COMPUTER AIDED PERFORMANCE ANALYSIS OF STAIRCASE FAULT TOLERANCE

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Abstract. This study is to investigate the performance of staircases in a building with some faulty staircases. In this building, any unexpected hazard or repairs may cause vertical escaping routes inaccessible. Therefore, it is crucial that architects should assess this condition, and the users also need to be aware of this problem. Facing those staircase faults, architects need to consider space usage, staircases arrangement, and pedestrian attributes. This paper proposes a method to model the pedestrian's movement in the interior space of above-mentioned building. We applied Monte Carlo simulation and Agent-Based Modeling method in a CAAD environment. And we will apply two case studies to bring forward some important discoveries and support our arguments.

1. Introduction

It has been well recognized to system designers that a system should be able to operate even when some components are unable to work normally. That is to say, a system should have enough ability to tolerate components' fault (Anderson and Lee, 1981). Such topics has been studied in computer science, mechanics, and commercial research for a long time (Karyagina, 1997), but there are few researchers ever explore their meaning and importance in architecture. Therefore, in this research, we will apply the concept of fault tolerance to try to examine the performance of staircases layout in public buildings when they are under repair or facing some hazards (fire, earthquake, and other accidents).

Most of the researchers who devote their efforts to the space layout problems always consider the staircases as the main and essential components in building layout (Jo and Gero, 1998; Liggett, 2000). Usually, architects check the appropriateness of staircases according to building codes in terms of size, amount and location (Templer, 1992). However, building codes which regulate general cases usually do not take fault tolerance into account.

2. Research Method

In this section, we propose an agent-based model to simulate the main components in a space. We give agents (people) in the model various properties, such as movement speed and response time. They move independently but interact with each other in the system. Accordingly, designers evaluate the performance of the system (staircase layout in this research) by measuring some criteria.

2.1 DECLARATION OF SYMBOLS

In this section, there are 10 symbols for denoting different items. They are as the following.
1. S: A situation, which indicates a floor status of spaces and pedestrian.
2. N: A number, which notes the number of staircases in S.
3. T : A period of time, which is the total evacuation time for all crows in S without any failed staircase.
4. T^k : There are k staircases fail to work, and T^k is the total evacuation time. (0<k<N)
5. a: Let a $= \frac{T^k}{T}$, it shows the increase time proportion.
6. D: D = {d | d are all the staircases on a floor}, i, j, …$\in$ D.
7. $T_{i,j..}$: i , j,…are the failed staircases,
T^k could be explicitly rewritten as $T^k_{i,j...}$.
8. $a_{i,j..}$: Rewriting fifth declaration as $a_{i,j..} = \frac{T_{i,j..}}{T}$.
9. ΔT: It shows evacuation time increased.
$\Delta T = T^k - T = T_{i,j..} - T = (a-1)\,T$
10. Max (X , Y, …) : It is the maximum of X , Y,…

2.2 TOLERANCE OF EVACUATION TIME

Pedestrians' evacuation time is commonly regarded as a basic safety requirement. We have some symbols as follows:
1. FT^k -- the maximum evacuation time requested by building code.
Design constraint: Max $(T^k_{ij...}, T^k_{jh...}, \ldots) < FT^k$

2. a^k-- the expected maximum time ratio of faulty situation to normal situation.

Design constraint: $\forall$ i, j, …$\in$ D, $\frac{T_{i,\,j..}}{T} < a^k$

3. NT -- a relative requirement about two conditions (k=0 and k>0).

Design requirement: $N?T^{n} \geq (N-k)\,T^{k}$

2.3 TOLERANCE OF CROWD BURDEN

We regard pedestrians running to staircases as crowd burden. In this section, we indicate that when there are some faulty staircases, it will increase another staircase's burden. If X fails, it increases Y's burden, the pedestrians increase from Y_0 to Y_x, then we express this phenomenon as:
$ß_y = Y_x / Y_0$, $ß_y$ is the pedestrian change ratio of Y.

To let every staircase serves roughly equal amount of the pedestrians is a reasonable consideration in design. However, staircase faults may destroy such balance. We calculate the standard deviation of the amounts of pedestrians associated with staircases to measure the degree of balance. A small standard deviation means that pedestrians use staircases more evenly.

Let S_n be standard deviation (SD) in faulty-free situation, and S_f be SD in faulty situation.

$$\Delta S = S_f - S_n \tag{1}$$

Equation 1 measures the degree of imbalance among staircase burdens. A high ΔS implies the usage of staircases is imbalanced.

3. Model and Agent

A proper model is essential in the study of the system. However, in this short paper, there are not enough pages for us to introduce our theoretical model for pedestrian movement on a floor space. Readers who are interested in detail description please refer to our paper (Chen and Lin, 2003). It will explain all the symbols for space, object and agent's activity.

3.1 VELOCITY DISTRIBUTION

The concept of Monte Carlo simulation is applied and discussed in this section (Mooney, 1997). We noticed that pedestrians have different walking velocity. Therefore it is necessary to consider this factor. After observing and analyzing pedestrians' walking in campus buildings, we calculate the pedestrians’ velocity distribution and get the following data, where there are

7 different speed intervals (V_1 -- V_7) with certain percentages. Most of the pedestrians have the velocity between 1.27 to 1.45 m/sec.

$P(x, V_1) = P(x, 2.23m/sec) = 1\ \%$, $P(x, V_2) = P(x, 1.69m/sec) = 10\ \%$
$P(x, V_3) = P(x, 1.45m/sec) = 37\ \%$, $P(x, V_4) = P(x, 1.27m/sec) = 30\%$
$P(x, V_5) = P(x, 1.13m/sec) = 13\ \%$, $P(x, V_6) = P(x, 1.02m/sec) = 8\ \%$
$P(x, V_7) = P(x, 0.92m/sec) = 1\ \%$

3.2 START-RUNNING-TIME DISTRIBUTION

Based on the evidence of recording an earthquake on tape, we notice that pedestrians take different time to respond to danger and start running. In this section, we assume the distribution of start-running-time as follows (unit: second).

$P(x, T_1) = P(x, Tx < 4) = 20\ \%$
$P(x, T_2) = P(x, 4 \leq Tx < 8) = 60\ \%$
$P(x, T_3) = P(x, 8 \leq Tx < 12) = 20\ \%$

The velocity distribution and start-running-time distribution may vary among buildings, people and time periods of the day.

We use model to simulate differences of attribute by drawing a random number between 0.00 and 1.00 and comparing it to the fixed probability of that event occurring for an individual with a given set of behavior characteristics. For example, assume that the speed probability of 2.23m/sec for an agent is 1%. If the random number drawn by the model is more than 0.00 and less than 0.01 for this agent, she is assumed to have 2.23m/sec velocity. If the number drawn lies between 0.01 and 0.11, then she is assumed to have 1.69 m/sec velocity, and so on. In order to give random variation to the agent's two statuses (velocity and start-running-time) by the Monte Carlo procedure, the model is routinely run with two separate random number sets and output the results are used to two distributions, velocity distribution and start-running-time distribution.

3.3 ACTIONS OF AGENTS

The following is an explanation of an agent's various actions. At first, we can try a random distribution model which gives an agent two attributes, for example, $Vx = 1.45m/sec$ and $Tx = 2$ sec. As for the other models used for modeling all the agents' various states and actions, Table 1, for instance, shows one agent's direction, moving distance, and rules of movement in every second.

TABLE 1. An agent's movement.

Time	Space	Applied Rule	Behavior	Move Direction	Move Distance
1	Sa	R1	Not start yet		0
2	Sa	R3	Start to run to the door	D(x, b)	1.45
3	Sa	R2	Wait		0
4	Sa	R3	Run to the door	D(x, b)	1.45
5	Sb	R5	Run to the staircase	D(x, Dx)	1.45
6	Sb	R6	Walk along a wall	D(x, p)	1.45
7	Sb	R4	Wait		0
8	Sb	R5	Run to the staircase	D(x, Dx)	1.45
9	Sb	R5	Run to the staircase	D(x, Dx)	1.45
10	D	R8	Arrive		0

In this case, the agent takes 10 seconds and 8.7 meters to run to his destination. Generally there are three kinds of space for movement on the agent's route: a room, a corridor, and a staircase. Before arriving at the destination, he can do several actions, including starting, running, waiting, walking along a wall, or arriving at the staircase. Every agent has his own actions, way to interact with other agents, and route to the staircase. That is, all agents' actions compose a dynamic process. This simulation process will end when the last agent arrives at the staircase. We use the computer to assist us to execute these models and to visualize the process.

4. Case Study 1

The first case study is about a subway station (Chung-Shang Station) of Taipei City. Figure 1 is the B1 plan of the underground building, which displays layouts of rooms, passages, staircases, etc. We label 4 staircases as "a", "b", "c", "d". Small dots represent pedestrians. (Total: 146 people).

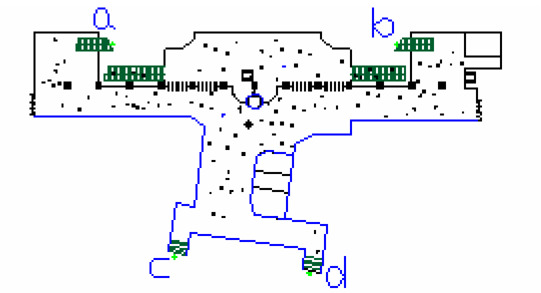

Figure 1. The floor plan of the case study building.

A simulation program is written by AutoLISP language and executed in an AutoCAD environment (Figure 2). We may locate agent with attributes, assign object positions, execute the activity rules, and visualise the dynamic process.

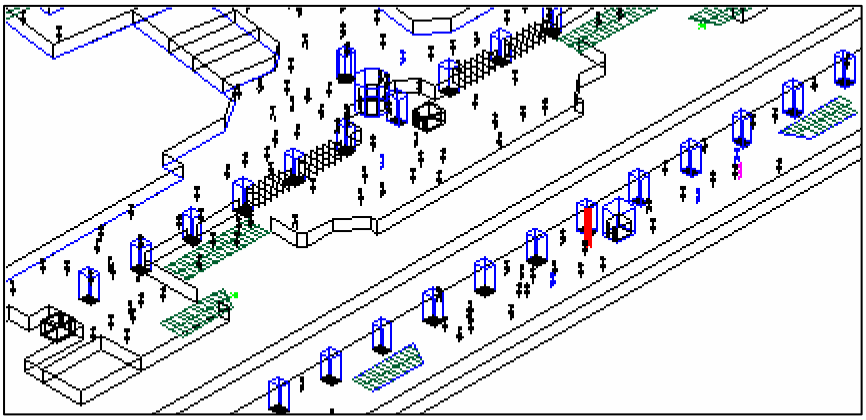

Figure 2. Simulation of agents, facilities, and spaces.

Table 2 illustrates some important or serious combinations of staircase faults.

TABLE 2. Simulation results.

Staircase		k	Evacuation time		Pedestrian going to each staircase				SD	ΔS
Available	Faulty				a	b	c	d		
a,b,c,d,		0	T	55	59	73	17	6	32.3	
b,c,d	a	1	T_a	114		91	55	9	41.1	8.8
a,c,d	b		T_b	100	95		16	44	40.1	7.8
a,b,d	c		T_c	56	62	72		21	27.0	-5.3
a,b,c	d		T_d	56	62	75	18		29.9	-2.4
c,d	a, b	2	T_{ab}	114			80	75	3.5	-28.8
a,b	c, d		T_{cd}	69	77	78			0.7	-31.6
b,d	a, c		T_{ac}	114		98		57	29.0	-3.3

4.1 FAULT TOLERANCE CHECKING

4.1.1 FT^k Value

If it requires FT^k value are: FT^1 -- 100sec, FT^2 -- 120sec,

then, k=1, Max $(T_a^1, T_b^1, T_c^1, T_d^1) = 114 > FT^1$, Not tolerable.

k=2. Max $(T_{ab}^{2}, T_{cd}^{2}, T_{ac}^{2}) = 114 < FT^2$, Tolerable.

4.1.2 a^k Value

If it requires $a^1 = 2.0$, $a^2 = 3.0$

then $\forall i \in D$, $\frac{T_i}{T} < a^1$, it is not true, $\frac{T_a}{T} = 2.1$, Not tolerable.

$\forall i, j \in D$, $\frac{T_{ij}}{T} < a^2 = 3.0$, it is true, Tolerable.

4.1.3 NT Value

When all staircases work normally, N = 4, $T^n = 55$. If it requires NT value is less than (4 x 55) / (4 - k), then when

k=1 , $T^1 \leq 220/(4-1) = 73.3$,

k=2 , $T^2 \leq 220/(4-2) = 110.0$

After checking NT value, we found that only T_c, T_d, T_{cd} can fit requirement, the other conditions are not tolerable.

4.2 FAULT INFLUENCE ON CROWD DISTRIBUTION

When some staircases fail, pedestrians may change their destinations, and the number of pedestrians toward each staircase may also change. Therefore, in this section, we discuss the fault influence on crowd distribution of staircases.

4.2.1 Discussion 1

1. For staircase a, when other staircase fails, $ß_b$ (95/59=1.6) is higher than $ß_c$, $ß_d$ (62/59=1.1). It means b's fail has a serious impact on staircase a.
2. For staircase b, when other staircase fails, $ß_a$ (91/73=1.2) is highest value, which means staircase b has more pedestrians to digest when a fails.
3. For staircase c and d, we may use same method to check each staircase.

4.2.2 Discussion 2

1. When k = 1, fault on staircase a make SD increase obviously, which stands for serious situation.
2. When c or d are faulty, SD values are less than 32.3 when there's no fault. It means that, in this case, fault on c or d make people going to staircase more balanced than in no fault circumstances.

5. Case Study 2

The second case study is about a campus building in National Taiwan University. Figure 3 is the 4th floor plan of the building, which displays layouts of rooms, corridors, staircases, etc. We label 5 staircases as "a", "b", "c", "d", "e". Small dots represent pedestrians. (Total: 173 people).

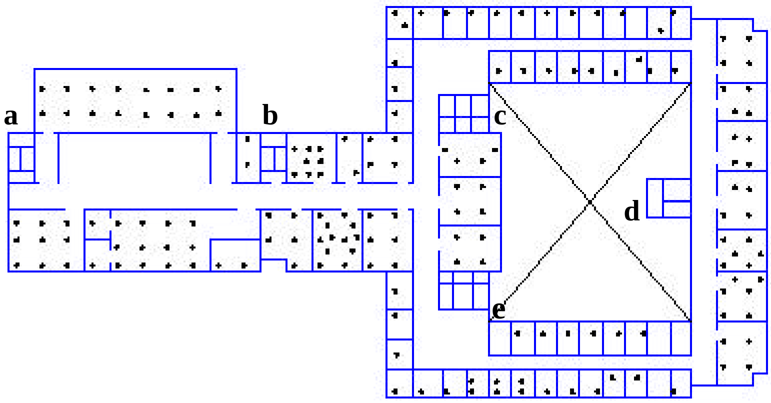

Figure 3. The floor plan of the 2nd case.

Table 3 illustrates some important or serious combinations of staircase faults in this case.

TABLE 3. Simulation results of 2nd case.

Staircase		k	Evacuation time		Pedestrian going to each staircase						
Available	Faulty		time		a	b	c	d	e	SD	ΔS
a,b,c,d,e		0	T	50	17	53	28	42	33	13.7	
b,c,d,e	a		T_a	61		70	28	42	33	18.8	5.1
a,c,d,e	b	1	T_b	65	41		44	42	46	2.2	-11.5
a,b,d,e	c		T_c	64	17	57		52	47	18.0	4.3
a,b,c,e	d		T_d	76	17	57	41		58	19.2	5.5
a,b,c,d	e		T_e	65	17	75	26	55		26.7	13.0
c,d,e	a, b		T_{ab}	98			80	42	51	19.9	6.2
a,b,d	c, e	2	T_{ce}	65	17	91		65		37.6	23.9
a,d,e	b, c		T_{bc}	65	43			54	76	16.8	3.1
b,c,e	a, d		T_{ad}	80		75	41		57	17.0	3.3
b,d	a,c,e	3	T_{ace}	65		108		65		30.4	16.7
d,e	a,b,c		T_{abc}	99				54	119	46.0	32.3
e	a,b,c,d	4	T_{abcd}	109					173		

5.1 FAULT TOLERANCE CHECKING

5.1.1 FT^k Value

If it requires FT^k value are: FT^1 -- 80sec, FT^2 -- 90sec, FT^3 -- 100sec,

then k=1, Max $(T_a^1, T_b^1, T_c^1, T_d^1, T_e^1) = 76 < FT^1$, Tolerable.

k=2. Max $(T_{ab}^2, T_{ce}^2, T_{bc}^2, T_{ad}^2) = 98 > FT^2$, Not tolerable.

k=3, Max $(T_{ace}^3, T_{abc}^3) = 99 < FT^3$, Tolerable.

5.1.2 a^k Value

If it requires $a^1 = 1.5$, $a^2 = 2.0$, $a^3 = 2.5$,

then $\forall i \in D$, $\frac{T_i}{T} < a^1 = 1.5$, it is not true, $\frac{T_d}{T} = 1.52$, Not tolerable.

$\forall i, j \in D$, $\frac{T_{ij}}{T} < a^2 = 2.0$, it is true, Tolerable.

$\forall i, j, k \in D$, $\frac{T_{ijk}}{T} < a^3 = 2.5$, it is true, Tolerable.

5.1.3 NT Value

When all staircases work normally, N=5, $T^n = 50$. If it requires NT value is less than (5 x 50) / (5 - k), then when

k=1 , $T^1 \le 250/(5-1) = 62.5$ k=2 , $T^2 \le 250/(5-2) = 83.3$

k=3 , $T^3 \le 250/(5-3) = 125.0$ k=4, $T^4 \le 250/(5-4) = 250.0$

After checking NT value, only T_b, T_c, T_d, T_e, T_{ab} can not fit requirement, the other conditions are tolerable.

5.2 OBSERVATION

These two cases in section 4 and 5 display some interesting results. It may not be proper to say which one is better, because they are different in many ways and the design requirements are not the same. However, from the simulation results, we may discover that the staircase fault tolerance must be considered in the design of space usage, staircase location and route arrangement. That's the reason why we argue architects need to take staircase fault tolerance into account. Figure 4 shows a comparison of maximum evacuation-time and k value of these two cases.

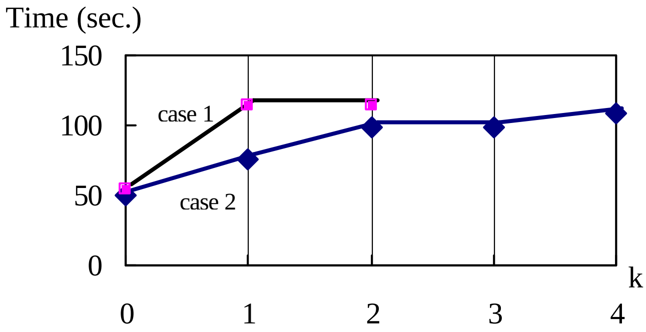

Figure 4. Maximum evacuation-time of case 1 and case 2.

6. Conclusion

In order to comply with various safety requirements of public buildings, designers should assess a variety of performances in case of emergency condition. Among them, this paper put emphasis on the performance of staircase fault tolerance in the space layout. With the assistance of simulation tools, we display how faulty staircases may cause serious results. Therefore, we argue that a safe staircase-layout shouldn't mean it has good performance at normal condition only, but also have the ability to tolerate certain staircase faults. It could potentially be a new item of evaluation and should be taken into account when an architect designs the space of a building.

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