

Article

Choosing a Water Distribution Pipe Rehabilitation Solution Using the Analytical Network Process Method

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Abstract: One of the major challenges faced by water companies around the world is the high level of water losses in distribution networks. This research paper presents a case study on the choice of the best technical solution for the rehabilitation of the water distribution network pipelines of Cluj-Napoca City, Romania. The analytical network process (ANP) method was used as the selection method, and calculations were performed using the Super Decisions 2.6.0 software. In the case study, five alternatives were analyzed based on seven criteria. The criteria taken into account in the decision-making included pipe diameter, pipe length, specific accomplishment duration, lifespan, pressure losses, price, and installation conditions, while the following methods were considered as rehabilitation alternatives: Compact Pipe, Slipline, Subline, Swagelining, and Pilot Pipe. Based on the highest global priority, we recommend choosing the Subline alternative as the method of rehabilitating water distribution pipes from asbestos cement pipes in the case of Cluj-Napoca City, Romania.

Keywords: water distribution networks; water loss reduction; rehabilitation water mains; trenchless technology; multi-criteria decision-making (MCDM); analytical network process (ANP); feedback structure

1. Introduction

1.1. Context

One of the main challenges facing water utilities worldwide is the high level of water loss in the distribution networks. According to the World Bank study, about 32 billion m³ of treated water is lost annually as leakage from urban water distribution systems around the world, while 16 billion m³ is used but not paid for [1].

The main problems faced by urban water distribution networks are old pipelines, frequent leakage, frequent failures, drinking water supply discontinuance, important water losses, high energy costs, and high costs with the rehabilitation of water distribution networks [2].

In this context, a smarter management of urban water distribution networks is needed to achieve higher levels of efficiency. Thus, the International Water Association (IWA) proposed that the leakage management process be improved in three different stages, namely: assessment, detection, and physical location [3].

A percentage of water that brings no revenue is indicated for Eastern European water supply systems and this percent ranges from 16 to 61% [4,5]. In Romania, the maximum allowable water losses from a water distribution system must not exceed 20% [6].

Causes of water loss include the following: pipe holes and longitudinal cracks, improper pipe fitting, gasket faults associated with the pipes used for the water distribution networks, old pipelines, road traffic, repairs to the road system, and high water pressure in water distribution networks.

If water distribution networks are made of pipes tightened with gaskets, a considerable part of the water loss occurs either due to incorrect pipe assembly or due to fatigue and aging of the material used to tighten the pipes [7].

Covelli et al. [7] states that most articles in the scholarly literature refer to the assessment of water losses through holes and longitudinal pipe cracks.

One of the methods of reducing water losses in water distribution networks is to install water pressure reducing devices. This purpose can be accomplished by means of flow or pressure control devices (throttle control valves (TCVs) or pressure reduction valves (PRVs) or by using small- or micro-turbines or pumps as turbines (PaT)), able to totally replace the PRVs or to be located in parallel or in series with them [8].

Determining the number of pressure reducing valves, positioning and setting them is a problem that requires optimization calculations [8,9].

Candelieri et al. [10] have conducted a study in which they have attempted to highlight the relationship between pressure variations and flow variations as well as pipeline sections that may be affected by leakage.

To locate leakage, Candelieri et al. [3] proposed combining chart-based analysis with traditional machine learning techniques (e.g., regression) to estimate the severity of leakage, which leads to leakage location improvement and helps water distribution network managers to define an intervention plan.

Several studies have proposed that localization be improved through the analysis of data collected by computer-based systems usually adopted in water distribution networks, such as supervisory control and data acquisition (SCADA), automatic metering readers (AMRs), GIS, and hydraulic simulation software [11].

In the field of drinking water production, one can optimize the following: production costs, water losses, the duration of water supply interruption, maintenance costs, and compliance with water quality requirements [12].

Since the 1970s, several articles have appeared on optimizing water distribution networks. The first field of research relates to the operation of pumps, because pump operation costs are the greatest expense for water companies around the world. The second field of research concerns the optimization of water quality in the water distribution network. This research field emerged in the 1990s.

Optimal operation of pumps is often formulated as a cost optimization problem. Pump operating costs are comprised of costs for energy consumption due to pump operation and costs due to the maintenance of pumps. The electricity costs have two components, namely, the costs of the electricity actually consumed and the electricity consumption tax [13].

Castro-Gama et al. [12] have implemented a pump operating program for the entire water distribution system in Milan. The results show that there is a potential to reduce electricity costs by up to 26%.

Soldi et al. [14] state that water distribution network managers can establish intervention/rehabilitation plans, even preventive ones, taking into account the vulnerability/resistance and damage chances of water distribution network components.

Resilience and vulnerability of networked infrastructures are strictly linked: while resilience is focused on a general evaluation of the robustness of the entire infrastructure, vulnerability is associated with a specific component, or set of components, to represent the possibility of being influenced by hazards/threats and the severity of the possible consequences [14].

When setting up the rehabilitation plan for water distribution networks, the concept of a “water-smart society” can be taken into account. This concept, where the true value of water is recognized and exploited, is transforming water distribution networks (WDNs) into “smart” water

networks, with a widespread adoption of advanced metering infrastructure (AMI), automatic metering readers (AMRs), data analytics, hydro-informatics, and automation technologies, enhancing water efficiency operations and optimizing the supply and demand cycle through a growing availability of real time data from the process [15].

The rehabilitation of drinking water distribution networks is a crucial aspect of sustainable urban development. The mismanagement of water systems can engender not only the disruption of supply but also the degradation of water quality and increased operating and capital expenditures [16].

1.2. Current State of Research

At the international level, the methods of choosing technical solutions for the rehabilitation of water distribution networks are focused on the following main areas: predictive models on pipe degradation [17,18], models for risk estimation [19], economic and financial analysis [20], social analysis [21], cost optimization [22], energy optimization [23,24], the analysis of CO₂ emissions on life cycle (LCE/LCA) [25], and multi-criteria methods [26].

Several software products have been designed in order to shorten the time required for substantiating the selection of technical solutions for the rehabilitation of water distribution systems.

Large et al. [27] performed the ranking of these software products in four categories, namely: Model M1, for assessing the deterioration of pipes, Model M2, for assessing the risks, Model M3, for economic analysis and financial analysis, and Model M4, for the multicriteria analysis [27,28].

Due to the difficult processes of optimization and reliability assessments of water distribution networks, most of the research focused only on the piping system, omitting other network components such as balancing tanks, pumps, or valves [29].

State-of-the-art projects in rehabilitation management for urban water networks focus mainly on one single network alone, while an integrated multi-utility approach is still seldom used [30].

Multi-criteria analysis (MCA) methods can be defined as a set of techniques for assessing decisional options based on several criteria expressed in different measurement units [31]. According to Xu and Yang [32], multiple criteria decision-making refers to making decisions in the presence of multiple and usually conflicting criteria [16,32]. Recent review papers identify hundreds of MCA techniques for ranking or scoring options, weighting criteria, and transforming criteria into commensurate units [31]. Boran et al. [33] say that one of the weaknesses of these traditional methods is that they do not take into account the relationship between the criteria used for the evaluation.

The main multi-criteria analysis methods used internationally in order to substantiate the decision in the field of water distribution networks are presented in Table 1.

Analyzing the data from Table 1, one may note that the analytic hierarchy process (AHP) method is one of the most popular multi-criteria methods used in the field of water distribution networks.

Harrison et al. [1] have noticed that there is a gap between developed decisional theories and applications. The deficiency of knowledge is even greater in developing countries, where these methods and tools are difficult to apply and therefore are not well understood or validated.

Following the bibliographic study performed, we have noticed that there are few articles in the scholarly literature using the AHP method in the case of drinking water distribution networks.

For easier calculations in the case of multi-criteria methods, in practice it is customary to use software programs.

Table 1. Multi-criteria analysis methods used in the field of water distribution networks.

No.	Method	References
1	AHP (Analytic Hierarchy Process)	[26,30,34–38]
2	The hybrid method of AHP and ANN (Artificial Neural Network)	[39]
3	Copeland	[40]
4	Electre II	[40,41]
5	Electre III	[16,30]
6	Electre TRI	[41,42]
7	Leader	[28]
8	PROMETHEE I	[16]
9	PROMETHEE II	[1,43,44]
10	PROMETHEE III	[30]
11	PROMETHEE GDSS (Group Decision Support System)	[45]
12	TOPSIS	[30]
13	Multiattribute value model (MAVM)	[46]
14	WSM (Weighted Sum Model)	[30]
15	Weighted Utopian Approach	[17]

Weistroffer et al. [47] inventoried a number of 79 MCA software packages implementing a variety of MCA methods [31,47].

1.3. The Purpose and Contributions of the Paper

The purpose of the paper is to contribute to the increasingly complex decision-making process concerning water distribution networks in a given locality.

An important contribution of this paper is to provide a methodology for choosing the best rehabilitation technology for water distribution networks.

2. Materials and Methods

2.1. Description of Study Area

Here we analyze the possibility of rehabilitating the water distribution networks of Cluj-Napoca City, Romania.

Following the inventory of existing pipeline types, it was concluded that the water distribution network in the city of Cluj-Napoca has a length of 479 km, with nominal diameters between 50 and 700 mm. It is made of various materials, depending on the knowledge and technology that existed during the period of construction, namely, ductile cast iron, gray cast iron, polyethylene, prestressed concrete, asbestos, and steel [28,48].

Figure 1 shows the percentages of the pipeline types that comprise the water distribution network in the city of Cluj-Napoca. Besides the inventory of pipeline types and their lengths, water losses from the water distribution system of Cluj-Napoca City have also been recorded. Figure 2 shows the percentage of water losses broken down by pipeline type.

Figure 2 shows that the largest water losses are recorded in asbestos pipes. Additionally, Figure 1 shows that the asbestos pipes have only a 14% share.

Given the fact that, in Cluj-Napoca, water distribution networks are quite old, the materials used to make water distribution networks are of poor quality, pipelines frequently break, and there are large water losses and frequent interruptions in the supply of drinking water, old pipes need to be replaced.

Considering the large water losses of the Cluj-Napoca water distribution system, a plan for the rehabilitation and modernization of water distribution networks must be established, starting with the asbestos pipes where the largest water losses are recorded [34].

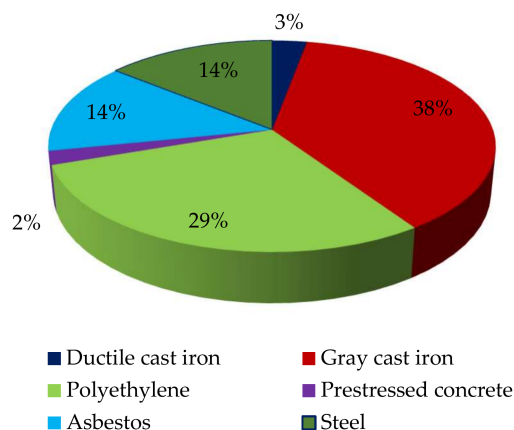


Figure 1. Pipeline type distribution [28].

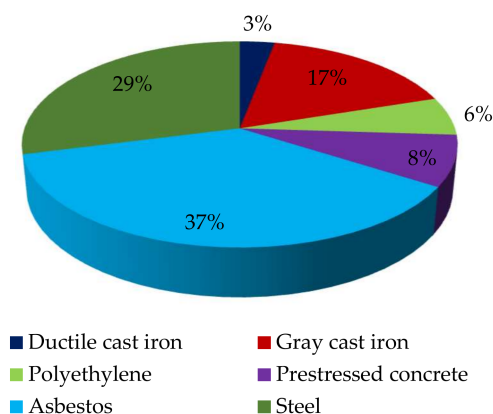


Figure 2. Water loss distribution broken down by pipeline type [28].

2.2. Materials

Asbestos pipes started to be manufactured at the beginning of the 20th century in Italy. The new type of pipe came with some advantages, so it began to spread rapidly in most European and North American countries. Between the 1950s and the 1960s, the asbestos pipes were the most used material for the construction of water supply networks. At present, most asbestos water pipes are near the end of their lifespan [49].

Asbestos pipes pose water quality problems and, according to European regulations, have to be replaced [50].

Water loss reduction options are selected after carrying out a water balance/audit. The water balance reveals the nature and magnitude of the decision problem and provides guidance on which strategy options to adopt.

The strategy options can then be selected from a rich menu developed by the IWA and the American Water Works Association (AWWA) based on many years of research [1].

Water distribution networks can be installed using open-cut or trenchless technologies. The open-cut/trenching conventional method involves executing a new pipe at a depth of 1–6 m, or of replacing an existing pipe in the ground, by creating an open trench along the entire work route. No-dig/trenchless technology involves building or restoring a ground-based, water or water-free tubular work without opening a trench along the way. The excavations are local for the launch of the machine or of the new pipeline and for the rebuilding of the connection, the excavations representing less than 5% of the length [50].

In this study, we analyze five alternatives, as follows: Compact Pipe, Slipline, Subline, Swagelining, and Pilot Pipe (see Table 2).

Table 2. Matrix of alternatives [48,51].

Alternative's Symbol	Alternative Name	Material of the Pipe to Be Rehabilitated	Material of the Rehabilitated Pipe	The Nominal Diameter of the Pipe (mm)	Distance (m)	Observations
A1	Compact Pipe	Concrete, asbestos cement, cast iron, steel, PVC	PE	100 ÷ 500	700	The PE inliner is delivered on site as molded in the form of "C". It is recommended for crowded urban areas.
A2	Slipline	Concrete, asbestos cement, cast iron, steel, PVC	PE, PVC	50 ÷ 1000	long	
A3	Subline	Concrete, asbestos cement, cast iron, steel, PVC	PE 80 or PE 100 with SDR 26 or SDR 80	75 ÷ 1600	long	The PE inliner is delivered on site as molded in the form of "U".
A4	Swagelining	Concrete, asbestos cement, cast iron, steel, PVC	PE, PVC	65 ÷ 1000	1000	
A5	Pilot Pipe	Concrete, asbestos cement, cast iron, steel, PVC	Steel, PE or other materials with high tensile strength	80 ÷ 1600	60 ÷ 80 m trenchless term	

In recent years, trenchless technologies have been used for construction and rehabilitation of buried utilities, such as gas pipelines, water distribution systems, sewer collection systems, and drainage culverts [52].

Pipeline renewal technologies may be divided into repair, rehabilitation, and replacement technologies [53]. Obviously, the water distribution network rehabilitation technologies may have their advantages, as well as their disadvantages.

Trojan and Costa [40] say that alternatives can be assessed using different criteria that are usually in conflict.

2.3. Methods

We propose multi-criteria methods for choosing technical solutions of rehabilitation of water distribution networks.

Two of the most important methods of multi-criteria decision-making (MCDM) are the AHP and the ANP. Because the ANP method (1996) is more recent than the AHP method (1980), a limited number of studies on this topic can be found. However, there are studies that have shown that the ANP method is superior to the AHP method [54].

Many decision problems cannot be structured hierarchically because they involve the interaction and dependence of higher-level elements on a lower-level element [55,56].

Saaty suggested the use of the AHP to solve the problem of independence among alternatives or criteria, as well as the use of the ANP to solve the problem of dependence among alternatives or criteria [54].

According to Cheng and Li [57], the ANP method incorporates both qualitative and quantitative approaches to a decision-making problem.

Nedjatia and Izbirak [54] assert that, for the decision-making process, when using qualitative and uncertain values, the use of the ANP method is preferable to the AHP method, so for the choice of pipeline rehabilitation technologies in water distribution systems, we propose the use of the ANP method.

The ANP method has been applied in many areas, such as quality [58], energy efficiency [59], civil engineering [60], renewable resources [61], environment [62], human resources [54], telecommunications [63], industry [64], health [65], finance [66], transportation [67], computer science [68],

thermal energy supply systems [69], wastewater treatment [70], methane gas systems [71], banking, government, marketing, and tourism [72].

In order to select technologies for the rehabilitation of pipes from water distribution systems, the ANP method should be used. The 14 steps involved will here be explained.

Step 1: Establishing the purpose and the objectives. Goals are broad statements of intent and desirable long-term plans. The goals and objectives are derived from the utility's vision and mission statements. The goals and objectives should involve considerations of economic, environmental and social sustainability. In practice, objectives are often conflicting and may be realized over a short-, medium-, or long-term period [1].

Issues related to the prioritization of alternatives or the general decision-making in water utility companies are always connected to conflicts of preference among managers who have different interests in attending to the company's goals [40].

Step 2: Identification of the decision-making criteria. At this stage, the decision-maker must identify a list of selection criteria for the evaluation of the alternatives.

Tscheikner-Gratl et al. [30] assert that, at the start of the decision-making process, the decision-makers need enough time to define the decision-making criteria.

Tlili and Nafi [16] assert that decision-making on the classification of alternatives to rehabilitate water distribution networks depends on the number of criteria used and the weighting assigned to each criterion, which makes the aggregation task more complicated.

Step 3: Identification of alternatives. At this stage, the options that may contribute to the accomplishment of objectives are identified.

Step 4: Forming the structure of the ANP network. Jayant et al. [73] assert that many decision-making problems cannot be built as hierarchic problems because of the (interior/exterior) dependences and of the influences between and inside the clusters (criteria and alternatives). ANP is very useful for solving such problems.

Not only does the importance of the criteria determine the importance of the alternatives as in a hierarchy, but also the importance of the alternatives themselves determines the importance of the criteria. Feedback enables us to factor the future into the present to determine what we have to do to attain a desired future [74].

To structure detailed ANP models, Saaty wisely introduces clusters, which refer to grouping of homogeneous elements together, such as alternatives, criteria, and subcriteria.

Hence, in this model, there is one cluster for objectives and one cluster for all evaluation criteria, and each of the evaluation criteria with their sub-criteria have their own clusters. The alternatives are grouped into one cluster [75].

Relationships in a network are represented by arcs, and the directions of arcs signify dependence [56].

Step 5: Forming the pairwise comparison matrices. Similar to the AHP method, the priorities in case of the ANP method are directly assessed by pair comparison [76].

There are two levels of pairwise comparisons in the ANP method: the cluster level, which is more strategic, and the node/element level, which is more specialized.

Cluster comparisons involve comparing clusters with other clusters. While pair comparisons on elements in clusters are made depending on their influence on each element in another group, they are related to elements in another cluster (external dependence) or elements in their own group (inner dependency) [77].

Should there be n elements to be compared, then the pairwise comparison matrix noted with “ A ” is defined as

$$A = (a_{ij})_{n \times n} = \begin{vmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{vmatrix}, \quad (1)$$

where $a_{ii} = 1$, $a_{ji} = 1/a_{ij}$, and $a_{ij} \neq 0$ [78].

The “ a_{ij} ” score in the pairwise comparison matrix represents the relative importance of the element from row (i) compared with the element from column (j) [68]. The pairwise comparison matrices are square matrices, with “ n ” elements on the line and “ n ” elements on the columns. In this context, for the “ n ” criteria, it is necessary to compare $n(n-1)/2$ pairs [79].

At this stage, the relative importance of each criterion relative to the other criteria is established, in order to determine the level of contribution of each criterion to the achievement of objectives [77].

The pair comparisons are made by the decision-makers who assess the pairs subjectively (initially based on verbal assessments—“equally important,” “slightly more important,” “absolutely more important,” and so on—and then an assignment of values on a scale from 1 to 9, which represents the degree of importance of one attribute towards another attribute). If the comparison between two criteria is reversed, then the importance value equals the reverse of the direct comparison value.

We used the Saaty scale for this purpose.

Step 6: Forming normalized matrices. Further, the values recorded in the pairwise comparison matrix are normalized, and the results are then recorded in the normalized matrix.

Saaty proposes several algorithms for approximating the relative weights [80,81]. There is still debate regarding approximation methods. A critical analysis of the weight calculation method can be taken from Bana and Vansnick [82,83]. In most articles, normalization is made by one of the following methods: the arithmetic average method [84,85], the geometric average method [86], and the difference method [87–91].

Further, we present the arithmetic average method, which supposes three steps:

- calculate the sum on each column of the pairwise comparison matrix using Equation (2);
- divide each element of the pairwise comparison matrix to the amount corresponding to its column using Equation (3);
- record the obtained values in the normalized matrix using Equation (4).

$$S_j = \sum_{i=1}^m a_{ji}, \quad (2)$$

$$a_{ji_{norm}} = \frac{a_{ji}}{S_j}, \quad (3)$$

$$A_{norm} = \begin{vmatrix} a_{11_{norm}} & a_{12_{norm}} & \dots & a_{1n_{norm}} \\ a_{21_{norm}} & a_{22_{norm}} & \dots & a_{2n_{norm}} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{n1_{norm}} & a_{n2_{norm}} & \dots & a_{nn_{norm}} \end{vmatrix}, \quad (4)$$

Step 7: Establishing local priorities. Based on the information recorded in the normalized matrix, local priorities are established using Equation (5), and the data are registered in a column matrix, according to the model presented in Equation (6). The respective matrix is called the local priority vector [92].

$$w_i = \frac{\sum_{j=1}^n a_{ijnorm}}{n} \text{ and } \sum_{j=1}^n w_i = 1, \quad (5)$$

$$W = \begin{pmatrix} w1 \\ w2 \\ \dots \\ \dots \\ wn \end{pmatrix}, \quad (6)$$

Step 8: Determining the consistency of the matrix. In order to determine the consistency factor of the matrices, we perform the following steps:

(a) Establish the average stochastic uniformity coefficient. The average stochastic uniformity coefficient, marked “*R*” is determined depending on the rank of the analyzed matrix, marked “*m*” based on Table 3 [93].

Table 3. Values of the average stochastic coefficient depending on the rank of the matrix [94–97].

(Order of Matrix)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
<i>R</i>	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

(b) Determine the uniformity coefficient. The uniformity coefficient “*CI*” is calculated based on Equation (7), as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (7)$$

where [35] $\lambda_{max} > n$. *n* is the number of elements to be compared.

$$\lambda_{max} = \sum_{i=1}^n \frac{(A \cdot w)_i}{n \cdot w_i}, \quad (8)$$

(c) Determining the consistency factor of the matrices.

The consistency factor of matrices “*CR*” is calculated based on Equation (9), as follows:

$$CR = \frac{CI}{R}, \quad (9)$$

When determining the consistency relation, one takes into account the following rule: if $CR \leq 0.10$, then the matrix is considered consistent, namely, the vector of the weights is well determined. When higher matrix consistency ratios are found, it is necessary to resume comparisons for that respective matrix [95].

Step 9: Forming the unweighted supermatrix. After having established the local priorities based on the pairwise comparison matrices, the following step consists in progressively forming three supermatrices, namely, the initial or unweighted supermatrix, the weighted supermatrix, and the limit supermatrix, which are square matrices and have the same number of elements.

The priority vectors obtained from the pairwise comparison matrix are recorded as column vectors relative to their control criterion, in a new matrix called the unweighted supermatrix, whose form is according to Equation (9) [74].

The unweighted supermatrix represents the influence priority of an element from the left part of the matrix on an element from the upper part of the matrix relative to a certain control criterion.

The resulted matrix must be a stochastic one, meaning that the sum of the values recorded in each column must be equal to that of each cluster individually [95].

$$W = \begin{pmatrix} & \begin{matrix} C1 \\ C1 \\ e11 \\ e12 \\ \dots \\ e1n1 \end{matrix} & \begin{matrix} C2 \\ e21 \\ e22 \\ \dots \\ e2n2 \end{matrix} & \dots & \begin{matrix} CN \\ eN1 \\ eN2 \\ \dots \\ eNnN \end{matrix} \\ \begin{matrix} C1 \\ C2 \\ \dots \\ CN \end{matrix} & \begin{matrix} e11 \\ e12 \\ \dots \\ e1n1 \end{matrix} & \begin{matrix} W11 \\ W21 \\ \dots \\ WN1 \end{matrix} & \dots & \begin{matrix} W1N \\ W2N \\ \dots \\ WNN \end{matrix} \end{pmatrix}, \quad (10)$$

where "CN" represents the cluster "N", "Nn" is the element n in the cluster "N", and "Wij" is the vector of the element influence [98–103].

In the unweighted matrix, "Wij" virtually represents a local priority matrix, and it results from a comparison of two clusters.

Each column of the "Wij" matrix is the priority vector resulting from a pairwise comparison matrix. This matrix virtually comprises the local priority vectors [104].

$$Wij = \begin{pmatrix} w11 & w12 & \dots & w1n \\ w21 & w22 & \dots & w2n \\ \dots & \dots & \dots & \dots \\ wn1 & wn2 & \dots & wnn \end{pmatrix}, \quad (11)$$

Step 10: Forming the weighted supermatrix. For each column block, the first entry of the local priority vector is multiplied with all of the elements of the first block of the respective column, the second entry with all of the elements of the second block of that column, and so on. Thus, the blocks of each column of the supermatrix are weighted, and the result is known as the weighted supermatrix, which is a stochastic one [56].

This "column stochastic" feature of the weighted supermatrix allows convergence to occur in the limit supermatrix [105].

Step 11: Forming the limit supermatrix. Finally, the weighted supermatrix is transformed into the limit supermatrix by raising itself to powers. The reason for multiplying the weighted supermatrix is because we wish to capture the transmission of influence along all possible paths of the supermatrix.

Raising the weighted supermatrix to the power "2k + 1", where "k" is an arbitrarily large number, allow convergence of the matrix, which means the row values converge to the same value for each column of the matrix. The resulting matrix is called the limit supermatrix, which yields limit priorities capturing all of the indirect influences of each element on every other element [105].

The limit supermatrix has the same form as the weighted supermatrix, but all of the columns of the limit supermatrix are the same [56].

The consistency of the element comparison is calculated as follows [33,104]:

$$W'_{\infty} = \lim_{k \rightarrow \infty} W^{2k+1}, \quad (12)$$

Step 12: Establishing the alternative ranking. The alternative ranking is established based on the global priority. Obviously, the alternative having the highest global priority ranks highest.

Step 13: Sensitivity analysis. Sensitivity analysis refers to the question of “what if” in order to see if the final answer is stable when entries are modified or to determine whether they are judgments or priorities [106].

Step 14: Choosing the best alternative. Eventually, the alternative with the highest global priority should be the selected one [56].

3. Results and Discussions

Step 1: Establishing the purpose and the objectives. The purpose of this study is to find the best technical solution for the rehabilitation of asbestos pipelines in order to reduce water losses in the water supply system of Cluj-Napoca City, Romania.

Step 2: Identifying the decision-making criteria. After the study of the scholarly literature and based on the available data, the decision-making criteria were selected. Table 4 presents the decision-making criteria used in the case study.

Table 4. The set of decision criteria [48,51].

Criterion	Name of Criteria	Type	Description
C1	Diameter of the pipe	maximized	It is advisable to select that alternative that can be used for the entire range of pipes used in water distribution networks.
C2	Length of the pipe	maximized	It is advisable to select that alternative that can be used for the longest possible pipelines.
C3	Period of time required for installation	minimized	It is preferable the installation to be as quick as possible.
C4	Lifespan	maximized	The lifespan of the rehabilitated pipe must be higher than the lifespan of the replaced pipe.
C5	Pressure losses	minimized	The pressure losses should be as low as possible.
C6	Price	minimized	The price for replacing the pipes should be as low as possible.
C7	Installation conditions	minimized	The alternative should not set special installation conditions.

Step 3: Identifying the alternatives. In Section 2.2, five alternatives were identified, namely, Compact Pipe, Slipline, Subline, Swagelining, and Pilot Pipe. The data concerning the selected alternatives are presented in Table 2.

Step 4: Forming the structure of the ANP network. The problem is decomposed into a network where nodes correspond to clusters. The elements in a cluster may influence some or all of the elements of any other cluster. These relationships are represented by arcs with directions. Additionally, the relationships among elements in the same cluster can exist and be represented by a looped arc [105].

The ANP network was drawn in the Super Decisions 2.6.0 software (Creative Decisions Foundation, version 2.6.0, Pittsburgh, PA, USA). In order to rank the five alternatives based on the seven criteria, the ANP method by Saaty and the Super Decisions 2.6.0 software were used. This software was chosen because the academic version of the Super Decisions 2.6.0 software is free.

Figure 3 represents the hierarchical structure of the process of choosing the technical solution for the rehabilitation of water distribution networks containing three clusters, namely the “goal” cluster, the “criteria” cluster, and the “alternatives” cluster. There is a feedback loop in the criteria cluster, indicating that the nodes in this cluster (the criteria) are compared to them. There is also a feedback loop in the alternatives cluster and the criteria cluster, indicating that alternatives can influence the criteria.

The hierarchical structure of the network analytical process for choosing the optimal alternative was drawn using the Super Decisions 2.6.0 software, based on the relationship between criteria and alternatives.

The relationships between the decision-making criteria specified in Figure 4 were identified.

Step 5: Forming the pairwise comparison matrices. In Table 5, we present the interaction between the elements of the decision-making process.

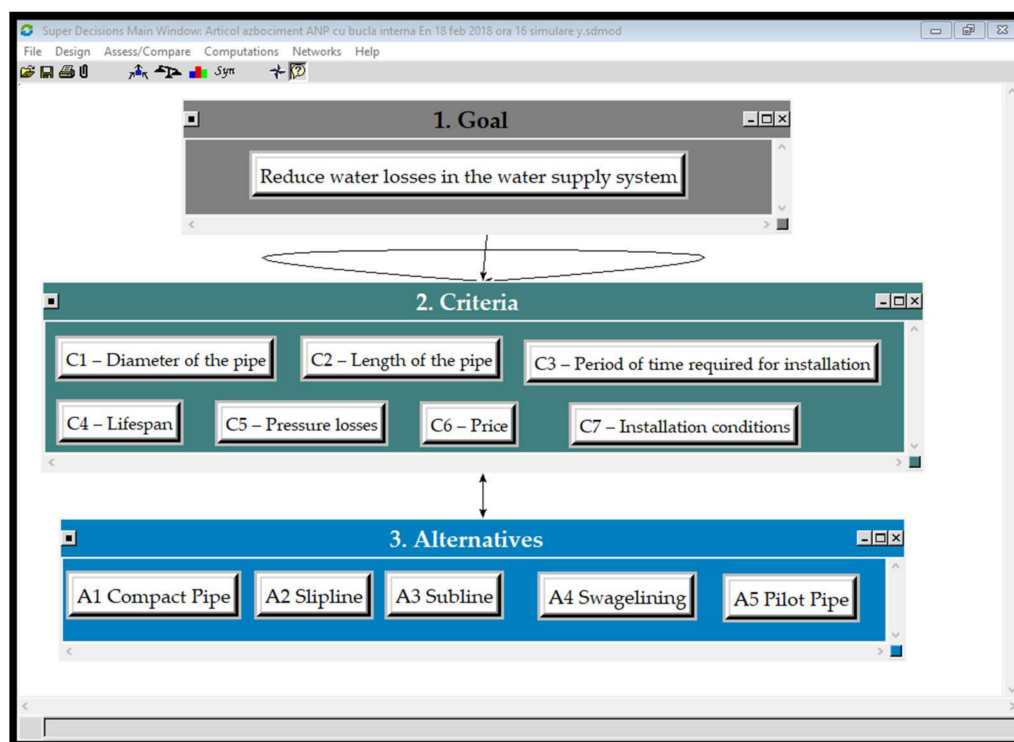


Figure 3. Ranking structure of the network analytical process for selecting the optimal alternative.

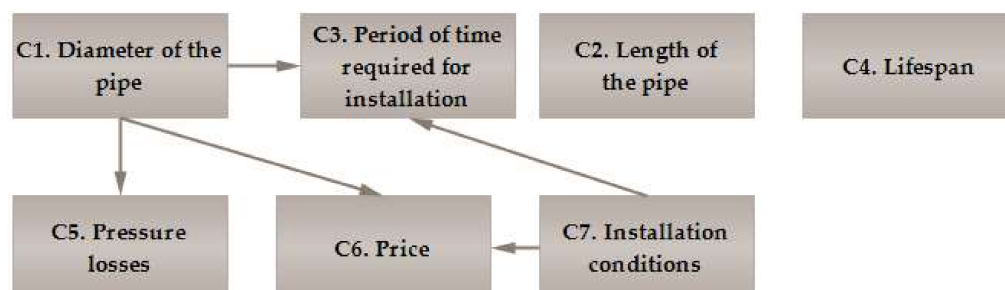


Figure 4. Relationships between the decision-making criteria.

Table 5. Interaction between the elements of the decision-making process.

Cluster		1. Goal		2. Criteria							3. Alternatives				
		C1	C2	C3	C4	C5	C6	C7	A1	A2	A3	A4	A5		
1. Goal															
2. Criteria	C1	x													
	C2	x												x	
	C3	x	x						x						
	C4	x													
	C5	x	x												
	C6	x	x						x						
	C7	x												x	
3. Alternatives	A1		x	x	x	x	x	x	x						
	A2		x	x	x	x	x	x	x						
	A3		x	x	x	x	x	x	x						
	A4		x	x	x	x	x	x	x						
	A5		x	x	x	x	x	x	x						

Remark: The symbol x represents the interaction between the elements of the decision-making process.

According to Table 5, for this case study, we may have a maximum of 39 pairwise comparison matrices, namely,

- 13 pairwise comparison matrices between the goal cluster and the 13 elements of the decision-making process mentioned in Table 5;
- 13 pairwise comparison matrices between the criteria cluster and the 13 elements of the decision-making process mentioned in Table 5;
- 13 pairwise comparison matrices between the alternatives cluster and the 13 elements of the decision-making process mentioned in Table 5.

For this case study, we identified 11 pairwise comparison matrices, namely,

- one matrix for comparing the criteria cluster in relation with the goal;
- two matrices that highlight the relationships between the decision-making criteria, as presented in Figure 4;
- one matrix that highlights the influence of alternatives on the criteria;
- seven matrices for comparing the alternatives in relation with the decision-making criteria, where one matrix was elaborated for each decision-making criterion.

Further, the analysis of pair comparisons was done using the Super Decisions 2.6.0 software. Entering data for pair comparisons with the Super Decisions 2.6.0 software can be done through the following methods: direct data input, use of the questionnaire method, use of the matrix method, use of the verbal method, and use of the graphical method. For this case study, the data input was performed using the default data input option: the questionnaire method.

As an example, one presents the work algorithm to compare the decision-making criteria in relation with the purpose proposed in the case study. Thus, in Figure 5, we present the questionnaire used for pair comparison between the seven decision-making criteria in relation with the goal.

Comparisons for Super Decisions Main Window: Articol azbociment ANP cu bucla internă 18 feb 2018.sdmod

1. Choose

2. Node comparisons with respect to Reduce water losses ~

3. Results

Node Cluster

Choose Node

Cluster: 1. Goal

Choose Cluster

2. Criteria

Graphical Verbal Matrix Questionnaire Direct

Comparisons wrt "Reduce water losses in the water supply system" node in "2. Criteria" cluster

1. C1 – Diameter o~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C2 – Length of ~

2. C1 – Diameter o~>=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. C3 – Period of ~

3. C1 – Diameter o~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C4 – Lifespan

4. C1 – Diameter o~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C5 – Pressure I~

5. C1 – Diameter o~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C6 – Price

6. C1 – Diameter o~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C7 – Installati~

7. C2 – Length of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C3 – Period of ~

8. C2 – Length of ~>=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. C4 – Lifespan

9. C2 – Length of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C5 – Pressure I~

10. C2 – Length of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C6 – Price

11. C2 – Length of ~>=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. C7 – Installati~

12. C3 – Period of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C4 – Lifespan

13. C3 – Period of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C5 – Pressure I~

14. C3 – Period of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C6 – Price

15. C3 – Period of ~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C7 – Installati~

16. C4 – Lifespan>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C5 – Pressure I~

17. C4 – Lifespan>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C6 – Price

18. C4 – Lifespan>=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. C7 – Installati~

19. C5 – Pressure I~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C6 – Price

20. C5 – Pressure I~>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C7 – Installati~

21. C6 – Price>=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. C7 – Installati~

Restore

Normal Hybrid

Inconsistency: 0.00250

C1 – Diam~ 0.06992

C2 – Leng~ 0.12857

C3 – Peri~ 0.06992

C4 – Life~ 0.12857

C5 – Pres~ 0.23722

C6 – Price 0.23722

C7 – Inst~ 0.12857

Completed Comparison

Copy to clipboard

Figure 5. The questionnaire used for pair comparison between the seven decision-making criteria.

The pair comparisons are made based on the Fundamental Scale of Saaty.

In Table 6, we present the values of the pair comparisons between the criteria in relation with the goal.

Table 6. Matrix of pair comparison between the criteria in relation with the goal.

Criteria Code	C1	C2	C3	C4	C5	C6	C7
C1	1.00	1/2	1.00	1/2	1/3	1/3	1/2
C2	2.00	1.00	2.00	1.00	1/2	1/2	1.00
C3	1.00	1/2	1.00	1/2	1/3	1/3	1/2
C4	2.00	1.00	2.00	1.00	1/2	1/2	1.00
C5	3.00	2.00	3.00	2.00	1.00	1.00	2.00
C6	3.00	2.00	3.00	2.00	1.00	1.00	2.00
C7	2.00	1.00	2.00	1.00	0.50	0.50	1.00

In Table 6, it can be seen that, in the matrix, diagonally, the value one is entered because a criterion is compared to itself.

Step 6: Forming the normalized matrices. Further, the values of the criteria comparisons in relation with the purpose are normalized using the Super Decisions 2.6.0 software.

Step 7: Establishing local priorities. After normalizing the values of the criteria comparisons in relation with the purpose, the local priority vector W_{21} is established (see Equation (13)).

$$W_{21} = \begin{pmatrix} 0.069918 \\ 0.128572 \\ 0.069918 \\ 0.128572 \\ 0.237225 \\ 0.237225 \\ 0.128572 \end{pmatrix} \quad (13)$$

Step 8: Determining the consistency ratio of the matrix. Following the application of the calculation algorithm, eventually, for the pairwise comparison matrix of the decision-making criteria in relation with the goal, we obtained a matrix consistency ratio of 0.00250, so the matrix fulfils the consistency requirement ($CR \leq 0.1$). In this case study, local priorities as well as the matrix consistency ratio were both established using the Super Decisions 2.6.0 software.

Moreover, similar calculations were performed for the other pairwise comparison matrices, after which it was found that, for all pairwise comparison matrices, the consistency ratio is less than 0.1; therefore, the matrices fulfill the consistency requirement ($CR \leq 0.1$).

Step 9: Forming the unweighted supermatrix. Starting from the ranking structure of the process presented in Table 7, for this case study, the supermatrix has the following form:

Table 7. Supermatrix form for this case study (W Value).

Cluster	1. Goal	2. Criteria	3. Alternatives
1. Goal	0	0	0
2. Criteria	W_{21}	W_{22}	W_{23}
3. Alternatives	0	W_{32}	0

where W_{21} is a vector representing the impact of the objective established over the criteria, W_{22} is a vector representing the dependency between the criteria, W_{23} is a vector representing the dependency between the criteria and the alternatives, and W_{32} is the vector representing the impact of the criteria on each alternative.

For this case study, the unweighted supermatrix was a square matrix with 13 lines and 13 columns, namely,

- one line and one column reserved for the goal cluster, having only one objective, namely, to reduce water losses in the drinking water distribution network;
- seven lines and seven columns reserved to the criteria cluster, namely, one line and one column reserved for each criterion;
- five lines and five columns reserved to the alternative cluster, namely, one line and one column reserved for each alternative.

Further, the unweighted matrix were elaborated based on the relative weights established for each pairwise comparison matrix (see Table A1). Thus, at the intersection between the line “2 Criteria” and column “1 Goal,” the relative weights obtained in the matrix of comparisons was entered between the criteria in relation with the established purpose (see Table A1). We proceeded similarly with the local weights established through the other matrices of the pairwise comparisons.

Step 10: Forming the weighted supermatrix. Based on the unweighted supermatrix, the weighted supermatrix was elaborated, and, in order to do this, the values from the unweighted supermatrix were multiplied with the weights corresponding to the cluster (see Table A2).

Step 11: Forming the limit supermatrix. The limit supermatrix is calculated by empowering the weighted supermatrix using Equation (12) (see Table A3).

Step 12: Establishing the alternative ranking. In Table 8, the alternative ranking obtained using the ANP method is presented.

Table 8. Alternative rankings.

Alternative Name	Global Priority	Place
A1 Compact Pipe	0.1804	3
A2 Slipline	0.1813	2
A3 Subline	0.3664	1
A4 Swagelining	0.1691	4
A5 Pilot Pipe	0.1028	5

Step 13: Sensitivity analysis. A sensitivity analysis was performed to check the robustness of the model. For this, the weight of each decision-making criterion was modified by $\pm 10\%$.

Sensitivity analysis was performed for all seven criteria, and the alternative preferences were as follows: 0.180 for Alternative A1, 0.181 for Alternative A2, 0.366 for Alternative A3, 0.169 for Alternative A4, and 0.103 for Alternative A5.

The Super Decisions 2.6.0 software allows for the establishment of the limit supermatrix to be carried out by a number of nine different variants, defined as calculus type, scaling by scalar, new hierarchy (without limit), new hierarchy (with limit), identity at sinks, sinks formula (straight normalize), sinks formula (normalize limits), Pre-2001 Version, and Pre-2000 Version.

In this context, we ran a simulation within the case study using the nine variants for the establishment of the limit supermatrix, and, after the simulation, the same result was obtained. The limit supermatrix presented in Table A3 was determined by the “calculus type” variant.

Therefore, after performing the sensitivity analysis, it was proved that the method used offered a very stable ranking of alternatives.

Step 14: Selecting the best alternative. The priorities obtained after assessing the alternatives (see Table 8) are as follows: 0.1804 for Alternative A1 (Compact Pipe), 0.1813 for Alternative A2 (Slipline), 0.3664 for Alternative A3 (Subline), 0.1691 for Alternative A4 (Swagelining), and 0.1028 for Alternative A5 (Pilot Pipe).

Based on the priorities obtained and on the sensitivity analysis, we recommend Alternative A3, namely, the Subline technology, considering that this alternative obtained the highest global priority.

4. Conclusions

This paper presents a case study on the choice of the best technical solution for the rehabilitation of asbestos pipelines in the city of Cluj-Napoca, Romania. The ANP method was used as the method of selecting a solution for the rehabilitation of the pipes, and calculations were carried out using the Super Decisions 2.6.0 software.

In the case study, five alternatives are analyzed based on seven decision-making criteria. The decision-making criteria taken into account to substantiate the decisions included pipeline diameter, pipe length, specific building duration, lifespan, pressure drops, price, and mounting conditions, while the alternatives were Compact Pipe, Slipline, Subline, Swagelining, and Pilot Pipe.

Based on the maximum global priority, we recommend choosing the Subline alternative as a method of rehabilitating the water distribution networks made of asbestos pipes in the case of Cluj-Napoca City, Romania.

The mathematical model presented is a flexible one, as it allows for the entry of new criteria, subcriteria, and alternatives. The methodology described in this paper can be modified and used depending on the specific situation of a given town.

In the future, we also recommend studying the ANP-GP method, which, in addition to the ANP method, uses objective programming. We recommend combining the fuzzy approach with the ANP method, as this would better fit the style of human thinking and seems to produce reliable results.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The unweighted supermatrix.

Cluster	1. Goal		2. Criteria							3. Alternatives				
		C1	C2	C3	C4	C5	C6	C7	A1	A2	A3	A4	A5	
1. Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	
2. Criteria	C1	0.06992	0	0	0	0	0	0	0	0	0	0	0	
	C2	0.12857	0	0	0	0	0	0	0	0	0	0	0.75	
	C3	0.06992	0.24931	0	0	0	0	0	0.25000	0	0	0	0	
	C4	0.12857	0	0	0	0	0	0	0	0	0	0	0	
	C5	0.23722	0.15706	0	0	0	0	0	0	0	0	0	0	
	C6	0.23722	0.59363	0	0	0	0	0	0.75000	0	0	0	0	
	C7	0.12857	0	0	0	0	0	0	0	0	0	0	0.25	
3. Alternatives	A1	0	0.07909	0.16649	0.18432	0.23077	0.34632	0.23077	0.19829	0	0	0	0	
	A2	0	0.13673	0.16649	0.34908	0.23077	0.34632	0.23077	0.16278	0	0	0	0	
	A3	0	0.24440	0.43320	0.18432	0.23077	0.13500	0.23077	0.24351	0	0	0	0	
	A4	0	0.13673	0.16649	0.18432	0.23077	0.13500	0.07692	0.24351	0	0	0	0	
	A5	0	0.40305	0.06734	0.09796	0.07692	0.03736	0.23077	0.15191	0	0	0	0	

Table A2. Weighted supermatrix.

Cluster		1. Goal		2. Criteria						3. Alternatives				
		C1	C2	C3	C4	C5	C6	C7	A1	A2	A3	A4	A5	
1. Goal		0	0	0	0	0	0	0	0	0	0	0	0	0
2. Criteria	C1	0.06992	0	0	0	0	0	0	0	0	0	0	0	0
	C2	0.12857	0	0	0	0	0	0	0	0	0	0	0	0.75000
	C3	0.06992	0.06233	0	0	0	0	0	0.06250	0	0	0	0	0
	C4	0.12857	0	0	0	0	0	0	0	0	0	0	0	0
	C5	0.23722	0.03926	0	0	0	0	0	0	0	0	0	0	0
	C6	0.23722	0.14841	0	0	0	0	0	0.18750	0	0	0	0	0
	C7	0.12857	0	0	0	0	0	0	0	0	0	0	0	0.25000
3. Alternatives	A1	0	0.05931	0.16649	0.18432	0.23077	0.34632	0.23077	0.14872	0	0	0	0	0
	A2	0	0.10255	0.16649	0.34908	0.23077	0.34632	0.23077	0.12209	0	0	0	0	0
	A3	0	0.18330	0.43320	0.18432	0.23077	0.13500	0.23077	0.18263	0	0	0	0	0
	A4	0	0.10255	0.16649	0.18432	0.23077	0.13500	0.07692	0.18263	0	0	0	0	0
	A5	0	0.30229	0.06734	0.09796	0.07692	0.03736	0.23077	0.11393	0	0	0	0	0

Table A3. Limit supermatrix.

Cluster	1. Goal								2. Criteria					3. Alternatives				
		C1	C2	C3	C4	C5	C6	C7	A1	A2	A3	A4	A5					
1. Goal		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Criteria	C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C2	0.16718	0.16718	0.16718	0.16718	0.16718	0.16718	0.16718	0.16718	0	0	0	0	0	0	0	0.16718	0.16718
	C3	0.01026	0.01026	0.01026	0.01026	0.01026	0.01026	0.01026	0.01026	0	0	0	0	0	0	0	0.01026	0.01026
	C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C6	0.03077	0.03077	0.03077	0.03077	0.03077	0.03077	0.03077	0.03077	0	0	0	0	0	0	0	0.03077	0.03077
	C7	0.05572	0.05572	0.05572	0.05572	0.05572	0.05572	0.05572	0.05572	0	0	0	0	0	0	0	0.05572	0.05572
3. Alternatives	A1	0.13282	0.13282	0.13282	0.13282	0.13282	0.13282	0.13282	0.13282	0	0	0	0	0	0	0	0.13282	0.13282
	A2	0.13343	0.13343	0.13343	0.13343	0.13343	0.13343	0.13343	0.13343	0	0	0	0	0	0	0	0.13343	0.13343
	A3	0.26967	0.26967	0.26967	0.26967	0.26967	0.26967	0.26967	0.26967	0	0	0	0	0	0	0	0.26967	0.26967
	A4	0.12445	0.12445	0.12445	0.12445	0.12445	0.12445	0.12445	0.12445	0	0	0	0	0	0	0	0.12445	0.12445
	A5	0.07570	0.07570	0.07570	0.07570	0.07570	0.07570	0.07570	0.07570	0	0	0	0	0	0	0	0.07570	0.07570

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