Optimization of Emergency Medical Service with Fixed Centers

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Abstract: The research reported in this scientific paper focuses on practical usage of optimization methods aimed at improving the service accessibility for clients spread over the whole Slovak Republic. The results of previous research confirmed by a computer simulation indicated that the weighted *p*-median problem is a suitable way of optimization. Here, we pay attention to the inconvenience of current ambulance stations deployment, which consists in the fact that there are same locations with two or more stations equipped with an ambulance vehicle. On the other hand, the standard weighted *p*-median problem formulation allows locating at most one station to one place. Furthermore, when searching for a better service center locations, the capacity of a center should be taken into account at least partially. Otherwise, the station with a high number of assigned clients would not be able to satisfy all the demands. Such result may be considered inacceptable. We believe that mentioned disadvantages could be overcome by fixing some stations, which will not be allowed to change their current location. The results of suggested optimization process are compared with the analysis of current ambulance stations deployment form more points of view.

1 INTRODUCTION

Emergency Medical Service (EMS), fire brigades and many other rescue systems are established to ensure rapid information, activation and effective usage and coordination of the forces and resources of rescue services in providing the necessary assistance. The role of such systems is to provide the affected person with the necessary assistance in the case of a threat to life, health or property without any delay to prevent from irreversible losses on health or life. Obviously, the quality and efficiency of the EMS system depends mainly on the number of stations operating in the considered area (in our case in the whole state) and on the location of the stations. Determining the right number of facilities is a very sensitive issue that must take into account two conflicting requirements. The first of them follows from the main mission of the EMS system - to save the life and health of the population. This task can be adequately fulfilled if the network of EMS stations is dense enough. Then the system is able to respond to an emergency call immediately and can provide first aid in a short time. On the other hand, there is a legitimate requirement for the efficient use of public resources, which limits the number of ambulance stations to be located. Limiting the number of service providing facilities results in an increase in their workload and a reduction in the availability of emergency care, as the nearest ambulance may be occupied at the time of an emergency call by providing a service to another patient. A situation in which a patient does not receive urgent medical care within a predetermined time limit is evaluated as a system failure (Brotcorne et al., 2003, Current et al., 2002, Doernet et al., 2005, Ingolfsson et al., 2008, Matiaško, Kvet, 2017). Therefore, this paper focuses on the strategic level of management of emergency health care. The main attention is paid to determining the optimal locations of EMS stations so that the accessibility of the service for patients is the highest possible. It can be assumed that the accessibility is the better the closer the EMS station is to the affected patient (Jánošíková, 2007).

The reasons to optimize the EMS system (to find new optimal service center deployment) may follow from more ideas, not only from establishing a new system. The necessity of system optimization usually follows from the fact that the distribution of demands changes in time and space. Naturally, the originally determined stations deployment may not fit now.

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Another reason for optimization of current EMS system consists in basic performance characteristics. Analysis of data given by EMS providers has shown that the average response time, i.e. time necessary to achieve the patient from the EMS station after an emergency call, has risen by almost one minute in the last years and thus the accessibility of urgent medical care for patients in critical condition has worsened. Such situation results not only in a deterioration in the availability of the service, but possibly in an increase in the number of unnecessary and avoidable deaths.

Furthermore, new roads have been built and the traffic has changed, too. Therefore, the deployment of current EMS stations should be regularly checked and optimized if necessary. We believe that some changes in the locations of EMS centers (without any change of their number) may contribute to improve average service accessibility for clients.

Let concentrate on the optimization process itself, now. It must be realized that there are several cities or smaller city districts, which are inhabited by a high number of potential patients. Such big demands for service are covered by more stations located at the same address. Such a situation needs to be taken into account also in the process of system optimization. There are several ways to cope with this problem. If we want to formulate a model that would allow locating more stations at the same place, we should follow the principle of multiple facility location problem as suggested in (Janáček, 2021). In such a case, the optimized design quality criterion should be based on the concept of generalized disutility. It means that the service does not have to be provided only by the nearest located EMS station, but by the nearest station being currently available (Kvet, Janáček, 2018, Kvet et al., 2019). If the minimized objective function takes into account only the distance or travel time from clients' locations to the nearest located source of urgent healthcare, than the mentioned modeling approach does not hold.

The optimization process studied in this paper is based on two steps. In the first phase, some of EMS stations get fixed. It means, they are not allowed to change their current location due to the large number of emergency calls assigned to them. The second phase of the optimization approach is based on the mathematical model, which searches for the best possible locations of the remaining stations.

The structure of this paper is organized as follows. The next section contains an analysis of current EMS stations deployment and it explains the emergency system in Slovakia. The third section contains the details about the suggested optimization strategy and the proposed mathematical model. In the fourth section, we provide the readers with a computational study, in which the results of suggested method are presented. This section contains also a comparison of the obtained results to the current state. Finally, the last section brings some brief concluding remarks and suggests new possible future research directions.

2 EMS SYSTEM IN SLOVAKIA

The Emergency Medical Service system represents a pre-hospital part of the urgent care provision, which forms the highest level of differentiated medical care. It can be also defined as providing the urgent health care to a person in such a condition in which their life or health is suddenly endangered and the affected person is dependent on the rescue service. The EMS system is a part of the Integrated Rescue System of the Slovak Republic.

In its current form, the EMS system in Slovakia operates 274 stations, which can be divided according to the type of crew into the following two groups:

1. ***RZP stations*** – The crew consists of two members - a paramedic and an ambulance driver, or two paramedics (one as a driver). There are currently 188 ambulances of this type in Slovakia. Some of them are equipped with an incubator to transport newborns.
2. ***RLP stations*** – The ambulance staff consists of three members: a doctor specialist in emergency medicine, anesthesiology and intensive care (or another specialization); paramedic and an ambulance driver, or a doctor with two paramedics. There are 86 such ambulances in the Slovak Republic.

In addition, the private company Air - Transport Europe, operates 7 stations of the Helicopter Rescue Medical Service. Some of the RLP ambulances are equipped with a mobile intensive care unit for the transport of critically ill patients. This special equipment follows from the decision of the Ministry of Health of the Slovak Republic based on the recommendation of the Emergency Medical Operations Center. In August 2014, the number of extra equipped RLP stations was set at 5. Other types of EMS ambulances, such as in the surrounding countries, are not recognized by Slovak legislation (Doerner et al., 2005, Marianov, Serra, 2002, Reuter-Oppermann et al., 2017, Schneeberger et al., 2016).

For completeness, the RZP stations are located in 166 different places (in some of them, there are two or even more). The RLP stations are placed totally in 80 locations. The total number of network nodes with at least one ambulance regardless of its type is 207. These 274 stations cover the demands of totally 2,934 municipalities spread over the area of Slovakia.

As mentioned in previous parts of the paper, the accessibility of the EMS is generally the better the closer is the service provider to the client location. From the point of the service access analysis, it is necessary to distinguish two basic approaches:

1. Take into account the average distance of all clients from the nearest station, regardless of its type. In the case of selected specific diagnoses from the first hour quintet, this view may not be appropriate, because the RLP needs to be present at the scene.
2. Analyze the distance only to the nearest RLP station. This value of service accessibility will be logically higher than in the previous approach, but in cases of specific diagnoses, it models the situation better.

The following Table I summarizes selected basic performance characteristics of the system not only for the entire system (RZP and RLP stations together), but also for RLP type stations separately. Let us remind that patients who need to be satisfied in the case of an acute life and health threat are concentrated in totally 2,934 municipalities. The municipality's weight can be expressed in many different ways:

1. Number of emergency calls of patients in critical or urgent condition (this number may not be proportional to the population of the municipality)
2. Absolute number of inhabitants sharing the location
3. The value of one (all municipalities have the same weight, the municipality size does not play any role)

In this computational study, we report the results for each possible weight of a client location. The final selection of the correct municipality weight is up to the decision-maker or other authority responsible for the decision-making process. The basic numerical characteristics to express the service accessibility are:

- Average time in minutes the ambulance vehicle needs to achieve the affected patient,
- Maximal time in minutes that the ambulance crew must travel to get to the farthest patient,
- Percentage of demands covered within 8 or 15 minutes from the nearest located station.

The service providers defined the limits 8 and 15 minutes according to their internal rules following from the standards of urgent healthcare.

Table 1: Analysis of current EMS stations deployment.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	31.5	31.5	31.5
	Average response time	5.73	5.72	7.75
	15 min percentage	98.29	98.48	93.76
	8 min percentage	73.28	73.03	48.06
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.98	7.99	11.72
	15 min percentage	86.75	87.09	69.97
	8 min percentage	53.97	53.50	20.79

The analysis of current EMS stations deployment shows many important things: The positive is that the current situation is not bad, rather the opposite. Almost 100 percent of requests can be satisfied within 15 minutes by the nearest located service center regardless the type of ambulance staff. On the other hand, the obtained characteristics indicate that the accessibility of the service provided by RLP stations only deserves a strong improvement. Therefore, this research paper introduces an optimization method to improve the current state. Presented approaches are suggested in such a way that they perform only little changes in current service center deployment with great effect on service accessibility. We expect that since the performed changes will not be too large, public authorities responsible for EMS system performance efficiency could accept them.

3 TWO-PHASE OPTIMIZATION OF CURRENT EMS SYSTEM

The main goal of this section is to provide the readers with the details of proposed optimization method suggested to achieve better EMS stations deployment mainly from the point of RLP stations performance efficiency.

As it was mentioned in the introducing section, the proposed optimization method is based on two phases. Since we want to make such a mathematical model, which avoids locating more than one center to the same place, and we assume the objective function to consider only the nearest EMS station for each client, the first phase of the algorithm consists in pre-processing those center locations, in which there are currently more than one facility.

The first phase does not contain any optimization. Its core idea consists in pre-processing the input data. Let us introduce necessary denotations to formulate the first phase precisely. We will use the set I to denote the set of locations, which are the candidates for ambulance station locating. Similarly, the symbol J will denote the set of served municipalities.

Obviously, the sets I and J can be the same as it is in our case. Each element $j \in J$ is connected with its weight denoted by w_j, which is usually an integer or real number. The coefficient w_j can be interpreted in many different ways. As already mentioned, it can be the number of expected emergency calls from the location j, it can express the number of inhabitants sharing the location j, etc. In our implementation of the algorithm, the weight w_j represents the number of calls of patients in a critical or urgent condition. The operators of current EMS stations provided us with the weights. Since the first phase may decrease the original values of w_j, we will use the symbol c_j to denote the final weight of a municipality j used in the next steps of the optimization process. In many cases, $c_j = w_j$, but there will be also some locations, for which $c_j < w_j$ or even $c_j = 0$. If $c_j = 0$ then all demands of the municipality $j \in J$ are covered by the stations located at j, which are not allowed to change their location. Furthermore, it can be generally assumed that an ambulance regardless of its type has limited capacity and it is able to serve only $Q = 19919$ calls. This value is the average number of calls assigned to one station. If a station must remain in its current location, it is excluded from further optimization. At the same time the weight w_j of given municipality j is reduced by Q in such a way that it can not drop below zero. If we denote the current number of stations in municipality j by the symbol r_j, then three different situations may occur:

1. If $w_j > r_jQ$, the stations cannot be relocated. The uncovered demand in municipality j that represents an input parameter of the model is $c_j = w_j - r_jQ$.
2. If $w_j > Q$ and at the same time $w_j < r_jQ$, then $\lfloor w_j / Q \rfloor$ stations must remain in the municipality, the others may be relocated. The uncovered demand in municipality j will be $c_j = w_j \bmod Q$.
3. If $w_j < Q$ and $r_j > 1$, one station must remain in the town, the others may be relocated. Municipality j is completely served by the fixed station and so the uncovered demand will be $c_j = 0$.

The last rule is related to managerial decisions made in the past. There are not apparent reasons why there are multiple stations in some small towns today (maybe a good hospital is nearby). Nevertheless, we try to respect them to some extent since severe changes in the current system may not be acceptable.

This way, we get the list of stations, which must stay at their current place and new values of the weights c_j. After the fixation of some centers in their current location, the type of stations must be decided about. We prefer fixing the RLP stations. If there are more stations that need to be fixed, we fix the RLP stations at the particular location first (if there are any) and then we add the remaining number of RZP stations. This first phase results in 48 fixed RLP and 19 fixed RZP stations according to the rules 1 and 2. The stations, which should be fixed according to the rule 3 are not added to the list of fixed station due to the following fact. The capacity of the previously fixed stations is fully utilized and the stations fixed according to the rule 3 have some free capacity to accept additional calls. Therefore, for each station fulfilling the rule 3 we add a separate constraint in the next step in order to keep the station located at its current place, but we allow to assign some additional calls to it. Let all such stations form the set F.

After obtaining the list of fixed centers and the list of stations for which we need additional constraint in the following mathematical model, we can formulate the second step of suggested optimization method. All centers, which are not fixed, should undergo an optimization process in order to find the best location to achieve the optimal value of used criterion. Since we have two types of EMS stations, first, we will find the best locations of the stations regardless their type, and then we will decide about the type of stations.

To formulate the mathematical model, we need to introduce further notation. As above, let the symbol I denote the set of candidates for EMS station locating. In our case, the set I contains all 2,934 cities and villages of Slovakia. The same elements are used to form the set J of used municipalities. As a weight of individual location $j \in J$ we use the coefficient c_j obtained from the first phase. As far as the objective function is concerned, it considers the average time the ambulance vehicle from the nearest center needs to achieve the affected patient. Let the time distance between the locations $i \in I$ and $j \in J$ be denoted by t_{ij}. Finally, we need the integer number p of stations to be located. In our case, $p = 274 - 48 - 19 = 207$. To complete the model, the decision about locating a EMS station at the location $i \in I$ will be modelled by a binary variable $y_i \in \{0, 1\}$. The location-allocation formulation of the model does not hold because of the model size (the sets I and J contain approximately 3,000 elements each) and the necessity to model assignment of clients to their located centers. The matrix of allocation variables would contain about 9 million variables (Avella et al., 2007). To overcome this obstacle, so-called radial formulation can be used (Avella et al., 2007, García et al., 2011, Janáček, 2008, Kvet, 2014, Kvet, 2015).

In accordance with the radial formulation, let the symbol m denote the largest value in the matrix $\{t_{ij}\}$, i.e. $m = \max\{t_{ij}: i\in I, j\in J\}$. For simplicity, we assume that all values in the matrix are integer. Of course, the radial formulation can be easily adjusted also for real values. For each location $j\in J$ and for each integer value $v = 0, 1 \ldots m-1$ we introduce a variable $x_{jv}\in\{0, 1\}$. This variable takes the value of one, if the time t_{j*} spent by travelling from the client located at $j\in J$ to the nearest EMS station is greater than the value of v and it takes the value of zero otherwise. Then, the expression (1) holds for each $j\in J$.

$$t_{j*} = \sum_{v=0}^{m-1} x_{jv} \tag{1}$$

Similarly to the set-covering problem, a binary matrix $\{a^s_{ij}\}$ must be computed according to the formula (2), in which $i\in I$, $j\in J$ and $v = 0, 1 \ldots m-1$.

$$a^v_{ij} = \begin{cases} 1 & \text{if } t_{ij} \le v \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

After these preliminaries, the radial model of the problem can be formulated by the expressions (3)-(8).

$$\mathit{Minimize} \quad \sum_{j\in J} c_j \sum_{v=0}^{m-1} x_{jv} \tag{3}$$

$$\mathit{Subject\ to}: \quad x_{jv} + \sum_{i\in I} a^v_{ij} y_i \ge 1 \qquad \mathit{for}\ j\in J, v = 0, 1, \ldots, m-1 \tag{4}$$

$$\sum_{i\in I} y_i = p \tag{5}$$

$$y_f = 1 \quad \mathit{for}\ f\in F \tag{6}$$

$$y_i \in \{0, 1\} \quad \mathit{for}\ i\in I \tag{7}$$

$$x_{jv} \in \{0, 1\} \quad \mathit{for}\ j\in J, v = 0, 1, \ldots, m-1 \tag{8}$$

The quality criterion of the design formulated by the objective function (3) expresses the sum of time distances from all clients to their nearest EMS station. The link-up constraints (4) ensure that the variables x_{jv} are allowed to take the value of 0, if there is at least one center located in radius v from the location j and the constraint (5) limits the number of located EMS stations by p. The constraint (6) follows from the first phase of suggested approach and its task is to arrange that the centers fixed according to the rule 3 stay at their current locations. The last obligatory constraints (7) and (8) keep the domain of the variables y_i and x_{jv}.

It must be realized that the optimal solution of the model (3)-(8) may bring such system design that differ from the current stations deployment a lot. If the proposed changes are too large, then they do not have to be accepted neither by private EMS providers nor by public authorities responsible for the service. Therefore, we suggest a simple model extension, which would limit the number of current stations, which can change their location. Such an extension is seemingly simple, but it can be achieved only with additional constraint. The problem is to define a change in center locating. Generally, a change is performed only in such a case, if there is a location, in which more centers will be located than there are currently. Therefore, we need to introduce a constant n_i for each $i\in I$. This constant takes the value of one, either if all EMS stations at the location i are fixed or if there is no station located at i. In case when only some of the current stations are fixed, but not all of them, this coefficient takes the value of zero. Then the model (3)-(8) can be extended by the expression (9), in which the parameter q limits the number of stations that are allowed to change their current location. The value of q is the parameter of suggested method.

$$\sum_{i\in I} n_i y_i \le q \tag{9}$$

By solving the model (3)-(9) we obtain the list of the optimal locations of EMS stations regardless of their types. The final decision about the type of each located ambulance can be made in a simple way. Let all EMS stations following from the result of the model (3)-(9) form a set of candidates for further processing. The model (3)-(8) can be used again to select the RLP stations from the set of all located centers. Obviously, the input data need to be adjusted.

To sum up the whole optimization approach, it is based on two phases. First, the biggest cities are solved and if there are more EMS stations located at the same place, some of them get fixed according to the defined rules. The stations which do not get fixed are subject of the optimization, which consists of two steps. In the first one, we find the optimal locations of all EMS station and then, we select the RLP stations from the set of all candidates.

4 COMPUTATIONAL STUDY

The main goal of performed computational study is to show and compare the obtained results for various settings of parameter q to the current EMS stations deployment. The results are summarized on the following Tables 2-7. Each table contains the results of different value of q. Note that the parameter q expresses the maximal number of centers, which can change their current location.

Table 2: Analysis of EMS system design obtained by suggested optimization approach, in which at most 10 percent of current EMS stations are allowed to be relocated.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	30.2	30.2	30.2
	Average response time	5.28	5.36	7.41
	15 min percentage	98.71	98.82	94.51
	8 min percentage	77.94	76.69	52.15
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.75	7.82	11.43
	15 min percentage	88.84	88.81	71.98
	8 min percentage	54.52	53.55	21.57

Table 3: Analysis of EMS system design obtained by suggested optimization approach, in which at most 20 percent of current EMS stations are allowed to be relocated.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	25.4	25.4	25.4
	Average response time	5.04	5.12	7.27
	15 min percentage	98.83	98.98	94.61
	8 min percentage	82.30	80.84	53.99
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.73	7.78	11.44
	15 min percentage	88.72	88.80	72.02
	8 min percentage	55.20	54.26	21.85

Table 4: Analysis of EMS system design obtained by suggested optimization approach, in which at most 30 percent of current EMS stations are allowed to be relocated.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	25.4	25.4	25.4
	Average response time	4.92	5.02	7.13
	15 min percentage	99.02	99.12	95.13
	8 min percentage	83.07	81.48	55.08
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.73	7.78	11.43
	15 min percentage	88.59	88.71	71.88
	8 min percentage	55.07	54.19	22.02

Table 5: Analysis of EMS system design obtained by suggested optimization approach, in which at most 40 percent of current EMS stations are allowed to be relocated.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	25.1	25.1	25.1
	Average response time	4.83	4.94	7.04
	15 min percentage	99.04	99.13	95.33
	8 min percentage	83.77	82.09	55.79
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.73	7.79	11.43
	15 min percentage	88.47	88.56	72.09
	8 min percentage	55.16	54.06	22.05

Table 6: Analysis of EMS system design obtained by suggested optimization approach, in which at most 50 percent of current EMS stations are allowed to be relocated.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	25.1	25.1	25.1
	Average response time	4.77	4.88	6.98
	15 min percentage	99.15	99.24	95.54
	8 min percentage	84.28	82.68	56.75
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.73	7.80	11.48
	15 min percentage	88.21	88.33	71.47
	8 min percentage	54.89	53.90	22.09

The last Table 7 reports the results of suggested optimization approach, in which the number of centers allowed to be relocated does not play any role. It means that the parameter q was set to the value of p. All centers could change their current locations, except of those being fixed. This way, the additional constraint (9) does not make any sense and it can be excluded from the model. Table 7 keeps the structure of previously reported tables.

Table 7: Analysis of EMS system design obtained by suggested optimization approach, in which all current EMS stations except for the fixed are allowed to be relocated.

	Indicator	**Municipality weight**		
		Calls	*Citizens*	*One*
Entire EMS system	*Maximal response time*	25.1	25.1	25.1
	Average response time	4.76	4.87	6.97
	15 min percentage	99.11	99.22	95.57
	8 min percentage	84.21	82.64	56.51
RLP only	*Maximal response time*	38.1	38.1	38.1
	Average response time	7.74	7.81	11.50
	15 min percentage	88.15	88.27	71.44
	8 min percentage	54.75	53.79	22.05

The results reported in Tables 2-7 show that the higher the number of stations allowed to be relocated, the better service accessibility can be achieved. In other words, the mathematical model respecting given limitations tries to locate the center in those places, in which they are the nearest to the demand points. On the other hand, if we look at the results for RLP stations only, the obtained results indicate that the coverage within the time limit of 15 minutes is quite good, but the coverage by the time of 8 minutes is still insufficiently weak. This observation deserves development of another approach aimed primarily at optimization of RLP stations.

As far as the computational time requirements of suggested approach are concerned, the computational times are not reported here. It must be noted that the first phase does not contain any optimization process and the fixation of EMS stations can be computed via one cycle very fast. The second phase consists in solving the above-described model (3)-(9) to obtain the optimal locations of all EMS stations and then, the model (3)-(8) is used again to select the RLP stations. The radial formulation makes the model simpler than the location-allocation formulation and thus, the optimal solution of the problem can be reached by about three minutes using a common notebook with standard technical parameters and basic equipment.

5 CONCLUSIONS

This paper was focused on practical usage of the optimization method based on the weighted *p*-median problem formulation. The goal of optimization was to achieve better access to urgent medical healthcare provided by private or public emergency agencies.

Suggested method was based on current station deployment analysis, which showed that there are some station locations with multiple facilities. This fact should be considered also in the optimization process. Such a request may cause several difficulties when formulating the model. The researchers could either create a model with multiple facility locations and apply the concept of generalized disutility or this obstacle could be handled in a different way.

The optimization approach studied in this paper is based on two phases. The first phase searches for such stations, that can not change their current locations for different reasons. After that, a simple model based on the weighted *p*-median problem is solved to obtain the optimal location of EMS stations. All located EMS stations become candidates for RLP, which are searched for by solving another mathematical model. Since the radial formulation enables us to solve real-world sized instances, we hope that suggested method can significantly contribute to the state-of-the-art in the field of service system optimization approaches. Obviously, this method is not the only possible way to improve current stations deployment.

Based on achieved results reported in previous section, the future research in this scientific are could be aimed at RLP stations, which could be primarily solved by the second phase of suggested algorithm. Another scientific topic to be studied could be focus on developing new algorithms, which would be able to apply different criteria and bring better results.

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