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Building Evacuation Time Optimization Using Constraint-Based Design Approach

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ABSTRACT

The number of large public buildings is growing rapidly in function and complexity, which cause the evacuation path in case of fire to be too long and complex increasing the evacuation time. In this paper, a constraint-based design approach is introduced to automatically generate the optimal position of the building evacuation door to minimize the length of the escape route, thus reducing the evacuation time. The position of the evacuation doors is ruled by design specifications and building structures, in this study, a constraint-based model which includes space constraints and design constraints is proposed to generate the optimal door positions which minimize evacuation distance. The optimal combinations of the evacuation doors positions are obtained with the branch and bound algorithm in the model. Compared with the existing work, this approach avoids repeated modification of the design drawings and has significantly reduced the evacuation time by automatically generating optimal door positions. In this paper, two different size case studies from two museums are analyzed to explain the performance of the proposed method. The results indicate that the evacuation door layout generated by our approach outperforms the original layout.

KEYWORDS

Building evacuation performance; constraint-based design; architectural design; evacuation door optimization

1.Introduction

With the development of the economy and the progress of society, the number of large-scale public buildings has increased significantly, there is a large amount of people gathering in the large public buildings such as museums, shopping malls, stadiums and metro stations (Lo et al., 2008; XIE et al., 2017). Most of these large-scale buildings have multiple function and large room capacity that cause the evacuation path is too long and complex and delay the evacuation time(Ran et al., 2014). Building code demonstrates the guideline for designing evacuation facility, however the main consideration of the code is to meet the basic requirement of safety instead of minimizing evacuation time. For example, according to Chinese fire code GB50016-2014, the distance from any point in the building to the exit should not exceed 15m (Ministry of Public Security of the People's Republic of China, 2014). This kind of rules just specify design constraints, but the evacuation performance of the constraints is not demonstrated in the regulations. The designers just need to follow the guidelines to design in a step-by-step manner, regardless of evacuation efficiency. Prescriptive fire code is a summary of historical experience, however, with the diversification of building functions, architectural design, rules are not always synchronized with recent building requirement. Thus, performance-based design method has received much attention.

Several approaches are proposed to evaluate the evacuation performance of the floor plan design(Kallianiotis and Kaliampakos, 2016). Khaled presented a model to evaluate the level of service in corridors and perform quickly checks on the corridor plan in the early design stage(Nassar, 2010). Ma combined a pedestrian space analysis model with an agent-based pedestrian model on Geographic Information System (GIS) based platform to automatically evaluate occupant’s movement with computer aided design(Ma et al., 2013). Some simulation software such as SIMULEX and EXODUS are developed to identify bottlenecks and weaknesses in the space and estimate the evacuation time for performance evaluation purpose.(Tserng et al., 2012).

Evacuation evaluation tools are commonly based on pedestrian behavior models which are used to improve the building layout and evacuation strategies. In this context, two main approaches have been used including: descriptive models and optimization models. Descriptive models focus on developing mathematic models to describe human behavior, individual characteristics, external environment and interactions among evacuees which influences movement. Yue proposed a pedestrian evacuation model to simulate evacuation with asymmetrical exits layout. This model contains an exit selection strategy which considers actual movement distance and imaginary waiting distance, it can be used in early design phase (Yue et al., 2011). Liao proposed a modified cellular automaton model to study the exit layout influence on evacuation efficiency, he found that different exits layouts produce different flow distributions which influences the ability of pedestrians to pass through the exits(Liao et al., 2014). Wu applied snowdrift game theory to pedestrian escape model to investigate the effect of egress time to different position of doors, he divided evacuees into three parts with different directions which fits human intuitive reaction. Based on model simulation, he found the best location of a door in a single room(Wu et al., 2015). Alizadeh takes various parameters (human psychology, placement of the doors, doors width, position of the obstacles) in a dynamic cellular automaton (CA) model to investigate how these parameters affect the evacuation time(Alizadeh, 2011). Wu et al. developed a route choice model integrating a voice warning system in large indoor spaces, their model can accurately simulate the stadium evacuation process(Wu et al., 2018).

Descriptive models can present realistic pedestrian movement and evacuation capabilities in pre-defined building plans considering various conditions. They can identify building layout shortcomings that may cause congestion or confusion. Nonetheless, they can't provide optimal solution for facility design, such as optimizing the layout to reduce evacuation time or congestion. Thus, optimization models are widely developed to deal with specific problem in evacuation process. By far, a large part of research efforts has been paid into route choosing and evacuee assignment, namely evacuation scheme. Chen and Feng proposed a fast flow control algorithm to assign evacuees to different doors by calculating minimum evacuation time(Chen and Feng, 2009). Kang proposed an integer programming model to assign multiple exits to different evacuees to minimize evacuation time in a complex building considering the congestion phenomenon at each exit(Kang et al., 2015). Heuristic algorithms have also been used to solve the evacuation route optimization problem. Abdelghany developed a modeling framework integrated genetic algorithm (GA) and a simulation model, GA is used for generating optimal evacuation plan for an exhibition hall with the guidance of plan evaluating by simulation model(Abdelghany et al., 2014). Liu and Zhang proposed an improved quantum ant colony algorithm to find an efficient evacuation plan from hazard zone to safety zone. Their approach can generate evacuation paths from multiple source nodes to multiple destinations(Liu et al., 2016).

In addition to the evacuation plan, the space layout also has a great influence on building evacuation. The location of the door is one of the critical elements that can influence the evacuation time (Kang et al., 2015). Optimizing position of doors to reduce evacuation time is a common issue faced in evacuation analysis. To date, considerable researches have been conducted to reduce evacuation time by changing position of evacuation doors. Tavares used simulation software to run 950 cases to discover which door position can minimize the egress time and he found the best solution to set two exits of equal size in a square room(Tavares, 2009). Heba developed a simulation model to compare evacuation time of four exit arrangement strategies (exits on one side, exits on adjacent sides, exits on opposite sides, and exits on all sides)(Kurdi et al., 2018). Li put in shortest-path and following-up behavior to his pedestrian evacuation model to find out the weakness of the floor plan and improved the evacuation efficiency by changing the exit location in a supermarket(Yue et al., 2011). Xie conducted a two-stage nested Monte Carlo simulation on a simple single room and found the optimal distance between exits with minimum evacuation time(Xie et al., 2016). These above-mentioned researches are aiming at changing the exit location to reduce the evacuation time. These methods are commonly using an evacuation simulation model to test various placements of the evacuation doors to find where the better door positions are. The simulation models can evaluate evacuation efficiency of different layout, but the designers can’t obtain the optimal evacuation design directly, they need to manual modify their floor plan and redo simulation until they obtain ideal solution. The revision process is time-consuming when facing buildings with complex layout and mainly depends on designer’s experience. Some optimization methods have also been developed to deal with the door position issue. Xie and Wang proposed optimization using genetic algorithm(GA) to solve the object function of evacuation time, it can search the best door location in a single room to minimize evacuation time considering occupant density(Xie et al., 2018). Kallianiotis and Kaliampakos adopt Pareto optimal solution to evaluate performance of all possible combination of exits location while considering compliance to exit design specification(Kallianiotis and Kaliampakos, 2016b). The existing methods focused on changing the last exits of a room to improve evacuation efficiency. However, when facing large-scale buildings with multiple rooms, the evacuation route will be connected by many doors in different, every door will have a significant impact on evacuation, every door location should be taken into consideration.

This paper deals the evacuation problem by establishing a constraint model that link the relative positions of all doors in the building in order to minimize the total evacuation length. The approach will generate the position of the doors and at the same time meets the design specifications. Comparatively to simulation-based approaches, approach in this paper avoids repeated modification of the design drawings and directly obtain the optimal evacuation door positions while keeping the building structure unchanged. The work flow of our method is shown in **Figure 1.**

The rest of this paper is organized as follows. In **Section 2**, we define the evacuation door design problem and then introduce the knowledge model and the algorithm for finding optimal solution. The application of the developed model to generate the optimal evacuation door for two real museums is presented in **Section 3**.

The discussion of the results is presented in **Section 4**. Finally, we make conclusions in **Section 5.**

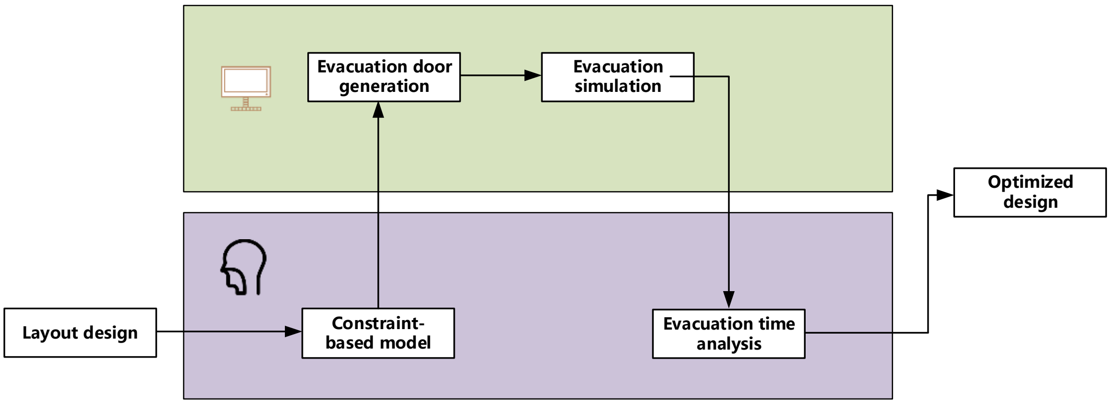

Figure 1. Constraint-based design approach of evacuation time optimization

2 Model development

2.1 Evacuation network and object function

The evacuation problem can be defined as a network with certain constraints. Building evacuation network is represented as a directed graph G = (N, A). Node represents gathering places of pedestrians such as rooms, corridors, doors, stairs and safety areas. Arc represents evacuation path between nodes. Generally, rooms are the starting nodes of evacuation, outdoor safety zones are the end nodes. The location of the door is fixed in many previous studies, but in our design problem, we select the evacuation door positions as movable points that can influence the distance of evacuation path. Every path has its length， the aim of this paper is to find the optimal door positions to minimize the length of all evacuation paths. Thus, in this study, we choose the doors as the nodes of the evacuation network.

The evacuation network in this paper is different from previous studies. For example, in the evacuation path selection problem, the architectural design has been completed and the layout of the building will not change, so the coordinates of all nodes in the network are constant value. However, in this paper, we are solving the door location problem of layout design phase, the coordinate of the evacuation door is a variable. There are two types of nodes P_i and D_i, P_i represents people gathering space, it is the starting point of the crowd, the coordinate of P_i is constant. D_i represents the position of the different doors, which is a decision variable in this study.

Following are definitions of some variable and parameters:

G (V, E) – evacuation network of the space.

L_{ij} – the length of the arc between node i and node j.

TP_i – the length of the evacuation path i.

P_i – evacuation reference point in the space (x_i, y_i).

D_i – coordinates of the location of door (X_i, Y_i).

O_i – the source node of path i.

E_i – the end node of path i.

Where L_{ij} has three kinds of representations:

When the arc length L_{ij} is composed of the evacuation reference point P_i and the evacuation door D_j:

$$L_{ij} = ((X_i - x_j)^2 + (Y_i - y_j)^2)^{\frac{1}{2}} \tag{1}$$

When the arc length L_{ij} is composed of the evacuation reference point P_i and evacuation reference point P_j:

$$L_{ij} = ((x_i - x_j)^2 + (y_i - y_j)^2)^{\frac{1}{2}} \tag{2}$$

When the arc length L_{ij} is composed of the evacuation door D_i and the evacuation door D_j:

$$L_{ij} = ((X_i - X_j)^2 + (Y_i - Y_j)^2)^{\frac{1}{2}} \quad (3)$$

The length of each evacuation path is a sum of the lengths of arcs on the path:

$$TP_i = \sum_{O_i}^{E_i} L_{ij} \quad (4)$$

The object function in this paper is to minimize evacuation distance of every path:

$$minTP_i \quad (5)$$

2.2 Knowledge model

Our approach and its implementation is based on a constraint programming approach, which importantly reduces the inherent combinatorial complexity for practical path finding optimization problems. The knowledge model developed encompasses the object model and the constraint model.

2.2.1 Object model

The object model holds the main elements corresponding to spaces, doors and paths. Each element has been defined as a class characterized by a set of attributes.

The space class is characterized by an identifier, and a set i of reference points (x_i, y_i) representing each space. The coordinates of the reference points are integer constrained variables.

The door class is characterized by an identifier, a reference point (X_i, Y_i) (mid of the width), and a width W. Except the identifier, the variables are integer constrained variables. Each variable is represented by a domain of possible values such as $X_i \in [a, b]$, $Y_i = c$.

The path class is represented by an identifier and a set of points (X_i, Y_i) to (x_i, y_i), from which the path passes through. These points can be space reference points and door reference points.

2.2.2 The constraint model

The constraint model is developed to define the possible position of the doors, including space constraints and design constraints:

(a) Space constraints

First, the door location should meet space constraints, the approach of door location generation doesn't change the original structure of the building. The door need to be located on the wall, so the moving range of the door position is on the wall which the door belongs to. **Figure 2** Shows the space constraint of a room, the green line is the moving range of the door, the space can be represented by the graph. For example, in the case of path R1D1R2, we have created a constrained variable corresponding to the sum of distance (R1, D1) and distance (D1, R2). In this model, the door positions are represented by a domain of possible values (i.e. door D1 has a fixed x but can be located at any y position of the wall represented by the green horizontal line in **Figure 2**).

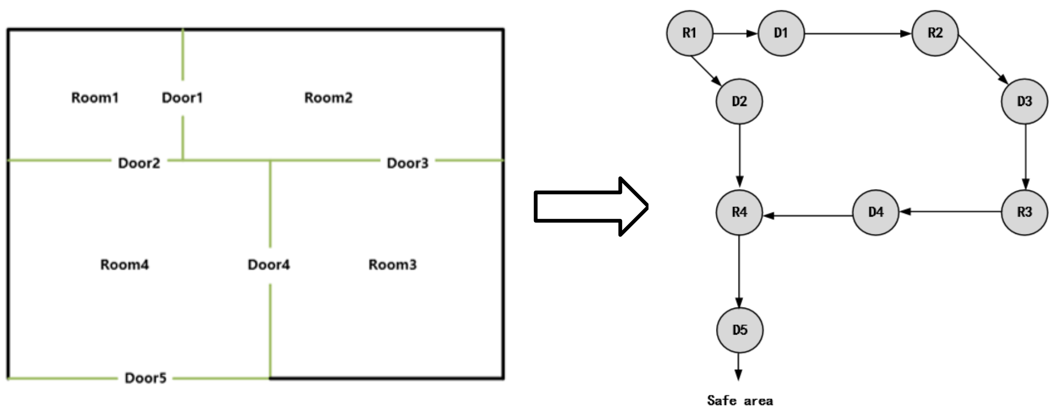

Figure2. Example of possible door location and graph representation (Space constraint)

(b) Design constraints:

The door location needs to meet design constraints because door location is restricted to some building specifications. Building specifications are not always the same in different countries, specifications have different security considerations. For example, Chinese regulation (Code for fire protection design of buildings, China,2014) doesn't include restricting the angle between farthest point and exit but Greek law (Greek Fire Brigade Headquarters, 1999) does. In order to ensure maximum evacuation safety, in this study the door location meets specifications of different countries at the same time.

2.3 Solution method

The problem involved in this research is moderate in scale, the solution time and space complexity are all within acceptable limits. Therefore, the branch and bound algorithm is adopted directly to obtain the optimal solution. The branch and bound algorithm is a solving technique widely used in various problems in operations research and combinatorial mathematics(Morrison et al., 2016). It is characterized by a shorter time to search for the optimal solution that satisfies the constraint. Usually, an objective function f(x) needs to be defined before the implementation of the branch and bound algorithm. In computer terminology, f(x) is often called a cost function, and the feasible domain composed of various constraints is recorded as a set S. All candidate solutions are included in the set S, and S is also regarded as the search space of the branch and bound algorithm. The branch and bound algorithm continuously divides the feasible search space S composed of constraints and solves the optimal objective function value in the shrinking value space. The pruning operation of the solution space S is called branch. For different branches, the function value of all feasible solutions of the branch is calculated by the exhaustive method. However, not all branches need to be exhaustive. In order to speed up the search efficiency in the branch and bound method, a limit function is designed. Once the optimal solution of the current subtree is found, it is not within the bound, for example, f(x) at the minimum value, if the minimum value of the subtree is greater than the minimum value that has been searched for, the subtree is deleted, and all subtrees under the subtree are no longer traversed. The tree structure of branch and bound algorithm is shown in **Figure 3.**

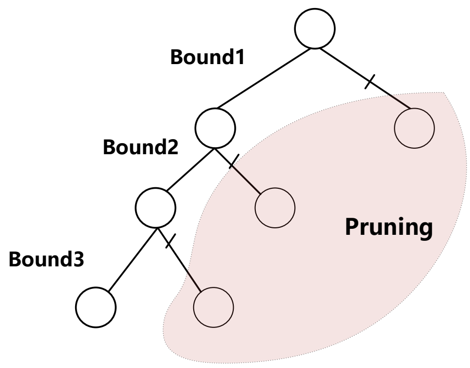

Figure 3. The tree structure of branch and bound algorithm

In this paper, our optimization approach consists in minimizing a cost function corresponding to the path distances. We have used Choco the Free Open-Source Java library dedicated to Constraint Programming to implement branch and bound method, it will lead to the determination of the global optimum (eventually global optima) of a path distance solution. First, we create a constrained variable representing the cost function and find an initial solution, and then we introduce a new constraint that the value of the cost variable must be better than in the initial solution. We repeatedly solve the new problem and tighten the constraint on the cost variable until the problem becomes insoluble: the last solution found is then the optimal solution. Thus, the optimal door locations which minimize the evacuation distance are generated by the algorithm.

3 Model application and validation

This study uses a constrained-based design method to generate the door locations of the building. Two existing buildings is selected to be prototype to explain the process of our model. The evacuation time simulation was performed on for both existing layout and the generated solution of new door positions to evaluate effect of proposed approach. **Figure 4** illustrate the workflow of approach proposed in this paper.

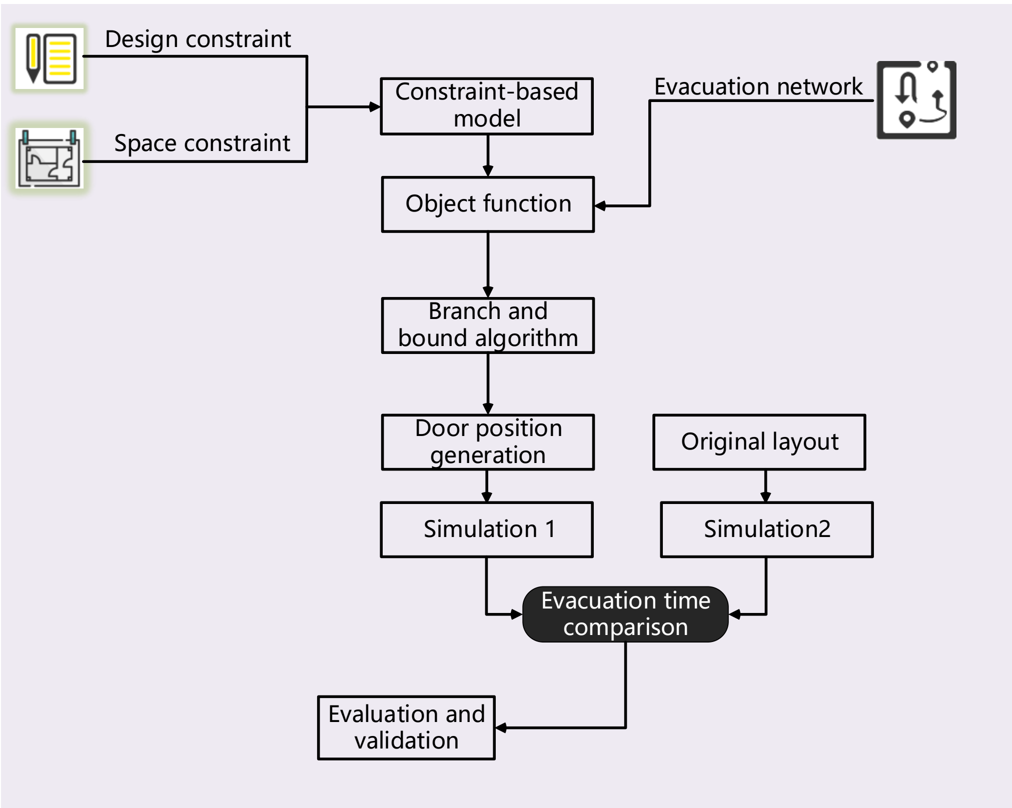

Figure 4. The framework of proposed method

3.1 Case study I

In this case, we have used one fire compartment of a Hubei Museum of Science and Technology in China as prototype. **Figure 5** indicates the existing evacuation routes of compartment in case of fire. This zone is about 30 meters long and 42 meters width, it has an area of 1625 square meters. Spaces are connected by corridors and doors, and two exits is connected to outside. When emergency occurs, people will choose different route to outside through these two exits. Pedestrians need to pass through too many doors and corridors when they reach the exit.

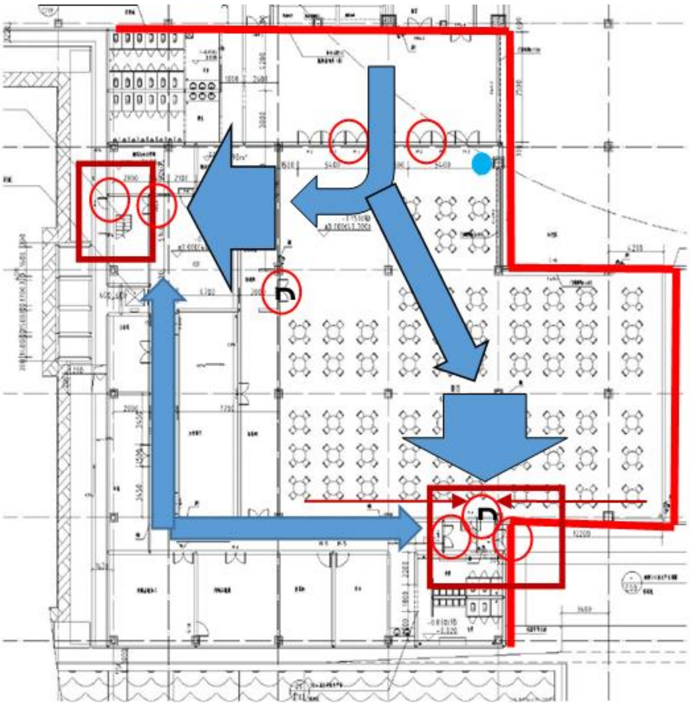

Figure 5. The existing evacuation pathway of the compartment(Author)

We have used a graph representation to mirror the evacuation routes where the filled circles represent the main spaces and the non-filled circles represent the doors. **Figure 6** illustrate the graph representation of the problem including space reference points, doors and different paths passing from space reference points to external doors leading to safe areas. The space point locations (from P1 to P8) indicate the most critical locations within each space and therefore represent the farthest positions to be taken into account in the case of fire and therefore an urgent evacuation.

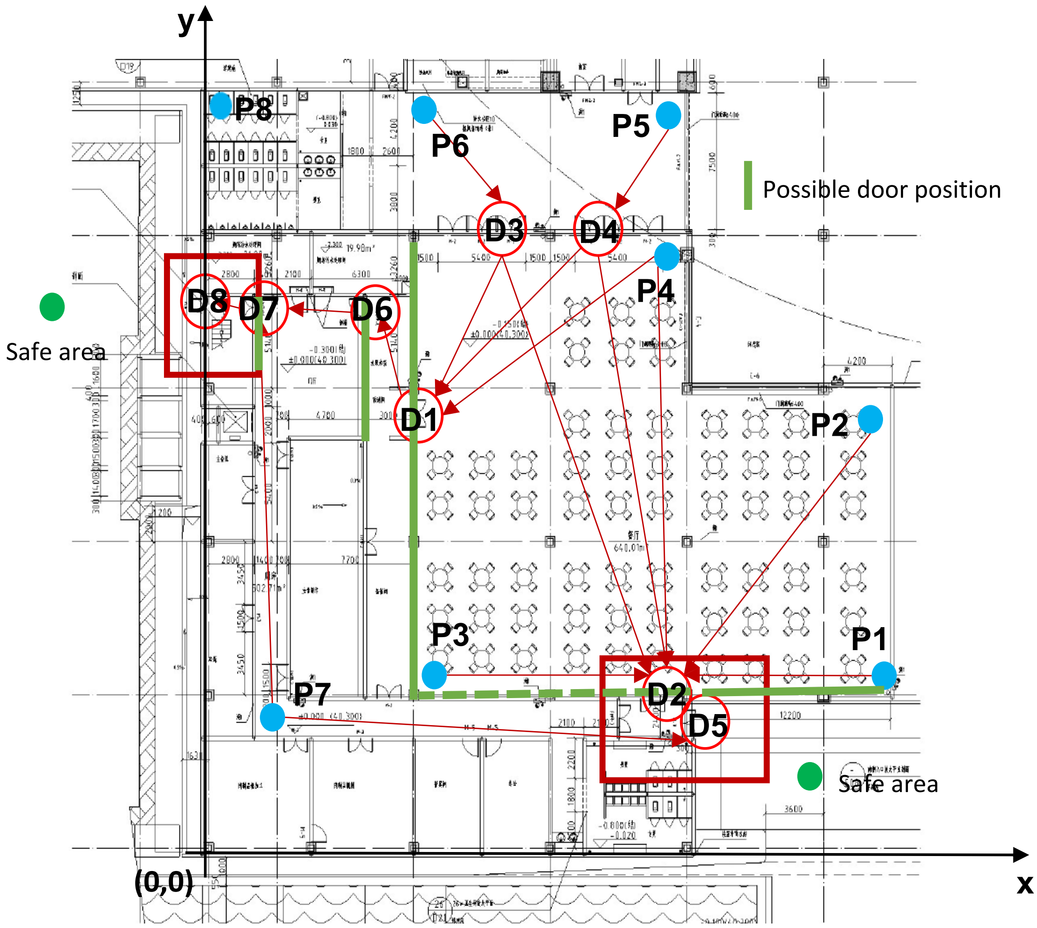

Figure 6. The graph representation of the evacuation path using constraint-based approach(Author)

Next, we have developed a constraint model including the main constraints characterising our problem, including:

(a) Design constraints:

As indicated in **Figure 7**. the angle between farthest point in space and two exits must be more than 45°. (Greek Fire Brigade Headquarters, 1999). For Example, the angle between **D2, D8 and P5** (See **Figure 6**.) must be more than 45°.

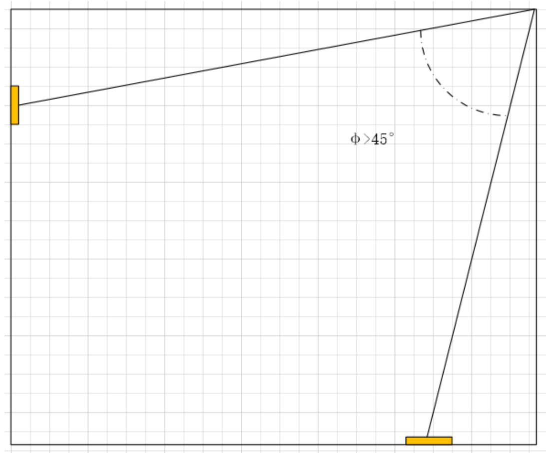

Figure 7. Angle between the Farthest point in the space(Author)

As indicated in **Figure 8**, the distance between the two safety exits must be greater than half the diagonal distance of the fire compartment (National Fire Protection Association, USA, 2009). For example, the distance between **D2, D8** must be greater than half the distance **between P1, P8** of the fire compartment (see **Figure 6**).

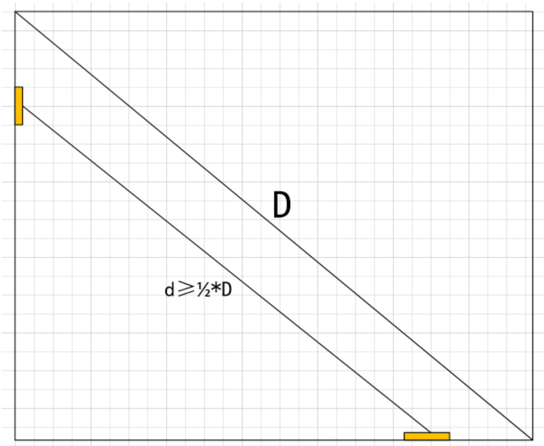

Figure 8. Distance between the two safety exits(Author)

Finally, as indicated in **Figure 9**, the farthest point in the room to the door should not be greater than 30m (Code for fire protection design of buildings, China,2014): distance (**P5, D8**) < 30 and distance (**P5, D2**) < 30(see **Figure 6**).

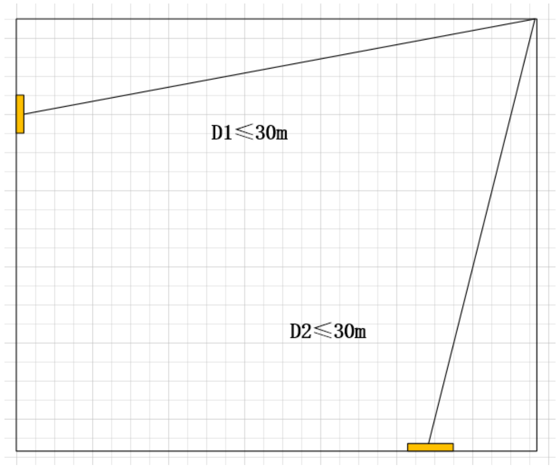

Figure 9. Distance between the farthest point and exits(Author)

(b) The space constraint:

In this case, the movement of D2 will affect the structure of the evacuation network. **Figure 10** illustrates the graph representation of the evacuation routes including the two options: option 1 and 2. Based on the position of D2, the evacuation path will take either configuration of option1 or configuration of option 2. Option 2 corresponds to D2 positioned in the external wall leading directly to the safe area, where option 1 corresponds to D2 leading to the corridor leading to D5. To model this configuration with two options using constraint-based design we have used a disjunctive constraint “or” with two options represented with a constraint variable VarOpt with a domain including two values VarOpt ∈ [option1, option2]. For example, in the case of the Path P2-safe area, the instantiation of VarOpt to option 1 will considers the path configuration including: P2, D2, D5, safe area. Where the instantiation of VarOpt to option 2 will consider the set: P2, D2, safe area.

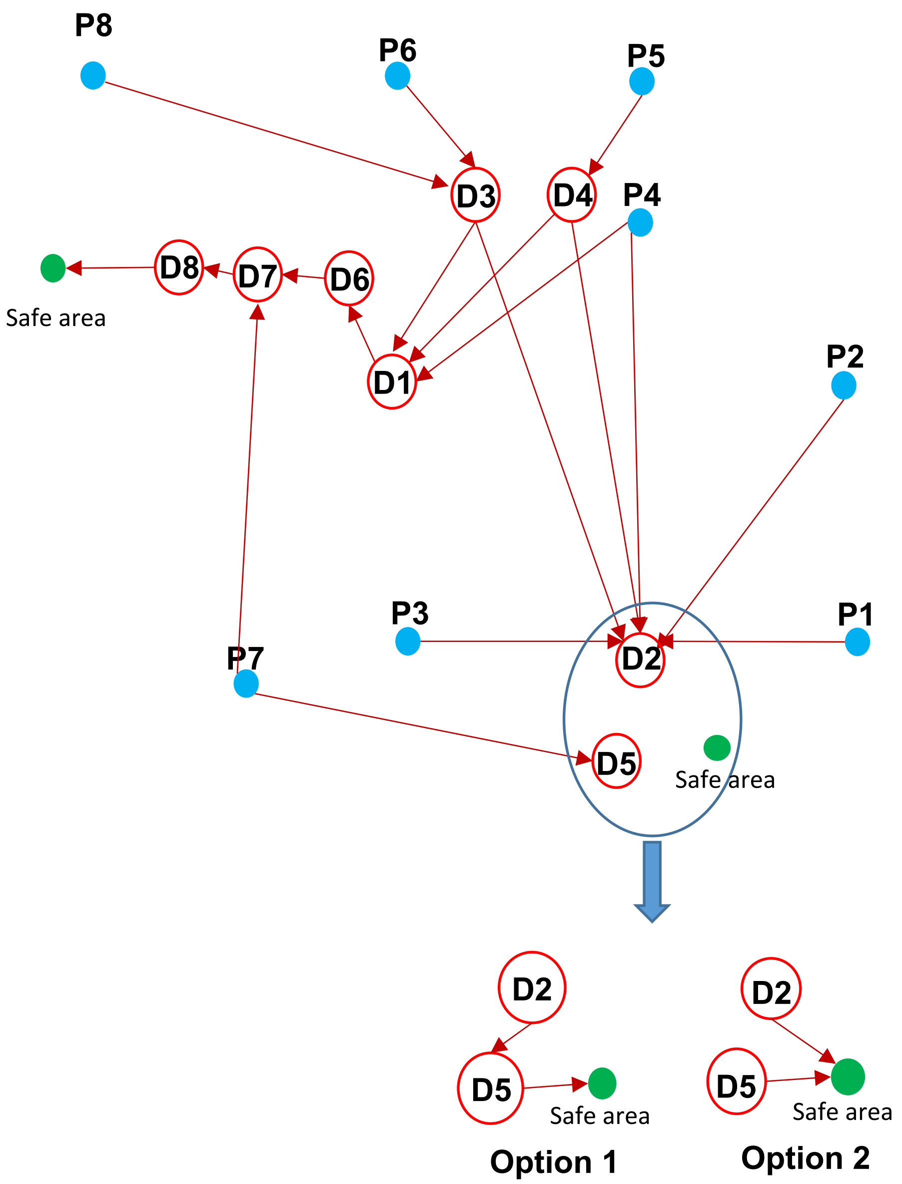

Figure 10. The graph representation of the evacuation path using constraint-based approach(Author)

Figure 11 illustrates the generated evacuation path minimising the distances from any point to the safe areas. The new door D1 and D2 positions generated by our approach are: D1: (0,29400) and D2 (29500,0).

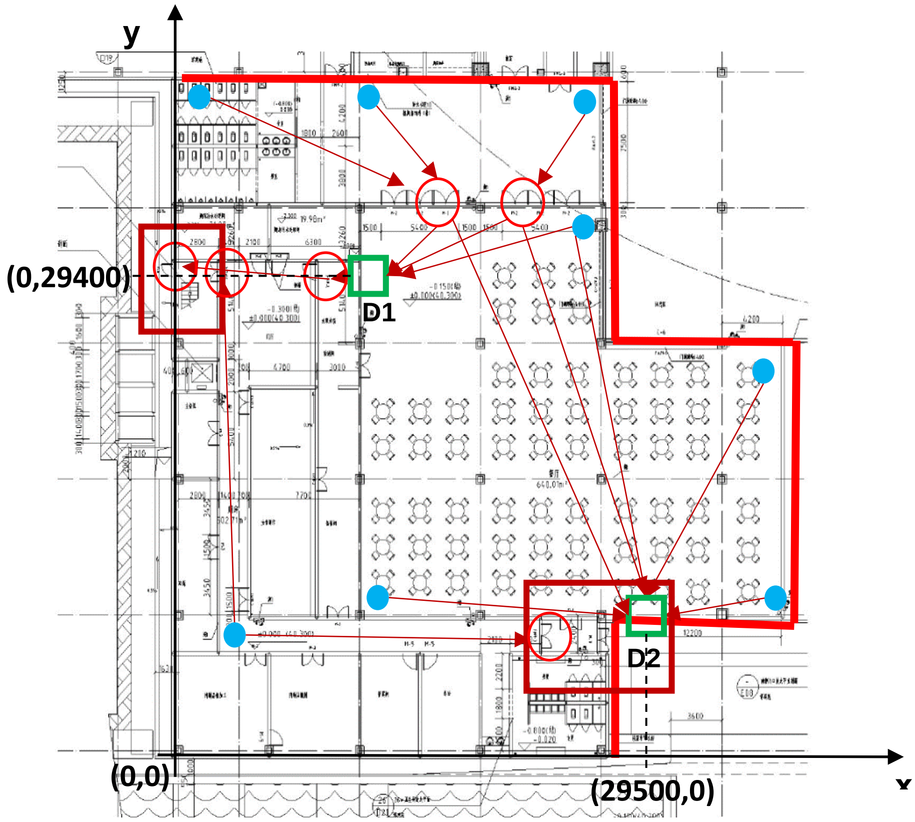

Figure 11. Generated solution with new door positions – option 2(Author)

3.2 Model validation-Case I

In this case, we have used "*AnyLogic*" the simulation modelling system to simulate the evacuation. "*AnyLogic*" is a commercial simulation modelling software, it is based on Social-force model. It can accurately simulate the interaction between the behaviour of the evacuees and the environment and present a realistic evacuation scenario.

We comprehensively considered the impact of different factors on the evacuation time, the simulation software includes some key parameters (occupant types, the velocity used, the total number of people). The speed of people will affect the time it takes to complete a path. The number of people determines the density per unit area which reflects the congestion in the room. People of different ages have different shoulder widths and back thicknesses, and the volume occupied in space will affect the number of people passing through the door per unit time. Next, we will initialize a set of basic parameters as a benchmark and then change these parameters of the people and repeat the experiment to validate whether the simulation results are stable.

At first, we set the initial parameters. We consider the characteristics of the museum's visitors and set three groups of visitors, we refer to the *"Simulex"* software handbook and choose different walking speed for people of different ages. The proportion, speed and body size of occupants are shown in **Table 1**. Then, we need to put pedestrian in the simulation model, according to Chinese fire code GB50016-2014, the average number of evacuees per safety evacuation gate should not exceed 250, so we set the pedestrian number to 500. Finally, we use these parameters in the simulation software and simulate the evacuation of the compartment. During the simulation, we will change these parameters to verify the performance of our approach.

As indicated in **Figure 12**, this is overall evacuation process of the original designed layout, the total evacuation time is 330 seconds, in this model we set 500 people in the museum.

Table 1. Basic setting of different occupants

Pedestrian type	Proportion	Average speed(m/s)	Body size (shoulder width m × back thickness m)
Child	30%	1.0	0.3×0.25
Adult	40%	1.2	0.4×0.3
Elderly	30%	0.8	0.5×0.25

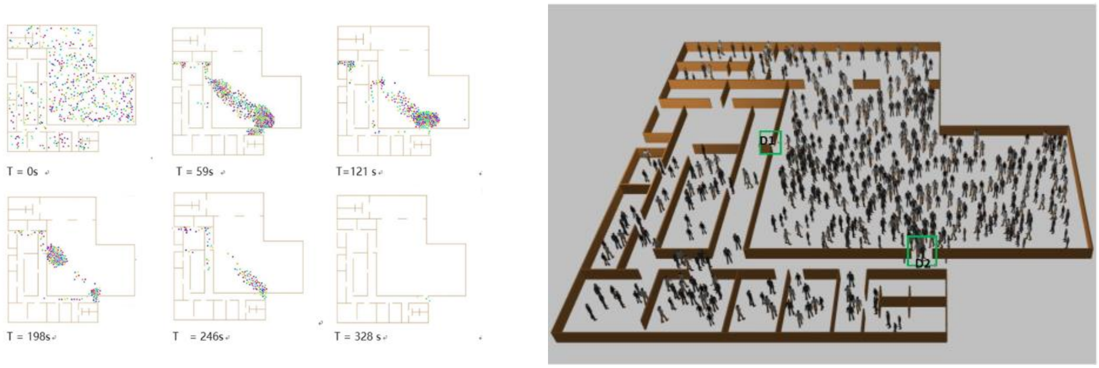

Figure 12. Evacuation simulation of original layout of the compartment(Author)

Next, we will use our generative approach mentioned in **Section 2** to generate new doors to minimize the evacuation route distances and then perform simulations to with the generated solution. In this simulation we keep the same parameters as in the previous one, the simulation process is shown in **Figure 13**, the result shows that the total time of evacuation amount is reduced to 263 seconds. This approach shows an improvement of the evacuation time by 67 seconds (about 20.3%)where in case of fire this time difference can be very important for the safety of the building users.

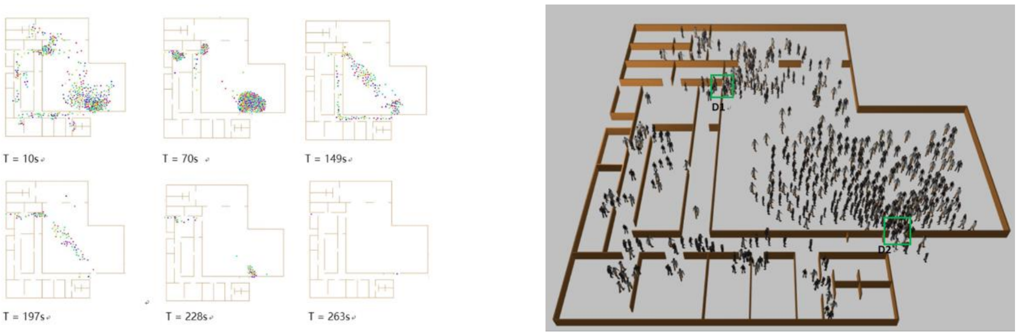

Figure 13 Evacuation simulation of the compartment as generated by our approach(Author)

As we mentioned in this section, for people of different ages, their movement speed and body type are different in an emergency, so the pedestrian composition and speed settings will affect the total time of evacuation. In addition, the number of people will also have an impact on the total time of evacuation. As the number of people increases, the congestion will intensify thus prolonging the total evacuation time. In order to further confirm if these parameters of people in the museum will affect the results, we will modify the parameters and conduct comparison experiments.

To confirm if the density of people in the museum will affect the results, the total number of people in the compartment will be changed in next simulation. We take one out of every 50 numbers from 100 to 500 as the total pedestrian number and keep the speed and occupant composition the same as in **Table 1**, then repeat evacuation simulations to compare original designed layout with our generated solution. **Figure 14** shows the evacuation time with different pedestrian amount, the reduction of evacuation time can be seen in **Table 2**, the result indicates that no matter how the total number of people changes, our solution with generating new doors outperforms the original designed one.

Table 2 Evacuation time(s) of original layout and generated solution with different pedestrian number(Author)

Pedestrian number	Original layout	Generated solution	Time difference	Percentage reduction
500	330	263	67	20.30%
450	301	240	61	20.27%
400	269	221	48	17.84%
350	267	216	51	19.10%
300	223	194	29	13.00%
250	180	162	18	10.00%
200	145	124	21	14.48%
150	136	119	17	12.50%
100	110	90	20	18.18%

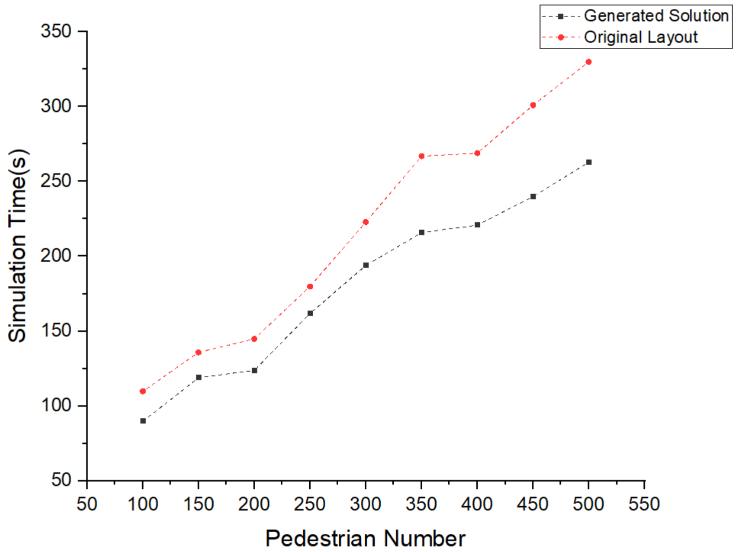

Figure 14 Evacuation time comparison between original layout and generated solution at different pedestrian number(Author)

We keep all the parameters the same as in **Table 1** except occupants' speed and type, we changed different pedestrian types as adults only and changed the speed of adults from 1.2m/s to 2m/s, then we conduct the simulation between the designed one and our solution. **Figure 15** show the evacuation time difference, after generating new doors, the total evacuation time have been changed from 252s to 203s, the time have been saved by 49s (19.3%). This outcome proves that even if the speed and occupant type have been changed, the evacuation efficiency of our new solution is still better than the original solution.

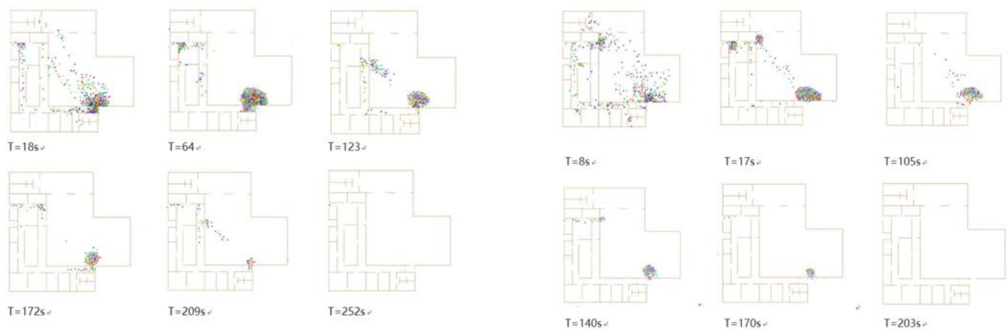

Figure 15 Evacuation simulation of original layout and generated solution (velocity = 2m/s, 500 people) (Author)

3.3 Case study II

The purpose of the Case study II is to validate the performance of our approach in an even larger space. We take a zone of a Chinese history museum as an example in this section, see **Figure 16**. This zone has a total area of approximately 3,500 square meters including historical museum halls, corridors and gardens. The total area of the three exhibition halls is about 2,600 square meters, exhibition halls are directly connected by fire doors and corridors. There are 3 safety exits (D10, D6, D12) in this area, people can reach safe area 1 and 2 through the corridors and exhibition halls in case of fire. There are 12 doors (from D1 to D12) and two safe areas (Safe area 1 and Safe area 2) in this zone, and points (from P1 to P5) represent each space.

The constraint model in this case also includes design constraints and space constraints. The orange-filled circles (P7, P6, P8) are added in **Figure 16** to represent the corners of this area. First, the angle between farthest point in space and two exits must be more than 45° (Greek Fire Brigade Headquarters, 1999). In this case, it means that the angle between D6(or D12), D10 and P6 must be more than 45°. Then, the distance between the two safety exits must be greater than half the diagonal distance of the fire compartment (National Fire Protection Association, USA, 2009). For example, the distance from D10 to D6 and D10 to D12 must be greater than half the distance between P8 and P7. It is worth mentioning that due to functional requirements, the vertical width of the plane has already exceeded the maximum evacuation distance required by the specification, so we didn't select the design rule about distance restrictions between the farthest point to the door as a constraint in this building.

Regarding space constraints, the only difference between this case and case I is that the movement of the doors in this case will not change the structure of the evacuation network, so we will not use disjunctive constraint which has been introduced in case Ⅰ.

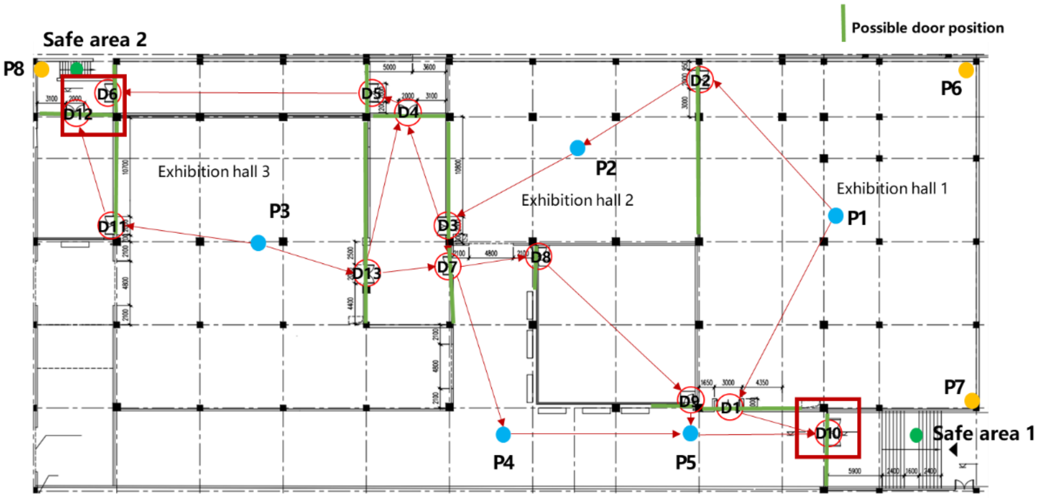

Figure 16. Original Layout and the graph representation of the evacuation path using constraint-based approach(Author)

When the constraint-based model has been established, we use branch and bound algorithm to obtain the optimal door locations which minimize the total distance of evacuation paths, the corresponding graph is shown in **Figure 17**. The new door positions generated by our method are as follows:

D1(83000,9000)	D2(72000,33000)	D3(45000,34000)
D4(36000,39000)	D5(36000,40000)	D6(9000,40000)
D7(45000,27000)	D8(54000,21000)	D9(67000,9000)
D11(90000,40000)	D12(90000,40000)	D13(36000,31000)

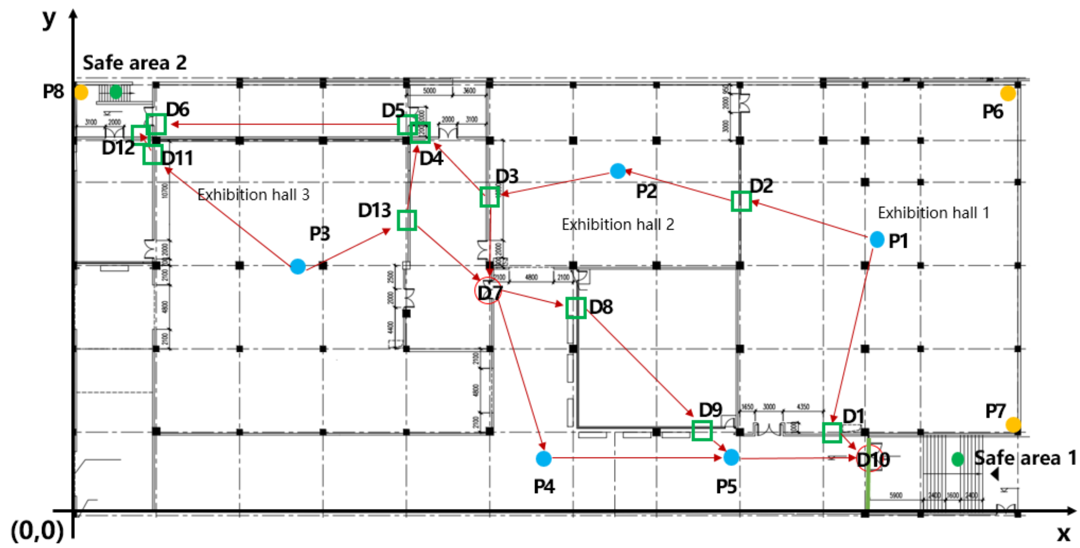

Figure 17. Generated solution and the graph representation of the evacuation path using constraint-based approach(Author)

3.4 Model validation-Case II

In this zone, there are more than two evacuation directions for each exhibition hall, people can select to reach one of two safety areas in case of fire. The main challenge of the building design is that the two safe exits to the outside between west and east are too far away. Once a route to a safe area is blocked by fire and smoke, the crowd will be evacuated to another safe area for a long distance. In the previous section we have generated the optimal evacuation door positions. In this section, we will test two scenarios: evacuation from safe area 1 and evacuation from safe area 2. The crowd needs to pass through the entire building to reach each safe area, if the evacuation time in both directions are shortened, then the evacuation effect of the building will be improved.

In this case, there are 3 exits directly to the safe area, according to Chinese fire code GB50016-2014, the average number of evacuees per safety evacuation door should not exceed 250, so we set the maximum pedestrian number to 750. We set the same initial parameters as case one, see Table 1. We take one out of every 50 numbers from 350 to 750 for simulation, the simulation scenario of two different layouts is shown in **Figure 18.** The evacuation time comparison results are shown in **Table 3** and **Figure 19**, the average reduction of evacuation time are 8%(to safe area 1) and 4.5%(to safe area 2). Then we change the occupant type as adult only and set speed at 1.2m/s and repeat the simulation, it has been reduced 11.8% (to safe area 1) and 5.4% (to safe area 2), the results are shown in **Table 4** and **Figure 20.**

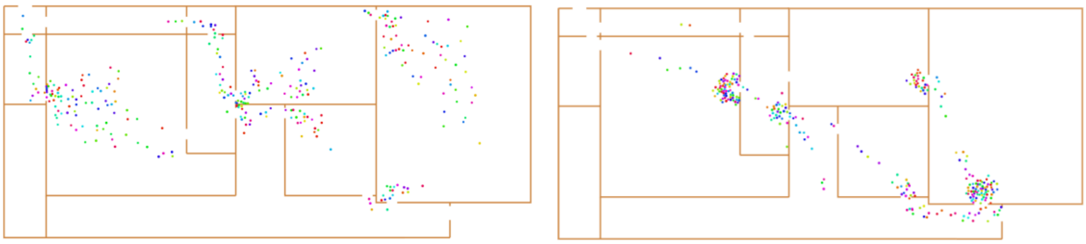

Figure18. Evacuation simulation of original layout(Left) and generated solution(Right) (Author)

Table 3. Evacuation time comparison when there are three types of people with different speeds(Author)

Pedestrian number	Original layout (safe area 1)	Generated solution (safe area 1)	Time difference	Percentage reduction	Original layout (safe area 2)	Generated solution (safe area 2)	Time difference	Percentage reduction
750	331	310	21	6.34%	397	363	34	8.56%
700	312	295	17	5.45%	345	325	20	5.80%
650	288	273	15	5.21%	341	313	28	8.21%
600	279	250	29	10.39%	304	291	13	4.28%
550	241	232	9	3.73%	291	284	7	2.41%
500	231	217	14	6.06%	254	247	7	2.76%
450	206	196	10	4.85%	239	218	21	8.79%
400	201	181	20	9.95%	222	210	12	5.41%
350	185	170	15	8.11%	194	198	-4	-2.06%
300	173	137	36	20.81%	181	180	1	0.55%

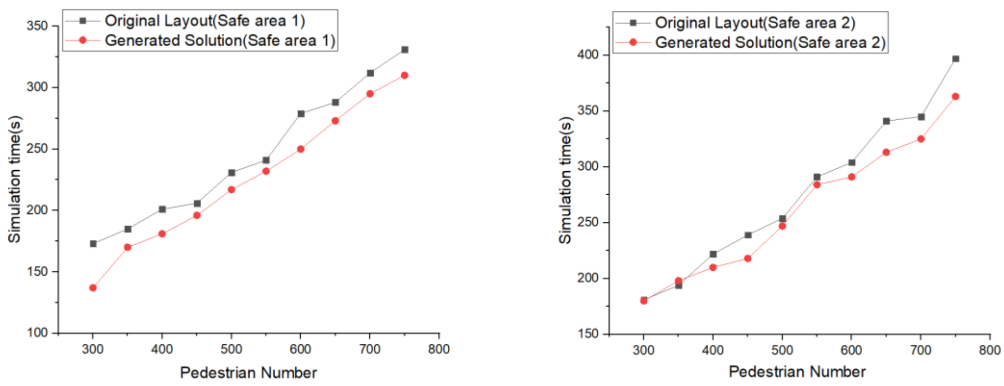

Figure 19. Evacuation time comparison when there are three types of people with different speeds(Author)

Table 4. Evacuation time comparison when there is one type of people with speed at 1.2m/s(Author)

Pedestrian number	Original layout (safe area 1)	Generated solution (safe area 1)	Time difference	Percentage reduction	Original layout (safe area 2)	Generated solution (safe area 2)	Time difference	Percentage reduction
750	339	302	37	10.91%	380	340	40	10.53%
700	321	275	46	14.33%	351	328	23	6.55%
650	290	265	25	8.62%	316	299	17	5.38%
600	273	244	29	10.62%	315	293	22	6.98%
550	255	223	32	12.55%	274	266	8	2.92%
500	237	210	27	11.39%	249	239	10	4.02%
450	208	184	24	11.54%	233	224	9	3.86%
400	190	164	26	13.68%	196	209	-13	-6.63%
350	179	151	28	15.64%	198	174	24	12.12%
300	157	143	14	8.92%	177	161	16	9.04%

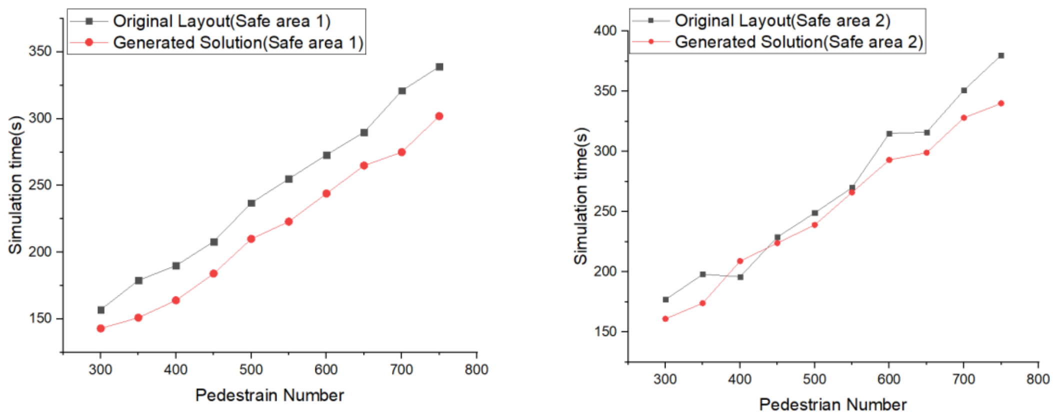

Figure 20. Evacuation time comparison when there is one type of people with speed at 1.2m/s(Author)

From the above results, we can find that in the case of different population density, population type and speed, whether it is to safe area 1 or to safe area 2, the average evacuation time of the new generated solution is less than the original design.

4 Discussion

To reduce the evacuation time of the building, a constraint-based design approach is developed to generate evacuation doors to minimize the evacuation path. In this study, we used two real project cases with different sizes in different museum to validate the performance of our approach and the results show that the average evacuation time of the building is reduced apparently with the solution generated by our approach. For the case study 1 implementing our method resulted in a 16.2% mean reduction of the evacuation time, while for the case study 2 resulted in a 7.5% mean reduction of the evacuation time. Notably, in case II, when 350 people passing through the safe area 2, the evacuation time of the original layout is 194s which is 4s (2%) less than 198s of the evacuation time of the generated solution (see **Figure 19**). When 400 people passing through the safe area 2, the evacuation time of the original layout is 196s which is 13s (6.6%) less than 209s of the evacuation time of the generated solution (see **Figure 20**).

From the simulation process we found it is because route choice of the people in the crowded area is not always the same in each simulation process (see **Figure 21**). Different route choice will lead to different evacuation time in the high density area. This situation usually occurs when people go to the safe area 2 and we found when people go to safe area 1 their route selection is relatively stable. This can explain why the results of the evacuation simulation to safe area 2 are not as stable as to the safe area

1. These minor difference in time does not significantly affect the average evacuation time of the generated solution, however, considering route choice behavior under different path length in our model in the future research may be a way to further reduce evacuation time.

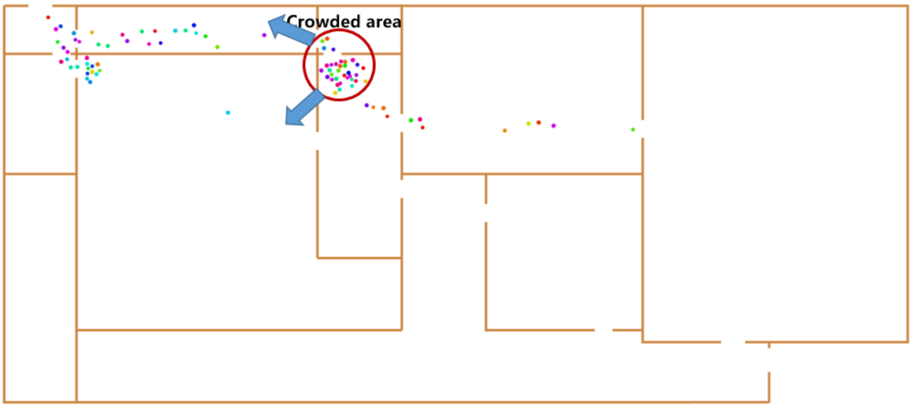

Figure 21. Different route choices in the crowded area in every simulation (to safe area 2)

5 Conclusions

This paper presents a new approach based on constraint programming and optimisation to minimise the evacuation time of a building in case of disaster or fire. Comparatively to previous work, this approach generates new doors positions while minimising the distances of evacuation. In order to illustrate how our approach improves evacuation efficiency, two real cases are presented in this paper, through the simulation at different number of people and different pedestrian composition and velocity, the total evacuation time has been significantly reduced after generating new doors by proposed approach. The proposed method in this study can provide a new perspective for evacuation design and provide a new tool to improve the evacuation performance of building layout.

In the further research, we will incorporate more factors from real evacuation scene, such as layout of the corridor and the furniture, route choice behavior, the arrangement of safety exit signs so that our model can be more capable to solve the problem of evacuation facility layout.

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