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A New Revised Group DEMATEL method with application on facility location problem

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Abstract

Multi-criteria methods are commonly used in facility location problem to evaluate different facility locations in the presence of a set of criteria in order to select the best facility location. The increasing availability of Internet-of-Things (IoT) data, can be a help in gathering the necessary data for the location evaluation. The paper proposes a New Revised Group DEMATEL (NRG-DEMATEL) multi-criteria method, aiming to analyse cause-and-effect relationships among a set of criteria. This method provides general conditions which imply the convergence to the null matrix of the sequence of powers of the initial relation matrix, hence the total influence matrix can be computed. DEMATEL is infeasible when the sequence of powers of the initial relation matrix does not converge to the null matrix. The NRG-DEMATEL can be applicable to all situations feasible or infeasible. For the cases that are feasible, our method leads to the same result as the original method DEMATEL. The causality diagram and the digraph, that can visualize the causal relationships of a set of criteria, are built with the NRG-DEMATEL method. In order to reduce the complexity of the digraph, a threshold value is set to filter out negligible effects. Two methods for computing the thresholds are considered in this paper: the arithmetic mean method and the arithmetic mean - standard deviation method. An application of the NRG-DEMATEL to hospital facility problem is realized.

Keywords: New Revised Group DEMATEL method; directed graph; facility location; Internet of Things

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1. Introduction

Facility location is the process of determining the optimal location for a facility to maximize its efficiency and profitability. The selection of a facility location is necessary process for newly established facilities. This process is impacted by many conflicting criteria. Multi-criteria methods have been used for ranking and selecting the most preferred alternative from a set of alternatives, often, in the case of conflicting criteria [1], [2]. Multi-criteria decision-making (MCDM) and multi-criteria methods are commonly used in facility location selection to evaluate different criteria simultaneously and select the best location. Multi-criteria methods are a good choice for solving location selection problems. An emerging challenge for location selection problem is the increasing availability of Big Data and Internet-of-Things (IoT) data which has led to the increase of the complexity of the MCDM methods [3]. IoT refers to the network of physical devices, vehicles, home appliances, and other items that are embedded with sensors, software, and connectivity that enable them to connect and exchange data. In facility location problem IoT sensors can collect data on location, traffic patterns, population density, weather conditions, water quality, noise levels and other criteria that can help determine the optimal location for a new facility. The IoT can also provide real-time data on facility performance, such as energy consumption.

The analysis of the influence between different facility location criteria, as well as their importance, play a vital role in the process of determining an optimal location. The multi-criteria DEMATEL method can be used to identify the most important criteria affecting a decision and to analyse cause-and-effect relationships among a set of criteria. Some recent applications of DEMATEL method in facility location problems can be found in: [4-8].

The present paper proposes a New Revised Group DEMATEL (NRG-DEMATEL) method, aiming to analyse cause-and-effect relationships among a set of criteria. The NRG-DEMATEL method guarantees that the sequence of powers of the initial relation matrix converges to zero, hence the total influence matrix can be computed. This method is used to identify the most important criteria, affecting a decision and to determine the direction and strength of relationships between them. In the first stage, the group of experts and the set of criteria are selected. In the second stage, the NRG-DEMATEL method is applied and the causality diagram and the digraph, that can visualize the causal relationships of criteria, are built. In order to reduce the complexity of the digraph, a threshold value is set to filter out negligible effects. Two methods for computing the thresholds are considered in this paper: the arithmetic mean method and the arithmetic mean - standard deviation method. An application of the NRG-DEMATEL for a hospital location selection is realized. In this case, the criteria that are relevant to hospital location selection include criteria such as proximity to IoT devices, connectivity, security, accessibility, and environmental factors. When a location for a hospital has to be selected, there are several criteria that should be considered to ensure that the hospital is located in an optimal location for the community it serves.

The remainder of the paper is structured as follows. Section 2 contains the NRG-DEMATEL method described in steps. An application of the proposed method to analyse cause-and-effect relationships among a set of criteria for a hospital facility location, in the context of IoT, is presented in section 3. Conclusions are given in Section 4.

2. The New Revised Group DEMATEL method

The DEMATEL (Decision Making Trial and Evaluation Laboratory) method was developed in the Battelle Memorial Institute of Geneva by Gabus and Fontela [9-10]. The DEMATEL method is a systematic approach for analysing complex decision-making problems. This method involves constructing a directed graph (digraphs), that represents the causal relationships among the criteria involved in a decision-making problem. These criteria are represented as nodes in the digraph, and the directed edges represent the causal relationships between them.

DEMATEL uses a combination of expert's knowledge and mathematical techniques to create a cause-and-effect matrix and can separate involved criteria into cause group and effect group. The method identifies the most influential criteria in the decision-making problem. These criteria are then prioritized for further analysis.

In comparation with the Analytical Hierarchy Process (AHP) method and the Analytical Network Process (ANP), DEMATEL method shows superiority in handling the internal relations among criteria. DEMATEL employs expert expertise to gain a better understanding of the relations between criteria.

In the paper [11] were analysed 3,521 papers, from the Scopus database, published in journals, conferences or books between 1981 and 2023 dealing with the DEMATEL method. Among the parameters considered are research outputs, the network of DEMATEL users, implementation subject areas, research zones, publication hosts. The conclusion is that DEMATEL is capable of dealing with modern problem-solving. The growth of the number of papers with combinations of methods which includes DEMATEL, for problem solving, is obvious.

In the DEMATEL method, the total influence matrix is computed by summing the powers of the initial relation matrix. This is based on the assumption that the limit of the matrix powers of the initial relation matrix is equal to zero. In the paper [12] it was shown that, in some cases, the sequence of powers of the initial relation matrix may not converge to zero and hence the series that defines the total influence may not converge. As a result, in [12] a revised DEMATEL method was proposed.

This paper proposed a New Revised Group DEMATEL (NRG-DEMATEL) method that provides conditions which imply the convergence to zero of the sequence of powers of the initial relation matrix, hence the total influence matrix can be computed. NRG-DEMATEL method is better than that presented in paper [12]. For the cases that are feasible, our method leads to the same result as the original DEMATEL method. In the same cases the method from paper [12] provides results closed to the original results from DEMATEL method.

The NRG-DEMATEL method, proposed in this paper, is presented in steps in the following.

Step 1. Identification of the decision target and the selection of a group of experts $E=\{E_1,E_2,...,E_p\}$

Step 2. Definition of the criteria set $C=\{C_1,C_2,...,C_n\}$ considered for the evaluation of causal relationships.

Step 3. Perform the evaluations of each criterion in relation to the other criteria, using the DEMATEL scale (0 for No-influence, 1 for Very low influence, 2 for Low influence, 3 for High influence and 4 for Very high influence).

Generate the initial direct-relation matrix for each expert *k*: $\mathbf{D}^{(k)}=\left(d_{ij}^{(k)}\right);i,j=1,2,...,n;k=1,2,...,p;$ $d_{ij}^{(k)}\in\{0;1;2;3;4\}$. The principal diagonal elements of matrix $\mathbf{D}^{(k)}$ are equal to zero: $d_{ii}^{(k)}=0$.

The evaluation is made, based on each expert's experience and expertise, for each pair of criteria from set *C*. The element $d_{ij}^{(k)}$ denotes the appreciation of the degree the criterion *i* influences the criterion *j*.

Step 4. The arrays of the initial direct-relation matrix $\mathbf{D}=\left(d_{ij}\right)$ are computed as the average of the corresponding arrays of matrices $\mathbf{D}^{(k)}$:

$$d_{ij}=\frac{1}{p}\sum_{k=1}^{p}d_{ij}^{(k)} \tag{1}$$

Step 5. Let *p* and *s* defined as follows:

$$p=\max\left(\max_{1\le i\le n}\sum_{j=1}^{n}d_{ij};\max_{1\le j\le n}\sum_{i=1}^{n}d_{ij}\right) \tag{2}$$

$$s=\begin{cases}p & \text{if } \max\limits_{1\le i\le n}\sum\limits_{j=1}^{n}d_{ij}\ne\max\limits_{1\le j\le n}\sum\limits_{i=1}^{n}d_{ij}\\ p+\varepsilon & \text{if } \max\limits_{1\le i\le n}\sum\limits_{j=1}^{n}d_{ij}=\max\limits_{1\le j\le n}\sum\limits_{i=1}^{n}d_{ij}\end{cases} \tag{3}$$

where ε is a small positive number.

Our method presents another way of calculation for parameter *s*, than that presented in paper [12].

Build, from the direct-relation matrix **D**, the $n\times n$ normalized initial direct-relation matrix $\bar{\mathbf{D}}=\left(\bar{d}_{ij}\right)$ as follows:

$$\bar{d}_{ij}=\frac{d_{ij}}{s} \tag{4}$$

In matrix $\bar{\mathbf{D}}$ all principal diagonal elements are equal to zero.

Step 6. The sequence of powers of the initial direct-relation matrix $\bar{\mathbf{D}}$ converges to zero. This implies that the series that defines the total influence matrix:

$\mathbf{T} = \bar{\mathbf{D}} + \bar{\mathbf{D}}^2 + ... = \sum_{m=1}^{\infty} \bar{\mathbf{D}}^m$ converges. Hence the $n \times n$ total influence matrix $\mathbf{T} = \left(t_{ij}\right)$ is calculated $\mathbf{T} = \bar{\mathbf{D}}\left(\mathbf{I} - \bar{\mathbf{D}}\right)^{-1}$ where **I** is the identity matrix. The matrix **T** serves for producing the causal diagram map.

Step 7. Matrix **T** allows to express a relation between the criteria, covering both direct and indirect influences. The sums of arrays from rows and the sums of arrays from columns of matrix **T** are calculated:

$$a_i = \sum_{j=1}^{n} t_{ij}; i = 1,2,...,n\,;\; b_j = \sum_{i=1}^{n} t_{ij}; j = 1,2,...,n \tag{5}$$

One can consider the vectors $\mathbf{a} = \left(a_1, a_2, ..., a_n\right)$ and $\mathbf{b} = \left(b_1, b_2, ..., b_n\right)$.

The importance vector denoted by $\mathbf{r}^+ = \left(r_1^+, r_2^+, ..., r_n^+\right)$ and the relation vector denoted by $\mathbf{r}^- = \left(r_1^-, r_2^-, ..., r_n^-\right)$ are calculated: $r_i^+ = a_i + b_i$ and $r_i^- = a_i - b_i$.

The element r_i^+ represents the total degree of influence among criteria, and the higher is its value, the higher is the importance of the criterion C_i. In addition, the element r_i^- represents the degree of causality among criteria. If r_i^- is positive, then criterion C_i influences other criteria, rather than being affected themselves, and belongs to the cause group. If r_i^- is negative, criterion C_i is influenced by other criteria and the criterion belongs to the effect group.

By mapping the vectors $\mathbf{r}^+$ and $\mathbf{r}^-$ the data can be displayed in a causality diagram. The causality diagram can visualize the causal relationships of criteria. The vector $\mathbf{r}^+$ represents the horizontal axis of the diagram called *importance*. The vertical axis, which is called *cause/effect relation,* is represented by vector $\mathbf{r}^-$. The horizontal axis "Importance" shows how much importance the criterion has, whereas the vertical axis "Relation" may divide criteria into the cause group and the effect group.

Step 8. Set a threshold value and obtain the digraph of criteria influences called the Impact Relations Map (IRM). In some situation, if all the information from matrix **T** is used to the IRM, the digraph would be too complex to show the necessary relations for decision making. Therefore, in order to reduce the complexity of the digraph, a threshold value is set to filter out negligible effects. Only criteria whose influence value in matrix **T** is higher than the threshold value can be chosen and converted into the IRM.

There are numerous methods developed for finding a DEMATEL threshold value. These methods can be divided into two categories; the traditional method and theoretical methods [13]. In the traditional method, a threshold value is set by experts and the IRM is drawn. Then the IRM is analysed by the experts and a new threshold value is set by increasing or decreasing the threshold if the digraph is too complex. Another method for determining a threshold is by using a specific formula or algorithm. This theoretical threshold for drawing the IRM. Some theoretical methods are [14]: the arithmetic mean method, arithmetic mean and standard deviation, the maximum mean de-entropy (MMDE), the maximum value of the diagonal elements of the matrix *T*.

Two methods for computing theoretical thresholds are considered in this paper: the arithmetic mean method and the arithmetic mean - standard deviation method.

The arithmetic mean method.

In this method the threshold is the arithmetic mean μ of the **T** matrix. The arrays of the matrix $\mathbf{G} = \left(g_{ij}\right); i, j = 1,2,...,n$ are calculated as follows:

$$\mu = \left(\sum_{j=1}^{n}\sum_{i=1}^{n} t_{ij}\right) / n\,;\; g_{ij} = \begin{cases} 1 & \text{if } t_{ij} \geq \mu \\ 0 & \text{if } t_{ij} < \mu \end{cases} \tag{6}$$

Matrix **G** is used for the IRM and the digraph design.

The arithmetic mean - standard deviation (MSD).

In MSD method the arithmetic mean μ and the standard deviation σ of the **T** matrix are calculated. The threshold is calculated as: $\theta = \mu + \sigma$. Other methods to calculate the threshold are [14]: $\theta = \mu + 1.5\sigma$ or $\theta = \mu + 2\sigma$

The arrays of the matrix $\bar{\mathbf{G}} = \left(\bar{g}_{ij}\right); i, j = 1,2,...,n$ are calculated as follows:

$$\mu=\left(\sum_{j=1}^{n}\sum_{i=1}^{n}t_{ij}\right)/\,n\,;\;\sigma=\sqrt{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\left(t_{ij}-\mu\right)^{2}\right)/\,n}\,;\theta=\mu+\sigma\,;\;\;\bar{g}_{ij}=\begin{cases}1 & \text{if } t_{ij}\ge\theta\\ 0 & \text{if } t_{ij}<\theta\end{cases} \tag{7}$$

This matrix $\bar{\mathbf{G}}$ is used for the IRM and digraph design.

3. Application of the New Revised group DEMATEL (NRG-DEMATEL) method to the facility location problem

The facility location problem is a critical process in any organization's strategic planning, and the Internet of Things (IoT) can be a valuable tool in this process. The aim of this section is to calculate and analyze the influence that exists between a set of criteria used in the location selection of a hospital, to create a causality diagram between these criteria and the digraph of criteria influences. For this purpose, the NRG-DEMATEL method will be used. The location selection for a hospital is a critical decision that can impact the quality of care provided by hospital, and the satisfaction of patients and healthcare providers. The NRG-DEMATEL method is applied to analyse cause-and-effect relationships among a set of criteria for a hospital facility location in the context of the Internet of Things (IoT). Sensors are used to collect data on traffic patterns, population density, and other factors that can help determine the optimal location for a new facility.

A group of three experts, with solid knowledge and experience in the field is chosen. These experts select a set of important criteria, based on experience and literature review. The criteria selected are:

C_1. Medical service demand (hospital demand at the location).

C_2. Cost (land cost, investment costs, building costs, travel costs).

C_3. Demographic structure (Population density, Age profile). IoT sensors are used to collect data on the number of people living in the area and their demographic characteristics to ensure that the hospital is located in a place where it will serve the greatest number of people.

C_4. Transport Infrastructure (Near main roads, Agglomeration effects, Availability of parking, Travel time). IoT sensors are used to collect data on traffic patterns and public transportation routes to determine the most accessible location.

C_5. Accessibility (Distance to existing hospitals, Distance to social centers, Medical suppliers, Easy access for ambulances, Closeness to the target area, IoT Communication network, IoT server placement, Water, Electricity, Internet connectivity). IoT sensors are used to collect data on the availability and reliability of these resources in different areas.

C_6. Location characteristics (Parcel size, Elevation, Park area, Possibility of expansion, Air and Water quality, Noise levels, Environment). IoT sensors can be used to monitor air and water quality, noise levels, and other environmental factors.

C_7. Risk (Disaster risk, Environmental risk).

Each expert, from the group of three experts, performs the evaluations of each criterion in relation to the other criteria, using the DEMATEL scale. The $\mathbf{D}^{(k)}$ (initial direct-relation matrix for each expert k) is build. Then the matrix **D,** based on Equation (1) is computed (Table 1). The maximum of the sum of arrays from rows and the maximum of the sum of arrays from columns in the matrix **D** are calculated. The maximum of the sum of arrays from rows = 22.333 and the maximum of the sum of arrays from columns = 20. Because the maximum on the sum of arrays from rows is different from the maximum on the sum of arrays from columns $s=p$ in equation (3) and ε is not considered in normalization.

The normalized initial direct-relation matrix $\bar{\mathbf{D}}$ and then the total influence matrix **T** are computed (Table 2).

The **a (**sums of arrays from rows) and **b** (the sums of arrays from columns) of matrix **T** are calculated. Then are calculated the $\mathbf{r}^{+}$ (importance vector) and $\mathbf{r}^{-}$ (relation vector) (Table 3).

By mapping the vectors $\mathbf{r}^{+}$ and $\mathbf{r}^{-}$ the data is displayed in a causality diagram (Figure 1). The causality diagram can visualize the causal relationships of criteria.

Table 1. The initial direct-relation matrix **D**

Criteria Symbols	C_1	C_2	C_3	C_4	C_5	C_6	C_7	Sum of rows
C_1	0.000	4.000	3.667	3.333	3.000	4.000	3.333	21.333
C_2	3.333	0.000	4.000	3.667	4.000	3.333	4.000	22.333
C_3	2.000	2.333	0.000	2.000	2.000	2.000	3.000	13.333
C_4	2.000	2.000	2.000	0.000	3.333	4.000	3.000	16.333
C_5	2.000	2.000	3.000	3.000	0.000	3.000	3.000	16.000
C_6	1.000	2.333	2.000	2.000	1.667	0.000	3.667	12.667
C_7	1.333	1.000	1.667	2.000	1.000	2.000	0.000	9.000
Sum of columns	11.667	13.667	16.333	16.000	15.000	18.333	20.000	

Table 2. The total influence matrix **T**

Criteria Symbols	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	0.233	0.420	0.456	0.440	0.408	0.504	0.517
C_2	0.369	0.273	0.475	0.460	0.450	0.491	0.550
C_3	0.232	0.265	0.202	0.282	0.268	0.308	0.368
C_4	0.256	0.284	0.319	0.235	0.348	0.422	0.414
C_5	0.255	0.281	0.351	0.349	0.215	0.381	0.408
C_6	0.182	0.249	0.266	0.266	0.239	0.207	0.373
C_7	0.158	0.162	0.206	0.218	0.172	0.238	0.172

Table 3. The importance and relation vectors

Criteria symbols	Criteria	**a**	**b**	$\mathbf{r}^+$	$\mathbf{r}^+$ ranks	$\mathbf{r}^-$
C_1	Service Demand	2.979	1.686	4.665	2	1.293
C_2	Cost	3.068	1.933	5.002	1	1.135
C_3	Demographic Structure	1.927	2.276	4.202	6	-0.349
C_4	Transport infrastructure	2.277	2.251	4.528	3	0.026
C_5	Accessibility	2.240	2.100	4.340	4	0.140
C_6	Location characteristics	1.782	2.551	4.334	5	-0.769
C_7	Risk	1.326	2.802	4.128	7	-1.477

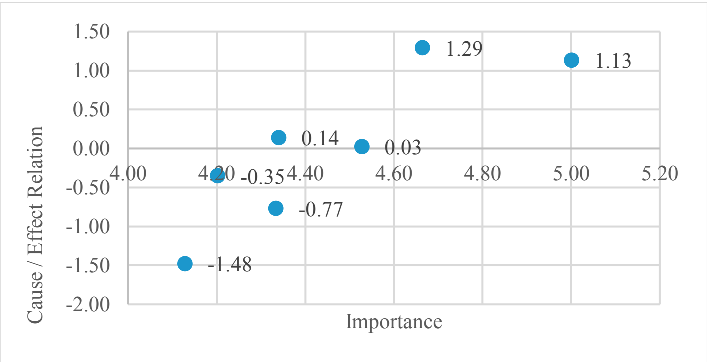


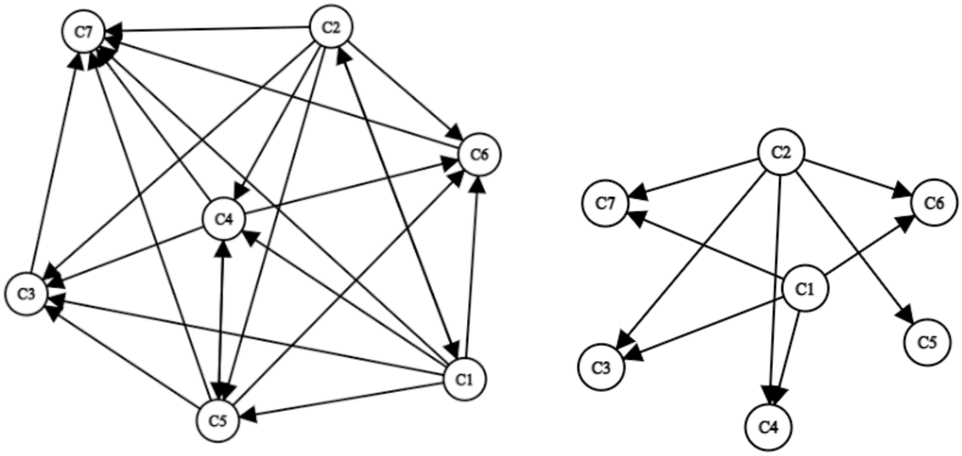
Figure 1. The causality diagram

From the importance point of view (according to Figure 1), the most important three criteria are Cost (C_2), Service Demand (C_1) and Transport Infrastructure (C_4). Among all criteria Cost (C_2) has the highest $\mathbf{r}^+$ value, showing that it is of the most importance for the hospital location selection.

The vertical axis divides criteria into cause group and effect group. Characterized by positive values ($\mathbf{r}^-$ Column of Table 3) the cause group includes Service Demand (C_1), Cost (C_2), Transport Infrastructure (C_4), and Accessibility (C_5). All of these criteria influence other criteria rather than being affected themselves. The cause group can be subdivided into criteria with low and high importance values ($\mathbf{r}^+$ column of the Table 3). The Service Demand (C_1) and Cost (C_2) criteria have very high relation values (1.293, 1.135, respectively), and very high importance values (4.686 and 5.002). Transport Infrastructure (C_4) has a positive relation value (0.026) but a high importance value (4.528). Changes in Transport Infrastructure (C_4) will have a high impact on other criteria.

Characterized by negative values, ($\mathbf{r}^-$ Column of Table 3), the effect group includes the Demographic Structure (C_3), Location characteristics (C_6) and Risk (C_7). These criteria are predominantly influenced by other factors rather than having high influencing power themselves. But Location characteristics (C_6) is strongly interconnected with other criteria ($\mathbf{r}^+ = 4.334$) and has a relation value that is only slightly negative ($\mathbf{r}^- = -0.769$). These values imply that this criterion is influenced by other criteria (Service Demand (C_1), Cost (C_2), Transport Infrastructure (C_4), and Accessibility (C_5)) but has considerable effects on other criteria (Demographic Structure (C_3) and Risk (C_7)). The Risk (C_7) criteria has neither strong importance ($\mathbf{r}^+ = 4.128$) nor strong influences on other criteria ($\mathbf{r}^- = -1.477$).

In order to reduce the complexity of the criteria relations, a threshold value is set to filter out negligible effects. The threshold calculated for **T** matrix with the arithmetic mean methods is μ=0.318. Only criteria whose influence value in matrix **T** is higher than the threshold value can be chosen and converted into the IRM. The digraph for the threshold μ=0.318 is illustrated in Figure 2 (a) and the digraph for threshold (MSD method) θ=0.424 is illustrated in Figure 2 (b).



a) (b)

Figure 2. The digraph for (a) μ= 0.318 and (b) θ= 0.424

For the MSD method, used to calculate the threshold, the number of relationships has decreased by a lot compared to the threshold calculated with the mean method.

4. Conclusions

The DEMATEL method has been widely used in many fields of applications. In this paper a new revised version of the original DEMATEL method, called NRG-DEMATEL method is proposed to solve the infeasibility that might occur in some cases. The NRG-DEMATEL can be applicable to all situations feasible or infeasible. For the cases that are infeasible, our method can provide a feasible solution with the help of a small positive constant ε.

In recent years, the development and utilization of IoT have attracted more attention, and thus, the facility location problems can benefit from using sensors to gather data on possible locations for a facility. The IoT data can help to improve the quality of planning and decision-making process in facility location problems. Using the NRG-DEMATEL method, an application was given for a hospital location problem in context of IoT. The importance group includes Cost, Service Demand and Transport Infrastructure criteria. Each of these criteria influence the other criteria. The cause group includes Service Demand, Cost, Transport Infrastructure, and Accessibility criteria. The digraph, for two thresholds, calculated with the help of mean method and MSD method, are built.

The proposed method can also be applied to other selection problems like project selection, cloud service selection, material selection and many selection decision problems from other fields.

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