# A Practical Application of the Delphi Method in Maintenance-Targeted Resource Allocation of Distribution Utilities

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*Abstract*—**Trying to find the most efficient and cost-effective decisions on the maintenance of different component types in power distribution systems is an increasingly challenging concern largely driven by the current financial constraints in distribution utilities worldwide. In regard to deal with this challenge, the paper presents a practical application of the Delphi method and the Modified Analytical Hierarchical Process (MAHP) that can be used to find the most critical component types of the system in order to assist in accordingly allocating the available maintenance budget. The proposed approach involves the experience and knowledge held by experts and the historical empirical performance data in the utility data management systems to create the associated decisions. The approach has been applied in the Alborz Distribution System in Tehran, Iran. The results obtained and the lessons learned are reported in detail.**

***Keywords- Analytical Hierarchical Process (AHP), the Delphi method, distribution system, maintenance, resource allocation.***

## I. INTRODUCTION

Practical and effective maintenance scheduling, planning, and management are reported as a major concern in power distribution utilities worldwide. This is because maintenance activities are one of the main expenditures in a distribution system and absorb a considerable portion of the available resources in a utility [1]. On the other hand, maintenance activities have been proven to play a significant role on the system overall performance. Improper management of maintenance strategies can lead to catastrophic outcomes from both technical and economical viewpoints [2]-[4].

Many utilities, however, still do not utilize an efficient asset management structure to help them focus the maintenance budgets where and when necessary. The annual budget assigned to maintenance in a distribution company should be reasonably distributed among the different component types. In this way, the priorities would be focused on the critical components of the system [5]. This approach can efficiently avoid missing opportunities for cost-effective decisions and is regarded as the first step toward modern maintenance scheduling approaches such as reliability-centered maintenance (RCM). In RCM, not only the system technical concerns involving reliability-oriented performance are the primary objective to deal with, but also the cost-effectiveness of the maintenance practices has considerable impact in decision making [6].

The application of RCM has increased considerably in recent years. Some publications illustrate the application of RCM to certain component types, e.g., circuit breakers [7], underground cables [8], voltage regulators [9], overhead lines [10], power transformers [11], and gas turbines [12]. Others have applied the RCM process to power transmission systems and the distribution sector. Reference [13] was an early application of RCM in distribution systems, and applied this concept to underground cables and overhead lines. Other surveys were triggered by [13], of which [14]-[17] can be noted which contain similar results and discussions. A multi-objective optimization approach was introduced in [18] to find the critical components of the distribution system using selected monetary indices. The literature on resource allocation to the system component types subject to maintenance is relatively rare. The authors of this paper are engaged in a wide study on the RCM applications in power systems. Some of the early works conducted by the authors provide the first steps toward an RCM framework in distribution systems that create the road-map to practically implement the process in a real world scenario [19]. The step by step implementation process is discussed and presented in detail in [20]. As a first attempt, [21] was devoted to identification of critical component types in power distribution systems using a fairly simple decision making approach. Complementary to [21], an attempt was made in [22] using fuzzy numbers to deal with some certain uncertain and imprecise judgments of the decision makers.

The previous efforts, however, could not practically extract the maximum benefit from the experts' knowledge and expertise, not only in defining the importance criteria in the budget allocation decision making, but also the weighting analysis that needs to be performed on the system component types [21], [22]. Other references also exist that focus on maintenance operational scheduling and consider the various component roles on the system and load point performance, but cannot be used for managerial budget-constrained decisions and upper-level maintenance management from an economical perspective [23]-[25].

The work in this paper was performed to improve what has been previously described in [21], [22] and this paper reports the lessons learned and the results gained from a practical implementation project studied in Tehran, Iran. The project was conducted on a distribution system under the management and control of the Alborz Distribution Utility in Tehran, Iran, and is focused on resource allocation of the utility when scheduling its annual maintenance plans.

The paper is structured as follows: Section II introduces the algorithm overall structure where the problem statement and the approach pursued in response is generally presented. The Delphi method and its application process to the problem under study is elaborated in Section III. Section IV is devoted to the introduction of the Modified Analytical Hierarchical Process (MAHP) method and its application in this paper. The study results are presented in the context of the application procedures in Section III and Section IV. The conclusions are summarized in Section V.

## II. Overall Structure of the Algorithm

The scheme proposed within the scope of this paper, as the outcome of a practical project, extracts the maximum amount of experts' and asset managers' knowledge and expertise in regard to finding the most critical component types in the distribution system from the system reliability perspective. In this reliability-oriented maintenance scheduling approach, the criticality criteria and factors were first found through a robust widely-used decision making approach, known as the Delphi method. This will let the decider get the most out of the utility experts' knowledge and expertise by repeated mutual exchange of information among them until a final decision is made. The proposed scheme then utilizes the capabilities of the Modified Analytical Hierarchical Process (MAHP) to handle all the interrelated or even contradictory factors of component criticality. In this way, the criteria are processed using an importance weighting mechanism via the utility experts and operation managers. The historical data and information associated with these criteria are mathematically processed to determine the final importance of the system component types under study. In this way, the most important and critical component types in power distribution system can be identified for an assigned maintenance planning time period. This process can be accomplished for a given planning horizon and can be updated as time moves on as the component importance and criticality may change over time. It may be, thus, reasonable to have this analysis done annually or every few years. The designated component types to absorb more of the annual maintenance budget are finally prioritized based on their importance and proportionally allocated a better distribution of the financial resources for maintenance. The proposed process is generally illustrated in Fig.1.

## III. Applicatiion of the Delphi Method

The Delphi approach is a decision-making method by which the experience, knowledge, and presumptions of expert panelists are iteratively focused on an issue or development process [26]. This methodology is employed especially when the understudied phenomenon is complex enough or where the topic is somehow delicate or the number of members in the decision group is relatively small.

Participants in this study were selected from experts and experienced operators in the Alborz Distribution Utility in Iran. They were asked to decide on the most important criteria that can be used to assess the components' criticality for maintenance resource allocation.

In the first step, the project researchers designed an open questionnaire on the topic and disseminated it to the pre-selected participants. The questionnaires were completed and returned in order for the project team to focus the opinions into a descriptive questionnaire and send it back to the experts to see if they agreed or not. Another questionnaire was then developed to get the revised opinions from the experts, based on the collective responses. This process was iteratively done several times until a final agreement was achieved. Application of this robust approach permits the decision makers and participants to modify their responses according to other opinions in the utility during the several rounds of iteration. This approach allows a final most-implementable and efficient solution to be identified. The practical steps of the Delphi application and the outcome criteria on component importance and criticality are illustrated in detail in Fig. 2. The defined criteria for the problem under focus in this utility that includes both low voltage (LV) and medium voltage (MV) levels of the distribution system are also introduced in Fig. 2. As can be seen in Fig. 2, in addition to the technical concerns and the influence of each component type on the reliability indices of the power distribution system, the economical factors were also regarded to be of considerable importance in the decision making process.

## IV. Modified-AHP Application

### A. *Background*

The Analytical Hierarchy Process (AHP) model was designed by T.L. Saaty [27] as a multi-criteria decision-making technique extensively employed in different applications worldwide. Both the qualitative and quantitative aspects can be effectively involved via a hierarchy of decision elements as generally illustrated in Fig. 3. Qualitative analysis through the pair-wise comparisons is performed on each possible pair in each cluster eventually leading to a weighting factor for each element within a level of the hierarchy (cluster) and also a ratio of consistency [28]. As a result, it actually makes the people's thinking hierarchical and quantitative.

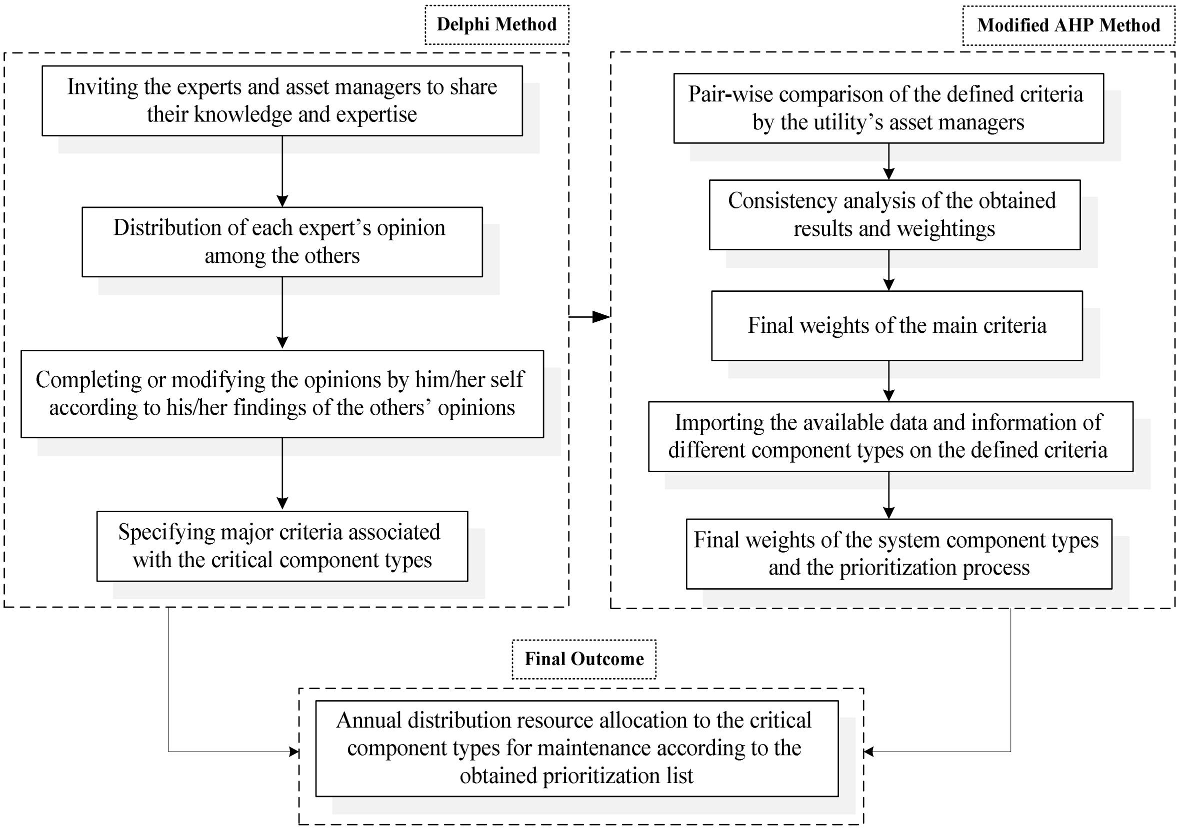


Fig. 1. The proposed procedure of maintenance resource allocation in power distribution systems

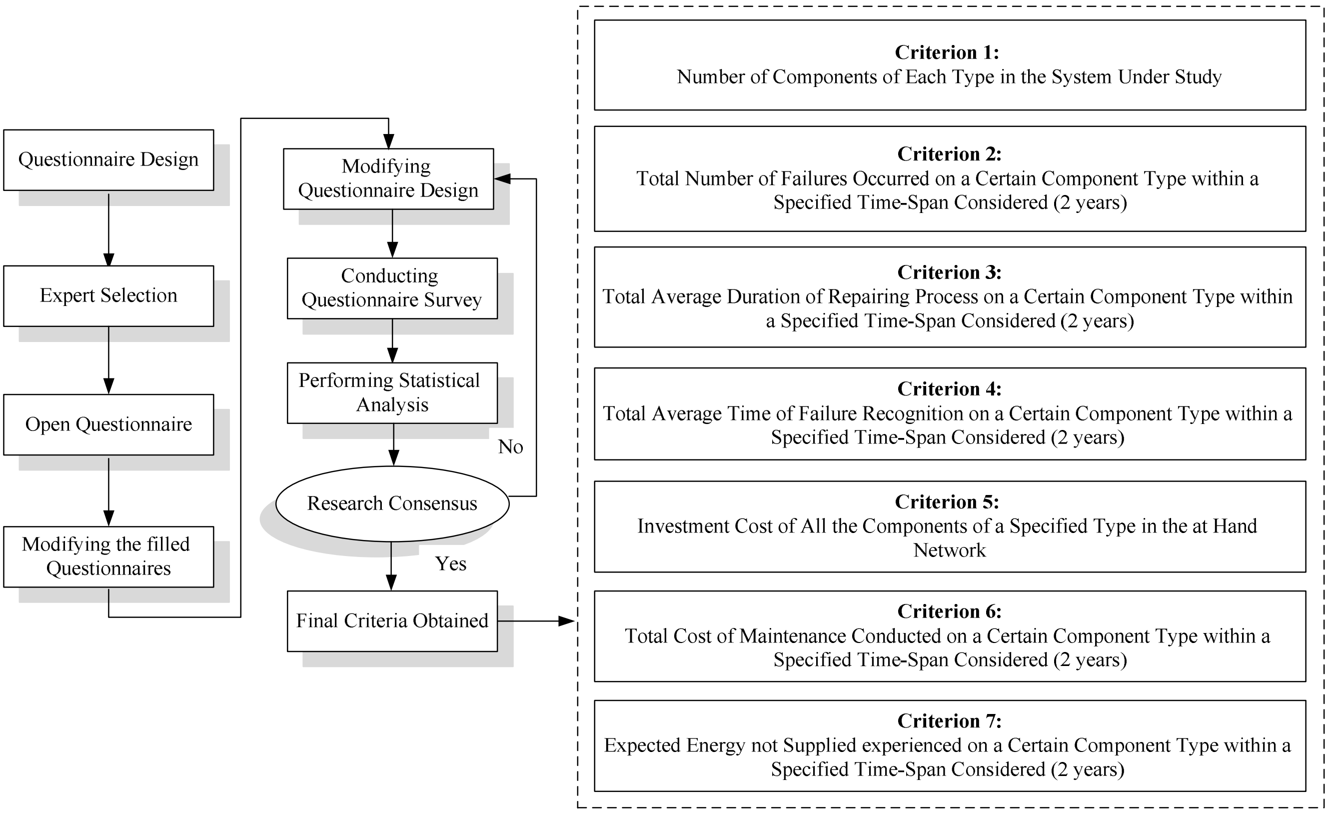


Fig. 2. The Delphi process in the decision making problem under study and the final outcome as the problem main criteria

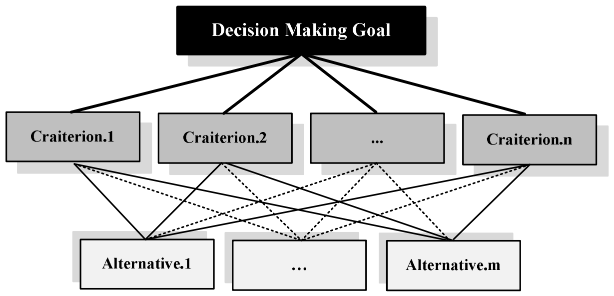


Fig. 3. Hierarchy Structure of the AHP modeling [28].

Generally speaking, the main steps of the AHP method are as follows [27], [28]:

**Step 1**: Assembly of the decision hierarchy in such a way that the decision making problem can be broken down into a hierarchy of interconnected decision elements. The main criteria have to be defined in this step. The overall goal is placed at the top, while the main attributes are on the sublevels as illustrated in Fig. 3 [28].

**Step 2**: The attributes in each level of the hierarchy have to be placed under pair-wise comparisons with the adjacent attributes with respect to their importance to the parent one. Decision tables can then be made, as demonstrated in Table I, where CRI. stands for criterion. The comparisons are conducted using the linguistic variables, in the 1-9 scales, as shown in Table II [28].

**Step 3**: Matrix-based mathematical calculations, e.g. eigenvector method, the weighted least squares method, or the goal programming method are then conducted on the achieved weighting tables and the relative weight of each decision element is estimated. For instance in this study, the final weight of each criterion can be obtained through the mean geometry of each row of the weighting matrix as in (1):

$$C_i = \sqrt[5]{C_{i1} \times C_{i2} \times C_{i3} \times C_{i4} \times C_{i5}} \quad (1)$$

where $C_{ij}$ is the pair-wise comparison weight of criterion $i$ with respect to criterion $j$, and $C_i$ is the final weight of criterion $i$.

**Step 4**: The weights of the criteria obtained through the analysis in Step 3 are utilized in another qualitative weighting process on the alternatives. The scores obtained reflect the weights given to each alternative in accordance with each criterion and can be then summed up to yield a final score for each alternative according to all the defined criteria.

In the proposed Modified Analytical Hierarchical Process (MAHP), the following modifications are introduced:

- The definition process of the main criteria for the decision making problem in Step 1 is gone through via the Delphi method and repetitive interaction of the utility experts and experienced personnel.
- Instead of performing the qualitative weighting process on the decision alternatives in Step 4, the historical data and empirical performance indices associated with each identified criterion are employed in a quantitative manner highlighting the role of data centers and energy management centers in the distribution utilities.

TABLE I
PAIR-WISE COMPARISON MATRIX IN AHP METHOD [22]

| | **CRI. 1** | **CRI. 2** | **CRI. 3** | **CRI. 4** | **CRI. 5** |
|---|---|---|---|---|---|
| **CRI. 1** | 1 | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ |
| **CRI. 2** | $C_{21}$ | 1 | $C_{23}$ | $C_{24}$ | $C_{25}$ |
| **CRI. 3** | $C_{31}$ | $C_{32}$ | 1 | $C_{34}$ | $C_{35}$ |
| **CRI. 4** | $C_{41}$ | $C_{42}$ | $C_{43}$ | 1 | $C_{45}$ |
| **CRI. 5** | $C_{51}$ | $C_{52}$ | $C_{53}$ | $C_{54}$ | 1 |
| **Final Weight** | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |

TABLE II
IMPORTANCE SCALES FOR JUDGMENT AND COMPARISON [28].

| **Scale** | **Definition** | **Explanation** |
|---|---|---|
| 1 | Equally important | Two options equally contribute to the objective |
| 3 | Moderately more important | Experience and judgment slightly favor one option over another |
| 5 | Strongly more important | Experience and judgment strongly favor one option over another |
| 7 | Very strongly more important | An option is strongly favored and its dominance demonstrated in practice |
| 9 | Exceedingly more important | The evidence favoring one option over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate preferences | … |

## *B. Application Procedure*

The most important criteria on the problem, i.e., the critical component identification in distribution systems, found through the Delphi method, are then inserted in the weighting process of the AHP method. This process, which leads to the final ranking of the defined criteria, is done using qualitative pair-wise comparisons made between each expert and operator individually and utilize some mathematical procedures to add up all the opinions into a single importance value for each criterion (via Eq. 1). The final importance values recognized by the experts and asset managers of the Alborz Distribution Utility via the AHP method for both low voltage (LV) and medium voltage (MV) level distribution components, are shown in Table III. Interested readers are referred to [21], [22] for more information on the mathematical background and the application of the AHP method in critical component identification in power distribution systems.

As it can be seen in Table III, criterion 4 (total average time of failure recognition), criterion 2 (total number of failures), and criterion 3 (total average repair duration) are identified as the most critical ones for the LV level of the utility under study and according to the operator's expertise and experience. At the MV level, the conclusions are similar in this case for this utility although it could be different in other utilities. It can be seen, however, in Table III that the final weights for the same criteria in LV and MV parts of the distribution system are different which illustrates the necessity of applying the proposed method separately for each voltage level. Another point to note is the ability of the Delphi method to find the most efficient criteria. As can be seen, all the criteria receive a weight based on their importance from the viewpoints of the participant experts and operators.

TABLE III
FINAL WEIGHTS OF THE DEFINED CRITERIA IN THE DECISION MAKING PROBLEM

| Criterion | LV Final Weight | MV Final Weight |
|---|---|---|
| Criterion 1 | 0.10062246 | 0.11711243 |
| Criterion 2 | 0.18426291 | 0.169855926 |
| Criterion 3 | 0.15910518 | 0.146055507 |
| Criterion 4 | 0.20402219 | 0.191245455 |
| Criterion 5 | 0.08226562 | 0.081476194 |
| Criterion 6 | 0.1174752 | 0.095265987 |
| Criterion 7 | 0.15224644 | 0.198988502 |

The quantitative data and information on the defined criteria and for the system components are incorporated in the analysis as a modification to the conventional AHP. This makes it possible to get the most out of the existing historical data and information on the system performance rather than just utilizing a qualitative analysis of the criteria. This combination of the qualitative analysis to get the operators' expertise together with the quantitative analysis to include the system historical performance leads to the most efficient solution. In so doing, a matrix demonstrated in Table IV can be constructed. The table can be completed using the associated values for each alternative (component types in this paper) for each criterion already defined. These values are obtained using the utility energy management system and data integration facilities. As soon as the table is completed, Eq. (2) can be employed to find the final weight of each component type.

$$K_i = \sqrt[5]{K_{i1}.C_1 \times K_{i2}.C_2 \times K_{i3}.C_3 \times K_{i4}.C_4 \times K_{i5}.C_5} \quad (2)$$

where, $K_{ij}$ is the normalized index of each component type $i$ regarding the criterion $j$, $C_j$ is the criterion weight calculated earlier via (1), and $K_i$ is the final weight of each component type. The component types to be focused on in the decision making process are set in both the LV and MV segments and the data and information on each of them according to the defined criteria are involved in the importance rate determination for each component type.

Data and information for the previous two consecutive years were used in this research and were obtained from the data and energy management system in the utility under study.

TABLE IV
QUANTITATIVE COMPLETING OF THE ALTERNATIVES WEIGHTING MATRIX

| ALTERNATIVE/CRITERION | CRI.1 | … | ... | CRI.5 | FINAL WEIGHT |
|---|---|---|---|---|---|
| **Alternative. 1** | $K_{11}$ | … | … | $K_{15}$ | $K_1$ |
| **Alternative. 2** | $K_{21}$ | … | … | $K_{25}$ | $K_2$ |
| **Alternative. 3** | . | … | … | . | . |
| **.** | . | … | … | . | . |
| **.** | . | … | … | . | . |
| **.** | . | … | … | . | . |
| **.** | . | … | … | . | . |
| **Alternative. M** | $K_{M1}$ | … | … | $K_{M5}$ | $K_M$ |

The remaining action is to calculate the final weight of each component type to be ranked and prioritized in an ascending order of magnitude. The component types that are assigned higher weights are deemed to be the most critical component types in the system and should receive more care from a maintenance viewpoint. These component types should be assigned a portion of the total annual maintenance budget according to the weights they receive from the analysis. This weight for each component type, and accordingly the resource allocation portion, should be updated as time moves on in different maintenance planning time intervals.

The analyses should be conducted at both LV and MV levels. The analysis and the final weights are shown for the LV component types in Table V. Table VI shows the most

TABLE VI
FINAL WEIGHTS OF EACH COMPONENT TYPE IN THE MV LEVEL

| Component Type | Final Weight |
|---|---|
| Transformer | 0.079698247 |
| Triplet Series Cable Termination | 0.101011469 |
| Overhead Disconnector | 0.030740665 |
| Ground Disconnector | 0.01770521 |
| Circuit Breaker | 0.041996461 |
| 20 kV Cable | 0.080816291 |
| Insulator | 0.150967921 |
| Arrester | 0.050069254 |
| Cut-out | 0.107545298 |
| MV Wire | 0.065520781 |
| MV Cement Pole | 0.082446213 |
| Recloser | 0.079687941 |
| Sectionner | 0.065140569 |
| MV Cross Arm | 0.046653681 |

TABLE V
FINAL WEIGHTS OF EACH COMPONENT TYPE IN THE LV LEVEL

| Final Weight / Component Type | Criterion 1 | Criterion 2 | Criterion 3 | Criterion 4 | Criterion 5 | Criterion 6 | Criterion 7 | Final Weight |
|---|---|---|---|---|---|---|---|---|
| | **0.10062246** | **0.18426291** | **0.15910518** | **0.20402219** | **0.08226562** | **0.1174752** | **0.15224644** | |
| Distribution Panel | 0.008347 | 0.006093 | 0.085474 | 0.046511 | 0.686622 | 0.702678 | 0.010422 | 0.16567118 |
| Main Breaker | 0.008452 | 0.092465 | 0.065602 | 0.069767 | 0.102653 | 0.092226 | 0.114498 | 0.07927156 |
| Feeder | 0.022987 | 0.35031 | 0.07109 | 0.069767 | 0.016468 | 0.015942 | 0.211408 | 0.1278216 |
| Fuse Base | 0.007332 | 0.004069 | 0.068658 | 0.069767 | 0.001224 | 0.001185 | 0.00426 | 0.02753564 |
| Self Support Cable | 0.001555 | 0.043653 | 0.099814 | 0.104651 | 0.028038 | 0.028546 | 0.068144 | 0.06146719 |
| LV Cable | 0.001139 | 0.045165 | 0.128040 | 0.348837 | 0.00198 | 0.001976 | 0.128479 | 0.11993493 |
| Wire | 0.003730 | 0.141611 | 0.102635 | 0.069767 | 0.001563 | 0.001449 | 0.277178 | 0.09953145 |
| Cement Pole | 0.125953 | 0.005915 | 0.123296 | 0.069767 | 0.141645 | 0.137549 | 0.013310 | 0.07745261 |
| Tap-Off | 0.722732 | 0.307729 | 0.075794 | 0.046511 | 0.011725 | 0.009881 | 0.161887 | 0.17774734 |
| Trans-to-Panel Cable | 0.097777 | 0.002979 | 0.179588 | 0.104651 | 0.008077 | 0.0085 | 0.010401 | 0.0635665 |

critical component types and the associated weights in the MV level for the distribution system under study. In the LV level, the Tap-off, Distribution Panel, Feeder and LV cable are respectively identified as the most important components in the system where maintenance resource allocation would lead to more influential impacts. In the MV level, it was concluded that the Insulator, Cut-out, Triplet-series Cable terminations are respectively the most critical component types which should receive higher resource allocation attention compared to the other component types. The maintenance budget can be proportionally allocated to the system component types based on the final weights assigned to each component type.

## V. Conclusion

The paper reports on the lessons learned and the results gained from an industrial project conducted in the Alborz Distribution Utility, Tehran, Iran. The project aimed to find the most critical component types of the distribution system in both LV and MV parts to accordingly allocate the maintenance annual budget. The proposed approach used the Delphi method to obtain maximum benefit from the experts' knowledge and expertise. After establishing the importance criteria, they were put through a qualitative weighting analysis using pair-wise comparisons in the AHP method. An analytic approach was utilized to incorporate the historical data of the component types under study in accordance with the defined criteria over the specified two-year period. The most critical component types are identified as the Tap-off in the LV part and the Insulator in the MV one. The maintenance budget can then be annually allocated according to the final normalized weight for each component type. The approach is dynamic and has to be conducted at the beginning of each maintenance planning period.

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