Canonical loadings	Canonical weights
Predictor set X^*				
x_1 number of stories/basement	0.71	0.24	-0.20	-0.37
x_2 number of stories	0.61	0.07	-0.26	-0.38
x_3 building area (m^2)	0.68	-0.03	-0.27	-0.71
x_4 architectural area (m^2)	0.92	0.02	0.03	0.24
x_5 cost index/building work (%)	0.01	0.01	0.14	-0.08
x_6 /exterior finishing work (%)	-0.19	0.03	0.06	-0.06
x_7 /interior finishing work (%)	-0.22	-0.04	0.31	-0.00
x_8 /other work (%)	-0.02	0.04	-0.10	-0.10
x_9 /services (%)	0.43	0.11	-0.44	-0.24
x_{10} estimation date	-0.08	-0.03	0.10	0.09
x_{11} unit cost (*1000Yen/m^2)	0.19	-0.09	-0.14	-0.08
x_{12} area index/fire escapes (%)	0.01	-0.02	-0.14	0.03
x_{13} /balcony (%)	-0.03	-0.01	0.04	0.07
x_{14} /public (%)	-0.07	-0.02	-0.03	-0.04
x_{15} /control (%)	-0.06	-0.01	0.06	-0.01
x_{16} /services (%)	0.48	0.08	-0.23	0.08
x_{17} number of spans/ridge direction	0.54	0.13	-0.16	0.07
x_{18} /bay direction	0.46	0.06	0.07	0.04
x_{19} typical span length/ridge direction(m)	0.13	0.04	-0.07	0.05
x_{20} /bay direction	0.20	0.01	-0.38	-0.12
x_{21} number of structural bays	0.70	-0.03	0.11	-0.09
x_{22} typical stractural bay spacing (m^2)	0.30	0.04	-0.40	-0.17
x_{23} number of columns/external	0.91	0.17	-0.06	0.08
x_{24} /internal	0.87	0.06	0.03	-0.08
x_{25} total length/external wall (m)	0.40	-0.04	-0.57	-0.34
x_{26} /girders (m)	0.70	-0.19	-0.32	-0.16
x_{27} /beam (m)	0.95	0.59	0.17	1.21
Explained variance	25.9%		6.2%	
Criterion set (cost index(%)) Y^*				
y_1 dry riser	0.39	0.18	-0.49	-0.34
y_2 sprinkler system	0.84	0.66	0.44	0.86
y_3 foam extinguishing system	0.30	0.19	-0.10	-0.13
y_4 Halon system	0.29	0.02	-0.40	-0.44
y_5 carbon dioxide extinguishing system	0.28	-0.08	-0.06	-0.30
y_6 smoke ventilation system	0.64	0.25	-0.18	-0.22
y_7 independent electric power source	0.34	0.07	-0.25	-0.24
y_8 emergency power source	0.50	0.17	-0.32	-0.07
y_9 fire alarm indicating equipment	0.15	0.03	-0.33	-0.20
y_{10} automatic fire alarm system	0.27	0.09	-0.29	-0.06
y_{11} interlocking device by smoke detector	0.21	0.02	-0.17	-0.02
y_{12} fire detection and alarm warning	-0.28	-0.08	0.32	0.12
Explained variance	18.0%		3.4%	
Canonical correlation	0.83		0.72	
Redundancy	0.18		0.03	

criterion when designers determine which fire protection equipment will be installed and how many items should be assigned to the building that they design.

Table 2 however, shows that the percentage of explained variance -- 25.9 and 6.2 percent for the criterion variables, and 18.1 and 3.4 percent for the predictor variables - are relatively small. Moreover, only about 21 percent (18.0+3.2) of the variation in the Y^*_{12}-set is accounted for by the X^*_{27}-set variate. Further, there are a number of algebraic sign reversals, and the rank ordering of variables varies substantially depending on whether the canonical weights or loadings are used.

Though canonical correlations suggest strong relations, and the structure of canonical loadings in these results demonstrates some similarity with those of the canonical weights, there are important differences due to multicollinearity. Thus, it is difficult for the canonical weights and loadings to be employed to determine the structure or relation between the 27 characteristics of a building and the 12 cost indices of fire protection equipment.

Based on these canonical loadings, the following results might be offered: designers who evaluate the installation of sprinkler systems (y_2) against the width within the buildings, total length of beams (x_{27}), architectural area (x_4) and number of external columns (x_{23}) [variate 1], and who decide to emphasise the installation of dry riser (y_1) or a sprinkler (y_2) by comparison between the width within the building, total length of external wall (x_{25}), and services cost index of the building (x_9) [variate 2].

5. DISCUSSIONS

5.1 A Standard for Fire Protection Investment

In this section is interpreted application of the CCM to the design standard of how to apply the cost of fire protection equipment.

Table 3 shows characteristics of building "A" for the applied calculation and the result by utilizing the CCM. Therefore, a standard for fire protection equipment is given by --

$$Y^{*}_{A12} = d_1y_{z1} + d_2y_{z2} + \ldots\ldots + d_{12}y_{z12} = 0.834x(-0.041) \qquad (6)$$

The stability of the CCM, however, is questionable because of the extrapolation: estimation date (x_{10}) is the variable for price fluctuations. As previously mentioned, the period of time that this estimation system covers ranges from March 1970 through December 1983, and calculation of a standard is extrapolated from 1984 retrogressively by the CCM.

Table 3. Characteristics of buildings for applied calculation and the result by utilizing the CCM.

Variables	Buildings		Z-score × Canonical weight	
	"A"	"B"	"A"	"B"
x_1 number of stories/basement	0.00	0.00	-0.101	-0.101
x_2 number of stories	7.00	8.00	0.089	0.118
x_3 building area (m^2)	642.00	588.00	-0.012	-0.007
x_4 architectural area (m^2)	4704.00	4704.00	0.019	0.019
x_5 cost index/building work (%)	26.73	26.73	0	0
x_6 /exterior finishing work (%)	14.55	14.55	0	0
x_7 /interior finishing work (%)	16.31	16.31	0	0
x_8 /other work (%)	1.59	1.59	0	0
x_9 /services (%)	25.30	25.30	0	0
x_{10} estimation date	5.00	5.00	-0.131	-0.131
x_{11} unit cost (1000Yen/m^2)	120.10	120.10	0	0
x_{12} area index/fire escapes (%)	0.92	0.92	0	0
x_{13} /balcony (%)	0.63	0.63	0	0
x_{14} /public (%)	17.60	17.60	0	0
x_{15} /control (%)	1.28	1.28	0	0
x_{16} /services (%)	4.24	4.24	0	0
x_{17} number of spans/ridge direction	4.00	4.00	0	0
x_{18} /bay direction	3.00	3.00	0.021	0.021
x_{19} typical span length/ridge direction(m)	7.00	7.00	0.009	0.009
x_{20} /bay direction	8.00	7.00	-0.001	-0.005
x_{21} number of structural bays	12.00	12.00	-0.010	-0.010
x_{22} typical stractural bay spacing (m^2)	56.00	49.00	0.010	-0.005
x_{23} number of columns/external	98.00	112.00	0.153	0.201
x_{24} /internal	42.00	48.00	0.064	0.077
x_{25} total length/external wall (m)	728.00	784.00	-0.088	-0.099
x_{26} /girders (m)	1624.00	1736.00	-0.164	-0.186
x_{27} /beam (m)	588.00	588.00	0.101	0.101
$0.834 \cdot X^*$			-0.034	0.002

5.2 A Trade-off for Fire Protection Investment

In this section is explained how application of the CCM to the trade-off between characteristics of the building and the fire protection equipment should be installed.

Table 3 also shows the characteristics of another building "B" for trade-off as compared with those of building "A". In this case, a standard for fire protection equipment is given by --

$$Y^*_{B27} = d1y_{z1} + d2y_{z2} + \ldots\ldots + d12y_{z12} = 0.834\text{x}(0.002) \qquad (7)$$

Let y_{z10} (automatic fire alarm system) and y_{z12} (fire detection and alarm warning) be the fire protection equipment for the trade-off, and assume that both items of fire protection equipment have similar effectiveness against fire protection, while other equipment is installed at the mean values. The following trade-off relations between building "A" and "B" can be defined --

$$0.091y_{z10} - 0.084y_{z12} = -0.034 \qquad (8)$$

$$0.091y_{z10} - 0.084y_{z12} = 0.002 \qquad (9)$$

where equation (8) is for building "A" and equation (9) is for building "B" in Table 3.

Now, to simplify this problem, either equipment of y_{z10} or y_{z12} should be selected. Under the above assumption, Table 5 shows the calculated cost indices of each item of fire protection equipment in case of one of above-mentioned two items is selected. The combination of building "A" and y_{z12} (fire detection and alarm warning) would be a better solution in this case.

Table 5. Calculated cost indices for fire protection equipment.

	Fire protection equipment	
Buildings	y_{10}	y_{12}
"A"	-0.036	0.014
"B"	0.124	-0.050

6. CONCLUSIONS

The results of CCA are as follows:

1) The variate pairs between characteristics of a building and cost indices of fire protection equipment are highly related, and also are available for a standard and a trade-off for investment model of fire protection equipment.

2) Based on the canonical loadings, designers evaluate the installation of sprinkler systems against the width within the buildings, and decide to emphasize the installation of dry risers or sprinkler systems by comparison between the width and service cost index of the buildings.

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