Numerical studies of Personnel Evacuation Model Based on Graphic Theory Model and Floyd Algorithm

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Abstract: This paper introduces a new Louvre tourist safety escape model. The model can be divided into two parts: a basic model without considering some special actual circumstances, an improved model considering the evacuation of tourists under some multiple scenarios. The model mainly uses the graphic theory model and the Floyd algorithm. In order to simplify the construction entities, we introduced the graphic theory model. Firstly, we divide the guide map of the Louvre into many small unit regarding each exhibition hall marked with a number as a mobile unit, so it can be treated as a point unit in the graphic theory model and the time cost between any two points can be taken as the line in the graphic theory model. Based on those, introducing the Floyd algorithm, we can calculate the best escape path of each mobile unit. After this, some special circumstances are considered into this model to make the model more reasonable and specific. This technique is highly promising to solve personnel safety evacuation porblem when an emergency occurs.

1. Introduction

The increasing number of terror attacks in France requires a review of the emergency evacuation plans at many popular destinations. The Louvre is one of the world's largest art museum, receiving more than 8.1 million visitors in 2017. The number of guests in the museum varies throughout the day and year, which provides challenges in planning for regular movement within the museum. The diversity of visitors will make personnel evacuation in an emergency even more challenging. However, for a certain tourist attraction, especially a high-rise building like the Louvre, there are not so many people who are studying the evacuation of people in these areas. Moreover, there are yet not any effective evacuation measures for a famous museum. In any event of an emergency, the situation may be extremely dangerous and even threatens the safety of personnel.

In conclusion, the Louvre is urgently demanding an emergency evacuation assessment and new evacuation strategies. With the aim of solving these problems, the purpose of this study is to provide some good strategies to improve the evacuation efficiency, for quick guidance of tourists to specific safe destinations, in a broad range of areas. The model can be divided into two parts: a basic model without considering some special actual circumstances, an improved model considering the evacuation of tourists under some multiple scenarios. With the help of this model, every independent exhibition hall in the Louvre can be designed an optimal path for visitors to escape to a safe destination.

1.1. BASIC MODEL

The whole evacuation process can be divided in to four steps: Reacting to alarm broadcast、Move within the same floor、Move between floors、Leaving out through a gate, and the solution of these four steps are as follows: 1.Reacting Time; 2. Moving Time Within a Floor; 3. Moving Time Between Floors; 4. Leaving Gate Time.

1.2. Reacting Time

Under general situation, native visitors can response to the emergency broadcast immediately, although there may be a short delay before they are aware of the emergency, the delays are so short that it can be neglected. therefore, we define that the reacting time(t_d) is 0s.

1.3. Moving Time Within a Floor

We know that time is determined by the distance and the velocity as the following formula:

$$t = \frac{\boldsymbol{d}}{\boldsymbol{v}} \tag{1}$$

Thus, we have to calculate the values of parameter "d" and "v".

To get the distance(d), the physical sizes of each hall in the Louvre are needed. Therefore, we have set up a model to represent the real sizes, that's: the characteristic model of exhibition halls, which is shown below.

1.4. The Characteristic Model of Exhibition Halls

It is known that each exhibition halls have its specific characteristics: length, width, tourist density, evacuation time. To determine these parameters, we need the following steps:

First, we can know the Louvre covers an estimated 253011 square meters. After processing the floor plan of the Louvre with gridding method, we can depict gridding on the tour map of the Louvre[12] and the whole picture can be divided into 2352 grids, each of them cover 107.6 square meters. The image of the 2^{nd} floor is shown below:

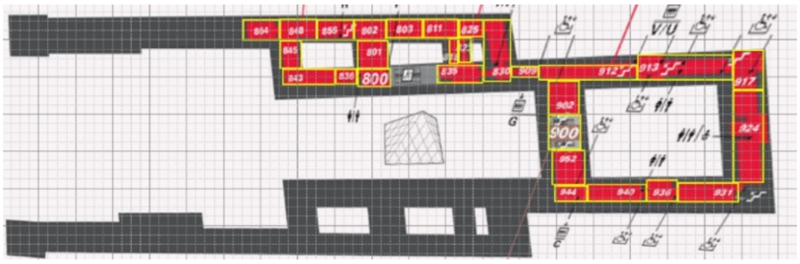

Figure 1. Tour Map of the 2nd Floor.

Secondly, we calculate the number of grids covered by the entire exhibition hall and the number of grids covered by each exhibition hall to figure out that the areas of all halls are added up to 103323.6 square meters. Using this data, we can count the number of grids that each hall has and calculate the real size according to the map scale. Because the data is kept secret, we can't find it, we define that the width of each hall is 15 square meters, so the length of each hall can be calculated via the following formula:

$$\text{length} = \frac{area}{width} \tag{2}$$

Thirdly, according to the reference[1], the velocity of the visitors can be determined by the density of the people in an exhibition hall. The formula is as follows:

$$v = -0.516 \times \ln(\rho) + 1.5499 \tag{3}$$

Where the parameter "ρ" is crowded density. To get the density of visitors, we can know the information that the number of visitors of the Louvre is estimated ten million[11], and from the "Affluence" application, we can get the schedule of the Louvre, which is shown below:

Table.1. Schedule of the Louvre.

Mon. Thur. Sat. Sun.	9: 00-18: 00
Wed. Fri.	9: 00-21: 45

Given that visitors need time to enter the museum and spread among exhibition halls, the effective duration can be regard as 11 hours on Wed. and Fri. and 7 hours on Mon. Thur. Sat. and Sun. and the average time (t_{av}) is $8.3h$. The time of Louvre opening to the public is 312of 365 days each year, and it opens about 8.3 hours on average. So, the average number of visitors per day is about 31963 persons and the average number of visitors per hour is about 3851 persons. Assuming that the average sightseeing time duration of visitors is 7 hours, so the number of visitors in the Louvre is about 26957 persons at a certain time. The total area of all halls is 103323.6 m^2, so the crowded density of the galleries in the Louvre can be calculated to be 0.26 persons/ m^2.

Because some of the artworks in the exhibition halls are so famous that will attract more people to visit, the crowded density in this hall is higher than the average level of 0.26. So, these halls can be thought as very crowded.

Further, relevant research shows the personnel density of buildings with different functions[10]. By searching for information, we can know that the value of ρ for "very crowded" is 1.2 to 2.0. Thus, the visitor density can be regarded as 1.2 of the halls which are very crowded.

Table.2. Personnel Density of Buildings with Different Functions.

Function	Personnel Density	Entertaining	Educational	Restaurant	Office	Residential
Personnel Density	1.2-2.0	0.4-1.0	0.7-1.0	0.5-0.8	0.2-0.5	0.1-0.2

Table.3. The very crowded exhibition halls of 2nd floor.

Floor	Exhibition Hall Number							
2F	801	822	837	811	912	917	940	952

Finally, based on the parameter we discussed above, we can obtain the evacuation time that crossing a particular hall cost using the *Formula-1, Formula-3*. All the characteristics of each hall is listed in the following table:

Table.4. The characteristics of each hall.

Characteristics	Formula & Value
Width	15m
Length	area / 15m
Visitor Density	0.26 &1.2
Evacuation Velocity	$v = -0.516 \times \ln(\rho) + 1.5499$
Evacuation Time	$t = length/v$

With this characteristic model, we can figure out the evacuation time within an exhibition hall, that is, how much time a visitor will cost while crossing a hall. In order to evacuate safely, visitors have to move among different halls and different floors. Based on this, we introduce graphic theory and establish a graphic theoretic model to calculated the time during those periods, with which we can regard each exhibition hall as a mobile unit, and calculate the time when visitors are moving among different halls within a floor.

We just take the 2nd floor as an example, and part of the characteristics of each exhibition halls are listed below:

Table.5. Partial values of each characteristic of each hall.

Hall Number	Grids Number	Area(a)	Length	Visitor Density	Velocity	Evacuation Time
864	6	645.6	43.0	0.26	1.76	24.45
843	12	1291.2	86.1	0.26	1.76	48.91
…	…	…	…	…	…	…

1.5. Graphic Theory Model

The evacuation process can be separated into two stages: moving within a floor and moving between floors. With the first Evacuation Rule 2, visitors will be led to the stairs which costs the least time to leave the current floor. Under such situation, the graphic theoretic is introduced to obtain the time that moving within a single floor cost.

When an emergency occurs, in order to evacuate from the building, visitors have to move from the hall they are in to the nearest stairways, and to achieve this goal, they have to move to the halls that are connected to the stairways first, and then they can leave the floor using these nearest stairways named “the exit hall”. Besides, when confronted with more than one practical choices of paths towards evacuation stairways, visitors are led to the path that takes the least time to pass through, which named “the best path”.

Graphic theory can simplify the museum structure entities and make it convenient for us to design the shortest path. Because the Napoleon Hall doesn’t have any halls, we just have to apply the graphic theoretic model to the resting four floors. Based on the graphic theory, we regard each hall as a point (a mobile unit), and the time consumption of moving from one hall to another can be regarded as the bonds between any two points. What’s more, the length of the bonds (time it costs from one hall to another) is the average time of any crossing two adjacent hall. Taking the hall NO. 864 and hall NO. 843 for instance, we regard these two halls as two point, so the length of the bonds between these two halls can be calculated as follows:

The equivalent time of crossing the hall NO. 864 is 24.45s; The equivalent time of crossing the hall NO. 843 is 48.91s. So, the time moving from the hall NO. 864 to the hall NO. 843 is (24.45+48.19) / 2=36.32 s, which is the length of the bonds between point NO. 864 and point NO. 843.

From what we have discussed above, we can obtain a series of point (representing all the halls) and the length of any two points (representing the average time between any two halls). In order to find the best path which costs the least time, we introduce Floyd algorithm. First, we establish a Floyd adjacency matrix for each floor based on the graphic theoretic model mentioned above. Take the adjacency matrix of the 2nd floor as an example:

Table.6. Adjacency Matrix of the 2nd floor.

	864	843	836	845	848	855	802	801	800	803	811	825	830	835	909	912	902	913	917	924	931	936	940	944	952	818	900
864	0	10000	10000	10000	30.56	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
843	10000	0	32.61	34.64	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
836	10000	32.61	0	10000	10000	10000	10000	10000	36.68	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
845	10000	34.64	10000	0	28.53	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
848	30.56	10000	10000	28.53	0	31.59	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
855	10000	10000	10000	10000	31.59	0	31.59	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
802	10000	10000	10000	10000	10000	31.59	0	32.49	10000	31.59	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
801	10000	10000	10000	10000	10000	10000	32.49	0	24.36	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
800	10000	10000	36.68	10000	10000	10000	10000	24.36	0	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
803	10000	10000	10000	10000	10000	10000	31.59	10000	10000	0	32.11	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
811	10000	10000	10000	10000	10000	10000	10000	10000	10000	32.11	0	28.03	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
825	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	28.03	0	33.63	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	28.03	10000
830	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	33.63	0	33.63	28.53	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
835	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	33.63	0	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	28.03	10000
909	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	28.53	10000	0	31.19	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
912	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	31.19	0	43.42	45.45	10000	10000	10000	10000	10000	10000	10000	10000	10000
902	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	43.42	0	10000	10000	10000	10000	10000	10000	10000	10000	10000	40.76
913	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	45.45	10000	0	50.94	10000	10000	10000	10000	10000	10000	10000	10000
917	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	50.94	0	65.21	10000	10000	10000	10000	10000	10000	10000
924	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	65.21	0	52.99	10000	10000	10000	10000	10000	10000
931	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	52.99	0	32.17	10000	10000	10000	10000	10000
936	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	32.17	0	35.36	10000	10000	10000	10000
940	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	35.36	0	33.77	10000	10000	10000
944	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	33.77	0	31.41	10000	10000
952	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	31.41	0	10000	45.67
818	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	28.03	10000	28.03	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	0	10000
900	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	40.76	10000	10000	10000	10000	10000	10000	10000	45.67	10000	0

With the help of MATLAB, we can get the following two matrixes of the 2nd floor:

Table.7. Path of the 2nd floor.

Hall Number		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
		864	843	836	845	848	855	802	801	800	803	811	825	830	835	909	912	902	913	917	924	931	936	940	944	952	818	900
1	864	1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2	843	4	2	3	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3	836	2	2	3	2	2	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
4	845	5	2	2	4	5	5	5	5	2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5	848	1	4	4	4	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
6	855	5	5	7	5	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
7	802	6	8	8	6	6	6	7	8	8	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
8	801	7	9	9	7	7	7	7	8	9	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
9	800	8	3	3	3	8	8	8	8	9	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
10	803	7	7	7	7	7	7	7	7	7	10	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
11	811	10	10	10	10	10	10	10	10	10	10	11	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
12	825	11	11	11	11	11	11	11	11	11	11	11	12	13	26	13	13	13	13	13	13	13	13	13	13	13	26	13
13	830	12	12	12	12	12	12	12	12	12	12	12	12	13	14	15	15	15	15	15	15	15	15	15	15	15	12	15
14	835	26	26	26	26	26	26	26	26	26	26	26	26	13	14	13	13	13	13	13	13	13	13	13	13	13	26	13
15	909	13	13	13	13	13	13	13	13	13	13	13	13	13	13	15	16	16	16	16	16	16	16	16	16	16	13	16
16	912	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	16	17	18	18	18	18	18	18	18	18	15	17
17	902	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	17	16	16	16	16	16	16	16	16	16	27
18	913	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	18	19	19	19	19	19	19	19	16	16
19	917	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	19	20	20	20	20	20	20	18	18
20	924	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	20	21	21	21	21	21	19	19
21	931	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	21	22	22	22	22	20	20
22	936	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	22	23	23	23	21	21
23	940	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	23	24	24	22	22
24	944	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	24	25	23	23
25	952	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	25	24	24
26	818	12	12	12	12	12	12	12	12	12	12	12	12	12	14	12	12	12	12	12	12	12	12	12	12	12	26	12
27	900	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	27

Table.8. Time Cost of Each Path of the 2nd Floor.

Hall Number		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
		864	843	836	845	848	855	802	801	800	803	811	825	830	835	909	912	902	913	917	924	931	936	940	944	952	818	900
1	864	0	93.73	126.3	59.09	30.56	62.15	93.74	126.2	150.6	125.3	157.4	185.5	219.1	241.5	247.6	278.8	322.2	324.3	375.2	440.4	493.4	509.2	473.9	440.1	408.7	213.5	363
2	843	93.73	0	32.61	34.64	63.17	94.76	126.1	93.65	69.29	157.7	189.8	217.9	251.5	273.9	280	311.2	354.6	356.7	407.6	472.8	525.8	541.6	506.3	472.5	441.1	245.9	395.4
3	836	126.3	32.61	0	67.25	95.78	125.1	93.53	61.04	36.68	125.1	157.2	185.3	218.9	241.3	247.4	278.6	322	324.1	375	440.2	493.2	509	473.6	439.9	408.5	213.3	362.8
4	845	59.09	34.64	67.25	0	28.53	60.12	91.71	124.2	103.9	123.3	155.4	183.4	217.1	239.5	245.6	276.8	320.2	322.2	373.2	438.4	491.4	507.2	471.8	438.1	406.6	211.5	361
5	848	30.56	63.17	95.78	28.53	0	31.59	63.18	95.67	120	94.77	126.9	154.9	188.5	211	217.1	248.3	291.7	293.7	344.7	409.9	462.9	478.7	443.3	409.5	378.1	182.9	332.4
6	855	62.15	94.76	125.1	60.12	31.59	0	31.59	64.08	88.44	63.18	95.29	123.3	157	179.4	185.5	216.7	260.1	262.1	313.1	378.3	431.3	447.1	411.7	377.9	346.5	151.4	300.9
7	802	93.74	126.1	93.53	91.71	63.18	31.59	0	32.49	56.85	31.59	63.7	91.73	125.4	147.8	153.9	185.1	228.5	230.5	281.5	346.7	399.7	415.5	380.1	346.3	314.9	119.8	269.3
8	801	126.2	93.65	61.04	124.2	95.67	64.08	32.49	0	24.36	64.08	96.19	124.2	157.9	180.3	186.4	217.6	261	263	314	379.2	432.2	448	412.6	378.8	347.4	152.3	301.8
9	800	150.6	69.29	36.68	103.9	120	88.44	56.85	24.36	0	88.44	120.6	148.6	182.2	204.6	210.7	241.9	285.4	287.4	338.3	403.5	456.5	472.3	437	403.2	371.8	176.6	326.1
10	803	125.3	157.7	125.1	123.3	94.77	63.18	31.59	64.08	88.44	0	32.11	60.14	93.77	116.2	122.3	153.5	196.9	198.9	249.9	315.1	368.1	383.9	348.5	314.8	283.3	88.17	237.7
11	811	157.4	189.8	157.2	155.4	126.9	95.29	63.7	96.19	120.6	32.11	0	28.03	61.66	84.09	90.19	121.4	164.8	166.8	217.8	283	336	351.8	316.4	282.6	251.2	56.06	205.6
12	825	185.5	217.9	185.3	183.4	154.9	123.3	91.73	124.2	148.6	60.14	28.03	0	33.63	56.06	62.16	93.35	136.8	138.8	189.7	255	307.9	323.7	288.4	254.6	223.2	28.03	177.5
13	830	219.1	251.5	218.9	217.1	188.5	157	125.4	157.9	182.2	93.77	61.66	33.63	0	33.63	28.53	59.72	103.1	105.2	156.1	221.3	274.3	290.1	254.8	221	189.6	61.66	143.9
14	835	241.5	273.9	241.3	239.5	211	179.4	147.8	180.3	204.6	116.2	84.09	56.06	33.63	0	62.16	93.35	136.8	138.8	189.7	255	307.9	323.7	288.4	254.6	223.2	28.03	177.5
15	909	247.6	280	247.4	245.6	217.1	185.5	153.9	186.4	210.7	122.3	90.19	62.16	28.53	62.16	0	31.19	74.61	76.64	127.6	192.8	245.8	261.6	226.2	192.5	161	90.19	115.4
16	912	278.8	311.2	278.6	276.8	248.3	216.7	185.1	217.6	241.9	153.5	121.4	93.35	59.72	93.35	31.19	0	43.42	45.45	96.39	161.6	214.6	230.4	195	161.3	129.9	121.4	84.18
17	902	322.2	354.6	322	320.2	291.7	260.1	228.5	261	285.4	196.9	164.8	136.8	103.1	136.8	74.61	43.42	0	88.87	139.8	205	219.1	187	151.6	117.8	86.43	164.8	40.76
18	913	324.3	356.7	324.1	322.2	293.7	262.1	230.5	263	287.4	198.9	166.8	138.8	105.2	138.8	76.64	45.45	88.87	0	50.94	116.2	169.1	201.3	236.7	206.7	175.3	166.8	129.6
19	917	375.2	407.6	375	373.2	344.7	313.1	281.5	314	338.3	249.9	217.8	189.7	156.1	189.7	127.6	96.39	139.8	50.94	0	65.21	118.2	150.4	185.7	219.5	226.2	217.8	180.6
20	924	440.4	472.8	440.2	438.4	409.9	378.3	346.7	379.2	403.5	315.1	283	255	221.3	255	192.8	161.6	205	116.2	65.21	0	52.99	85.16	120.5	154.3	185.7	283	231.4
21	931	493.4	525.8	493.2	491.4	462.9	431.3	399.7	432.2	456.5	368.1	336	307.9	274.3	307.9	245.8	214.6	219.1	169.1	118.2	52.99	0	32.17	67.53	101.3	132.7	336	178.4
22	936	509.2	541.6	509	507.2	478.7	447.1	415.5	448	472.3	383.9	351.8	323.7	290.1	323.7	261.6	230.4	187	201.3	150.4	85.16	32.17	0	35.36	69.13	100.5	351.8	146.2
23	940	473.9	506.3	473.6	471.8	443.3	411.7	380.1	412.6	437	348.5	316.4	288.4	254.8	288.4	226.2	195	151.6	236.7	185.7	120.5	67.53	35.36	0	33.77	65.18	316.4	110.9
24	944	440.1	472.5	439.9	438.1	409.5	377.9	346.3	378.8	403.2	314.8	282.6	254.6	221	254.6	192.5	161.3	117.8	206.7	219.5	154.3	101.3	69.13	33.77	0	31.41	282.6	77.08
25	952	408.7	441.1	408.5	406.6	378.1	346.5	314.9	347.4	371.8	283.3	251.2	223.2	189.6	223.2	161	129.9	86.43	175.3	226.2	185.7	132.7	100.5	65.18	31.41	0	251.2	45.67
26	818	213.5	245.9	213.3	211.5	182.9	151.4	119.8	152.3	176.6	88.17	56.06	28.03	61.66	28.03	90.19	121.4	164.8	166.8	217.8	283	336	351.8	316.4	282.6	251.2	0	205.6
27	900	363	395.4	362.8	361	332.4	300.9	269.3	301.8	326.1	237.7	205.6	177.5	143.9	177.5	115.4	84.18	40.76	129.6	180.6	231.4	178.4	146.2	110.9	77.08	45.67	205.6	0

Matrix 1: Path design matrix; matrix 2: Time cost matrix

Path design matrix: path that takes the shortest time are given in this matrix 1.

Time cost matrix: how much time it takes of the corresponding path in matrix 1 are listed.

Based on our work mentioned above, all the best route of each mobile unit on every floor can be calculated. Meanwhile, the corresponding time can also be got. However, in reality, a visitor can only successfully evacuate from the building through stairways that is connected to a couple of specific halls. Therefore, we filter the calculation results, other paths are eliminated except those that end with a hall connected to a stairway. In this way, we have gained the shortest time, and the corresponding evacuation path.

Table.9. Part of the Shortest Path of the 2nd floor.

Mobile Unit	Shortest Time Cost(s)	Adjacent Stairs	Corresponding Downstairs
864	62.15	855	557
843	69.29	800	500
836	36.68	800	500
…	…	…	…

1.6. Moving Time Between Floors

Given that not all floors are connected to the gates, visitors may need to move between floors more than once to reach the escape gate and it will take more time to go down the stairs. The calculation process are as follows:

The outdoor height of the Louvre is about 28 meters, the wall thickness is about 0.6 meters, and the dome is about 3m. So, the indoor net height of the Louvre is $28 - 3 - 0.6 \times 3 = 23.2\text{m}$

Besides, there are three floors above the ground, so that the average net height of each floor is about 23.2/3 = 7.7 meters. As we all known, it's obvious that the height of each stairs is equal to the average net height of each floor, so the height of each stair is 7.7 meters. Because the indoor stair inclination is optimally 20° to 45° and there is no access for us to know the stair inclination of the Louvre, so we just assume that the inclination is 30°, so the length of the inclined plane is 7.7/sin (30°) = 15.4m.

From the following chart, which is obtained from the reference7, we can know that while evacuating, the speed of the visitors is between 0.82-1.12m/s. Neglecting the negative effects of some extreme situations, we define the moving velocity of the crowd as 0.97 m/s.

Table.10. Personnel Movement Parameters in Different Situations.

Mobile Mode	Velocity (m/s)
Evacuation Horizontal Movement	1.1-1.467
Evacuation Staircase Movement	0.82-1.12

Therefore, the time that moving across a single stairway cost is 15.4/0.97=16.0s.

1.7. Leaving Gate Time

The leaving gate time represents the time that costs when a visitor go through the evacuating gates of the Louvre, which is the last step of the whole evacuation process. According to our assumption 8, there are four available exits.

Since visitors can directly leave the building through the Lion Gate and the Arch Gate on the ground floor of the Syrian Gallery, we define that the leaving gate time of these two exits is 0 s.

For hall NO.424, hall NO.312 and hall NO.388, visitors can leave the Louvre directly. Therefore, using the Floyd algorithm mentioned above, we can know the visitors that can directly leave the building.

For visitors in other halls, they can only leave the Louvre by moving to the lower ground floor. According to the principle of the shortest time, those visitors will go through hall NO.100, hall NO.170 and hall NO.131. These visitors will convergence at the Napoleon Hall and leave the Louvre through the subway station and pyramid exit.

There will be an obvious confluence effect for visitors who move from the lower ground floor to the Napoleon Hall. For the visitors in the lower ground floor, except for those who leave the Louvre moving through hall NO.424, NO.312, NO.338, all the rest of people will gather at the Napoleon Hall to leave the museum. The hall numbers are:

Hall Number	160	169	164	183	181	180	179	170
Visitor Density	0.26	1.2	0.26	1.2	0.26	0.26	0.26	1.2
Grid Number	8	7	4	6	7	4	4	7.5

Base on the characteristic model of exhibition halls, we know the following information of the

Hall Number	174	173	130	132	102	105	100
Visitor Density	0.26	0.26	0.26	0.26	1.2	0.26	0.26
Grid Number	4.5	2	8	12	10.5	8	2

Napoleon Hall:

Table.11. Characteristics of the Napoleon Hall.

Hall Number	Exit	Corridor	Stairway
Grid Number	27	11	52

While evacuating from the pyramid Exit, the visitor density is:

$$\rho = \frac{\sum_{n=100}^{183} g(n) \times \rho(n)}{g(NH)} = 1.03 \quad (4)$$

Based on *Formula-3*, we can calculate the corresponding velocity which is 1.545 m/s. Observing the floor plan of the characteristic model of exhibition halls, we can get the effective length of the stairway on the Napoleon Floor is about 60 meters. Therefore, the time that visitors on this floor spend to leave the Louvre through pyramid exit is 60/1.545=38.83s

According to the assumption 10, the spiral stair's length is twice as much as normal stairways, so that the time spent on passing the spiral stairway is twice as much as normal ones, that is 32s. Therefore, visitors who choose to leave the Louvre through the pyramid entrance will totally spend 38.83+32=70.83s.

When visitors choose to leave the Louvre by Subway Station Exit, the visitor density will be:

$$\rho = \frac{\sum_{n=100}^{183} g(n)\times\rho(n)}{g(NH)+g(CR)+g(PE)} = 0.6 \quad (5)$$

With the help of *Formula-3*, we can obtain the corresponding velocity: 1.63m/s. Observing the floor plan in the characteristic model of exhibition halls, we know the effective length from the stairways to the entrance is about 140 meters. Therefore, visitors who use Subway Station Exit will totally spend 140/1.63=85.91s.

Therefore. we can get those movement date for those people who leave the Louvre through the Subway Station Exit and the pyramid exit and the date as follows:

Table.12. Evacuation Information of the Subway Station and Pyramid Entrance.

	Visitor Density (㎡/person)	Velocity (m/s)	Effective Length(m)	Effective Time of Evacuation	Time Spent on Stairways	Leaving Exit Time
Pyramid Exit	1.03	1.545	60	38.83	32	70.83
Subway Station Exit	0.6	1.63	140	85.91	0	85.91

We can know from the chart above that: while evacuating from the Napoleon Hall, the path towards the pyramid exit is shorter but more crowded, thus people move more slowly. Whereas the path towards the subway station is longer but less crowded, thus people move more quickly. Such difference is reasonable in reality.

The values of those two leaving time for these two paths are quite close (70.83s&85.91s), to simplify our calculation, we use both of their average value 78.37s.

Based on the characteristic model of exhibition halls and the graphic theoretic model, we can integrate the basic model in this paper which can solve the evacuation program and calculate the total evacuation time.

In this way, we have gained the shortest time, and the corresponding evacuation path:

Table.13. Total Evacuation Time of Each Exhibition Hall of the 2nd Floor.

2F	Hall Number	864	843	836	845	…	952	818	900	803	924
	Evacuation Time	251.7s	308.7s	276.2s	249.7s	…	205.3s	154.4s	79.07s	252.7s	125.6s

Table.14. Matching Table 1.

2F	Hall Number	864	843	836	845	…	952	818	900	811	936
	Target Hall	855	800	800	855	…	931	835	900	835	931

Table.15. Matching Table 2.

2F	1F	GF	LGF
	535	200	102
855	557	218	102
…	…	…	…
800	500	-	

The least time is shown in Matching Table 1 moving within a floor, and the corresponding relationship between the exhibition halls connected by stairs are listed in Matching Table 2. To utilize those two tables, there are 3 steps:

Find the position of the original hall (NO.1) and its best path matching to the hall (NO.2) in the below in Matching Table 1

Find the position of the target hall (NO.2) matching the original hall (NO.3) in Matching Table 2

Find the position of the hall (NO.3) found in table 2 in Matching Table 1 again.

Then, repeating the step 2 and 3 until arriving at one of the exits.

We can know from the following table: *Total Evacuation Time of Each Exhibition Hall* that the slowest visitor is the one in hall 843, who totally spends 308.7s. Since the evacuation time of the Louvre should be the time when the last person successfully leaves the building. Therefore, generally the evacuation time of the Louvre is 308.7s.

2. Improved model

With the basic model mentioned above, we are able to describe the evacuation process and evaluate it. Because our work is based on the assumption of a huge fire, Thus the available safe egress time(ASET) of the fire can be applied to our model. The average area of a single exhibition hall is about 702.8 square meters, and the dangerous height of the smoke is 2 meters[12]. So the ASET of the Louvre can be got :

$$\mathrm{ASET} = \frac{702.8 \times 2}{2} = 702.8s \tag{6}$$

In order to make our model more flexible and more widely suitable, we establish the improved model .

We employ AHP model to calculate all values.

Situation Y_0: There are three factors that can account for the influences: the percentage of the disabled or special people (PD), the degree of physical strength (PS) and the panic level (PL).

We employ 1-9 scale in the pairwise comparison matrixes to assess the influences of these three factors. It is easy for us to know that the influences of PS are bigger than the influences of PD and the influences of PL are bigger than the influences of PS. So, the pairwise comparison matrix can be shown as follows:

$$\begin{bmatrix} 1 & \frac{1}{4} & \frac{1}{8} \\ 4 & 1 & \frac{1}{2} \\ 8 & 2 & 1 \end{bmatrix}$$

With the eig () function in MATLAB function library, we obtain the characteristic value and the feature vector of the pairwise comparation matrix, which is shown as follows:

$$\mathrm{w} = [0.077 \;\; 0.308 \;\; 0.615] \;\; \lambda = 3 \tag{7}$$

In addition, we use consistency indicators to test the matrix. When the test fails, it is required to make a new paired comparison or to modify the existing paired comparison matrix.

$$\mathrm{CI} = \frac{(\lambda - \mathrm{n})}{(\mathrm{n} - 1)} = 0 \tag{8}$$

The parameter n is the matrix order, which is 3 and the corresponding random consistency index RI = 0.58, CI < RI thus the result in can serve as the weight vector.

In the basic model, we assume that the visitors are all healthy and full of energy and the panic level is medium. This situation is named as situationY_0. For the improved model, we aim at these two situations and regard them as special situations :

Situation Y_1 : The Louvre has a large number of disabled people who need to be evacuated;

Situation Y_2 : The Louvre has a large number of old people who need to be evacuated;

We set up pairwise comparison matriex for each of these situations and the calculation process is the same as the basic model Y_0.

Situation Y_1: Since the disabled move slower than physically health people, thus their presence will render slow down the evacuation speed of the whole group slower.

When there are more disabled people than normal, their PS will decrease a fraction and their PC will increase. We make comparisions between Y_0 and Y_1 :

$$B1(\mathrm{PC}) = \begin{bmatrix} 1 & \frac{1}{9} \\ 9 & 1 \end{bmatrix} \qquad B2(PS) = \begin{bmatrix} 1 & \frac{1}{2} \\ 2 & 1 \end{bmatrix} \qquad B3(PD) = \begin{bmatrix} 1 & \frac{1}{2} \\ 2 & 1 \end{bmatrix}$$

B1 means the ratio of PC in Situation 1 to that in normal situations is 9:1 , and the results are shown below.

We can know from the TABLE 15. that all the CI_ks can pass the consistency indicators test. The combination weight of the Situation Y_1 is 0.68771. And the combination weight of the basic model is 0.31229.Therefore, the delay coefficient of Situation Y_1 is: 0.68771/0.31229=2.2

Situation Y_2: When there are more old people than normal, their PS will decrease whereas the PC remains a relatively stable standard, their PL increase a fraction. We make comparisions between Y_0 and Y_2 :

$$B1(\mathrm{PC}) = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \qquad B2(PS) = \begin{bmatrix} 1 & \frac{1}{9} \\ 9 & 1 \end{bmatrix} \qquad B3(PD) = \begin{bmatrix} 1 & \frac{1}{2} \\ 2 & 1 \end{bmatrix}$$

B2 means that the ratio of PS in Situation 2 to that in normal circumstances is 9:1 , the calcuation results are shown below.

We can know from the TABLE 15. that all the CI_ks can pass the consistency indicators test. The combination weight of the Situation Y_2 is 0.72775. And the combination weight of the basic model is 0.27225. Therefore, the delay coefficient of Situation Y_2 is: 0.72775/0.27225=2.67.

Table.16. Weight Vector Result of Situation 1, Situation 2.

k	1	1	2	2	3	3
w_k	0.1	0.5	0.33	0.1	0.33	0.33
	0.9	0.5	0.67	0.9	0.67	0.67
λ_k	2	2	2	2	2	2
CI_k	0	0	0	0	0	0

The delay coefficients k of the three situations are :

	Situation 1	Situation 2	Normal Situation
Delay Cefficient	2.2	2.67	1
The Shortest Evacuation Time(s)	319.5	263.2	702.8

The meaning of the relative relationship between the velocity of tourists under special situations and that under normal circumstances is obtained by weighting calculation. Since the delay coefficient is the ratio of the combination weight under special situations to that under normal circumstances, its reciprocal is also the ratio of the speed of tourists under special circumstances to that under normal circumstances. In special cases, the effective length of the traveler's path remains unchanged, so the delay coefficient is the ratio of the shortest evacuation time in special cases to the shortest evacuation time in normal conditions. the time is :$\mathrm{T}_a = \mathrm{t}_a \times \mathrm{k}$ when in the three cases,

The ASET is 702.8s, thus the shortest evacuation time of these three situation is:

Situation 1 Y_1 /Situation 2 Y_2	702.8/k=319.5s/702.8/k=263.2s

The exhibition halls with unsatisfactory condition one does not exist, that is, the proportion of the disabled among visitors to the Louvre will not affect the safe evacuation of other visitors in the Louvre.

Under the second situation, in case of emergency, PS visitors are visiting the above hall, they will not be able to evacuate safely. In order to solve this problem, it can be seen from the observation that these halls are concentrated on the second floor of Rechelieu hall, and the museum leaders should be considered to set up special passage for the elderly in Rechelieu hall, or to add simple stairs under emergency situations in these halls.

The exhibition halls that are not satisfied with the second situation are as follows :

Exhibition Halls	843	836	801	564
Evacuation Time(s)	308.7	276.1	263.8	279.5

3. Conclusion

Based on the escape route in our model, the total evacuation time of the Louvre is 308.7s when the disabled are not considered and the panic level is medium. The ASET of the Louvre is 702.8s, all visitors can escape safely. When these special circumstances are taken into consideration, successful evacuation can still be accomplished.

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