Relationships and Causal Structure among Building Design Parameters of Dwelling Unit in Multi-unit Residential Building

Kozo KADOWAKI (M. Eng.) and Seiichi FUKAO (Dr. Eng.)

Abstract

With the sustainability of the built environment becoming a major issue of the day, extended use of buildings with appropriate refurbishment has been increasing importance. The past researches proved that disentangling base building and fit-out enables easier customization or refurbishment in multi-unit residential building. However, disentanglement of base building and fit-out is not a sufficient condition for an appropriate refurbishment, because the design content of the base building, such as the story height and lighting conditions, strongly affect the content of the design of fit-out and are closely related to the choice range in fit-out designing.

The design of building fit-out is nothing but an agglomerate of the design of various segments designated as fit-out segments. Similarly to the base building restricting the fit-out, these segments affect the content of the design for other segments. Elucidating the mutual effects of such segments of multi-unit residential buildings is a crucial problem for grasping the fit-out design that a base building can accommodate and will provide a key to formulating a building system that permits a wide variety of refurbishment. This study aims to quantitatively grasp the effects of the design items on other items of each dwelling unit to obtain useful data for formulating a sustainable building system.

We collected drawings (building plans, building sections, dwelling unit plans, dwelling unit sections and so on) of 160 multi-unit residential buildings built after 1980 in Japan, and sampled one dwelling unit from each building to analyze. We measured 157 items that indicate building partial design characteristics from drawings, and calculated correlation coefficients of all the combinations of 133 quantitative items out of the aforementioned 157 items. We examined the relationships and their significances, and obtained a quantitative causal structure model among the items using covariance structure modeling. The important results are as follows:

1) The items can be divided into three categories: vertical cross section design category, utility design category and floor plan design category. Story height is the most influential in vertical cross section designing and utility designing. Lighting condition is the most influential in floor plan designing.
2) There is little relationship between vertical cross section designing and floor plan designing at a glance, however, sectional planning and equipping have a close relationship, and equipping and floor planning influence mutually.

Keywords: Open Building, Dwelling Unit Design, Interior Refurbishment, Correlation, Covariance Structure model

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1. INTRODUCTION

With the sustainability of the built environment becoming a major issue of the day, extended use of buildings with appropriate refurbishment has been increasing importance. When designing a multi-unit residential building, an open building approach has been found effective, in which the base building (structural frames, common utilities, etc.) is clearly separated from fit-out (interior joinery, unit utilities, etc.) for the ease of refurbishment as attempted in so-called S/I residential buildings designed with a separate skeleton and infill.

The theoretical grounds for separating fit-out from the base building include the differences in their service lives and the parties in charge. Meanwhile, the service lives or demand for refurbishment may widely vary from one building component to another even if they are similarly designated as those for the base building or fit-out. For this reason, refurbishment of multi-unit residential buildings can widely vary from minor changes of the surface materials to large-scale changes to existing structural framing. In other words, the simple division into the categories of base building and fit-out may not always be appropriate, as segments to be refurbished can vary depending on various conditions.

When considering long-term use of such a building, the separation of fit-out from the base building is expected to facilitate a solution to possible changes in the housing requirements due to changes in the family makeup, tenants, and social values. At the time of new construction, it is also expected that various demands from the residents can be incorporated in the fit-out design. In fact, however, simple separation of fit-out from the base building does not guarantee the creation of the required variety of fit-out. The design content of the base building, such as the story height and lighting conditions, strongly affect the content of the design of fit-out and are closely related to the choice range in designing. The legislative framework for the stepwise supply of buildings has been gradually improving in Japan, such as the approval of registration while a building is partially a skeleton as of 2002. It has therefore been increasingly important to grasp the ranges of fit-out design that can be accommodated by the base building.

The design of building fit-out is nothing but an agglomerate of the design of various segments designated as fit-out segments. Similarly to the base building restricting the fit-out, these segments affect the content of the design for other segments. Elucidating the mutual effects of such segments of multi-unit residential buildings is a crucial problem for grasping the fit-out design that a base building can accommodate and will provide a key to formulating a building system that permits a wide variety of

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refurbishment.

This study aims to quantitatively grasp the effects of the design items on other items of each dwelling unit to obtain useful data for formulating a sustainable building system.

2. STUDY PROCEDURE

This study deals with reinforced concrete and steel-framed reinforced concrete (including concrete-filled steel tube structures) medium- to high-rise multi-unit residential buildings built in Japan since 1980, whose drawings (plans and elevations of the buildings and dwelling units) were collected. One hundred and sixty dwelling units were selected by extracting one unit from each building for analysis. However, units on the top or bottom floors and duplex units were excluded. The reason for limiting the objects to buildings constructed since 1980 is that the unit utilities and structural framing methods affecting the horizontal and vertical cross section designing of dwelling units are regarded as similar to those currently used for general multi-unit residential buildings since then, with such equipment as bathroom units, gas water heaters, and mechanical ventilation using ducts having been standardized.

In addition to the basic information on the 160 cases including the owner and year of construction, the values of 157 items characterizing the design of each dwelling unit were then measured from documentation such as the drawings. For numerical data of 133 items out of 157, correlation coefficient matrix were made to investigate the strength and meaning of correlations. Note that the number of missing values was zero in the 133 items.

3. SAMPLE OVERVIEW

Since the samples for analysis were not randomly extracted, preliminary analysis was conducted to examine them, while investigating the differences from the population, i.e., the set of all reinforced concrete and steel-framed reinforced concrete multi-unit residential buildings built since 1980 in Japan.

The samples under analysis are overviewed in Table 1. Each case was classified into three categories: standard projects, unconventional projects (including non-residential experimental units), and other projects (including those designed by architects with particular design refinement), with the number of each group being given in Table 1. When classified by the owner, the largest number is attributed to Kodan[1)], followed by the private sector, local governments, and other public corporations, with the public sector accounting for approximately two thirds. The unconventional projects are also considered to account for a higher percentage than in the population as a whole.

Table 1 Samples Overview

Owner / Category	Local Government	Kodan (HUDC or UDC)	Other Public Housing Corporation	Private Sector	Total
Standard Project	13	5	49	34	101
Unconvential Project	4	12	17	22	55
Other Project	1	0	1	2	4
Total	18	17	67	58	160

Table 2
Years of Construction

Year of Construction	Number
1980-1984	18
1985-1989	37
1990-1994	42
1995-1999	34
2000-2004	22
Unknown	7

Table 3 Structural Types

Structural Type	Number
Bearing Wall System	36
Wall-Frame System	35
Frame System	78
Moment-Resisting System	11

Table 4 Access Types

Access Type	Number
Balcony	87
Staircase	47
Elevator Core	20
Middle Corridor	3
Others or Unknown	3

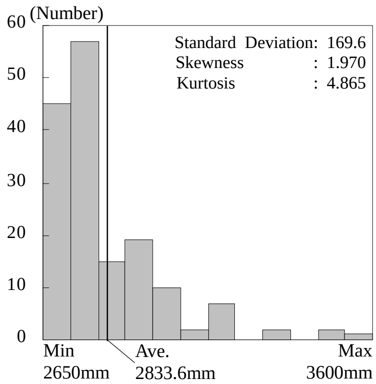

Fig.1 Distribution of Story Heights

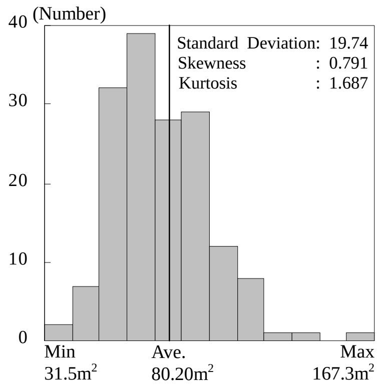

Fig.2 Distribution of Total Unit Areas

Tables 2, 3, and 4 give the distributions of the years of construction, structural types, and access types, respectively. The years of construction are distributed with no marked differences between the year groups, though with a slight scatter. Seven cases with unknown years of construction were included in the samples, as these were evidently judged as having been built in the 1980s or later from the data. No marked differences were found either in the distributions of the structural and access types.

Figures 1 and 2 show the distributions of the story height and total unit areas, respectively. No marked deflection is observed in the story height and area, either. The skewness[2)] and kurtosis[3)] of the story height distribution are both slightly high, significantly deviating from the normal distribution. However, it is considered to be an adequate distribution in view of the fact that the story height tends to be kept low while the lower limit is around 2,600 mm. The total unit areas distribute approximating the normal distribution, with the skewness and kurtosis being low. However, units with an area of over 100 m^2 account for a large ratio of approximately 14% (23 out of 160 cases), presumably due to the high percentage of unconventional units in the samples. It should be noted that the ratio of units with an area of over 100 m^2 among the standard-type units is approximately 10% (10 out of 101 cases), whereas those among unconventional units account for 20% (11 out of 55 cases).

As stated above, it cannot be denied that the samples under analysis are slightly

Table 5 Definitions and Statistics of the Items

Item			Definition	Unit	Statistics		
					Min. Max.	Ave. Sta. Dev.	Skew. Kurto.
Profile Design	1	Ceiling Height of the Base Building	The story height minus the standard slab thickness.	mm	2470.0 3360.0	2646.2 157.9	2.380 6.995
Profile Design	2	Standard Ceiling Height	The ceiling height of a standard sitting room.	mm	2300.0 2700.0	2461.6 73.6	1.132 1.295
Profile Design	3	Horizontal Length of Openings per Unit Area	The depth of the plenum above suspended ceiling (length between the finished ceiling surface and ceiling slab) of a standard sitting room.	mm	0.0 600.0	69.7 100.8	2.495 8.748
Profile Design	4	Standard Depth of Underfloor Space	The depth of the underfloor space (length between the floor slab and finished floor surface) of a standard sitting room.	mm	0.0 730.0	117.5 114.3	2.808 9.386
Profile Design	5	Maximum Depth of Underfloor Space	The maximum depth of a double floor.	mm	30.0 730.0	233.1 98.6	2.499 8.856
Profile Design	6	Maximum Floor Level Difference	The maximum level difference of finished floor surfaces excepting those at the main entrance and bathroom. A negative value is used for a lower level than the standard finished floor level.	mm	-400.0 192.0	40.8 87.7	-2.168 9.140
Profile Design	7	Slab Level Difference	The level difference of slab surfaces where applicable. For reversed beams, the length between the beam top surface and slab top surface.	mm	0.0 600.0	105.4 124.3	1.537 2.615
Profile Design	8	Lower Slab Area	The area of a lowered slab where applicable.	m^2	0.000 110.885	15.649 25.393	2.283 4.555
Utility Design	9	Maximum Distance between Utility Equipment and Drainage Stack	The maximum horizontal distance between utility equipment and drainage stacks connected to the equipment by underfloor piping. For drainage stacks placed outside the area of the dwelling unit, the maximum distance from the equipment to the peripheral wall	m	0.000 13.299	3.049 1.658	2.440 10.016
Utility Design	10	Index to Complexity of Plan Shapes of Spaces Involving Water	The total perimeter of spaces involving water excepting the kitchen divided by the square root of the area of such spaces. This index increases when the spaces involving water are located apart from one another or in complicated shapes.	m / m^2	3.239 7.685	4.848 0.748	0.846 0.079
Utility Design	11	Minimum distance between space involving water and peripheral wall	The minimum distance between a space involving water excepting the kitchen and the peripheral wall of the dwelling unit.	m	0.000 4.700	1.315 1.571	0.580 -1.332
Utility Design	12	Number of Drainage Stack	The number of drainage stacks connected to the utility equipment of the dwelling unit. The number is one when multiple drainage stacks are contained in a pipe shaft.	-	1 4	2.106 0.723	-0.062 -0.841
Utility Design	13	Ratio of Drainage Stacks Designed within the Dwelling Unit	The number of drainage stacks designed within the dwelling unit divided by the total number of drainage stacks.	-	0.000 1.000	0.677 0.421	-0.784 -1.137
Plan Design	14	Total Area of Dwelling Unit	The total area of the dwelling unit.	m^2	31.540 167.296	80.196 19.746	0.791 1.686
Plan Design	15	Index to Complexity of the Plan Shape of the Dwelling Unit	The perimeter of the dwelling unit divided by the square root of its area. This index expresses the complexity of the shape of the unit and increases when the peripheral wall is indented.	-	4.021 5.988	4.538 0.353	1.525 3.186
Plan Design	16	Effective Length of Wall Surface Capable of Natural Lighting per Unit Area	The total horizontal cross-sectional length of walls in which openings can be designed divided by the area of the dwelling unit.	m / m^2	0.065 0.478	0.228 0.093	0.749 -0.293
Plan Design	17	Ratio of Exterior Walls not Facing Shared Areas	The ratio of the total horizontal cross-sectional length of walls facing outside (excluding shared areas) in which openings can be designed to the total length of walls in which openings can be designed.	-	0.368 1.000	0.729 0.187	-0.300 -1.435
Plan Design	18	Horizontal Length of Openings per Unit Area	The total horizontal cross-sectional length of openings divided by the area of the dwelling unit.	-	0.081 0.439	0.211 0.058	0.917 1.275
Plan Design	19	Ratio of Private Rooms	The total area of private rooms divided by the area of the dwelling unit.	-	0.177 0.654	0.449 0.071	-0.262 1.216
Plan Design	20	Ratio of Common Rooms	The total area of common rooms (living room, dining room, kitchen, etc.) divided by the area of the dwelling unit. The areas of storage spaces accessible only through common rooms are included. Storerooms are excluded.	-	0.152 0.576	0.330 0.065	0.143 1.093
Plan Design	21	Ratio of Corridors	The total area of corridors divided by the area of the dwelling unit. The areas of storage spaces accessible only through corridors are included. Storerooms are excluded.	-	0.051 0.199	0.106 0.028	0.632 0.972
Plan Design	22	Ratio of Spaces Involving Water	The total area of spaces involving water excepting the kitchen. The areas of storage spaces accessible only through spaces involving water are included. Storerooms are excluded.	-	0.072 0.176	0.112 0.020	0.687 0.670
Plan Design	23	Ratio of windowless sections	The total area of windowless private rooms, common rooms, spaces involving water, corridors and storerooms divided by the area of the dwelling unit.	-	0.000 0.653	0.306 0.128	-0.110 -0.480
Plan Design	24	Ratio of Windowless Private Rooms	The total area of windowless private rooms divided by the total area of private rooms.	-	0.000 0.549	0.051 0.133	2.464 4.671
Plan Design	25	Ratio of Windowless Common Rooms	The total area of windowless common rooms divided by the total area of common rooms.	-	0.000 1.000	0.336 0.293	0.696 -0.164
Plan Design	26	Ratio of Windowless Corridors	The total area of windowless parts of corridors divided by the total area of corridors.	-	0.000 1.000	0.836 0.316	-1.721 1.525
Plan Design	27	Ratio of Windowless Spaces Involving Water	The total area of windowless spaces involving water divided by the total area of spaces involving water. The kitchen is excluded.	-	0.000 1.000	0.807 0.310	-1.294 0.230
Plan Design	28	Average Area of Private Room	The average area of private rooms. The areas of storage spaces accessible only through private rooms are included in the areas of the private rooms.	m^2	9.119 20.223	12.300 1.933	1.200 1.819
Plan Design	29	Number of Private Rooms	The number of private rooms.	-	1 5	2.950 0.759	-0.266 1.016

dissociated from the population. However, since the samples show no marked deflection, the analysis results are considered to be useful, though they should not be lightly generalized.

4. QUANTITATIVE INVESTIGATION INTO MUTUAL EFFECTS

4.1 Extraction of Items

One hundred and thirty-three items characterizing the design of the segments of 160 dwelling units under analysis were extracted, and their values were measured. Note that some of the items represent the same items measured differently.

Among these items, the definitions and statistics of 29 items used for the present study are listed in Table 5. The items were classified into three categories for convenience: those related to the vertical cross section design, utility design, and plan design, and are so grouped in the table.

Though some items show significantly large skewness and / or kurtosis, no particular change of variables was conducted.

4.2 Investigation of Correlation Coefficient Matrix

4.2.1 Outline of Mutual Effects of Items

The correlation coefficients of all combinations of 133 items for which the data were

Table 6 Correlation Coefficient Matrix

0≦| r |≦0.2   **0.2<| r |≦0.2**   **0.4<| r |≦0.7**   **0.7<| r |≦1.0**

		Vertical Cross Section Design								Utility Design					Plan Design															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	Ceiling Height of the Base Building		.24	.63	.72	.70	-.54	.69	.67	.53	.29	.07	-.38	-.34	.25	-.09	-.08	-.07	-.02	-.19	.14	.08	.05	.06	-.03	.02	-.01	.01	.22	-.01
2	Standard Ceiling Height	.24		-.18	-.18	-.16	-.01	-.05	-.06	-.07	.14	.05	-.01	.12	.18	.01	.00	.00	.08	-.12	.10	.15	-.14	-.01	-.04	-.01	.04	.05	-.02	.11
3	Horizontal Length of Openingsper Unit Area	.63	-.18		.21	.34	-.20	.33	.25	.34	.28	.10	-.22	-.29	.27	-.02	-.10	.01	-.11	-.24	.19	.13	.01	.06	.11	-.07	.05	-.05	.15	.00
4	Standard Depth of Underfloor Space	.72	-.18	.21		.82	-.58	.76	.75	.52	.06	-.05	-.35	-.32	-.03	-.14	.00	-.09	.02	-.06	.05	-.11	.20	.03	-.12	.09	-.07	.01	.18	-.15
5	Maximum Depth of Underfloor Space	.70	-.16	.34	.82		-.50	.86	.67	.57	.09	-.05	-.44	-.41	.09	.04	.07	-.01	.05	-.03	.00	.02	.08	-.06	-.13	.04	-.16	-.05	.29	-.08
6	Maximum Floor Level Difference	-.54	-.01	-.20	-.58	-.50		-.71	-.69	-.41	-.03	-.03	.26	.17	-.11	.06	-.05	.08	-.02	.03	.01	.00	-.08	.06	.11	.05	.05	.04	-.19	.04
7	Slab Level Difference	.69	-.05	.33	.76	.86	-.71		.83	.61	.07	-.01	-.45	-.44	.12	-.02	.08	-.03	.08	-.07	.04	.02	.01	-.10	-.12	-.05	-.15	-.05	.26	-.06
8	Lower Slab Area	.67	-.06	.25	.75	.67	-.69	.83		.58	.03	-.02	-.43	-.40	.16	-.06	.04	-.03	.05	-.07	.07	-.01	-.02	-.07	-.04	-.08	-.08	-.04	.21	-.02
9	Maximum Distance between Utility Equipment and Drainage Stack	.53	-.07	.34	.52	.57	-.41	.61	.58		.04	.00	-.58	-.57	.22	-.16	-.13	-.04	-.06	-.07	.11	-.02	-.08	.00	-.03	.02	.01	.03	.15	.08
10	Index to Complexity of Plan Shapes of Spaces Involving Water	.29	.14	.28	.06	.09	-.03	.07	.03	.04		.08	.12	.00	.13	.06	-.06	-.01	-.02	-.01	-.01	.08	-.01	.04	.08	-.06	.12	.06	-.01	.10
11	Minimum Distance between Space Involving Water and Peripheral Wall	.07	.05	.10	-.05	-.05	-.03	-.01	-.02	.00	.08		-.01	.27	.00	-.23	-.40	-.39	-.27	-.09	.07	.16	-.20	.22	.12	-.01	.11	.50	-.22	.09
12	Number of Drainage Stack	-.38	-.01	-.22	-.35	-.44	.26	-.45	-.43	-.58	.12	-.01		.43	-.08	.06	.11	.08	.05	.05	-.04	-.11	.11	-.01	.02	-.05	.00	.00	-.10	-.01
13	Ratio of Drainage Stacks Designed within the Dwelling Unit	-.34	.12	-.29	-.32	-.41	.17	-.44	-.40	-.57	.00	.27	.43		-.23	-.07	-.19	-.17	-.15	-.04	.05	-.05	.08	.18	.06	.14	.07	.23	-.27	-.07
14	Total Area of Dwelling Unit	.25	.18	.27	-.03	.09	-.11	.12	.16	.22	.13	.00	-.08	-.23		.31	.16	.26	.13	.02	-.02	.32	-.50	-.33	-.02	-.35	-.07	-.20	.45	.64
15	Index to Complexity of the Plan Shape of the Dwelling Unit	-.09	.01	-.02	-.14	.04	.06	-.02	-.06	-.16	.06	-.23	.06	-.07	.31		.47	.45	.41	.15	-.16	.23	-.31	-.40	-.01	-.33	-.30	-.29	.25	.21
16	Effective Length of Wall Surface Capable of Natural Lighting per Unit Area	-.08	.00	-.10	.00	.07	-.05	.08	.04	-.13	-.06	-.40	.11	-.19	.16	.47		.58	.80	.27	-.20	.02	-.26	-.74	-.27	-.50	-.30	-.61	.12	.22
17	Ratio of Exterior Walls not Facing Shared Areas	-.07	.00	.01	-.09	-.01	.08	-.03	-.03	-.04	-.01	-.39	.08	-.17	.26	.45	.58		.40	.04	.04	-.02	-.19	-.44	-.14	-.34	-.15	-.36	.18	.16
18	Horizontal Length of Openings per Unit Area	-.02	.08	-.11	.02	.05	-.02	.08	.05	-.06	-.02	-.27	.05	-.15	.13	.41	.80	.40		.25	-.20	.06	-.20	-.61	-.26	-.44	-.26	-.39	.03	.23
19	Ratio of Private Rooms	-.19	-.12	-.24	-.06	-.03	.03	-.07	-.07	-.07	-.01	-.09	.05	-.04	.02	.15	.27	.04	.25		-.89	-.22	-.24	-.38	-.21	.02	-.30	-.20	-.13	.61
20	Ratio of Common Rooms	.14	.10	.19	.05	.00	.01	.04	.07	.11	-.01	.07	-.04	.05	-.02	-.16	-.20	.04	-.20	-.89		-.12	.08	.28	.16	-.03	.34	.12	.08	-.53
21	Ratio of Corridors	.08	.15	.13	-.11	.02	.00	.02	-.01	-.02	.08	.16	-.11	-.05	.32	.23	.02	-.02	.06	-.22	-.12		-.26	-.06	.11	-.26	-.12	.06	.10	.13
22	Ratio of Spaces Involving Water	.05	-.14	.01	.20	.08	-.08	.01	-.02	-.08	-.01	-.20	.11	.08	-.50	-.31	-.26	-.19	-.20	-.24	.08	-.26		.42	.03	.35	.13	.16	.08	-.62
23	Ratio of windowless sections	.06	-.01	.06	.03	-.06	.06	-.10	-.07	.00	.04	.22	-.01	.18	-.33	-.40	-.74	-.44	-.61	-.38	.28	-.06	.42		.37	.64	.45	.57	-.17	-.40
24	Ratio of Windowless Private Rooms	-.03	-.04	.11	-.12	-.13	.11	-.12	-.04	-.03	.08	.12	.02	.06	-.02	-.01	-.27	-.14	-.26	-.21	.16	.11	.03	.37		-.20	.04	.09	-.12	-.06
25	Ratio of Windowless Common Rooms	.02	-.01	-.07	.09	.04	.05	-.05	-.08	.02	-.06	-.01	-.05	.14	-.35	-.33	-.50	-.34	-.44	.02	-.03	-.26	.35	.64	-.20		.13	.26	-.13	-.24
26	Ratio of Windowless Corridors	-.01	.04	.05	-.07	-.16	.05	-.15	-.08	.01	.12	.11	.00	.07	-.07	-.30	-.30	-.15	-.26	-.30	.34	-.12	.13	.45	.04	.13		.17	-.07	-.17
27	Ratio of Windowless Spaces Involving Water	.01	.05	-.05	.01	-.05	.04	-.05	-.04	.03	.06	.50	.00	.23	-.20	-.29	-.61	-.36	-.39	-.20	.12	.06	.16	.57	.09	.26	.17		-.19	-.16
28	Average Area of Private Room	.22	-.02	.15	.18	.29	-.19	.26	.21	.15	-.01	-.22	-.10	-.27	.45	.25	.12	.18	.03	-.13	.08	.10	.08	-.17	-.12	-.13	-.07	-.19		-.20
29	Number of Private Rooms	-.01	.11	.00	-.15	-.08	.04	-.06	-.02	.08	.10	.09	-.01	-.07	.64	.21	.22	.16	.23	.61	-.53	.13	-.62	-.40	-.06	-.24	-.17	-.16	-.20	

measured were calculated. The correlation coefficient matrix of 29 items given in Table 5 is tabulated in Table 6.

Principal component analysis was then conducted starting from the correlation coefficient matrix to clarify the mutual effects of the 29 items. By terminating the analysis with principal components having an eigenvalue of 1 or more, eight principal components were identified. Table 7 gives their eigenvalues, contributions, and cumulative contributions. As the eigenvalues and contributions of the first and second principal components are significantly higher than the other principal components, the scatterplots of their factor loads were made as shown in Fig. 3. Note that the signs of the factor loads of the second principal component are all reversed.

The scatterplots of the factor loads of the first and second principal components reveal that the items related to the vertical cross section design and utility design are concentrated near the first axis, whereas those related to the plan design are gathered near the second axis. This indicates that the vertical cross section and utility design of dwelling units are closely related to each other, whereas the plan design is determined relatively independently.

In regard to such items as the standard ceiling height$_2$[4)], index to the complexity of the plan shape of spaces involving water$_{10}$, and ratio of corridors to the whole dwelling unit$_{21}$, the absolute values of the factor loads of the first and second principal

Table 7 Eigenvalues and Contributions of Principal Components

Principal Component	Eigenvalue	Contribution	Cumulative Comntibution	Principal Component	Eigenvalue	Contribution	Cumulative Comntibutio
1st	5.909	0.204	0.204	5th	1.413	0.049	0.597
2nd	5.179	0.179	0.382	6th	1.299	0.045	0.641
3rd	2.473	0.085	0.468	7th	1.265	0.044	0.685
4th	2.327	0.080	0.548	8th	1.190	0.041	0.726

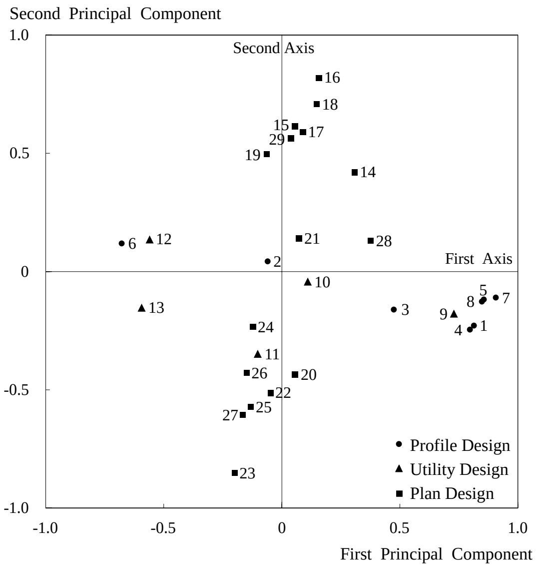

Fig. 3 Scatterplots of the Factor Loads of First and Second Principal Components

components are low, indicating that these are determined independently of other items.

4.2.2 Mutual Effects among Items Related to Vertical Cross Section Design and Utility Design

Among the items related to the vertical cross section design, the ceiling height of the base building$_1$ (story height minus slab thickness) is strongly correlated with the largest number of items. However, the items directly correlated with the ceiling height of the base building$_1$ are the standard ceiling height$_2$, standard depth of plenum (above ceiling)$_3$, standard depth of underfloor space$_4$, maximum depth of underfloor space$_5$, and slab level difference$_7$, while others are indirectly correlated via these items[5)]. Among the items that appear to be directly correlated with the ceiling height of the base building$_1$, the correlations with the standard depth of plenum$_3$, standard depth of underfloor space$_4$, and maximum depth of underfloor space$_5$ are strong, whereas the correlations with the standard ceiling height$_2$ is weak. The results of the principal component analysis also indicate that the standard ceiling height$_2$ is designed independently of other vertical dimensions. This can be attributed to the fact that not a few projects adopt a design process in which the story height is determined after assuming a certain ceiling height and allowing for the necessary depths of the plenum and underfloor space.

The standard depth of undefloor space$_4$ is rather strongly correlated with the lower slab area$_8$, i.e., the area of the lower level of a two-level slab. A strong correlation is also observed between the lower slab area$_8$ and the maximum distance between utility equipment and drainage stack$_9$. Taking the above into consideration, an increase in the story height may indirectly contribute to an increase in the degree of freedom for arranging the utility equipment and spaces involving water. On the other hand, the index to complexity of the plan shape of spaces involving water$_{10}$ is not correlated with the lower slab area$_8$ or maximum distance between utility equipment and drainage stack$_9$, supporting the idea that securing a vast space under the floor does not appear to lead to free arrangement of spaces involving water. Nevertheless, the number of drainage stacks$_{12}$ shows a strong negative correlation with the maximum distance between utility equipment and drainage stack$_9$, suggesting that, when the space is not large enough to accommodate long horizontal pipes, drainage stacks are localized to deal with the plan design for spaces involving water. This is supported by the fact that the ratio of drainage stacks designed within the dwelling unit$_{13}$ increases as the maximum distance between utility and drainage stack$_9$ decreases.

The standard depth of underfloor space$_4$, maximum depth of underfloor space$_5$, and slab level difference$_7$ also show strong negative correlations with the maximum floor level defference$_6$. Securing a large depth of the underfloor space is effective also in installing barrier-free facilities in the dwelling unit.

4.2.3 Mutual Effects of Items Related to Plan Design

The item of paramount importance among those related to plan design is the length of wall surface capable of natural lighting per unit area$_{16}$. This is an index to the natural lighting condition of a dwelling unit, whose relation with the degree of freedom of room layout in multi-unit residential buildings is pointed out (Sasaki et al. 2000; Hanazato et al. 2003). Its interesting relationships with various items were also found in the present study.

The first thing to note is its strong negative correlation with the ratio of windowless sections$_{23}$. The ratio of exterior walls not facing shared areas$_{17}$ also shows a strong negative correlation with the ratio of windowless sections$_{23}$.

When comparing the numbers of windowless rooms by their uses, the number is small for private rooms$_{24}$, for which natural lighting is required in principle no matter how small the length of wall surface capable of natural lighting per unit area$_{16}$ may be and how high the ratio of windowless sections$_{23}$ the design may result in. On the other hand, a short length of wall surface capable of natural lighting tends to lead to increases in the numbers of windowless common rooms$_{25}$ and windowless spaces involving water$_{27}$. This indicates that, for dwelling units with insufficient natural lighting, rooms other than private rooms tend to be arranged in non-peripheral spaces. Also, the length of wall surface capable of natural lighting per unit area$_{16}$ is weakly correlated with the average area of private rooms$_{28}$ and with the number of private rooms$_{29}$ to a similar extent. In other words, when natural lighting is insufficient, it is difficult to divide the unit into small sections. The degree of freedom of the plan design is low for such a unit.

A relatively strong negative correlation is observed between the length of wall surface capable of natural lighting per unit area$_{16}$ and minimum distance between spaces involving water and peripheral walls$_{11}$. This indicates that spaces involving water tend to be designed in the center of a unit when natural lighting is insufficient. In order to improve the degree of freedom for the layout of spaces involving water, it is important not only to secure a large story height and ample space under the floor but also to design a unit having a wide frontage to allow sufficient natural lighting.

The average effective length of wall surface capable of natural lighting per unit area calculated for each access type is as follows: 0.196, 0.279, 0.252, and 0.085 for the access types through balcony, staircase, elevator core, and middle corridor, respectively. The average ratio of windowless sections to the total area of the unit for each access type is as follows: 0.345, 0.236, 0.305, and 0.444 for the balcony, staircase, elevator core, and middle corridor access types. These results show that the building design and unit layout design strongly affect the design of each unit, and therefore warrants further discussion.

5. CAUSAL STRUCTURE AMONG ITEMS OBTAINED BY COVARIANCE STRUCTURE ANALYSIS

The results of former chapter revealed that the items affect one another in a complicated manner, with the mutual relationships producing chain effects. The mutual relationships were structuralized using covariance structure analysis. Fig. 4 illustrates the causal structure among the items related to vertical cross section and utility design.

Such diagram must strongly help us to grasp the range of fit-out design that can be accommodated by base building. However, there is still room for improvement in the mathematical model. The authors intend to build more useful model that indicates the whole causal structure of unit design.

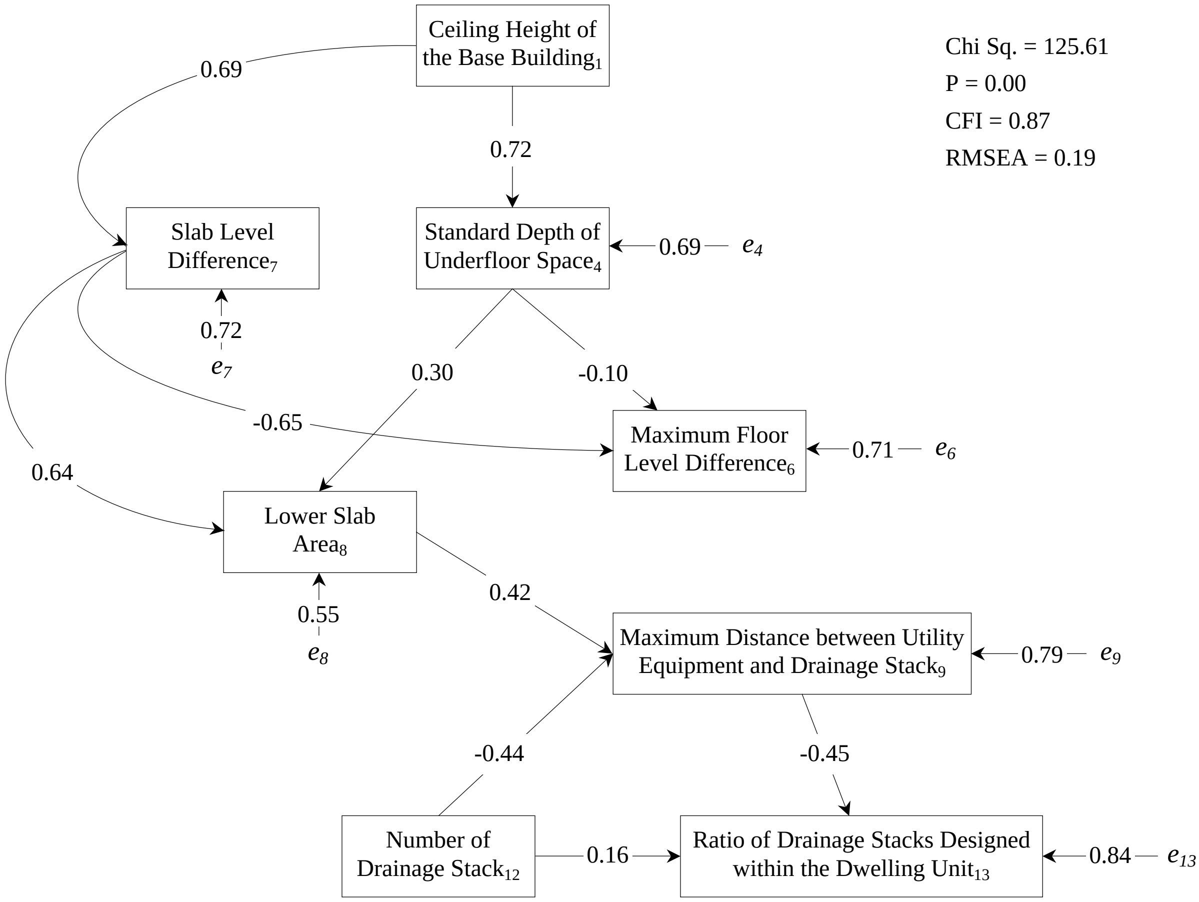

Fig. 4 Causal Structure among the Items Related to Profile and Utility Design

6. CONCLUSIONS

In this study, items characterizing the design of each dwelling unit of multi-unit residential buildings were extracted, and their mutual effects were quantitatively grasped. Detailed analysis of the results elucidated each item's effects on various aspects of the unit design. The mutual relationships were structuralized using covariance structure analysis.

The left tasks of this research are as follows: 1) improvement of the mathematical model that indicate causal structure of dwelling unit design, and 2) establishment of a technique to grasp the range of fit-out design that can be accommodated by base building.

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Notes

1) Refers to the Housing and Urban Development Corporation and the Urban Development Corporation.

2) Skewness, $\sqrt{b_1}$, is an index to the degree of symmetry of a distribution expressed by the equation below. The skewness of a symmetric distribution is 0.

$$\sqrt{b_1} = \sum_{i=1}^{n} \left(\frac{x_i - \bar{x}}{s} \right)^3 / n \qquad (1)$$

where $\bar{x}$ = average, s = standard deviation, n = number of data points.

3) Kurtosis, b_2 , is an index to the shortness of the tails of a distribution expressed by the equation below. The kurtosis of a normal distribution is 0.

$$b_2 = \sum_{i=1}^{n} \left(\frac{x_i - \bar{x}}{s} \right)^4 / n - 3 \qquad (2)$$

4) The subsequent subscript numbers following the name of the items correspond to the numbers in Tables 5 and 6.

5) Significant correlation between two items can be interpreted in two ways: direct relationship between them and indirect relationship via another item. In order to determine the interpretation to be adopted, it is necessary to check whether or not the items are conditionally independent. However, this paper only presents a hypothesis. The results of such checking will be discussed in another paper.

6) Part of this paper is under contribution to *AIJ J. Archit. Plann.*

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