Design of Emergency Evacuation Scheme for Louvre

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Abstract. In this paper, we used four steps in analyzing the optimal model of evacuation within the Louvre. For step 1, we refer to the traffic concept in the Dynamic Network Flow Model to define the export throughput. For step 2, considering that the original floor plan is segmented with pixel points as a unit with high complexity and little meaning, we simplify the floor plan when the model is guaranteed to be true. For step 3, we first mark the exit node, make its dual graph, and draw the point chain containing the exit node, which can divide the original image into several pieces according to the area. Breadth-First Search from each egress node can mark themselves with color, ownership and other information. For Step 4, in order to get the optimal segmentation which satisfies the definition of reasonable segmentation edge set, we use Genetic Algorithm to solve the optimization problem. A sequence consisting of the sequence numbers in the set of Edge-Cut is encoded as a gene in the Genetic Algorithm and iterated by the Theory of Chromosome Cross-Variation to obtain an optimal solution. Finally, we have designed a scientific and complete emergency evacuation plan.

1. Introduction
Located on the North Bank of the Seine River in the center of Paris, the Louvre is the first of the four museums in the world [1]. As one of the largest and most popular art museums in the world, the Louvre has been attracting more and more visitors in recent years. Between January and December 2017, the number of visitors to the Louvre rose sharply to 8.1 million, up 10 per cent from 2016 [2]. After the tourism boom of 2016, the Louvre has more visitors and is under pressure from more tourists. Although in recent years, the interior of the Louvre has been carefully designed and renovated [3]. The exhibition space and exhibits have been rearranged. The exhibition area has been increased, the display effect has been greatly enhanced. But there are still unavoidable safety risks in the venue.

At the same time, the increase in the number of terrorist attacks in France and the instability of the domestic environment have also increased the security risks of the Louvre to a certain extent. For example, on 3 February 2017, a man armed with a knife attempted to break into the Louvre Museum and attacked soldiers stationed there.

2. Model Development
2.1. Simplification of Model
When we create the model, we consider that the segmentation of the planar graph has some difficulties. At the same time, in the actual evacuation plan people generally use the form of zoning planning. As a result, the floor plans of each floor of the Louvre were extracted, simplified and partitioned. In this
process, we removed the unnecessary factors in the floor plan, and divided the exhibition hall into a certain small area. At the same time, we ignore the area of the corridor, only consider the connectivity of the corridor to the graph, and regard the corridor as the edge connecting each pavilion. Through the above steps we further abstract out each area, viewing the pavilion as a node, the channel as a side. The pavilions and passages on each floor converge to form an undirected graph. In this way, it is easier to analyze the model in the next step if the model is true.

In this model, we set the corresponding properties for each node and edge. The information carried by each node includes: area, crowd density, predecessor and successor. Each side contains information such as endpoints, traffic, and length. For ease of recording and understanding, we distill the contents of each node into Figure 1.

![Figure 1. Details of nodes](image1)

After refining the attributes shown above for each node, we summarize the abstract edges such as elevator, staircase, corridor for different channels. From this we created the connected graph as shown in the following figure according to the different position and internal structure of each floor. The five floors of the Louvre are laid out in plan, and the elevator connects each floor. The graph includes a total of 148 partitions, that is, 148 nodes, 166 edges. Based on the simplified floor plan, the undirected graph retains the information of the building structure and the crowd density. Thus, the model can be simplified without distortion and can be easily analyzed by graph theory.

2.2. Analysis of Cut Edge and Dual Graph

2.2.1. Cut Edge. An undirected graph constructed from the above simplified model, instead of an extended exit flow plane, the exit nodes would mark the depth or breadth-first search of the graph as well as the passing nodes. We select some edges into the cut edge set E, then there is such a set. After removing the edges in the set, the original graph is perfectly divided into several connected point sets, and each point set has only one exit point. We call such a set E a reasonable set of edges.

A reasonable set of divided edges is shown in Figure 2.

![Figure 2. Divided edges](image2)
2.2.2. Dual Graph. To facilitate our analysis of the internal relations of a reasonably segmented edge set, we apply a regular deformation to the graph above:

1. The edges of the original graph are regarded as the set of points of the new graph.
2. The Grid (topological plane), which is formed by the edges and points of the original graph, is regarded as the edge set of the new graph.

The new graph is called the Dual Graph of the original graph. Take the Figure 7 above as an example. Its Dual Graph is Figure 3 as follows:

The above-mentioned deformation can be expressed more strictly as a kind of graph operation. And the operation is reversible:

\[ G' = \text{inv}(G) \quad G = \text{inv}(G') \]  

It can be seen that in the original graph, there is no obvious connection between the reasonable segmentation edge sets. But in the dual graph, all the corresponding points in the reasonable segmentation edge sets exist in the form of point chains in the dual graph. It is convenient for us to analyze the edge set from the angle of graph theory.

From the point of view of dual graph, for any kind of segmentation, we can use a dual graph point set 01 sequence, that is, the edge set of the original graph 01 sequence. You can specify rules for several graphs to assign values to nodes in the original or dual graph.

2.3. Genetic Algorithm

2.3.1. Brief view. From the cut edge theory of the graph above, we need to find a reasonable cut edge set is not enough, it is not a necessarily segmentation. That is, the segmentation of the corresponding evacuation plan to get the overall evacuation time is not necessarily small. So we have to look for reasonable (satisfying the definition of reasonable edge) and better segmentation. We need an algorithm to solve this optimization problem-genetic Algorithm. The Best Block model is the best evacuation time, so the best evacuation time formula is:
Among them, the connected graph \( G(Ex_i) \) is a unicorm diagram containing the exit nodes obtained by reasonably splitting the edge sets. \( f(G(Ex_i), \rho) \) means he time required for all personnel to be evacuated by the exit in the area of \( G(Ex_i) \) covered by the population density \( \rho \).

Since the Louvre’s plan is divided into 148 key nodes, and 166 edges guarantee its connectivity and building structure, an undirected graph is generated. We combine cut edges as gene sequences. A better solution can be obtained theoretically by iteratively reasonable and superior chromosomes.

2.3.2. Encode and Initialization. The serial number of the side of the cut edge is taken as the gene sequence \( A = [..., e_i, e_{i+1},...] \). Through the graph theory BFS, the cut edge number in the figure is found to correspond to the encoding process. The decoding process means that some of the edges in the annotation map are not passable. At the same time, several export nodes are expanded at the same time. They are dyed in the original picture. Each round randomly selects an area under the jurisdiction of the egress node for expansion. Until there is no unstained node in the original picture. Finally, the segmentation map is encoded to obtain a set of gene sequences.

2.3.3. Adaptive Function. For each sequence \( A_i \), the corresponding undirected graph segmentation method and the connected block point \( Ex_i \) containing each exit \( G(Ex_i) \) can be obtained. As mentioned earlier, the pros and cons of a split can be evaluated by the overall time taken for the evacuation plan corresponding to that split. And the shorter the segment, the better solution we will have. The fitness function can be selected:

\[
F(A_i) = \frac{1}{e_{\text{total}}}
\]

\[
t_{\text{total}} = \max(f(G(Ex_i), \rho))
\]

So how to calculate \( f(G(Ex_i), \rho) \) becomes the main calculation problem of fitness function. At present, the main algorithms to simulate crowd evacuation and traffic are dynamic network flow model and cellular automata model. Both of them can get better simulation of the traffic model within a certain scope of their application.

2.3.4. Select the cellular automaton according to the Louvre. Although there is no exact length data, the floor plan of the Louvre website gives the details of the structure and distribution of the exhibition area. Because the cellular automata can simulate the influence of the building structure on the crowd flow. It can modify the evolution rules of the cellular automata according to the characteristics of different crowd, the simulated crowd is more robust. So we choose to use cellular automata to simulate evacuation, and calculate the time of evacuation.

2.3.5. Type-directed gene-directed cells. For different cells, there are mainly different types (normal people, disabled people) and different blocks. As a result, their transfer equation is also different. Consider the cellular automata as a discrete model in both space and time. We need to divide the original plan of the Louvre into a uniform two-dimensional grid. But considering the multi-storey structure of the Louvre, in the stairs and elevator access is three-dimensional structure. We only consider extending the three-dimensional grid in the stairs and elevators. (though in proportion to the actual size of the plan).

Each grid is the equivalent of a cell. Each grid point corresponds to a position hazard, according to the Position Hazard of the grid point in its domain, the next time the mobile state is determined. Each time step is 0.5 seconds, and the cells throughout the building are renewed every time.
The danger level for each grid point is equal to the serial number of its breadth-first search in the exit grid set. The breadth-first search formed by the blocks of each graph assigns a danger value to the cells in the region, and each cell moves first to the low risk squares around it, and does not move if its value is lowest. As the formulary follows:

\[
\begin{aligned}
    d(x_i, y_i, z_i) &= \begin{cases} 
    \text{bfs} & (x_i, y_i, z_i) \notin G(E_{x_i}) \\
    +\infty & \text{otherwise}
    \end{cases} \\
    D &= \min \left\{ d(x-1, y, z), d(x+1, y, z), d(x, y-1, z), d(x, y, z-1) \right\} \\
    (x', y', z') &= (x_{\text{access}}', y_{\text{access}}', z_{\text{access}}')
\end{aligned}
\]  

(4)

Among them, \( d(x', y', z') \) on behalf of the danger level of \((x', y', z')\). When the cell does not belong to the Connected Block, the danger value is set to positive infinity. When a cell or wall is occupied in the grid, the hazard value is set to positive infinity. At the same time each cell has a different type, called \( \text{type}(x, y, z) \), corresponding to its surrounding 8 grid, the current cell in the surrounding 8 grid feasible path can go, otherwise it can not go. This is type-driven. For example, \( \text{type}(x, y, z) \) on behalf of the type of the formulary \( \text{access} \) \( \text{type}(x, y, z)[x-1][y][z]=1 \). Then next time the cell goes to location \((x-1, y, z)\).

In combination with gene and type orientation, the rules of cellular transfer are as follows:

Set time and the formulary follows:

\[
(\begin{aligned}
    (x' + \Delta_x, y' + \Delta_y, z' + \Delta_z) &= (x_{\text{access}}', y_{\text{access}}', z_{\text{access}}') \\
    (x_i + 1, y_i, z_i), (x_i - 1, y_i, z_i), (x_i, y_i + 1, z_i), (x_i, y_i, z_i + 1), (x_i, y_i, z_i - 1), (x_i, y_i - 1, z_i)
\end{aligned})
\]

(5)

There are 27 subsequent states. For the convenience of calculation and selection, the following state of a certain type of cell is assumed:

When it's impassable:

\[
\text{access}[\text{type}(x, y, z)][x_i][y_i][z_i] = +\infty
\]

(6)

When it's passable

\[
\text{access}[\text{type}(x, y, z)][x_i][y_i][z_i] = 1
\]

(7)

The final choice is as follows:

\[
D = \min \left\{ \text{access}[\text{type}(x', y', z')][x_i'][y_i'][z_i'] \cdot d(x', y', z') \right\}
\]

(8)

2.3.6. **Selection function.** The fitness of each chromosome group is obtained from the fitness function, and the probability of each chromosome being selected is:
For Selection, we use the Roulette Wheel Algorithm; there are two roulette wheel algorithm to select two adaptive individuals, cross mutation.

2.3.7. Crossover. For the encoding of gene sequence in this model, it is the serial number of the cut edge mapped to a split graph. The edge-cutting sequence only reflects the non-connectivity of this edge. To get the corresponding segmentation graph, you need to consider the structure of the graph itself. If the form of a simple exchange of genes, then the resulting offspring decoding the division is not necessarily a reasonable division, the image can be said that the offspring have a genetic disease, can not survive. In order to maintain the number of population has to do continuously roulette selection algorithm. This wastes a lot of computation and time, and can lead to more intractable problems. That is, the offspring of good individuals may die from genetic diseases, so that good genes can not be retained, which is certainly not optimal.

Therefore, the individual crossover should take into account the structure of the original graph. Set $G_{\text{decode}}(A)$ as the segmentation map obtained by decoding the gene sequence. If two gene $A_i$ and $A_j$ sequences are selected by the Roulette Algorithm, $G_{\text{decode}}(A_i)$ and $G_{\text{decode}}(A_j)$ the segmentation graph they generated.

The specific cross-cutting processes are as follows:

1. The segmentation graph after decoding two sequences is obtained.

2. For the split graph of the genes of the offspring, we take the split graph generated by the two parents, and alternate the positions of each exit node $G(E_i)$, and merge $A_{x,t+1}$ into the decoding graph of the offspring:

   \[ G_{\text{decode}}(A_{x,t+1}) = \bigcup_{i=0}^{N} G_{\text{decode}}(A_i)(E_x) \]  

3. The details of the merge operation $G_{\text{decode}}(A_{x,t+1})$ are that the initial count of the nodes in is 0, and the number of times they are overwritten in $G_{\text{decode}}(A_i)(E_x)$ during the merge is recorded. Suppose a gene sequence is decoded to produce a simple segmentation model -- a square with only four corners. The black lines represent splitters, and the colored squares represent different gene sequences.

4. The best-case scenario $G_{\text{decode}}(A_{x,t+1})$ is a reasonable split graph in which all nodes are covered $G_{\text{decode}}(A_i)(E_x)$ exactly once. Then you can code $G_{\text{decode}}(A_{x,t+1})$ directly to a reasonable and healthy offspring.

5. It is unreasonable that some nodes are covered many times, that is, the graph $G_{\text{decode}}(A_{x,t+1})$ is not completely separated, there are two or more exit nodes in the region connected together. As shown in Figure 4.
Figure 4. Area nodes

Where A and B represent two parent genes obtained by decoding the segmentation, a simple cross rule for the offspring of C1, C3 export segmentation way choose to inherit the parent. The C2, C4 export segmentation way to inherit the parent B. As can be seen from the gray part of figure C above.

So, we're going to do a contraction adjustment on each one. Put each exit node into the queue and do the breadth-first search. First search the reasonable range of each exit node $G_{decode(A_{exit})}$. That is, the red and blue part of C above. Then the Middle Node count greater than 1 node edge expansion. Until there are no such violations.

Finally, the dual map of the original map, coding, we can get a reasonable gene sequence after adjustment. The process and results are shown in Figure 5 and Figure 6.

Figure 5. Coding process
Another unreasonable is that some of the nodes $G_{decode(A_{j+1})}$ are not covered by $G_{decode(A_j)}(E_{x_i})$, that is, the original graph is divided into more than N (the number of exit nodes). Where C2 is crossed, exit 1,3 splitting inherits parent B, and exit 2,4 splitting inherits parent A. See the blank portion of figure C above, the extra portion of the C2 decoding map that has been split.

The process is similar to the point above and each $G(E_{x_i})$ needs to be widened. We take all the exit nodes as the starting point, complete the reasonable part of the breadth-first search, and then extend the edge of the node $G_{decode(A_{j+1})}$ with the count less than 1. Until there are no such violations.

Finally, the dual map of the original map, coding, we can get a reasonable gene sequence after adjustment. The process and results are shown in Figure8 and Figure9.

**2.3.8. Termination Conditions.** Set the maximum number of iterations N=2000. If during its iteration, the difference between the optimal value of the offspring and the optimal value of the parent is less than $\epsilon ps$, the evolutionary process can also be terminated.

**2.4. Evacuation Sequence**

| EXIT | Area number |
|------|-------------|
| Glass pyramid | 100~105, 130~137, 160~186, 236~305, 308~316, 500~526 |
| Carrousel Gallery | 200~218, 219~230, 535~564, 800~803, 811~835, 836~864 |
| Lions Gate | 400~403, 405~423, 424~433, 700~711, 712~717, 728~734, 900~913 |
| Art door | 317~338, 339~348, 601~622, 633~640, 641~663, 917~931, 936~952 |
3. Conclusion
Based on the study of the Louvre emergency evacuation strategy, we combine the above established models and the various analytical methods provided. We make the following specific recommendations for the evacuation route of the Louvre:
Figure 7. Evacuation route suggestions

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