

# An Evacuation Efficiency Contribution Index of Public Building's Space Models

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**Abstract:** Evacuation efficiency of public buildings are closely related to their space structures. However, there is lacking of correlating analysis methods of both of them, which lead to the ignoring of evacuation efficiency contribution not able to support the space structure design of public buildings. In this paper, we proposed a concept of hierarchical organization map of public buildings, then proposed a quantitative measurement method of evacuation efficiency contribution for space structure combination models of public building. This paper developed an prototype system to implement this method, and testing of 7 building design plans were shown to validity the proposed method. This method can make up the lacking of quantitative measurement approach of evacuation efficiency, which can provide scientific reference for architecture design in order to meet the requirements of evacuation performance of public buildings.

**Keywords:** Public building evacuation; Building Space; Combination model; contribution index

## 1. Introduction

Rapid urbanization has dramatically changed the public buildings and urban form [1]. Faced with an increasing number of uncertain safety factors, there is a growing emphasis on the evacuation efficiency of public buildings. Evacuation efficiency of public buildings has a very close relationship of space layout in it. It need to achieve a harmonization of functions and evacuation needs in a scientific and rational manner, which should be on base of public building space analysis theory and methods. This theory is also a very important, urgent research questions for in the field of building studies.

The connection between architectural space units is an important concerns by architects and researchers. There are some architectural space combination fuzziness and scale resistance, which are difficult to be defined accurately. Some scholars conducted the research of building space combinations, such as, the typical form of space combinations [2,3], the space division from a viewpoint of behavior in the space environment [4], including: parallel, centralized, linear space, radiant, cluster, grid-style,

courtyard and other space combined models. These space can also be combined with nature of functional requirements, volume size, traffic routes and other factors. These space can be used to create a complex architecture by separating and dividing, convergence with the transition, comparing with the change in the axis, repeating with reproduction, guidance and hinted penetration, circulation, order and sequence techniques and so on. These studies focused on spatial form [5], the function [6], the behavior of [7], and even space integration [8]. In the aspect of evacuation of building space, Zheng summarized all building evacuation simulation methods [9]. Other scholars carried out some simulated evacuations of architectural space [10], efficiency [11], impact rule [12], the engineering design [13], etc. However, the research community lacks some quantitative and analytical tools to assess the efficiency of the effective contribution of the evacuation. Xu [14] studied the combination modes of public building space, and research the differences of efficiency contribution of these modes. This paper focuses on the efficiency contribution of public buildings by proposing an evacuation contribution index, to make up lacking of quantitative assessment tools for architectural design.

## 2. Proposed index

### 2.1. Hierarchical organization map of public building space

Public building space combination mode determines the evacuation skeleton path in the evacuation process, affecting the overall output of the evacuation efficiency. And a single combination determines the way of evacuation with a fixed dynamic aggregation manner, affecting evacuees initial routing decision. Both of them are very important for the evacuation process. In order to analyze the effects of different space combination model on evacuation efficiency, we propose a hierarchical organization map of public building space (Figure 1) concept, which is defined as follows:

$$G = \{G^1\} = \{G_1^2, G_2^2, \dots, G_i^2, \dots, G_n^2\},$$

$$CG^2(G_1^2, G_2^2, \dots, G_i^2, \dots, G_n^2) \\ = \{ \{ \dots \{ G_{i1}^3, G_{i2}^3, \dots, G_{im}^3 \}, \\ CG_i^3(G_{i1}^3, G_{i2}^3, \dots, G_{im}^3), \dots \}, CG^2(G_1^2, G_2^2, \dots, G_i^2, \dots, G_n^2) \} = \dots \quad (1)$$

$$G_i^k = \{ \{ G_1^{k+1}, G_i^{k+1}, \dots, G_n^{k+1} \}, \\ CG^k(G_1^{k+1}, G_i^{k+1}, \dots, G_n^{k+1}) \} \quad (2)$$

$$G^k = (V^k, E^k) = \{ \{ v_1, v_2, \dots, v_{n^k} \}, \\ \{ e_1, e_2, \dots, e_{m^k} \} \} \quad (3)$$

$$CG^k = (CV^k, CE^k) = \{ \{ cv_1, cv_2, \dots, cv_{n^k} \}, \\ \{ ce_1, ce_2, \dots, ce_{m^k} \} \} \quad (4)$$

where  $v$  is the node in one hierarchy map, which represents a unit abstracted from the low level of hierarchy map;  $e$  is the vertex in a hierarchy map, which represents the connection relationship between different nodes;  $cv$  is the sub-map of same hierarchy map, for example the node in hierarchy  $K$  in figure 1;  $ce$  means the logical connection relationship between sub-maps, for example the edge in hierarchy  $K$  in figure 1. The node in a high-level hierarchy represent a sub-map of lower-level hierarchy map consisting of nodes. These nodes make up a individual space combination model.

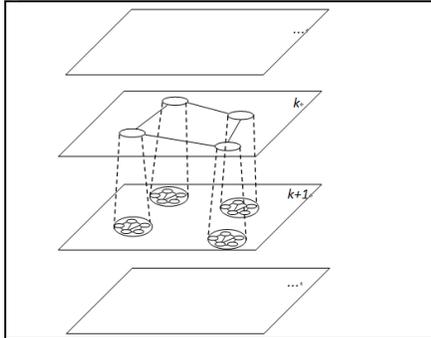


Fig. 1: Hierarchical organization map of public building space.

This hierarchical organization map of public building space has several characteristics, such as relative independence of spatial expression of public buildings, evacuated hierarchy of public building space, the importance differences of public building space, etc. This map is a basic organization to analyze the contribution index in this paper.

## 2.2. Evacuation contribution index

This paper presents a concept of evacuation efficiency contribution index to describe the relative contribution of the different space combinations. In general, for a particular space, each individual was evacuated with the shortest time, the shortest path, the more evacuated number of individuals, then the efficiency contribution of this space is higher. Based on this concept, we define evacuation contribution index (ECI) as follows:

$$\Phi_G(G_i^1) = \sum_{j \in G_i^0} (G_j^2) = \dots \\ = \sum \dots \sum_{l \in G_i^k} \Phi_G(G_l^k) \quad (5)$$

$$\Phi_G(G_l^k) = \sum_{j \in v_{j^k}} f(v_{j^k}) / \Delta T(G_l^k) \quad (6)$$

$$f(v_{j^k}) = \sum_{j \in P_i} \left( \frac{Dist(p_j, v_{j^k})}{Length(v_{j^k})} \times \frac{\varphi}{T(p_j, v_{j^k})} \right) \quad (7)$$

where  $G$  is the hierarchical organization map of public building space.  $k$  is the maximum hierarchy level,  $\Phi_G(G_l^k)$  is the Evacuation contribution index of  $G_l^k$ ,  $\Delta T(G_l^k)$  is the evacuation time period of  $G_l^k$ ,  $Dist(p_j, v_{j^k})$  is the trajectory length of individual  $p_j$  in building unit  $v_{j^k}$ ;  $T(p_j, v_{j^k})$  is the activity time of individual  $p_j$  in building unit  $v_{j^k}$ ;  $Length(v_{j^k})$  is the length of building unit  $v_{j^k}$  along the trajectory,  $\varphi$  is the parameter,  $f(v_{j^k})$  the efficiency contribution index value of  $v_{j^k}$ .

## 3. Experiments and analysis

This paper developed an evacuation simulation prototype system (Fig.2) based on C++ language, and some tools including Qt GUI, and Ggnuplot.

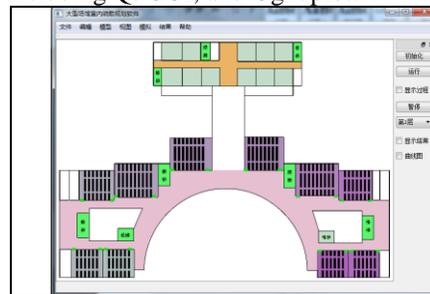


Fig. 2: The prototype system.



Fig. 3: The building design plans, and a hierarchical organization map of public building space in plan #2.

Using this prototype system, the paper analyzed against seven architectural exhibition designs, all of them are under a same design specifications, so they can be compared each other. Figure 3 lists seven architecture design plans, and a hierarchical organization map of public building space in plan #2.

Figure 4 shows the evacuation curve of seven architectural design plans. As can be seen, compared results of the evacuation efficiency is: plan #3> plan #7> plan #1> plan #4> plan #2> plan #6> plan #5. plan #3 and 7 have obvious advantages, they have a high efficiency. For example, in the first 30 seconds, plan #2 has a very high evacuation efficiency. plan #5 and 6 have a disadvantage of low efficiency. Plan# 2 has a high evacuation efficiency in first 30 seconds, but followed with a slow evacuation efficiency. Plan# 4 has a low efficiency in first 52 seconds, but after that, it has a good efficiency. Plan# 5 always has a low efficiency performance, Plan#4 and 6 race in the before and after 52 seconds but they are approximate on the whole.

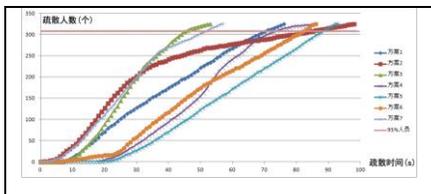


Fig. 4: The building design plans, and a hierarchical organization map of public building space in plan #2.

Figure 5 and 6 shows ECI values of plan #1-7. This paper discuss them as follows:

# 1: The plan consists of three main parts: p1, p2, p3 areas. They are linear combination model, the ECI of these areas are 3.488277(14.95%), 3.668355 (29.35%), 12.98834 (55.70%).

# 2: The plan consists of five main parts: p1-p5 areas. They are linear combination model, the ECI of these three

areas are 12.76764(37.31%), 5.068523(14.81%), 2.498229(7.30%), 6.272746(18.33%), 7.613017(22.25%), 3.488277(14.95%), 3.668355(29.35%), 12.98834 (55.70%).

# 3: The plan consists of centralized mode (p1 and p3) and linear model (p2), their ECI values are: 21.02347, 8.859732, 4.77401. The contribution of centralized mode is 25.79748 (= 21.02347 + 4.77401) (74.44%), evacuation efficiency of the linear spatial patterns is 8.859732 (25.56%).

# 4: The plan includes a centralized space (p1), and linear space (p2, p3, p4). Their ECI values are 14.93906, 8.68651, 9.155914, 5.87792. The ECI of centralized space is 14.93906 (38.64%), while ECI of linear space is 23.72034 (= 8.68651 + 5.87792 + 9.155914) (61.36%).

#1		#2		#3		#4	
Obj.	ECI	Obj.	ECI	Obj.	ECI	Obj.	ECI
Room							
r1	0.868558	r1	2.023256	r1	2.666667	r1	1.304348
r2	1.219512	r2	1.264933	r2	1.708185	r2	1.385661
r3	0.515625	r3	3.939993	r3	1.72043	r3	1.5625
r4	0.55914	r4	1.46654	r4	1.666578	r4	3.157895
r5	0.488069	r5	1.25523	r5	1.699717	r5	1.365188
r6	0.62069	r6	0.245705	r6	2.085747	r6	1.081081
r7	0.488177	r7	0.203879	r7	1.411765	r7	1.128881
r8	0.544892	r8	1.470588	r8	0.527038	r8	1.011378
r9	0.4372	r9	0.223394	r9	1.466993	r9	1.039861
r10	0.365505	r10	0.155014	r10	1.066351	r10	2.242991
r11	1.690141	r11	1.604863	r11	0.832972	r11	1.476015
r12	0.954447	r12	2.016807	r12	0.851869	r12	0.375
r13	1.494396	r13	0.656592	r13	1.257862	r13	3.339518
r14	0.578815	r14	1.093168	r14	4.460967	r14	0.1264
r15	0.543232	r15	3.108808			r15	0.1237
r16	0.84063	r16	1.783944			r16	1.930295
r17	0.593926	r17	1.718277				
r18	0.506887	r18	2.980132				
r19	0.467906						
passway							
p1	2.619718	p1	4.09322	p1	7.517348	p1	3.953488
p2	3.178082	p2	1.511713	p2	3.383686	p2	1.834862
p3	3.748505	p3	0.748469	p3	0.313043	p3	4.922504
		p4	1.559074			p4	5.87792
		p5	2.914508				

Fig. 5: The ECI values for plans #1-4.

#5		#6		#7	
Obj.	ECI	Obj.	ECI	Obj.	ECI
room					
r1	1.73913	r1	1.318681	r1	1.18283
r2	1.407349	r2	0.75	r2	2.917923
r3	1.495683	r3	1.354839	r3	1.153846
r4	1.444043	r4	1.324921	r4	2.414487
r5	1.607143	r5	1.193182	r5	0.1255
r6	1.612181	r6	1.127517	r6	1.350844
r7	1.83908	r7	1.142857	r7	2.144772
r8	1.165803	r8	1.344	r8	1.552393
r9	1.374046	r9	0.910076	r9	0.1214
r10	1.435407	r10	1.258427	r10	2.014268
r11	1.702128	r11	0.786885		
r12	0.1219	r12	0.923077		
r13	0.742574	r13	0.920539		
r14	0.1232	r14	0.84507		
		r15	1.232575		
		r16	0.975044		
		r17	1.381958		
		r18	1.191489		
		r19	1.289332		
		r20	1.033846		
		r21	1.28		
		r22	1.19403		
		r23	1.476274		
		r24	0.733496		
		r25	1.223598		
		r26	1.20603		
passway					
p1	5.856515	p1	2.049339	p1	3.492063
p2	4.362416	p2	3.946995	p2	2.421796
p3	1.720567	p3	1.630058	p3	5.182186
		p4	1.19949		
		p5	1.811668		
		p6	1.054283		
		p7	2.045939		

Fig. 6: The ECI values for plans #5-7.

#5: The plan includes radiant (p1 and p2) and linear space (p3). Their ECI values are 16.99613, 5.10499, 7.39795. The ECI of radiant space is 22.10112 (= 16.99613+ 5.10499) (74.92%), the ECI of linear space is 7.39795 (25.08%).

#6: The plan consists concentrated space (p1, p6), and linear space (p2-5 and p7). Their ECI are 5.503194 (13.27%), 4.580155 (11.04%), 7.412935 (17.87%), 6.89418 (16.62%), 6.936172 (16.72%), 6.495469 (15.66%),

3.655011 (8.81%). The ECI sum of the concentration space is 11.99866 (28.93%), and the sum of linear space 29.47845 (71.07%).

#7: This plan includes two centralized space(p1-2,p3). Their ECI values are 10.12731 (38.50%), 3.815642 (14.50%), 12.36446 (47%). p1 and p2 form a centralized space which contributes 13.94296 (53%) while p3 is 12.36446 (47%).

#### 4. CONCLUSIONS

These analysis proved the effectiveness of the proposed index, which provides a useful method to measure the evacuation contribution of public building spaces, and can be used to optimize building design plan when considering evacuation efficiency.

**Acknowledgements:** I would like to thanks Wang Luyao, Liu Ziyuan, Ma wenjuan, Ni Jiming, Qi Qige, Lu Ting, Xu Yuanfang for their design works.

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