GIS Based Emergency Management Framework for Large-scale Events: A Case Study of the Torch Relay Activity

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ABSTRACT
Due to the high popular concentration of large-scale events, once an emergency (like a stampede) occurs, it will often cause severe casualties. Moreover, since the widespread of the COVID-19, the prevention of the novel coronavirus should also be considered during mass gatherings. How to reduce the probability and potential consequence of emergencies is of great significance. This research designs an emergency management framework using ArcGIS-based geographic information technology for large-scale events. To verify the effectiveness of our framework, we take the Winter Olympic torch relay in university as an example. The paper is mainly divided into two parts, emergency resource allocation and the emergency prevention model. The former part focuses on the site selection of emergency sentries and emergency hospitals during the torch relay. In the latter part, an emergency prevention model is designed for two significant emergencies: stampede and epidemic.

Keywords
Arcgis, large-scale event, emergency management, epidemic prevention.

INTRODUCTION
The 2022 Winter Olympic Game will be held in Beijing, the capital of China. Before the Olympic, a series of torch relay events will be held, which can not only show Chinese cultural traditions to all over the world but also promote the Olympic spirit of unity and friendship. However, the Olympic torch relay event will inevitably be accompanied by a large number of spectators gathering, which is likely to cause emergencies such as the stampede and the epidemic outbreak. Especially in the context of the post-epidemic era, how to prevent and control the epidemic when organizing such large-scale events is very essential. Therefore, this research designs a large-scale event emergency management framework based on GIS technology to prevent these two significant emergencies.

There is a large volume of researches using GIS technology in emergency management. One of the significant applications of GIS is to analyze the emergency evacuation route during emergencies and the emergency resilience of urban road networks. Kubisch et al. (2019) investigated the entire evacuation process from evacuation decision-making to arriving at emergency refuges based on the standardized expert questionnaires and GIS technology. Besides, this research took a Chilean community as a case study. Widera et al. (2017) proposed several
requirements for transport planning during disaster relief processes which are derived from previous pieces of literature and research projects. Applying Dijkstra's algorithm in GIS technology, Rybansky (2014) established an optimal route planning model for the emergency evacuation, which considers various obstacles due to the emergency. Nicoara and Haidu (2014) adopted the GIS-based network analysis method to seek the shortest emergency medical rescue route, which considers the possible obstructions or prohibition on the urban road network.

Using the spatial network analysis combined with multi-objective function based on GIS, researchers have also been able to study emergency management. Rottkemper and Fischer (2013) established a multi-objective optimization function concerning the optimal distribution of relief supplies. This research fulfilled rescue needs while reducing costs as much as possible and assisted in making quick decisions after disasters. Tsai and Yeh (2018) applied GIS technology and multi-objective function to study the service coverage of existing refuges in tourist parks and analyze whether the existing refuges can meet emergency needs. According to the filter result of spatial network analysis, Wu and Weng (2011) built the refuge site selection model. Hashemi and Alesheikh (2013) combined the agent-based model and GIS technology to study the location of evacuation sites during earthquakes, taking into account a variety of personnel composition after the earthquake.

Meanwhile, many researchers have utilized various technologies to assist emergency management of large-scale events in metropolitan areas. Cai et al. (2018) analyzed the urban road network during large-scale events through the minimum cost and maximum flow algorithm in GIS and conducted an experimental evaluation with the real data from Beijing. Combining semantic technique along with GIS technology, Barcaroli et al. (2019) established an automatic risk assessment method for metropolitan areas. The researchers then conducted a case study in Rome. Romanowski et al. (2015) adopted data mining techniques to obtain emergency data from past emergencies and combined GIS technology to build an emergency decision-making model for large-scale events. Wang and Yang (2010) used the Delphi method to construct an emergency management system to assist in emergency management during large-scale events.

Nevertheless, there are certain drawbacks associated with existing studies. Most of the literature focuses on emergency management of natural disasters, while relatively few works involve emergency management for large-scale events. These studies mainly focus on a single course in emergency management, such as traffic decision-making or stampede early warning. Furthermore, due to the outbreak of the COVID-19, it is necessary to consider epidemic prevention during organizing large-scale events. This research will take stampede as well as epidemic into account, and propose a comprehensive GIS-based emergency prevention framework for large-scale activities.

**METHOD**

This paper is mainly divided into two parts, emergency resource allocation and emergency prevention model, as shown in Figure 1. At the outset, the torch relay handover points were determined according to the reality of the campus. On this basis, the path planning algorithm was employed to determine the torch relay route. Subsequently, the location-allocation algorithm was adopted for the site selection of the emergency sentries so that the emergency sentries can cover the torch relay route as much as possible. Ultimately, spatial network analysis, which takes the distribution of roads and residences into account, was used to choose the site for the temporary hospital.
Two major emergencies that may occur in mass gatherings were analyzed in the latter part. Concerning stampede, combined with campus occupant density factors such as the torch relay route and road distribution, spatial network analysis was applied to evaluate the possibility and potential consequence of the latent stampede. Consequently, the comprehensive risk of the latent stampede was assessed. It follows that the emergency evacuation and rescue routes for the high-risk areas were planned according to the nearest facility algorithm.

With regard to the potential epidemic, the vehicle routing problem algorithm (VRP algorithm) was used to design the disinfection route for multiple groups of medical workers. GPS positioning technology, along with the dynamic tracking analysis, was applied to analyze the influence coverage of the suspected patients.

In Figure 1, the location-allocation algorithm, the nearest facility algorithm, and the vehicle routing algorithm are mainly based on the computed result of the total road length. While applying the location-allocation algorithm, the torch relay handover points are set as the emergency service demand points, and candidate emergency sentries are set along the road. ArcGIS will calculate the distance from the candidate emergency sentries to each service demand point. Thus, the candidate emergency sentry with the shortest total distance is selected. While applying the recent facility algorithm, refuges (including playgrounds, green spaces, and gymnasiums on campus (Li et al., 2006) and hospitals are set as emergency facilities. In contrast, stampede high-risk areas are set as demand points, thereby obtaining the shortest evacuation and rescue routes. In the vehicle routing algorithm, the torch relay handover points are set as the stopping point in the VRP analysis; the emergency sentries are set as the start point and end point of each group of medical workers. ArcGIS will traverse different route combinations to determine the shortest disinfection route.

When performing a spatial network analysis, it is essential to analyze multiple influencing factors and establish a multi-objective function. For example, during the site selection of the emergency hospital, on the one hand, it needs to meet the emergency medical needs when an emergency occurs; on the other hand, it needs to be as close to the road and dormitory area as possible to facilitate medical treatment. While evaluating the possibility of campus stampede, road density and occupant density should be taken into account; equally, while evaluating the consequence of campus stampede, it is vital to overall consider the distribution of refuges and hospitals. Each emergency problem contains various influencing factors, as shown in Figure 2. When analyzing these influencing factors, this research introduces some quantitative indicators, as shown in formulas (1)-(3):
Here, \( \text{dist}^\pm((x, y)|m) \) represents the reclassified Euclidean distance between the point \((x, y)\) and an \(m\)-type area pattern (such as refuge or dormitory). \((X_{mi}, Y_{mi})\) represents the coordinate of all \(m\)-type area patterns. \( \text{density}^\pm((x, y)|n) \) represents the reclassified density of \(n\)-type line pattern (such as sidewalk) at the point \((x, y)\), and \(L_{ni}\) represents the length of the line pattern in the pixel. \(S\) represents the area of the pixel. \( \text{slop}^\pm(x, y) \) represents the reclassified slope at the point \((x, y)\), and \(H\) represents the elevation data at the point. \( f^\pm \) represents the reclassification algorithm based on Jenks natural discontinuity point. Due to the calculated Euclidean distance are not intuitively displayed, the reclassification algorithm needs to be applied to classify and score each index on a scale of 1-10. The Jenks reclassification algorithm classifies based on the natural discontinuities inherent in the data, which can appropriately classify similar data and make the difference between each group as significant as possible (Chen et al., 2013). \( f^+ \) indicates that the reclassified result is positively correlated with the original data, and \( f^- \) indicates that the reclassified result is negatively correlated with the original data.

**CASE STUDY: TORCH RELAY EVENT IN THE COLLEGE CAMPUS**

Since the Winter Olympics torch relay events will be carried out in several university campuses in Beijing, this article takes a Beijing campus as an example to carry out emergency prevention and control research for the large-scale event. The road network and building geographic data in this research are derived from OSM open-source maps (Haklay and Weber, 2008).
Emergency Resource Allocation

Torch Relay Route Planning

Due to the crowded characteristics, the torch relay route should be considered into the subsequent emergency prevention and control method. Thus, the torch relay route must first be planned according to the reality of the campus. Considering factors such as well-known buildings on the campus, this study selected 33 torch relay handover points such as the Central Main Building, Zijin Student Dormitory, and Jinchun Garden. Hence, 32 torchbearers will carry out the torch relay. After determining the torch relay handover points, the ArcGIS path planning algorithm is used to determine the optimal torch relay route. The result is shown in Figure 3.

Site-selection for Emergency Sentries

During the torch relay, to cope with a latent emergency like a stampede, it is crucial to set up several temporary sentries on the campus for a quick response. Due to limited emergency resources, the total number of emergency sentries should be restricted. According to the distribution of torch relay handover points, the school is divided into four areas. Assuming that each area establishes an emergency sentry, the service scope of each emergency sentry is shown in Table 1. The location-allocation algorithm is applied to choose the site for the emergency sentries. The result is shown in Figure 4.

Table 1. Emergency Sentries Service Scope

<table>
<thead>
<tr>
<th>Emergency Sentries Number</th>
<th>Main Service Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sentry No. 1</td>
<td>Along the Handover Points 1-8</td>
</tr>
<tr>
<td>Sentry No. 2</td>
<td>Along the Handover Points 9-16</td>
</tr>
<tr>
<td>Sentry No. 3</td>
<td>Along the Handover Points 17-22</td>
</tr>
<tr>
<td>Sentry No. 4</td>
<td>Along the Handover Points 23-33</td>
</tr>
</tbody>
</table>

In Figure 4, it is assumed that the running speed of emergency guards is 200 meters per minute, and the allowed emergency response time is set to two minutes. The service area accessibility algorithm in ArcGIS was adopted to analyze the coverage area of the emergency sentry (blue area in the figure) within two minutes. The Origin-Destination cost matrix from the emergency sentries to the torch relay handover points is shown in Table 2. The
shortest emergency response time is 0.03 minutes, the longest emergency response time is 2.81 minutes, and the average emergency response time is 1.45 minutes. The emergency response time of 85% of the torch relay handover points is within 2 minutes. This suggests that the emergency sentry can cover the torch relay route in a short time, and therefore can make a timely and effective emergency response after a potential stampede occurs.

Figure 4. Emergency Sentries Coverage

Table 2. Sentries-Facilities OD Cost Matrix

<table>
<thead>
<tr>
<th>Sentries-Facilities</th>
<th>Shortest Distance (Meters)</th>
<th>Shortest Time (Minutes)</th>
<th>Sentries-Facilities</th>
<th>Shortest Distance (Meters)</th>
<th>Shortest Time (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>556.0</td>
<td>2.78</td>
<td>3-18</td>
<td>253.0</td>
<td>1.27</td>
</tr>
<tr>
<td>1-2</td>
<td>352.7</td>
<td>1.76</td>
<td>3-19</td>
<td>155.0</td>
<td>0.78</td>
</tr>
<tr>
<td>1-3</td>
<td>158.2</td>
<td>0.79</td>
<td>3-20</td>
<td>101.5</td>
<td>0.51</td>
</tr>
<tr>
<td>1-4</td>
<td>107.7</td>
<td>0.54</td>
<td>3-21</td>
<td>321.0</td>
<td>1.61</td>
</tr>
<tr>
<td>1-5</td>
<td>140.6</td>
<td>0.70</td>
<td>3-22</td>
<td>340.5</td>
<td>1.70</td>
</tr>
<tr>
<td>1-6</td>
<td>399.6</td>
<td>2.00</td>
<td>4-23</td>
<td>289.17</td>
<td>1.45</td>
</tr>
<tr>
<td>1-7</td>
<td>264.1</td>
<td>1.32</td>
<td>3-24</td>
<td>185.6</td>
<td>0.93</td>
</tr>
<tr>
<td>1-8</td>
<td>356.1</td>
<td>1.78</td>
<td>4-25</td>
<td>204.9</td>
<td>1.02</td>
</tr>
<tr>
<td>1-9</td>
<td>562.2</td>
<td>2.81</td>
<td>4-26</td>
<td>6.8</td>
<td>0.03</td>
</tr>
<tr>
<td>2-10</td>
<td>373.1</td>
<td>1.87</td>
<td>4-27</td>
<td>244.4</td>
<td>1.22</td>
</tr>
<tr>
<td>2-11</td>
<td>154.9</td>
<td>0.77</td>
<td>4-28</td>
<td>246.9</td>
<td>1.23</td>
</tr>
<tr>
<td>2-12</td>
<td>20.6</td>
<td>0.10</td>
<td>4-29</td>
<td>354.8</td>
<td>1.77</td>
</tr>
<tr>
<td>2-13</td>
<td>202.4</td>
<td>1.01</td>
<td>4-30</td>
<td>508.8</td>
<td>2.54</td>
</tr>
<tr>
<td>2-14</td>
<td>388.8</td>
<td>1.94</td>
<td>4-31</td>
<td>325.9</td>
<td>1.63</td>
</tr>
<tr>
<td>2-15</td>
<td>325.1</td>
<td>1.63</td>
<td>4-32</td>
<td>383.6</td>
<td>1.92</td>
</tr>
<tr>
<td>2-16</td>
<td>459.7</td>
<td>2.30</td>
<td>4-33</td>
<td>401.7</td>
<td>2.01</td>
</tr>
<tr>
<td>2-17</td>
<td>443.3</td>
<td>2.22</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Site-selection for Emergency Hospital

Considering that the existing school hospital may not be able to meet the emergency needs, this research proposes to construct another emergency hospital on the campus to improve the campus stampede resilience. The following five factors should be considered when selecting the location for the emergency hospital: (1) To facilitate emergency hospital to dispatch ambulances for emergency response, it should be close to the roadway; (2) To facilitate people to seek medical treatment, emergency hospitals should be close to student dormitories and living quarters; (3) The emergency hospital should be built in a relatively flat area to facilitate medical rescue; (4) For the balanced distribution of medical resources, the new hospital should be far away from the existing school hospital; (5) To facilitate the emergency hospital to transfer the wounded, the emergency hospital should be close to the emergency refuges. The weighting formula for site selection is shown in formula (4):

\[
F(x, y) = 0.2 \times \text{density}^+(x, y)|\text{Roadways}| + 0.1 \times \text{density}^+(x, y)|\text{Sidewalks}| \\
+ 0.1 \times \text{dist}^+(x, y)|\text{Student dormitories}| + 0.1 \times \text{dist}^+(x, y)|\text{Residential Areas}| \\
+ 0.15 \times \text{slop}^-(x, y) + 0.15 \times \text{dist}^-(x, y)|\text{School Hospital}| + 0.25 \times \text{dist}^+(x, y)|\text{Refuges}|
\]  

(4)

After calculating the site selection weighting score, the area with the highest score is selected. Besides, considering that the construction area could not be too small, the mode filtering tool is applied to remove the isolated pixels. Given the above, the suitable areas for building emergency hospitals are obtained, as shown in the green area in Figure 5. It can be seen that the areas suitable for the new emergency hospital are mainly concentrated in the northeastern part of the campus. Excluding areas with existing buildings, the optimal location of emergency hospitals is determined in the area marked by the red circle in Figure 5.

![Figure 5. Suitable Location for Emergency Hospital](image)

Emergency Prevention Model

Stampede Safety Assessment

According to the Chinese national standard "GB/T 33170 Safety Requirements for Large-scale Events", before large-scale events are carried out, it is demanded to conduct a comprehensive safety assessment in the event venue. During a safety assessment, it is fundamental to consider the combination of possibility and potential consequence
comprehensively.

Due to the stampede are more likely to occur in densely populated areas, the stampede possibility multi-objective function should include the following three factors: (1) Since the torch relay route will draw a large crowd, the stampede risk is positively correlated with the distance of the torch relay route; (2) A large number of pedestrians and vehicles will gather around the road, so the stampede risk is positively correlated with road density; (3) Some gathering points on campus such as canteens and well-known tourist attractions will gather a large number of people, so the stampede risk is positively correlated with the distance of these gathering points. Likewise, the stampede consequence multi-objective function should involve the following three factors: (1) Due to the shorter emergency rescue time, the potential consequence is negatively correlated with the distance of the hospitals. (2) Due to shorter emergency rescue time, the stampede potential consequence is negatively correlated with the distance of the emergency sentries. (3) Due to faster evacuation speed, the stampede potential consequence is negatively correlated with the distance of the evacuation sites. The calculation formulas for stampede probability, consequence and comprehensive risks are shown in formula (5)-(7):

\[
L(x, y) = 0.25 \cdot \text{dist}^+(x, y)|\text{Handover Points}| + 0.25 \cdot \text{dist}^+(x, y)|\text{Relay Route}|
+ 0.2 \cdot \text{density}^+(x, y)|\text{Roadways}| + 0.1 \cdot \text{density}^+(x, y)|\text{Sideways}|
+ 0.2 \cdot \text{dist}^+(x, y)|\text{Gathering Points}|
\]

(5)

\[
C(x, y) = 0.35 \cdot \text{dist}^+(x, y)|\text{Refuges}| + 0.35 \cdot \text{dist}^+(x, y)|\text{Hospitals}|
+ 0.3 \cdot \text{dist}^+(x, y)|\text{Emergency Sentries}|
\]

(6)

\[
R(x, y) = L(x, y) \ast C(x, y)
\]

(7)

The results of the stampede possibility and potential consequence are shown in Figure 6, and the result of the comprehensive risk assessment is shown in Figure 7. It can be seen that there are several high-risk areas on the campus that are densely populated and far away from hospitals or refuges—these areas concentrated in the southeast gate, especially around the concert hall, the student apartment, and the library. During the torch relay event, attention should be attached to potential safety hazard checking and controlling in these areas.
When designing an emergency management framework for the torch relay event, it is crucial to plan the emergency evacuation routes from risk points to refuges as well as the emergency rescue routes from hospitals to risk points in response to the potential stampede accidents. Based on the comprehensive risk assessment result in Figure 7, 10 high-risk points are selected in the high-risk area, and the shortest routes to the refuges are analyzed using the nearest facility algorithm in ArcGIS, as shown in Figure 8(a). Similarly, the emergency rescue routes of the hospital to the risk points can also be analyzed, as shown in Figure 8(b). Once there is an emergency such as a stampede occurs, emergency evacuation and emergency rescue can be carried out according to the planned route.
Epidemic Disinfection Route Planning

Organizing large-scale events under the new normal of the Post-epidemic era, how to carry out scientific and effective epidemic prevention is of great significance to the smooth conduct of large-scale events. In order to prevent the spread of the epidemic, it is fundamental to conduct regular disinfection along the torch relay route. Therefore, in this research, four groups of medical workers are organized to set off from 4 emergency sentries to disinfect along the torch relay route. Through a vehicle routing algorithm, route planning can be performed for these four groups of medical workers. The disinfection road between two torch relay handover points is called a section. Set the disinfection time required for each section to 5 minutes, and set the maximum number of disinfection sections that each group is responsible for to 9. The disinfection routes for four groups are shown in Figure 9, and the time required for each group shown in Table 3. After VRP path planning, the torch relay route can be eliminated within 1 hour.

![Disinfection Route]

Table 3. Disinfection Time for Each Group

<table>
<thead>
<tr>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.19 min</td>
<td>51.01 min</td>
<td>55.39 min</td>
<td>48.57 min</td>
</tr>
</tbody>
</table>

Suspected Patient Tracking Analysis

During the holding of large-scale events, in order to prevent cluster transmission, it is fundamental to quarantine people with suspected symptoms such as cough and fever in time. The spectators of the torch relay event will be supposed to feedback on their real-time position on the campus according to the mobile phone's GPS positioning function. Moreover, the spectators should also report whether they have a cough, fever, and other suspected symptoms through the mobile app. Then map out the real-time location in ArcGIS, and set a 30-meter buffer zone for epidemic transmission for each person. Subsequently, apply the dynamic tracking function of ArcGIS to analyze the location and status of every spectator. When a spectator has cough symptoms, a yellow warning frame is highlighted outside the buffer zone; when a spectator has fever symptoms, a red warning frame is highlighted outside the buffer zone. Using the tracking analysis function, the track and close contacts of suspected symptoms can be obtained.

Figure 10 is a simulated tracking analysis on September 11, 2021. Figure 10(a) is at 10 a.m. Several students watch the torch relay along the route. Among them, student B report a mild cough, and a yellow warning is highlighted outside the 30-meter buffer zone of student B. Figure 10(b) is 11 a.m. Student B, who had previously coughed, report fever and a red warning is highlighted. Student A, who had been in contact with him, also has
cough symptoms. Meanwhile, student G is within the potential spread zone. Therefore, the three students A, B, and G, should be quarantined immediately.

CONCLUSION

This research designs an emergency framework for large-scale events, which includes emergency resource allocation and emergency prevention model. First, Given the population distribution characteristics during the torch relay event, the location of emergency sentries was determined. Then, the site of the emergency hospital was chosen based on multiple factors such as road distribution and residential distribution. Next, according to the stampede possibility and consequence obtained from the spatial network analysis, the risk map of the stampede accident was superimposed to identify high-risk stampede areas. At last, it follows that emergency escape and rescue routes in high-risk areas were planned. Applying the VRP algorithm, this research has identified the disinfection route for multiple groups of medical workers. Subsequently, the influence coverage of possible suspected patients was traced and analyzed. The large-scale events emergency management framework will contribute to reducing the possibility and the potential consequence of emergencies such as stampede and epidemic effectively.

Some improvements can be made in the future to assist large-scale emergency management: (1) The scale of the selected area in this research is relatively small, and the subsequent research concerning large-scale emergency management can be carried out in larger scale areas such as cities. (2) More factors like topographic condition could be considered in spatial network analysis to improve the multi-objective function. (3) This research is based on the dynamic tracking function of Arcgis to analyze the close contacts manually; a further study could introduce the trajectory similarity calculation model to realize the automatic tracking of the close contacts.

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