World Academy of Science, Engineering and Technology
International Journal of Architectural and Environmental Engineering
Vol:17, No:1, 2023

A Quantitative Model for Determining the Area of the "Core and Structural System Elements" of Tall Office Buildings

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***Abstract*—**Due to the high construction, operation, and maintenance costs of tall buildings, quantification of the area in the plan layout which provides a financial return is an important design criterion. The area of the "core and the structural system elements" does not provide financial return but must exist in the plan layout. Some characteristic items of tall office buildings affect the size of these areas. From this point of view, 15 tall office buildings were systematically investigated. The typical office floor plans of these buildings were re-produced digitally. The area of the "core and the structural system elements" in each building and the characteristic items of each building were calculated. These characteristic items are the size of the long and short plan edge, plan length/width ratio, size of the core long and short edge, core length/width ratio, core area, slenderness, building height, number of floors, and floor height. These items were analyzed by correlation and regression analyses. Results of this paper put forward that; characteristic items which affect the area of "core and structural system elements" are plan long and short edge size, core short edge size, building height, and the number of floors. A one-unit increase in plan short side size increases the area of the "core and structural system elements" in the plan by 12,378 m^2. An increase in core short edge size increases the area of the core and structural system elements in the plan by 25,650 m^2. Subsequent studies can be conducted by expanding the sample of the study and considering the geographical location of the building.

***Keywords*—**Core area, correlation analysis, floor area, regression analysis, space efficiency, tall office buildings.

I. Introduction

FINANCIAL concerns play the utmost role in the design of tall office buildings. Accordingly, the size of the areas which provide financial gain is an important design criterion [1]. In a tall office building, the area of the core and structural system elements are the areas that do not provide financial gain.

In the literature, many studies investigate rental/profitable areas in the plan layout of tall office buildings [1], [6]-[8]. However, most of these studies are based on a literature review. They are not putting forward quantitative solutions. Additionally, these studies focus on profitable areas. They neglect non-profitable areas which are areas of the core and the structural system elements. Characteristic items of the plan layout which are effective on the "area of the core and the structural system elements" come forward as other neglected items. In specific, none of the research papers which investigate tall buildings focus on the relation between "characteristic items of plan layout" and area of the core and the structural system elements. From this point of view, the research problems of this study are as follow:

- Which characteristic items of a tall building affect the area of the "core and the structural system elements"?
- What is the size and direction of the relations between these characteristic items and the area of the "core and the structural system elements"?
- Is it possible to put forward a meaningful equation between these characteristic items and the area of the "core and the structural system elements"?

Based on these questions, the objective of this study is to develop a multiple regression model that demonstrates the relationship between the area of the core and structural system elements and characteristic items which are effective in this area. It is assumed that at the design stage this numerical equation (regression model) helps tall building designers and stakeholders to hold a view about profitable and non-profitable areas while making decisions about characteristic plan items of tall office buildings. Also, the method of using the regression model in this specific area holds out a new research area for researchers.

A. Outline of the Research

The study was carried out on 15 tall office buildings from which the most data were obtained through the existing literature. First, the floor plans of these 15 tall office buildings were digitally produced in a computational environment. Using these digital floor plans, the area of the core and the structural system elements and the characteristic items of tall buildings were numerically calculated. Then, the correlation of each characteristic item, which is assumed to have considerable influence on the area of the core and the structural system elements was studied.

Finally, multiple regression analysis was performed. The weight of each characteristic item on the area of the core and the area of the structural system elements was revealed. Using the results of the analyses, an equation that explains the numerical relations between the area of the core and structural system elements and characteristic items which are effective in this area was obtained.

B. Limitations of the Research

In a tall building, depending on the function of the building, design decisions about the size and the location of the core and

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structural system elements may vary. For instance, technical spaces in a tall office building, a tall residential building, or a tall hospital building have different areas. For this reason, the function of the tall buildings examined in the research is limited to office buildings.

Tall buildings can be designed in the tapering, twisting, setback, or curvilinear forms with aesthetic concerns and/or a desire for prestige. Achieving the highest space efficiency is not always the primary goal with these unusual forms. Floor plans in these tall buildings also change throughout the height of the building [2]. Therefore, tall buildings with extraordinary forms are out of the scope of this study. In the research, tall buildings having a typical office layout that is repeated without changing throughout the building were examined.

Additionally, the sample of the research is limited to 15 buildings because of the difficulties concerning obtaining reliable data on tall buildings. The typical office floor plans of the buildings were created by digital production. Information about floor plans was obtained with the literature review. 15 tall buildings which are the sample of the research can be seen in Fig. 1.

II. Characteristic Items and Area of the Core and Structural System Elements

A. *Defining Characteristic Items*

In this study, characteristic items of tall buildings were determined by the literature review. There is a strong relationship between the form, the cost efficiency, and the space efficiency of the buildings. Early studies which investigate the relationship between the form and the efficiency of buildings go back to the 1970s. These studies mostly investigate the shape complexity of buildings [3]. Reference [3] creates indices for making assessments about the form and the cost efficiency of the buildings.

Some of these indices are the length/breadth index and plan/shape index [3]; shape efficiency index; plan compactness ratio and mass compactness ratio which are both developed by Strathclyde University [4]. By using these indices, generalizations about the relations between the building forms and the economic profitability were made. For instance, according to [5] the plan form, which is close to square in quadrangular form, provides economic profitability by decreasing the wall/plan area ratio. As the plan shape becomes irregular, the floor space efficiency of the buildings decreases.

In a study conducted by [6], the floor plans of 5 office buildings with different plan length/width ratios were investigated in terms of floor area efficiency. According to the results obtained, the floor area efficiency increases as the plan length/width ratios of the buildings approach "1".

Reference [7] analyzed the relation between geometric properties and cost efficiency of the building. According to the study, cost efficiency is achieved by using square forms in constructing the walls and foundations, and rectangles for the layout of the inside of the building.

15 TALL OFFICE BUILDINGS

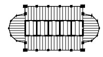
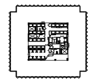
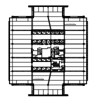
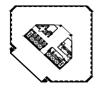
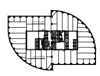
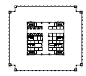
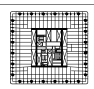
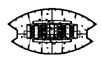
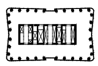
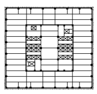
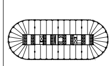
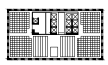
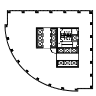
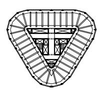
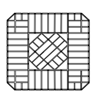
#	Name	Plan Layout	Location	Height (m)	Number of Floors	Completion Year
1	Di Wang Tower		Shenzen USA	384	79	1996
2	Aon Center		Chicago USA	346,3	82	1973
3	New York Times Tower		New York USA	318,8	52	2007
4	Jp Morgan Chase Building		Houston USA	305,4	75	1982
5	Wells Fargo Plaza		Houston USA	302,4	71	1983
6	First Canadian Place		Toronto Canada	298,1	72	1975
7	Cheung Kong Center		Hong Kong China	282,8	63	1999
8	Naberezhnaya Tower		Moscow Rusia	268,4	61	2007
9	Fortune Finance Center		Beijing China	267	60	2014
10	First International Building		Dallas USA	217	56	1974
11	1400 Smith Street		Houston USA	210,5	50	1984
12	780 3rd Avenue		New York USA	173,7	49	1983
13	17 State Street		New York USA	165,3	44	1988
14	Riverside Center		Brisbane Australia	142	39	1986
15	Kobe Commerce Industry and Trade Center		Kobe Japan	110,06	26	1969

Fig. 1 The sample of the research

However, none of these studies concern tall buildings and the necessities of tall buildings. Building height, space efficiency, and cost efficiency are highly related. Reference [8] put forward that building costs are increasing approximately 8% per 10 floors. This increase is mainly caused by the additional costs of services and elevators and the additional costs of the structure. Similarly, according to [9], tall buildings are less efficient than low-rise buildings because their structure is larger, and more core area is needed due to larger vertical systems and distribution systems.

One of the studies which concern the necessity of tall buildings is performed by [10]. In this study, 10 multi-used tall buildings were investigated in terms of space efficiency. Parameters including functions, lease span, floor-to-floor height, vertical transportation, site area, FAR (Floor Area Ratio), building height, the number of floors, building size at the base and top, aspect ratio, and the structural system were analyzed. Based on the results of the case studies, a set of quantitative analyses was performed to show the relationship among design factors.

Reference [11] investigated the space efficiency of the 10 highest buildings in the world and Turkey in terms of plan geometry, lease span, story height, the area of the core, the structural system type, and material. According to the study, the main variables which affect the space efficiency in tall buildings are relevant to the structural system and the design of the core. These variables are followed by the plan geometry, lease span, and story height.

In another study conducted by [12], based on a 405 m high super-tall building, the relations between structural properties (such as the influence of outriggers, different shapes, and the layouts of structural plane and elevation) and structural efficiency were studied. Also, a calculation formula concerning structural efficiency is defined. According to the study, structural efficiency can be improved by triangulating the plan shape, using mega columns, the peripheralization of the plan layout, tapering the elevation shape, and setting the bracing structure in the elevation.

Efficiency is defined by the ratio between the net area and the gross floor area [13]. In a tall office building, the area difference between the gross floor area and the net area is caused by the area of the core and the structural system elements. Thus, space efficiency in a tall office building depends on the area of the core and structural system elements. Concerning these studies, plan long edge size, plan short edge size, plan length/width ratio, core long edge size, core short edge size, core length/width ratio, slenderness, story height (m), building height (m), and the number of stories are determined as parameters which are effective in the space efficiency. Accordingly, these characteristic items are investigated in this study.

B. Relativities of Characteristic Items and Area of the Core and Structural System Elements

In the research, characteristic items which affect the area of the core and structural system elements in the plan layout were examined. These items are seen in Fig. 2.

Relations between the values of each characteristic item and the area of the core and structural system elements were considered with a scatter diagram. Then, correlation coefficients (r) between each characteristic item, and the area of core and structural system elements were calculated. Additionally, the level of the significance of the relations between the values of each item, and the area of core and structural system elements were examined. According to the results of the correlation analysis, plan long edge size, plan short edge size, core short edge size, building height, and the number of stories had a high correlation with an area of core and structural system elements. However, plan length/width ratio, core long edge size, core length/width ratio, slenderness, the number of basement floors, and the story height did not have a significant correlation with the area of core and structural system elements. The results are shown in Fig. 3.

		Charecteristic Items											
		Plan long edge size (m)	Plan short edge size (m)	Plan lenght/widht ratio	Core long edge size (m)	Core short edge size (m)	Core lenght/width ratio	Core area (m^2)	Slenderness	Building height (m)	Number of stories	Story height (m)	Area of core & structural system elements
1	Di Wang Tower	68,50	35,50	1,93	44,16	12,75	3,46	563,00	9,00	384,0	79,00	3,75	587,0
2	Aon Center	59,13	59,13	1,00	30,11	29,83	1,01	898,13	5,85	346,3	82,00	3,86	951,0
3	The New York Times Tower	57,90	44,40	1,30	28,17	20,48	1,38	576,80	6,80	318,8	52,00	4,19	543,0
4	Jp Morgan Chase Building	49,00	49,00	1,00	30,38	20,60	1,47	575,24	6,23	305,4	75,00	-	538,0
5	Wells Fargo Plaza	65,44	47,88	1,37	38,92	15,34	2,54	596,94	6,31	302,4	71,00	4,00	660,0
6	First Canadian Place	57,66	54,88	1,00	28,85	27,40	1,05	790,49	5,43	298,1	72,00	3,86	891,0
7	Cheung Kong Center	47,60	47,60	1,00	25,45	21,91	1,16	422,61	6,00	282,8	63,00	4,20	432,0
8	Naberezhnaya Tower	76,00	42,00	1,81	43,30	15,06	2,88	554,37	6,39	268,4	61,00	4,30	688,0
9	Fortune Finance Center	61,28	39,19	1,56	43,30	16,00	2,71	692,80	6,81	267,0	60,00	-	841,0
10	First International Building	53,34	53,34	1,00	31,38	29,61	1,06	929,00	4,06	217,0	56,00	3,81	1055,0
11	1400 Smith Street	77,55	32,64	2,38	55,26	8,55	6,46	453,88	6,44	210,5	50,00	3,96	526,0
12	780 3rd Avenue	38,00	21,59	1,76	18,30	9,70	1,89	177,00	8,00	173,7	49,00	3,51	212,0
13	17 State Street	34,72	34,72	1,00	17,46	17,23	1,01	230,00	4,76	165,3	44,00	3,66	248,0
14	Riverside Center	53,49	49,80	1,00	29,59	25,46	1,16	408,00	2,84	142,0	39,00	3,48	418,0
15	Kobe Commerce Industry and Trade Center	36,90	36,90	1,00	18,45	18,45	1,00	340,40	2,98	110,1	26,00	3,84	349,0

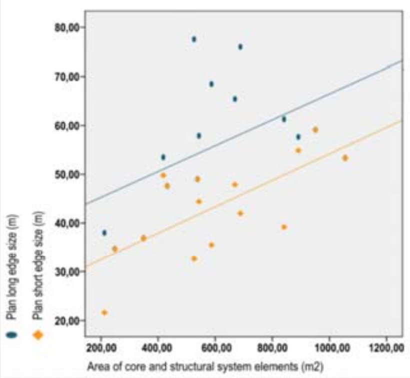
Fig. 2 Data of characteristic items

Architectural Items	Area of core and structural system elements (m^2)	
	r (*r: Pearson's correlation coefficient* *ar: Sperman's correlation coefficient*)	***p*** (*Level of significance* **p<0,05* ***p<0,01*)
Plan long edge size (m)	0,546	0,035*
Plan short edge size (m)	0,691	0,004**
Plan lenght/widht ratio	- 0,006[a]	0,984
Core long edge size (m)	0,419	0,12
Core short edge size (m)	0,552	0,033**
Core lenght/width ratio	0,043[a]	0,879
Slenderness	-0,125	0,656
Story height (m)	0,286	0,343
Building height (m)	0,561	0,030*
Number of stories	0,573	0,026*

Fig. 3 The correlation between characteristic items and area of core and structural system elements

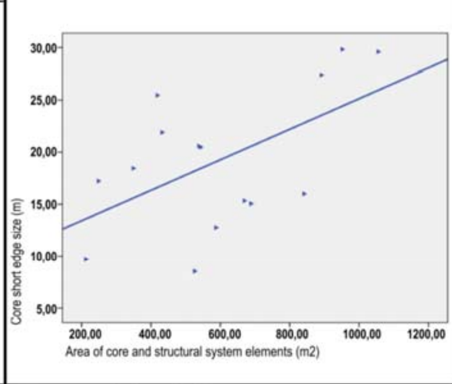
According to the analysis plan, long edge size, plan short edge size, core short edge size, the building height and the number of stories affect the area of the core and the structural elements, so the correlation was positive (Fig. 4).

	Area of the core and structural elements	
	r	p
Plan long edge size (m)	0,546	0,035*
Plan short edge size (m)	0,691	0,004**



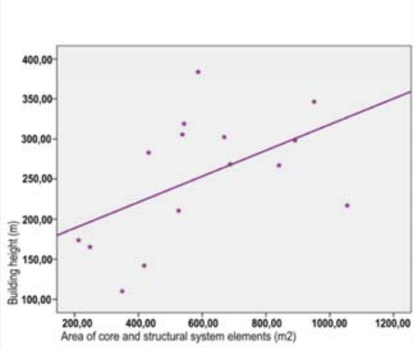
r: Pearson correlation coefficient
ªr: Sperman's correlation coefficient
Level of significance (p): *p<0,05; **p<0,01

	Area of the core and structural elements	
	r	p
Core short edge size (m)	0,552	0,033**



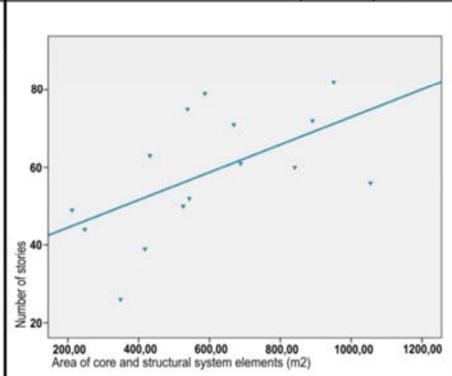
r: Pearson correlation coefficient
ªr: Sperman's correlation coefficient
Level of significance (p): *p<0,05; **p<0,01

	Area of the core and structural elements	
	r	p
Building height (m)	0,561	0,030*



r: Pearson correlation coefficient
ªr: Sperman's correlation coefficient
Level of significance (p): *p<0,05; **p<0,01

	Area of the core and structural elements	
	r	p
Number of stories	0,573	0,026*



r: Pearson correlation coefficient
ªr: Sperman's correlation coefficient
Level of significance (p): *p<0,05; **p<0,01

Fig. 4 Scatter diagrams of relativities

III. Evaluation Formula of the Area of the Core and Structural System Elements of Tall Office Buildings

A. Formulation of the Area of Core and Structural System Elements of Tall Office Buildings

Characteristic items which affect the area of core and structural system elements are plan long edge size, plan short edge size, core short edge size, the building height, and the number of stories. These characteristic items were subjected to linear regression analysis (backward) for putting forward a regression equation. According to the results of the regression analysis, these items were found to affect the area of the core and structural system in the plan by 63.5% [$(R^2) = 0.635$]. The significance value of the model (p) is 0.002. The model is statistically significant ($p < 0.01$).

As a result of the analysis, a one-unit increase in plan short side size increases the area of the core and structural system elements in the plan by 12,378 m^2 ($p = 0.002$; $p < 0.01$). An increase in core short edge size increases the area of the core and structural system elements in the plan by 25,650 m^2 ($p = 0.001$; $p < 0.05$) (Fig. 5).

	β	t	p	%95 (Confidence interval-CI) Lower	Upper
Constant	-586,856	-2,0562	0,025*	-1085,97	-87,740
Plan short edge size	12,378	4,015	0,002**	5,662	19,094
Core short edge size	25,650	4,242	0,001**	12,474	38,827

*p<0,05 **p<0,01

β: *Coefficients.*
p: *Level of significance.*

Fig. 5 The results of the regression analyses

According to the regression analyses, the regression model is as follows (Fig. 6).

Area of the Core and Structural System Elements	= (-586,856) + [12,378 x (Plan Short Edge Size)] + [25,650 x (Core Short Edge Size)]

Fig. 6 The regression model

B. Testing Evaluation Formula

The regression model was tested on 15 tall office buildings that constitute the sample of the research. Fig. 7 shows the comparison of existing values of the area of core and structural system elements, and the numerical values obtained by using the regression model.

		Charecteristic Items											Testing Regression Model		
		Plan long edge size (m)	Plan short edge size (m)	Plan lenght/widht ratio	Core long edge size (m)	Core short edge size (m)	Core lenght/width ratio	Core area (m²)	Slenderness	Building height (m)	Number of stories	Story height (m)	Area of core & structural system elements (Existing Values) (m²)	Formula results: Values obtained by regression formula (m²)	Difference between existing values and formula results
15	Kobe Commerce Industry and Trade Center	36,90	36,90	1,00	18,45	18,45	1,00	340,40	2,98	110,1	26,00	3,84	**349,0**	**343,1**	**5,9**
4	Jp Morgan Chase Building	49,00	49,00	1,00	30,38	20,60	1,47	575,24	6,23	305,4	75,00	-	**538,0**	**548,1**	**-10,1**
13	17 State Street	34,72	34,72	1,00	17,46	17,23	1,01	230,00	4,76	165,3	44,00	3,66	**248,0**	**284,9**	**-36,9**
2	Aon Center	59,13	59,13	1,00	30,11	29,83	1,01	898,13	5,85	346,3	82,00	3,86	**951,0**	**910,2**	**40,8**
3	New York Times Tower	57,90	44,40	1,30	28,17	20,48	1,38	576,80	6,80	318,8	52,00	4,19	**543,0**	**488,0**	**55,0**
6	First Canadian Place	57,66	54,88	1,00	28,85	27,40	1,05	790,49	5,43	298,1	72,00	3,86	**891,0**	**795,3**	**95,7**
7	Cheung Kong Center	47,60	47,60	1,00	25,45	21,91	1,16	422,61	6,00	282,8	63,00	4,20	**432,0**	**564,3**	**-132,3**
12	780 3rd Avenue	38,00	21,59	1,76	18,30	9,70	1,89	177,00	8,00	173,7	49,00	3,51	**212,0**	**70,8**	**141,2**
10	First International Building	53,34	53,34	1,00	31,38	29,61	1,06	929,00	4,06	217,0	56,00	3,81	**1055,0**	**832,9**	**222,1**
5	Wells Fargo Plaza	65,44	47,88	1,37	38,92	15,34	2,54	596,94	6,31	302,4	71,00	4,00	**660,0**	**399,3**	**260,7**
14	Riverside Center	53,49	49,80	1,00	29,59	25,46	1,16	408,00	2,84	142,0	39,00	3,48	**418,0**	**682,6**	**-264,6**
8	Naberezhnaya Tower	76,00	42,00	1,81	43,30	15,06	2,88	554,37	6,39	268,4	61,00	4,30	**688,0**	**319,3**	**368,7**
1	Di Wang Tower	68,50	35,50	1,93	44,16	12,75	3,46	563,00	9,00	384,0	79,00	3,75	**587,0**	**179,6**	**407,4**
11	1400 Smith Street	77,55	32,64	2,38	55,26	8,55	6,46	453,88	6,44	210,5	50,00	3,96	**526,0**	**36,5**	**489,5**
9	Fortune Finance Center	61,28	39,19	1,56	43,30	16,00	2,71	692,80	6,81	267,0	60,00	-	**841,0**	**308,6**	**532,4**

Fig. 7 Comparison of existing values of the area of "core and structural system elements" and the numerical values obtained by using the regression model

As seen in Fig. 7, the difference between existing values and the obtained values are ± 100 m^2 in tall buildings which can be listed as Kobe Trade and Industrial Center (5 m^2), JP Morgan Chase Building (10.1 m^2), 17 State Street Building (36.9 m^2), Aon Center (40.8 m^2), The New York Times Building (55 m^2) and First Canadian Center (95.7 m^2). All of these buildings have a square form. In other words, the plan aspect ratios of these buildings are "1" except for The New York Times Building. The New York Times Building, on the other hand, has a 1.3 aspect ratio and a plan shape close to a square. As the plan form of the building approaches from square to rectangular, the difference between the existing values and the obtained values increases.

From this point of view, the difference between the existing values and obtained values was subjected to another correlation analysis with the plan aspect ratios of all the structures forming the sample. The correlation coefficient between these two values showed a high relationship of 0.78. The analysis verifies that as the plan aspect ratio of a tall office building increases, in other words, as the building form approaches from square to rectangular, the difference between the existing areas and the areas obtained as a result of the model increases (Fig. 8).

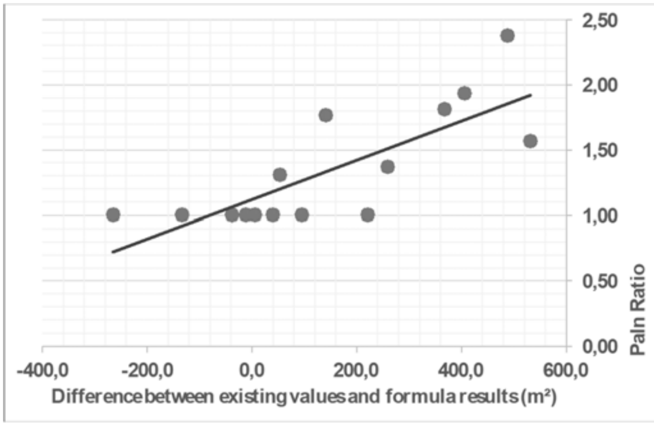


Fig. 8 Scatter diagram between "difference of the existing values and the obtained values" and "plan ratios"

IV. Conclusion

In this study, characteristic items which affect the area of the core and structural system elements were identified. Then, the relations between these characteristic items were investigated by correlation and regression analyses. The results are as follows:

1) There is a positive correlation between the area of the core and structural system elements and the plan long edge size, plan short edge size, and core short edge size. The correlation coefficients (r) of these correlations are 0,546; 0,691 and 0,552 respectively. As the plan, long edge size, plan short edge size, and core short edge size increase, the area of the core and structural system increases.
2) The result obtained in the research supports the literature review. In tall office buildings, as the edge lengths of the plan layout increase, the area of that building grows, and accordingly the number of users increases. The increase in the number of users brings along the growth of the area, which is allocated to the vertical circulation elements, lobbies, service areas, and so on. Due to these reasons, the area of the core increases.
3) There is a positive correlation between the area of the core and structural system elements and the building height and the number of floors. The correlation coefficients (r) of these correlations are 0,561 and 0,573 respectively. When the height and/or the number of floors increase, the area of

the core and structural system elements also increases. As the height and/or the number of floors increase, horizontal loads which affect the building structure increase. This augmentation led to an increase in the area of structural system elements. An increase in the height and/or the number of floors cause also in the area of the vertical circulation elements because of the increase the number of users. So, the area of the core increases.

4) According to the results of the study, there is not a significant correlation between the area of the core and structural system elements and the planned height/width ratio, core long edge length, core height/width ratio, slenderness, the number of basements, and the floor height.
5) Correlation analyses show that the number of floors, the height of the building, plan long edge size, plan short edge size, and core short edge size are effective characteristic items in the area of the core and structural system elements. Regression analysis between these effective characteristic items and the area of the core and the structural system elements shows that a one-unit increase in the plan short edge size brings along a 12,378 m^2 increase in the area of the core and structural system elements; and a one-unit increase in core short edge size increases this difference by 25,650 m^2.

In this research, the geographical location of the building is not taken into consideration. In addition, the research was conducted on the typical office floor plans of the buildings.

1) Considering all floor plans of the building,
2) Increasing the number of samples of the research,
3) Considering the geographical location of the building and horizontal-vertical loads affecting the building,
4) Expanding the sample of the study with buildings having different functions such as residential, hotel, mixed, and so on,
5) Expanding the sample of the study with buildings that have sloping faces

stand out as current research areas.

ACKNOWLEDGMENT

This article is produced from the doctoral dissertation: Improving a Model for Determining Space Efficiency of Tall Office Buildings.

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