Multi-Criteria Emergency Route Planning Based on Analytical Hierarchy Process and pgRouting

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Abstract: Routing calculation has an important role to play in emergency responses and decisions. For example, it can help ambulances to take one patient to the hospital as fast as possible. This paper presents the implementation of an alternative method to calculate the travel-time of the route, according to the location of an accident and the situation at the destination point. The minimum travel-time from the accident point to the nearest hospital is calculated and some others parameters are taken into account such as the availability of beds in the targeted hospital and the patient’s state. The method is based on an adaptation of the pgRouting algorithm with an analytical hierarchy process (AHP) for the Emergency Route Decision Planning (ERDP). First, a weighted travel-time model was built based on a minimum time-consumption criteria, with the consideration of three impedance factors that are influencing the ERDP. Then, AHP was used to calculate priority weights of the impedance factors and taken into account for every parameter which is related to the travel-time consumption. Further, a new and improved routing algorithm was implemented using and extending pgRouting to obtain the weighted travel-time according to the situation of the destination point.

The integration of AHP and pgRouting constitutes a powerful tool for analysing both road conditions and the conditions at the destination point. It can be used for evacuation planning after natural disasters.

Key words: pgRouting, Road Condition, Weighted travel-times, Analytical Hierarchy Process (AHP), Emergency Route Decision Planning (ERDP)

1. Introduction

The use of the shortest distance method is not sufficient to improve the Emergency Route Decision Planning (ERDP) systems in the context of complex road networks. Other parameters such as road condition and situation at possible destinations must be taken into account in ERDP. Our concern here is to focus on giving priority weights to road condition and situation at target destination, and to incorporate a weighting scheme in the pgRouting algorithm, in order to compute more realistic emergency routing scenarios. Moreover, the presence of diversified conditions of traffic at different time of the day was considered to find the best and fastest itinerary at different hours, after an accident occurred.

ERDP is one of the most important methods regarding route planning. Its applications for flooding, forest fires, earthquakes or tsunamis should be optimized and computed efficiently soon after such disasters occur. Such decisions are quite complex because many different elements must be taken into account in the calculations. In order to improve their efficiency, the Analytic Hierarchy Process (AHP) was chosen for our research.

AHP is a theory of measurement through pairwise comparisons in order to assess the relative weight of multiple criteria and to derive priority scales. The comparisons are made using a scale of absolute decisions that represents the importance of one criterion compared to others. The decision may be inconsistent and measuring inconsistency and improving decisions is a major concern of the AHP (Saaty, 2008).

The main objective of this work is to enhance ERDP using pgRouting algorithm and AHP analysis, in order to calculate weights for the impedance elements. The routing algorithm is based on the assumption that patient state (PS) is serious or stable and the number of available bed (AOB) in each hospital are known. Moreover, it is also assumed that the real road network conditions are available. Using pgRouting algorithms and AHP, ERDP allows us to compute scenarios and to determine the best suitable routes under present conditions of target, route and destination.
The pgRouting is a C language library which supports shortest path algorithms like Dijkstra, a-star and shooting-star. These algorithms assume that the edge weights are static and their values do not change with the current road conditions (Donati et al., 2008). The pgRouting extends the PostGIS/PostgreSQL geospatial database to provide geospatial routing functionalities. The classical pgRouting algorithm, such a Dijkstra function, select a route result based on the minimum cost (distance) of the roads network (Kastl and Junod, 2010).

In ERDP, it is mandatory that the road weight must take many elements impacts of road and non-road attribute into account (Cherrie and Dickson, 2006). AHP is used for quantitatively establishing calibration ratings by assigning priority weights to the elements, depending on their perceived relative importance for the computation of the route result. Thereby, the road weight which expresses the synthesis of existing conditions is used for ERDP. This approach is only valid when there is a set of reliable standards against which alternatives can be assessed to determine their relative importance. Thus, this method can be used for route planning, but also for in logistics, evacuation after disaster and other purposes.

2. Methodology

2.1 Classical pgRouting algorithm

The pgRouting algorithm such as Dijkstra function is one of the algorithms to minimize the costs from the start point to the end point (shortest distance on the road network). It is based on a graph that contains a set of nodes V and set of edges E (An edge here denotes a road segment in the real road network), defined by pair of nodes. Each road E (i, j) has a weight (or cost) W (i, j), which in its basic form represents the distance between the two nodes of the road segment. A value is assigned to each node, which is the sum of the costs from the start node to the node itself. Given a network with known road cost, the shortest path problem comprises of finding the shortest distance from a source node A to a specific node in the node set V. In particular, this path is selected out of all the possible paths by choosing the one for which the sum of traversing cost is minimum. The shortest path from the starting point to the destination can be effectively achieved using these steps. The Dijkstra algorithm has been widely used in routing systems, even in our previous work on route system for dynamic networks (Choosumrong et al., 2010).

2.2 The concept of using the pgRouting capabilities to modify the costs by calculating AHP

The routing services provided by the pgRouting algorithm represent a powerful tool to help in emergency situations. However, the current urban road networks are unable to accommodate the everyday heavy traffic, and this poses a serious problem while deploying emergency services such as ambulance, using the classical pgRouting algorithm, for which the time factor plays a crucial role. In order to find the optimal route between two given points, either the shortest path between them or the route having minimum travel-time is to be selected (Yang and Li, 2010). Regarding ERDP, the route presenting the minimum travel-time must be preferred to the routes having the shortest distance. Thus, the use of the classical pgRouting algorithm was confronted with some limitations for using it in a real situation.

In order to optimize the travel-time, the various impedance factors playing a significant role in deciding such as speed limit and junction delay, must be analysed to determine the optimal route with the minimum travel-time (Cherrie and Dickson, 2006). The AHP was adopted to achieve this goal.

The AHP is a structured practice for representing hierarchically the elements of a problem. It can enable decision makers to represent the interaction of multiple elements in complex and unstructured situations. The procedure is based on the pairwise comparison of decision elements with respect to attributes or alternatives. A pairwise comparison matrix \( M \times M \) is formed, where \( M \) is the number of elements to be compared (Chakraborty et al., 2011). The AHP is an extensively used multi-criteria decision-making method, which has been applied to a wide variety of decision. We need to decompose the decision to present it in an organised way in order to generate priorities. Firstly, the problem must be defined and the kind of knowledge sought determined. Then, the decision hierarchy must be structured, from the top level, through intermediate levels (criteria on which subsequent elements depend) to the lowest level, which is usually a set of alternatives that allow the construction a set of pairwise comparison matrices. Each element in an upper level (Level 2) is used to compare the elements in the level immediately below (Level 3) with respect to it. Then, the results obtained from the comparisons are used to weigh the priorities in the level immediately below (sub-criteria). Finally, the weighing process must be continued and added until the final priorities of the alternatives (Saaty, 2008).

AHP was also adopted for judgments in ERDP in order to build the optimal travel-time model for routing systems. Firstly, the most important elements that influenced the emergency routing decisions were chosen. As it was difficult to determine which impedance element should be more important, and also because it was difficult to quantify the element to build the travel-time model, the AHP was used to compare and calculate the weight of elements, and to evaluate those influences. Using the weighted elements allowed us to enhance the pgRouting algorithm and to implement the ERDP model for emergency routing in pgRouting. Similar approach was also demonstrated...
Table 1. The AHP scale for paired comparisons

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equally important</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>3</td>
<td>Moderately important</td>
<td>Experience and judgment slightly favour one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>Very important</td>
<td>Experience and judgement strongly favour one activity over another</td>
</tr>
<tr>
<td>7</td>
<td>Extremely important</td>
<td>An activity is favoured very strongly over its dominance is demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Extremely more important</td>
<td>The evidence favouring one activity over another one is of the highest possible order of affirmation</td>
</tr>
</tbody>
</table>

2.3 AHP structure and criteria selection

The AHP is a process that converts multidimensional complexity into an integrated single dimension scale of priorities which is the appropriate approach for ERDP. This section explains how to structure the complex problems. For priority score creation, the ERDP has been categorized into three main criteria (Level 2) which are the condition of roads and the availability of beds (AOB) at several nearest hospitals. Figure 1 shows the structure of AHP as a basic concept of model adopted in this study. In the sub-criteria (Level 3), the consideration of the road condition elements has been focused on several important points contributing to the travel-time, such as speed limit and junction delay. The criteria have been reset iteratively till all the elements in Level 2 agreement are reached (Sattayaprasert et al., 2008).

This study pays special attention to develop a routing model based on available road condition data. The hierarchy of AHP structure allows multiple criteria analysis (MCA) for all the possible alternative routes, in order to justify the total magnitude of transportation cost for ERDP logistics of the route alternative. The basic principle of pgRouting allows us to compute the route from a shortest travel-time (minimum cost) for all the alternative routes. Furthermore, the ratio scale used in the AHP approach enables us to compare tangible alternatives with criteria that are either tangible or intangible at the same time.

Once the structure of the ERDP decision is designed, one needs to calculate the weight of each element in order to give a priority weight to all elements.

2.4 Calculation of priorities

The AHP method uses two different techniques to determine the weights or the priorities: One is the Lambda Max ($\lambda_{\text{max}}$) technique and the other is the geometric mean method (Crawford and Williams, 1985). The geometric mean method was adopted in our research and the weights or priorities in a pairwise comparison matrix $A$ are calculated by the following equation (1) and (2):

$$v_i = \prod_{j=1}^{n} (a_{ij})^{1/n}, \ i = 1, 2, ..., n \quad (1)$$

$$w_i = \frac{v_i}{\sum_{j} v_j} \quad (2)$$

where $v_i$ is the geometric mean of the elements of the $i$-th row of matrix $A$, $a_{ij} (i = 1, 2, ..., n)$ are the values in the pairwise comparison matrix and $n$ represents the number of alternatives.

2.5 Consistency verification

The essential idea of the AHP is that a matrix $A$ of rank $n$ is only consistent if it has one positive eigenvalue ($\lambda_{\text{max}}$) equal to $n$, where $n$ is the number of criteria and $\lambda_{\text{max}}$ is the biggest eigenvalue, while all other eigenvalues are zero. In a practical approach, Saaty (1977) developed the unique variable called the Consistency Index (CI), in order to measure the deviation from a consistent matrix (Alonso and Lamata, 2006). The CI can be calculated by the following equation (3):

$$CI = \frac{\lambda_{\text{max}} - n}{(n - 1)} \quad (3)$$
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The Consistency Ratio (CR) is also introduced to help the analyst to make a decision based on the revision of the matrix. It is defined as the ratio of the CI to the Random Index (RI) which is a CI for randomly generated matrices (Alonso and Lamata, 2006). The value of \( \lambda_{\text{max}} \) is required for calculating the CR with the following equation (4):

\[
\text{CR} = \frac{\text{CI}}{\text{RI}}
\]

The comparison matrix will be considered to be consistent if there exists if CR < 0.1, otherwise the comparison matrix should be modified and all calculation should be performed again until the consistency ration meets the need (Kong and Liu, 2005). The various values of RI are shown in Table 2.

### 3. Results

#### 3.1 Pairwise Comparison Matrix

AHP consists in constructing pairwise comparison matrices and in extraction some weights by means of the principal eigenvector. Using a pairwise comparison matrix for \( n \) elements, the decision maker indicates how much element \( i \) is more important than element \( j \). The judgments are synthesized in order to determine the relative priority weight of the criteria. The decision making process in this study through the use of AHP can be described as follows. First, when comparing the main criterion element of Level 2, the Road Condition (RC) can be considered as moderately important (with a value of 3, referring to the AHP scale for paired comparisons in Table 1 with values from 1 to 9 to rate the relative preferences for two elements in the hierarchy with respect to their parent) when compared to the PS (Patient State). On the contrary, the AOB value (Availability of Bed) appears as less important (Value of 5) than RC. These values are placed in the first row of the matrix (Step I in Table 3). Then, in the second row’s third column of the matrix, when comparing PS with AOB, it appears moderately important (Value 3). Given that RC = 3PS, RC = 5AOB and PS = 3AOB, the initial matrix can be constructed, at Step I in Table 3. Subsequently, one has to divide each column entry by the column total value in order obtain the geometric mean (Step II and Step III in Table 3). One must finally to calculate the average value of every row (Step III in Table 3). At this stage, one can obtain the priority weight of RC, PS and AOB (RC = 63.70%, PS = 25.83% and AOB = 10.47%). Once the priority weighted value of the main criteria is determined, the comparison of the sub-criteria in Level 3 (Tables 4) is needed to give the priority weight for each RC sub-criteria element. The weights for all the other criteria at Level 3 and Level 2, as well as \( \lambda_{\text{max}} \), the largest eigenvalue of the pairwise comparison matrix (See the result of \( \lambda_{\text{max}} \) in Table 5 and Table 6), and CI and CR for Level 2 and 3, were calculated using the equations (3) and (4). Then, the weighting of the sub-criteria elements can be achieved, and the results are presented as Step III in Table 4. Therefore, from the priority weight of RC, the element in Level 2 equals to 63.70%
Table 3. Pairwise comparisons between criteria (Level 2)

<table>
<thead>
<tr>
<th>Step I</th>
<th>Step II</th>
<th>Step III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Geometric mean</td>
<td>Normalized geometric mean</td>
</tr>
<tr>
<td>RC</td>
<td>PS</td>
<td>AOB</td>
</tr>
<tr>
<td>PS</td>
<td>1/3</td>
<td>1/1</td>
</tr>
<tr>
<td>AOB</td>
<td>1/5</td>
<td>1/3</td>
</tr>
<tr>
<td>Σ</td>
<td>1.5333</td>
<td>4.3333</td>
</tr>
</tbody>
</table>

λ_{max} = 3.0385, CI (Consistency Index) = 0.0193, and CR (Consistency Ratio) = 0.0332

Table 4. Pairwise comparisons between criteria (Level 3)

<table>
<thead>
<tr>
<th>Step I</th>
<th>Step II</th>
<th>Step III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Geometric mean</td>
<td>Normalized geometric mean</td>
</tr>
<tr>
<td>RC</td>
<td>PS</td>
<td>AOB</td>
</tr>
<tr>
<td>PS</td>
<td>3/1</td>
<td>1/1</td>
</tr>
<tr>
<td>AOB</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>Σ</td>
<td>4.5000</td>
<td>1.6667</td>
</tr>
</tbody>
</table>

λ_{max} = 3.0536, CI (Consistency Index) = 0.0268, and CR (Consistency Ratio) = 0.0462

Table 5. Result of λ_{max} in Pairwise comparisons Level 2

<table>
<thead>
<tr>
<th>Σ column</th>
<th>Normalized geometric mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>1.5333</td>
</tr>
<tr>
<td>PS</td>
<td>4.3333</td>
</tr>
<tr>
<td>AOB</td>
<td>9.0000</td>
</tr>
</tbody>
</table>

λ_{max} = 3.0385

Table 6. Result of λ_{max} in Pairwise comparisons Level 3

<table>
<thead>
<tr>
<th>Σ column</th>
<th>Normalized geometric mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>4.5000</td>
</tr>
<tr>
<td>PS</td>
<td>1.6667</td>
</tr>
<tr>
<td>AOB</td>
<td>6.0000</td>
</tr>
</tbody>
</table>

λ_{max} = 3.0536

Table 7. The result of priority weight for all elements

<table>
<thead>
<tr>
<th>Priority Weight of Impedance elements</th>
<th>Road Condition</th>
<th>The Patient's state</th>
<th>Availability of beds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63.70%</td>
<td>25.83%</td>
<td>10.47%</td>
</tr>
<tr>
<td>Distance</td>
<td>15.88%</td>
<td>37.81%</td>
<td>10.00%</td>
</tr>
<tr>
<td>Speed Limit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junction Delay</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
but the total of priority weight in sub-level is 100%. The priority weight in the sub-criteria was recalculated and Table 7 showing the new priority weights of all elements was obtained.

The $\lambda_{\text{max}}$ value is calculated by multiplying the values of $\Sigma$ column and Geometric Mean and $\lambda_{\text{max}}$ value for all elements. This can be accepted because the value equals the amount of elements. Then, the CI and CR values are calculated from formulas (3) and (4). The RI value is used from Table 2.

Thus, the judgment formed in the criteria matrix (Table 3 and Table 4) is acceptable if a limit is used, as suggested by Saaty (1997), a CR value of less than 10% demonstrates a good consistency of the judgment.

3.2 Integration of the AHP priority weights value with the pgRouting algorithm

Based on the pairwise comparison between criteria in Level 2 and Level 3, the priority weight of each element was taken into account to compute the weight value. In order to combine AHP weighted elements with pgRouting, each segment of the road network data must be redefined in the minimal travel-time for ERDP depending on the PS and the AOB values. The combination of the weighted elements with the road length is needed to compromise the impedance element for the ERDP, which results in the minimal travel-time for ERDP. The concept of integrating AHP into the classical Dijkstra algorithm is presented in the following Figure 2.

4. Discussion

This study used both AHP and pgRouting algorithm in order to implement the ERDP model. AHP was used to generate priorities weight values for all the elements to be used in the pgRouting algorithm for the computation of the minimum cost (weight) value. The classical pgRouting algorithm and AHP analysis based on pgRouting are now well accepted by the scientific community. Although pgRouting algorithm is not a complete solution that considers conditions at source/target and the problems affecting the real road networks, it has an important role to play for creating better emergency routing systems.

Several studies about enhanced emergency routing planning with the travel-time depending on the road network (Cherrie and Dickson, 2006) have been attempted, but none have used AHP to generate the priority weight of the elements. Some other studies were carried about AHP with routing planning (Huang, 2004; Ohta et al., 2007; Sattayaprasert et al., 2008), but most of them use a static alternative route in terms of direct distance, road width and type and junction delay, between the start node and the destination node. In order to obtain more alternative routes on dynamic networks, in terms of emergency routing planning modelling, the present study is an enhancement of the pgRouting algorithm by integrating AHP. This allows us to compute the best route from any start node (alternative way in a dynamic network) to the destination node.

As mentioned before, the Dijkstra algorithm is widely used in current GIS-based routing applications. Figure 4 (a) shows the result of classical Dijkstra function in pgRouting algorithm which computes the shortest distance from the minimum cost based on a graph $G = (V, A)$. In this example, if the state of the patient is not in the Code Red condition (A "Code Red" means that the patient needs to be resuscitated or needs very intensive care), and hospital A and hospital B have no AOB, then the shortest part from the start node (accident point) to hospital C is computed, using the Dijkstra function. In this case, the other elements such as junction delay or road width are ignored in the calculation. Therefore, due to the lack of consideration of the real road situation, this routing scheme will not be adopted for ERDP as the ambulance would be delayed by the narrow road width and the long junction delay. We can also assume that the high populated places would also influence ambulance velocity. It would rather uses the other route to the destination. Figure 3 shows the chart of a logical system for ERDP.

With the AHP analysis to enhance the pgRouting algorithm for ERDP, from a graph $G = (V, A)$, it is calculated after the priority weights value were taken into account with a graph $G = (V, E_D \cup E_s \cup E_j)$ where $E_D$ is the distance value, $E_s$ is the speed

![Figure 2. The integration of AHP and the Dijkstra algorithm for ERDP](image-url)
Multi-Criteria Emergency Route Planning Based on Analytical Hierarchy Process and pgRouting

Figure 3. The chart of the logical system for ERDP

(a)  (b)

Figure 4. Routing result comparison between the classical pgRouting algorithm (a), (c) and the ERDP function (b) and (d) are the different ERDP result when the route is computed during normal hours (a), (b) and traffic peak time (c), (d).
limit value and $E_j$ is the junction value. The experiment was carried out under the same assumed conditions, and the result compared with the classical Dijkstra was presented in Figure 4 (b). The difference between two routing schemes lies in the consideration of impedance elements considered in this research. In this example, when comparing the results between classical Dijkstra and ERDP function, the one from the ERDP function have a longer distance but faster travel time than the result from the classical Dijkstra function. The resulting route produced by the pgRouting algorithm enhanced with AHP corresponds to the best ERDP after an accident would happen. Thus, the integration of the AHP within pgRouting can provide more preferable routes for than the one obtained using the classical algorithm. Figure 4 (c) and Figure 4 (d) present different routes from the accident point to the hospital, when the accident occurs in the same place but at peak hour. In this example, we assume that the traffic conditions are always the same, without any peak. Figure 4(c) shows the resulting route for an accident which calculated by Dijkstra function whereas Figure 4(d) shows the resulting route which calculated by ERDP function after an accident which occurred during 7:00 AM - 8:30 AM and 5:00 PM - 6:00 PM, which correspond to the traffic peak time. Indeed, most people go to work or school and go back home during these time slots, leading to heavy traffic. For example, the roads where the schools are located might present traffic jams during the peak times. Such road segments are shown in red color in Figure 4(d), and their speed parameter is reduced to 15 km/h. The routing result calculated by Dijkstra function (Figure 4(c)) is not changed when comparing with the result which occurred in the normal hour (Figure 4(a)) but with the ERDP function the routing result is changed between the normal hour (Figure 4(b)) and peak time (Figure 4(d)) accident occurred.

5. Conclusion

The use of Free and Open Source Software library such a pgRouting algorithm is recommended to find the shortest path on the graph. However, providing only the shortest distance is not sufficient to improve ERDP system in the complex road networks, and the minimum travel-time is an important element to take into account.

AHP allows the decision makers to determine which criteria calls for greater consideration based on their subjective preferences, especially when the factors in consideration do not have a common scale of measurement, or are intangible with no existing scale of measurement.

Integrating AHP analysis into the pgRouting algorithm allows us to analyse ERDP. The simulations were carried out under the same assumed conditions, and the results were compared with the one obtained with the classical pgRouting algorithms and presented.

This study suggests that AHP analysis can be integrated in pgRouting and that it can be used to analyse accessibility and compute the best suitable routes. Using this method, a preferable route scheme can be achieved which have a significant meaning in emergency routing for ambulances. Finally, the analytical method may be useful to analyse and improve emergency responses for other disaster evacuation planning needs.

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References


要旨

階層構造分析法と pgRouting を用いた多基準緊急ルート解析

シッティチャイ サムロング・ベンガテシュ ラワワン・ニコラ ポゾン

ルート検索処理は緊急対応や緊急決定時に重要な役割を果たす。例えば、出来ただけ早く患者を救急車で病院へ搬送する場合である。本論文では目的地での事故の位置情報をもとに、ルートの移動時間を計算する手法を示す。ここでは事故地点から一番近い病院までの最小移動時間を推定された病院のベッド数や患者の状態などを考慮したいくつかのパラメータが計算される。この手法は緊急ルート決定計画（ERDP）のための階層構造分析法（AHP）である pgRouting アルゴリズムにもとづいている。最初に重み付けられた移動時間モデルは ERDP に影響する 3 つの障害要因とともに最少の移動時間の設定がおこなわれる。その後、AHP は移動時間に関係するすべてのパラメータを考慮し、障害要因の優先順位を計算する。さらに、目的地の状況に従って重み付けられた移動時間を検索する新しい改良されたルート検索アロギズムを pgRouting の中に実装した。

AHP と pgRouting の統合により、道路と目的地の状況の両方を分析する効果的なツールとなった。このことは、自然災害後の避難計画にも有効である。

キーワード：pgRouting, 道路状況, 重み付けられた移動時間, 階層構造分析法, 緊急ルート決定計画