A Novel Computational Mathematical Model for Team and Route Selection of the Emergency Response Operations

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ABSTRACT

During the daily operations of emergency response, the decision maker is faced with the complex challenge of selecting a team and route in a short time period to respond and attend to the emergency. This study presents the combined use of the Analytic Hierarchy Process (AHP), the Élimination Et Choix Traduisant la Realité II (ELECTRE II), and the Dijkstra algorithm to deal with such situations. First, the AHP method is implemented to rank the aspects that are most relevant to a given emergency. Subsequently, this ranking is employed in ELECTRE-II to determine which emergency response team is best prepared to provide support. In the last stage of the proposed model, regarding the geographic coordinates of the team and the emergency, the Geographic Information System (GIS) utilizes the Dijkstra algorithm to regulate the most suitable route for assistance.

Keywords-AHP; ELECTRE II; GIS; Dijkstra algorithm; emergency response operations

I. INTRODUCTION

Public safety organizations deal with the most diverse situations every day. Emergency services, such as police, fire, and health services, encounter unprecedented challenges as the nature, form, and pattern of the risks faced by society increase and change [1-2]. The main objective of incident management is to provide emergency services as quickly as possible to the affected areas [3]. To achieve this goal, numerous factors must be assessed and considered in a relatively short decision-making period. Particularly in emergency response, issues such as the number of rescuers, resources, and equipment, as well as the routes to be followed and spatial attributes, are crucial for estimating response times. In these situations, managers often need to be equipped with tools to help with planning and management and promote better assistance [4]. Several incident management tools are available, including Multi-Criteria Decision Making/Aid (MCDM/A).

MCDM/A is a tool that implements the knowledge of experts in computational mathematical procedures to model complex problems and support decision-making [5-6]. MCDM/A approaches differ from each other in terms of data aggregation, normalization, structuring, output type, and application kinds [7]. For example, in emergency operations, rescue agencies must organize staff and materials quickly and coherently according to the emergency needs. However, the decision criteria for the distribution of emergency resources are often diverse, along with a lack of information acquisition due to the complexity of the event [8]. In this impasse, multi-criteria methods, such as AHP and ELECTRE-II, may contribute to modeling these problems.

In addition to the administrative support management process, reaching the incident site in a short time is also crucial, as it can be a determining factor in the success of the assistance provided. In this process, many factors, such as road width, speed limits, and traffic volume, affect route selection [9]. One strategy that helps decide on an ideal route is the use of the Dijkstra algorithm associated with GIS. The Dijkstra algorithm is based on graph theory, whereas its dynamics correlate with finding the path with the lowest cost from a starting to a destination node by comparing the weights of the paths to identify the most efficient pattern [10]. GIS offers powerful resources for network analysis and urban traffic network management [4]. GIS are systems for processing and storing geospatial data, vectorization, and real-time visualization of objects and events, also providing a robust set of geospatial analytical tools and strategic support for management decisions [11].

Responding to an incident is a complex task, as it involves both administrative and spatial processes. In situations entailing these characteristics, many studies have combined MCDM/A with a GIS in several ways. In [12], the AHP method was combined with GIS to determine flood risk zones. In [13], these methods were combined to analyze fire risks in factories. In [14], a similar method was used to analyze landslides to plan support routes for an event. In [15], TOPSIS and GIS methods were combined to build a flood-support environment. Despite the great applicability of this combination, there is a scarcity in the necessity for overcoming MCDM/A, in which overcoming relationships are built between alternatives and there are computational limitations due to the large spatial dataset [16-18].

This study combines MCDM/A with GIS in a different approach, using a model that focuses on the dynamic situation of an incident call. In emergencies, the manager must quickly decide to meet the demands of the incident and determine which team and route are the most appropriate for assistance. To assist him, the AHP and ELECTRE-II methods were combined with the Dijkstra algorithm, due to the flexibility and robustness of multicriteria methods combined with the potential of GIS for spatial problems.

II. METHODOLOGY

A. Analytic Hierarchy Process (AHP)

AHP enables a combination of rational and irrational intuitive values in decision-making through a pairwise comparison approach [19-20]. The ability to model the thought processes of experts allows for the decomposition of complex problems into a hierarchical arrangement of criteria and sub-criteria. The dynamics of its application comprise the stages of structuring the model, the comparative judgment of alternatives and criteria, and the synthesis of priorities. As a starting point for the application of AHP, the structuring of the model comprises the decomposition of a complex decision problem into a hierarchical structure of criteria, as shown in Figure 1.

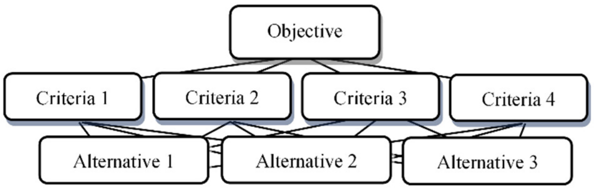

Fig. 1. Hierarchical structure of AHP.

Figure 1 shows the hierarchical structure of the AHP method, showing the arrangement in levels, where the top level establishes the general objective of the problem. The next level includes multiple criteria involved in the solution, and the possible alternatives are at the last level. After structuring, the paired judgment stage follows, where expert knowledge is used based on experience, intuition, and expertise to determine the relevance of one criterion over another with a focus on the main objective, using a numerical scale to transform verbal assessments into numbers. The values derived from the judgments were used to construct comparison matrices. Thus, A can be formulated as an $n \times n$ matrix, for n criteria:

$$A = \begin{array}{c} C_1 \\ C_2 \\ \dots \\ C_n \end{array} \begin{bmatrix} C_1 & C_2 & \dots & C_n \\ 1 & a_{12} & \dots & a_{1n} \\ \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{1n} & 1/a_{2n} & 1 \end{bmatrix} \quad (1)$$

where n is the number of criteria to be evaluated, C_i is the criterion i, and a_{ij} is the weight of criterion i to criterion j. Matrix A must satisfy the condition of reciprocity (i.e., if C_i is a_{ij} more preferable than C_j, then C_j is $1/a_{ij}$ times more preferable than C_i). From the judgment matrix, the importance or relative weight of the criteria can be calculated through normalization as:

$$w_{Cn_i} = \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}} \quad (2)$$

Normalization produces a single estimate of the ratio scale underlying the judgments [21]. In real-world problems, it is impossible to obtain a perfectly consistent judgment matrix after a pairwise comparison [22]. This is due to the possibility of uncertainty on the part of decision-makers when comparing certain elements [23]. In this context, the consistency index was introduced to measure the coherence of judgments [24]:

$$CI = \frac{\lambda_{máx} - n}{n-1} \quad (3)$$

where CI is the consistency index, n is the number of criteria evaluated, and λ_{max} is the eigenvector of A. A consistency relationship (CR) was also proposed to determine whether the value of CI is appropriate. CR is determined by the ratio between the values of the consistency index CI and the random consistency index RI according to:

$$CR = \frac{CI}{RI} < 0.1 \sim 10\% \quad (4)$$

where CI is the consistency index and RI is a random index that relies on the dimension of the matrix being compared. RI is a tabulated value derived from an experiment with a sample size of 500 filled with random values from the scale [25]. The accepted limit for CR is 0.1. If the CR exceeds this value, the evaluation procedure should be repeated to improve consistency. When CR is within the expected range, the method leads to an approximation of the decision-maker's priorities.

B. Method of Elimination and Choice Translation Reality (ELECTRE-II)

ELECTRE-II is part of a family of methods based on the aggregation of preferences [26], which also works with paired comparisons of actions, but with an overcoming approach [27]. To apply this method, A was considered as a set of actions and g_i(a) as the evaluation of any of these actions according to the criterion i (i = 1, 2, …., n). Applying the overclassification relation to the elements of the set, A can be defined if an alternative a outranks b. This gives aSb, if alternative a is at least as good as alternative b. After evaluating the criteria, the next step is to calculate the agreement and disagreement matrices, which are constructed using the agreement and disagreement indices. The ELECTRE-II method uses concordance indices, which is the extent to which one alternative outperforms the other based on a comparison between the criteria by:

$$C(a,b) = \frac{1}{W}\sum_{j:gj(a)\geq gj(b)} w_j \qquad (5)$$

where $W = \sum_{j=1}^{n} w_j$

and disagreement, which is the performance disadvantage of one alternative over another based on a comparison between the criteria, as defined in:

$$D(a,b) = 0, se\ g_j(a) \geq g_j(b) \forall_j \text{ or}$$

$$D(a,b) = \frac{1}{\delta} max_j\left[g_j(b) - g_j(a)\right], n.c$$

$$with\ \delta = max_{c.d.j}\left[g_j(c) - g_j(d)\right] \qquad (6)$$

where *g* is the evaluation of the actions and *δ* is the amplitude of the criteria for each alternative. In ELECTRE-II, strong and weak agreement and disagreement thresholds (c_1, c_2, d_1, d_2) are used to find strong and weak overclassification relations (S^F) and (S^f), respectively, which are calculated using:

$$aS^F b\ if\ = \begin{cases} C(a,b) \geq c_1 \\ D(a,b) \leq d_1 \\ \sum_{j:gj(a)>gj(b)} w_j > \sum_{j:gj(a)<gj(b)} w_j \end{cases} \qquad (7)$$

$$aS^f b\ if\ = \begin{cases} C(a,b) \geq c_2 \\ D(a,b) \leq d_2 \\ \sum_{j:gj(a)>gj(b)} w_j > \sum_{j:gj(a)<gj(b)} w_j \end{cases} \qquad (8)$$

Ordering is determined through two preorders constructed using two over-ranking relations (S^F, S^f). In S^F, a ranking is made in descending order of the alternatives, while in S^f the ranking must be in ascending order. Once the two rankings are established, the final step in ELECTRE-II is to order them according to their average rankings. This establishes a complete order of the classification [28].

C. GIS and Dijkstra Algorithm

The spatial nature of emergency response is fundamental for the construction of efficient routes. Road networks in urban areas occasionally suffer from obstructions, whether due to road obstructions, traffic jams, or other types of adversity, causing traffic to be blocked [21-22, 29]. Under these circumstances, the layers of data provided by a GIS and associated with the Dijkstra algorithm can be useful in creating new routes that speed up the service. Determining the shortest path is a fundamental problem in graph theory [30]. Based on the graph theory, Dijkstra's algorithm can search for the shortest path between two vertices. The wide spectrum of its applications ranges from routing problems in communication networks to robot motion planning and highway and power line engineering [31]. This algorithm accepts the input of a graph *G* that has weights between two interconnected nodes, a starting and an ending node that is the destination of the route [32].

Consider a weighted graph *G* with *n* vertices numbered from 1 to *n*. Let *d*[*v*] be the current distance from the source vertex *s* to vertex *v* and *w*(*u*, *v*) be the weight of the edge that connects *u* and *v*. The algorithm maintains a set *S* of vertices whose shortest distances from *s* are known. The algorithm can be understood as follows:

```
1. Initialization:
   d[s]=0
   d[v] = ∞ for v ≠ s
   S = ∅
2. For each vertex v in G:
   S = S ∪{v}
   For each vertex u adjacent to v in G:
      If d[v] + w(u,v) < d[u]:
         d[u] = d[v] + w(u,v)
3. Remove v from S
4. Repeat step 2 and 3 until S is empty
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Finally, the vector *d* will contain the shortest distances from the source vertex *s* to all other vertices in the graph. The algorithm has the potential to extract complex geographic information for network analysis [33]. To achieve this, the vertices corresponding to geographic coordinates are connected by polylines representing roads or transport routes [34]. Therefore, by linking it to a GIS, the road network can be adapted to source-destination problems by attaching the information that a GIS offers (types of street structure, afforestation, and flow) to the attribution of weights used in the algorithm to build the ideal access route to events.

D. The Proposed Model

The proposed model is an integrated MCDM/A and GIS approach comprising the AHP-ELECTRE II methods and the Dijkstra algorithm, as shown in Figure 2.

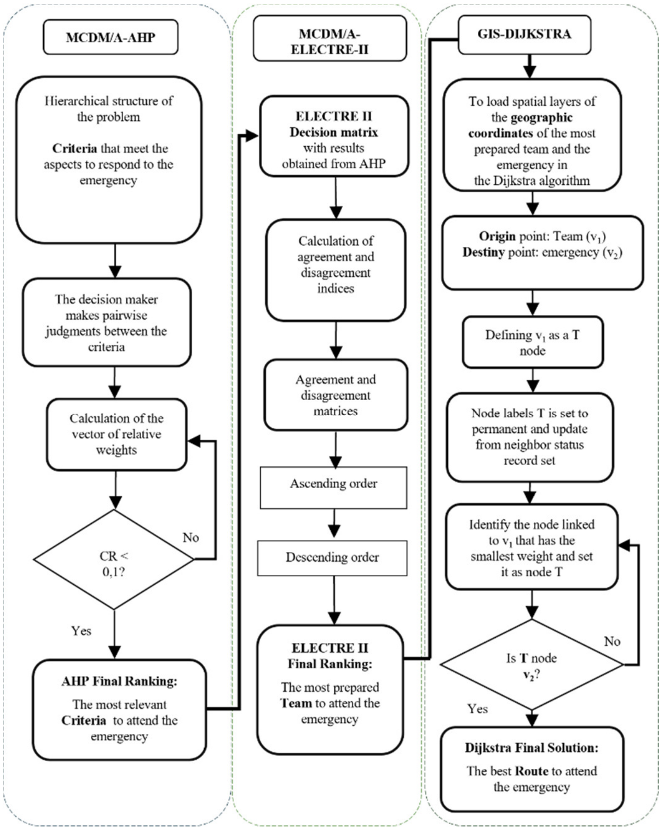

Fig. 2. Proposed model.

First, the most relevant criterion for occurrence is determined using the AHP method. At this stage, the experience of the manager helps determine the importance of each criterion, generating a ranking of the most important criteria [35]. The values of these criteria are used as weights in the ELECTRE-II decision matrix, which determines the team that is most prepared for support. Consequently, the ELECTRE-II method provides an outperforming relationship between teams. This relationship consists of ordering teams according to the assistance conditions. This configuration, in addition to providing the most suitable team, also allows switching to a second or third team, or a team that is more prepared for the situation, thus bringing more agility and dynamism. When considering the coordinates of the support team and its occurrence in a GIS, the Dijkstra algorithm can be used to calculate the access routes.

III. APPLICATION EXAMPLE: EMERGENCY WITH DANGEROUS PRODUCTS

To demonstrate the proposed method, an example of an emergency incident with dangerous products was used. In this context, given the changes over the last few decades, there has been a continuous increase in the rates of accidents with dangerous products, along with associated adverse impacts such as human, environmental, and economic losses [36]. To intervene in these accidents, services such as those provided by fire departments are often requested to inspect and isolate sites [37]. To prepare the model, the criteria presented in [38] were considered for the categories of equipment, accessories, and vehicles. When considering the necessary criteria for this occurrence, an example of decision modeling based on the AHP method can be constructed as shown in Figure 3.

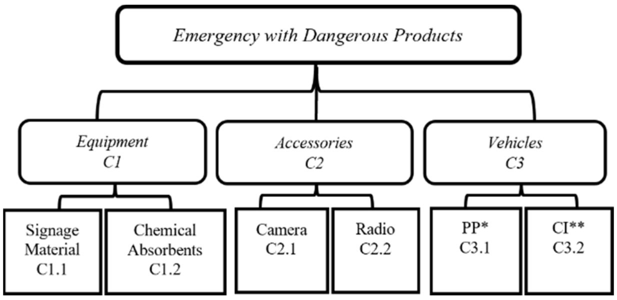

Fig. 3. The hierarchical structure of the example based on AHP (PP*: Vehicle for dangerous products | CI**: Fire fighting vehicle)

Table I shows the results of paired comparisons of the process after the hierarchy involves judging the criteria, evaluating the consistency of the judgments, and synthesizing the priorities using the AHP method.

TABLE I. RESULTS OF PAIRED COMPARISONS OF CRITERIA

Criteria	Equipment	Accessories	Vehicles
Equipment	1	5	1/3
Accessories	1/5	1	1/7
Vehicles	3	7	1

To evaluate consistency, the *CR* was calculated using (4):

$$CR = \frac{CI}{RI} = 0{,}05$$

If $CR < 0.1$, the judgments are considered consistent. Following this process, pairwise comparison matrices are constructed for the subcriteria. Table II presents the general classification.

TABLE II. CLASSIFICATION RESULTING FROM THE AHP METHOD

Criterion weight	Sub-criterion weight	Cumulative weight	Classification
C1: Equipment $w = 0.283$	C1.1: Signage Material w = 0.266	0.075	4
	C1.2: Chemical absorbents $w = 0.734$	0.207	3
C2: Accessories $w = 0.074$	C2.1: Camera $w = 0.680$	0.053	5
	C2.2: Radio $w = 0.320$	0.023	6
C3: Vehicles $w = 0.643$	C3.1: PP $w = 0.630$	0.405	1
	C3.2: CI $w = 0.370$	0.237	2

As shown in Table II, among the evaluated criteria, the vehicles had the highest weights, followed by the equipment and accessories. The cumulative weights of the criteria from the AHP method were considered for team classification using the ELECTRE-II method, as shown in Table III. At this stage, the method helps to decide which team is the most appropriate to support the incident.

TABLE III. ELECTRE-II METHOD EVALUATION

Alternatives	Equipment		Accessories		Vehicles	
	C1.1	**C1.2**	**C2.1**	**C2.2**	**C3.1**	**C3.2**
Team 1	3	5	6	3	2	5
Team 2	6	4	7	4	6	8
Team 3	2	5	3	7	4	6
Weights	**0.075**	**0.207**	**0.053**	**0.023**	**0.405**	**0.237**

Using the agreement index in (5), the concordance matrix shown in Table IV is obtained. The discordance matrix according to (6) is shown in Table V.

TABLE IV. CONCORDANCE MATRIX

	Team 1	Team 2	Team 3
Team 1	0.000	0.207	0.335
Team 2	0.793	0.000	0.776
Team 3	0.872	0.230	0.000

TABLE V. DISCORDANCE MATRIX

	Team 1	Team 2	Team 3
Team 1	0	1	1
Team 2	0.25	0	0.75
Team 3	0.75	0.75	0

Once the agreement and disagreement matrices are obtained, the agreement and disagreement thresholds must be established. Thus, based on the values of the matrices, the thresholds can be defined as: $C_1^* = 0{,}85$, $D_1^* = 0{,}50$; $C_2^* = 0{,}76$; and $D_2^* = 0{,}65$. Having established limits, overcoming relationships are constructed according to the following rule: If $C(a,b) >= C^*, D(a,b) \leq D^*$, the alternative a is strongly superior to the alternative b. Based on this rule, a dominance matrix (Table VI) was defined to establish strong (S^F) and weak (S^f) relationships.

TABLE VI. DOMINANCE MATRIX

	Team 1	Team 2	Team 3
Team 1	0	–	–
Team 2	S^F	0	S^f
Team 3	S^F	–	0

In Table VI, overclassification relationships can be observed based on established thresholds. In this case, Team 3 S^F Team 1 indicates that Team 3 significantly outperforms Team 1. Considering these relationships, the ordering can be performed through ascending and descending distillation processes. The descending preorder is constructed by taking the set of best alternatives, those that outperform other alternatives, and descending to the worst. In contrast, the ascending preorder is constructed by starting with the set of "worst" alternatives, those that are outperformed by other alternatives, and moving up to the best. Therefore, the final classification is as follows: Team 2 > Team 3 > Team 1, where Team 2 exceeds Team 3 and 1, and Team 3 exceeds Team 1. This configuration helps in situations where the indicated team is occupied, and the ordering of the second team with a greater support capacity can take over the occurrence, contributing to the dynamics of the phenomenon.

By ordering the teams, it is possible to define a route using Dijkstra's algorithm. Therefore, the spatial coordinates of the indicated support teams and their occurrence constitute the problems of origin and destination. In this example, a simulation of Dijkstra's algorithm was performed using the open-source Flutter user interface development kit, based on the Dart programming language [39]. For this simulation, an area covering a graph with 20 nodes was considered, with the initial node containing the geographic coordinates of the support team and the final node containing the geographic coordinates of the incident. This graph consists of streets and accesses. Figure 4 shows the possible access routes and Table VII shows a list of possible routes using the Dijkstra algorithm. According to Table VII, the most efficient route is {B, C, D, I, O} which leads to the incident at the lowest cost. Therefore, in this example, using initially the AHP method, the proposed model allowed the assessment of the criteria necessary to respond to emergency calls involving dangerous products (equipment, accessories, and vehicles). Subsequently, using ELECTRE II, the model made it possible to determine which of the teams was best able to deal with the incident (Team 2). In the last stage of the model, Dijkstra's algorithm determined the best route to respond to the incident (route {B, C, D, I, O}).

Fig. 4. Access routes.

TABLE VII. POSSIBLE ACCESS ROUTES

	Route	Cost	
Origin	B, G, M, N, S	(1+1+3+3+2+1) = 11	**Destination**
	B, G, H, I, O	(1+1+5+3+2+1) = 13	
	B, C, D, I, O	(1+3+1+1+2+1) = 9	
	B, A, F, L, Q, R, S	(1+2+6+3+2+4+2+1) = 21	
	B, C, H, N, S	(1+3+4+3+2+1) = 14	

IV. CONCLUSION

This paper presented a mathematical computational model based on two multi-criteria methods combined with the Dijkstra algorithm to support emergency operations. Compared to previous studies, this method stands out for its dynamic approach to the incident support process, proposing an arrangement that combines the robustness of multi-criteria methods and the efficiency of the Dijkstra algorithm. One of the purposes of this study was to incorporate the experience of decision-makers into a model that considers their expertise combined with spatial dynamics in responding to incidents. To achieve this, a multi-criteria approach was used that enables the transformation of experience into numerical values in complex decision problems. Due to the complex characteristics of an incident, the AHP and ELECTRE-II methods sought to address the importance of specific values for a given incident and how to use the best resources offered by support teams. In the decision matrix of the ELECTRE-II method, adding the weights of the AHP method, which is used to determine the most important criteria for a given situation, provides a better approach to selecting the team that is best prepared to help.

One of the concerns considered was the search for a method that would bring about an ordering of support teams so that when it is impossible to have one, the manager could have a sequence of teams as an option. In this case, the ELECTRE-II method was quite competent by considering strong and weak overcoming relationships in its final ordering. Furthermore, the choice of this method contributes to the lack of overcoming methods in these scenarios. In addition to the administrative nature of resources, Dijkstra's algorithm and GIS were used to consider the spatial dynamics of the phenomenon in determining routes. In this strategy, spatial information from the GIS is considered and weighted in the algorithm. Therefore, by combining MCDM/A with GIS, the presented formulation seeks to contribute to a more holistic scope of the incident by adding an administrative aspect and covering the spatial part.

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