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PageRank vs. ANP: A Comparative Analysis for Prioritizing Maintenance Activities in Industrial Water Distribution Systems

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Abstract: This paper proposes the implementation of the PageRank algorithm as an alternative to the Analytic Network Process (ANP) for prioritizing maintenance activities in water distribution systems. We demonstrate the comparable performance of the PageRank algorithm to the ANP by comparing the results obtained from a previous conference paper that utilized the ANP for decision-making in sustainability-related problems involving water distribution systems feeding manufacturing industries. The ANP is commonly used for decision-making in complex systems, but has limitations such as subjective weighting and handling large datasets. In contrast, the PageRank algorithm, originally designed for web page ranking, offers a scalable and objective approach for analyzing complex systems. To showcase the effectiveness of the PageRank algorithm, we compare the results obtained from the ANP in our previous conference paper with the PageRank algorithm. Our findings reveal that the PageRank algorithm yields identical results to the ANP, while addressing its limitations. The results of this study demonstrate the viability and effectiveness of the PageRank algorithm in achieving identical outcomes as the ANP, with potential advantages in scalability and objectivity. The proposed implementation of the PageRank algorithm as an alternative to the ANP offers a promising approach for prioritizing maintenance activities in water distribution systems, as similar considerations can be extended to any sector of activity.

Keywords: Sustainability Factors, Maintenance Management, Multi-Criteria Decision-Making, Page Rank Algorithm, Industrial Systems

1. INTRODUCTION AND OBJECTIVES

The effective management of maintenance in complex systems necessitates the achievement of strategic goals and adherence to specific principles. Establishing a robust maintenance system is crucial for identifying maintenance trends, as it facilitates regular exploration of the system's state and streamlines business operations while safeguarding assets and preventing breakdowns. However, minimizing the environmental impact poses a significant challenge, particularly in the industrial sector, as maintenance activities may deplete resources, consume energy, and result in potentially harmful emissions or dust, thereby negatively affecting the environment.

The development of structured and flexible methodologies capable of achieving reliable results is of paramount importance in the field of maintenance and sustainability. Not only do such methodologies provide a systematic approach to addressing complex maintenance challenges, but also they enable organizations to integrate sustainability considerations into their decision-making processes. By improving existing techniques, proper methodologies enhance the accuracy and efficiency of maintenance interventions while minimizing their environmental impact. Moreover, they contribute to the advancement of sustainable practices by enabling organizations to prioritize interventions based on specific criteria, such as resource efficiency, energy consumption, and emissions reduction. The development and application of suitable methodologies play a vital role in driving innovation and continuous improvement in the field of maintenance, fostering a more sustainable future for industrial operations and ensuring long-term environmental protection.

In this paper, we first analyze a case study that was developed in our previous research (Carpitella et al., 2022), focusing on how sustainability aspects intersect with the implementation of interventions based on specific maintenance policies. In Carpitella et al. (2022) we examined the water supply system feeding a manufacturing company, and proposed a Multi-Criteria Decision-Making (MCDM) approach based on the use of the Analytic Network Process (ANP) for evaluating the sustainability aspects in the prioritization of maintenance interventions for industrial water supply systems. Multi-criteria ranking algorithms can indeed account for the multiple factors that decision-

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makers typically weigh when choosing between options. Specifically, in the present research, we propose a different resolution problem, the PageRank algorithm, as an alternative methodological approach to capture the relationships of reliance between sustainability variables and the most important maintenance components. We herein lead the application of the PageRank algorithm by using the same input data collected in Carpitella et al. (2022), demonstrating that the produced results are identical to those achieved via ANP. The motivation of our study refers to the fact that, with respect to traditional MCDM approaches based on the use of ANP, the PageRank algorithm has a strength in its scalability, as it can handle large and complex networks with numerous interconnected data, making it suitable for analyzing complex systems. Additionally, it provides an objective approach for evaluating the importance or influence of nodes in a network.

The paper is organised as follows. Section 2 provides a literature review about the main topics of research. Section 3 reminds to the proposed methodological approach and section 4 presents the comparison of results. Conclusions and future developments are discussed in section 5.

2. LITERATURE REVIEW

In the engineering field, complex decision-making problems often arise due to the multitude of options available, along with the need to consider multiple factors (Li and Wu, 2022). Such problems require a systematic approach that involves evaluating and comparing different options based on various criteria, also in consideration of their mutual correlation (Dui et al., 2023).

Ranking is a fundamental aspect of this approach, playing a critical role in decision-making processes as well as information retrieval (Pourbahman et al., 2023). A well-defined ranking system can help engineers prioritize options and allocate resources efficiently. This ensures that the most effective solution is identified, that resources are utilized in the most efficient manner possible, and that information is effectively screened (Lee et al., 2012). The importance of ranking is further pronounced in large-scale engineering projects that involve multiple stakeholders, where the complexity of the decision-making process increases substantially (Benítez et al., 2018). Ranking also helps to identify and resolve conflicts between different stakeholders by presenting a clear and objective framework for decision-making (Mahlalela et al., 2022).

Furthermore, ranking plays an essential part in evaluating trade-offs when comparing different options. By identifying and evaluating the relative importance of different factors such as cost, feasibility, environmental impact, and technical requirements, engineers can make informed decisions that balance competing priorities effectively (Carpitella et al., 2022). In addition, ranking systems support in making decisions that are consistent with broader organizational objectives, by ensuring that individual decisions align with the overall mission and goals of the company (Encenzo et al., 2023). Effective ranking systems aims to provide a transparent and consistent approach to decision-making, ensuring that the final decision is based on rational and objective criteria while reducing the potential for bias or subjectivity (Tavana et al., 2015). This increases the reliability and credibility of the decision-making process, enhancing the confidence of stakeholders in the decision-making outcome and, eventually, the global level of business performance (Benítez et al., 2019).

Ranking is one of the most common output that can be derived from such structured frameworks as MCDM methods. These techniques are designed to handle complex decision-making problems for which the ranking process represents a key enabler in comparing and evaluating alternatives based on a set of significant criteria (Ecer, 2021). The ranking process involves assigning weights to each criterion and assessing the performance of each alternative based on these criteria. The results of the assessment are then used to rank the alternatives in order of preference. The ranking process helps to identify the most preferred alternative, based on the set of criteria that have been established (Benítez et al., 2020). The importance of ranking in MCDM methods lies in its ability to provide a clear and consistent framework for evaluating alternatives. By establishing a set of criteria and assigning weights to each criterion, decision-makers can prioritize the criteria that are most important to them. This enables them to make a decision that is consistent with their preferences and values. As previously stated, several MCDM methods provide ranking as an output. They have been widely used in various engineering fields to support decision-making, e.g., project selection (Vijayakumar et al., 2022), product design (Liu, 2011), energy system planning (Ali et al., 2022), facility location (Farahani and Asgari, 2007), and materials selection (Hosouli et al., 2023), among others. Some of them are briefly recalled in the following.

The Analytic Hierarchy Process (AHP) (Saaty, 2001) is a popular MCDM method that involves breaking down a decision problem into a hierarchy of criteria and sub-criteria. It allows decision-makers to rank alternatives based on their overall performance, which is determined by the weighted sum of their performance on each criterion. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang et al., 1981) is a MCDM method that ranks alternatives based on their similarity to the ideal solution. The ideal solution is determined by the best performance on each criterion, while the worst solution is determined by the worst performance on each criterion. Alternatives are ranked based on their distance from the ideal solution. The Simple Additive Weighting (SAW) (Malczewski, 1999) is a relatively straightforward MCDM method that ranks alternatives based on the weighted sum of their performance on each criterion. It can be carried out by assigning weights to each criterion and multiplying the weight by the performance score for each criterion. Alternatives are ranked based on their overall weighted score. ELECTRE (ELimination Et Choix Traduisant la REalité) (Roy, 1991) is a family of MCDM methods capable to achieve complementary results. Some of them, e.g., ELECTRE III and IV, are aimed at ranking alternatives based on their performance relative to other alternatives. They require the creation of a set of preference thresholds for each criterion, which represent the minimum level of performance required for an alternative to be considered acceptable. Alternatives are then ranked based on their performance relative to the preference thresholds.

The Analytic Network Process (ANP) (Saaty, 2004) is a decision-making methodology developed as a natural extension of the AHP. Both AHP and ANP are used to analyze complex decision problems by breaking them down into smaller, more manageable components. However, ANP is unique in that it can handle decision problems with interdependent and interactive criteria, unlike the AHP (Jorge-García and Estruch-Guitart, 2022). In ANP, a decision problem is represented as a network of elements and relationships between them (Magableh and Mistarihi, 2022). The elements are the criteria or alternatives being considered in the decision-making process. The relationships between the elements can be either direct or indirect, depending on their interdependence.

One of the strengths of ANP is its ability to handle both quantitative and qualitative criteria, allowing decision makers to consider multiple dimensions of a decision problem. The method can also handle a wide range of criteria types, including tangible and intangible factors, such as social, environmental, and ethical impacts. Additionally, ANP can be used to analyze complex decision problems with multiple levels of criteria and sub-criteria, enabling a comprehensive evaluation of the decision problem (Lapcın, 2021). However, one of the weaknesses of ANP is the complexity of the method, which requires a high level of expertise and effort to implement effectively. ANP can be a complex and computationally intensive process (Wang et al., 2015), which can be a significant limitation in practical applications where time and resources are limited.

Given the potential of ANP as a decision-making methodology, we recognize the need for an alternative approach that can produce the same results in terms of ranking with less computational effort. By doing so, we aim to make the benefits of ANP more accessible to a wider range of decision-makers and enable more efficient and effective decision-making processes.

3. MATERIALS AND METHOD

The PageRank algorithm can be applied to any graph structure to get an idea of the most important nodes in the graph (where important here means with an highest impact on the goal) Brin and Page (1998). The Mathematics around the PageRank algorithm mostly concerns Markov chains. By considering the case study implemented in Carpitella et al. (2022), we use the unweighted matrix as the transition matrix, containing the transition probabilities. The winners are the maintenance alternatives with the highest impact.

The basic idea relates to how a search engine's effectiveness depends on the quality of the results it returns. There may be millions of online sites with a specific term or phrase, but some of them will be more related or important than others. The first pages returned by the search engine contain often the most pertinent content. Modern search engines employ methods of ranking the results to provide the "best" results first that are more elaborate than just plain text ranking. One of the first but most influential algorithms for computing the relevance of web pages is the PageRank algorithm, initially implemented in the Google search engine. The idea that PageRank brought up was that, the importance of any web page can be judged by looking at the pages that link to it: when creating a web page i that includes a hyperlink to the web page j, this means that we consider j relevant and important for the corresponding topic. Additionally, j is considered a relevant page if there are a lot of pages that link to it. On the other hand, if j has only one backlink, but that comes from an authoritative site k, we say that k transfers its authority to j; in other words, k asserts that j is important. Whether we talk about any link type, we can iteratively assign a rank to each web page, based on the ranks of the pages that point to it. To this aim, we begin by picturing the Web net as a directed graph, with nodes represented by web pages and edges represented by the links between them. For a state space $\mathcal{S} \subseteq \mathbb{N}_0$ we define a Markov chain (on $\mathcal{S}$) as a sequence $(X_t)_{t=0,\dots}$ of random variables X_t, such that

(1) (Markov property)
$$P(X_{t+1} \mid X_0, \dots, X_t) = P(X_{t+1} \mid X_t);$$
(2) (Time homogeneity) $P(X_{t+1} = s' \mid X_t = s)$ is independent of t, for every $s, s' \in \mathcal{S}$.

Here the intuition is that we imagine the Markov chain to be a random variable evolving through time. The reason why we care about the time homogeneity property is that it allows us to define for every pair of states $s, s' \in \mathcal{S}$ the transition probability $p_{s,s'} := P(X_{t+1} = s' \mid X_t = s)$ for some, or equivalently any, $t \in \mathbb{N}_0$. These transition probabilities can be displayed through a graph structure related to the unweighted matrix in Fig. 1. To enable ease

	GOAL	SF1	SF2	SF3	SF4	SF5	MI1	MI2	MI3	MI4	MI5
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SF1	0.20	0.00	0.10	0.00	0.60	0.20	0.50	0.60	0.60	0.60	0.20
SF2	0.30	0.00	0.00	0.00	0.00	0.00	0.20	0.10	0.10	0.10	0.20
SF3	0.10	0.00	0.30	0.00	0.40	0.00	0.10	0.10	0.10	0.10	0.20
SF4	0.30	0.00	0.30	0.00	0.00	0.80	0.10	0.10	0.10	0.10	0.20
SF5	0.10	0.00	0.30	1.00	0.00	0.00	0.10	0.10	0.10	0.10	0.20
MI1	0.20	0.30	0.30	0.20	0.20	0.20	0.00	0.00	0.25	0.00	0.50
MI2	0.15	0.03	0.10	0.15	0.05	0.10	0.30	0.00	0.25	0.00	0.00
MI3	0.20	0.05	0.10	0.15	0.20	0.25	0.30	0.00	0.00	0.00	0.50
MI4	0.15	0.02	0.10	0.10	0.05	0.05	0.10	0.00	0.25	0.00	0.00
MI5	0.30	0.60	0.40	0.40	0.50	0.40	0.30	0.00	0.25	1.00	0.00

Fig. 1. ANP Unweighted Matrix (Carpitella et al., 2022)

of notation we define the transition matrix T as the $N \times N$ matrix, where N is the number of nodes, with entries $T_{s,s'} := p_{s,s'}$.

Namely, the stationary distribution associated to a Markov chain is a discrete distribution $\pi : \mathcal{S} \to \mathbb{R}$ such that $\pi T = \pi$, where T is the transition matrix and π as a row vector of length N. By starting with a random choice of π and updating π's values by simply traversing the graph according to the transition probabilities, it will converge to the stationary distribution.

If a Markov chain has an aperiodic state and every state can be reached by every other state, then it has a unique stationary distribution. Further, if we let π_0 be the uniform distribution on the state space and define $\pi_{n+1} = \pi_n T$ with T being the transition matrix, then the π_n's converge to the stationary distribution.

4. CASE STUDY

In the study presented in Carpitella et al. (2022), a decision-making problem was examined, focusing on the interconnections between sustainability factors (treated as evaluation criteria) and maintenance interventions (treated as alternatives to be ranked). The decision hierarchy structure, as shown in Figure 2, illustrates the relationships and dependencies within the decision-making process. At the highest level of the hierarchy, the primary goal of the decision-making process is defined. This goal serves as the overarching objective that guides the evaluation and ranking of maintenance interventions. The second level of the hierarchy comprises the criteria that contribute to achieving the overall goal. These criteria include sustainability factors that are identified as highly influential and have a significant impact on long-term maintenance in the manufacturing sectors. The interdependence among these criteria is taken into account, acknowledging the complex relationships and dependencies between different sustainability factors. Moving down to the third level of the hierarchy, we encounter the alternatives, which represent the maintenance interventions being evaluated. These alternatives are assessed based on the criteria established at the second level, allowing for the prioritization and ranking of interventions accordingly. To provide a clearer understanding of the criteria, we will briefly recap and expand on their explanations in the following sections.

SF_1: Availability rate: this sustainability factor encompasses two critical aspects - raw materials and skilled labor. Raw materials are essential for conducting maintenance activities, while skilled labor plays a crucial role in ensuring the effectiveness and efficiency of maintenance operations.

SF_2: Government policies: government policies can significantly impact the internal and external factors of a company, thereby influencing its ability to provide a safe and suitable environment for human resources. Compliance with government policies related to environmental regulations, labor laws, and safety standards can affect the sustainability of maintenance activities in manufacturing sectors.

SF_3: Training and education: training and education play a pivotal role in driving organizational growth by promoting the integration of modern technologies and innovative learning methods. Ensuring a well-trained and educated workforce can enhance the sustainability of maintenance activities in manufacturing processes, as it enables employees to acquire and apply new skills and knowledge.

SF_4: Machine modernization: upgraded machines can contribute to the competitiveness and sustainability of manufacturing industries by optimizing performance, improving product quality, and minimizing breakdowns and failures. Regular machine modernization efforts can enhance the effectiveness and efficiency of maintenance activities, leading to improved overall sustainability.

SF_5: Employee competence: employee competence refers to the level of skills and expertise possessed by the workforce in executing their job responsibilities. Enhancing employee competence through training and development initiatives can support organizations in achieving sustainable maintenance practices in manufacturing processes, as competent employees are better equipped to identify and address maintenance issues effectively.

The PageRank algorithm is going to be practically applied to analyse relations existing within the set of elements and to eventually derive a ranking of maintenance interventions on the basis of the previously described sustainability factors. Alternatives to be ranked are described in the following.

MI_1: Redundant electric pumps: having redundant electric pumps in place can enhance the reliability and availability of the water supply system, as it provides a backup option in case of pump failures, reducing downtime and ensuring continuous water supply.

MI_2: Preliminary supply of special parts: maintaining a preliminary supply of special parts can ensure timely availability of critical components, reducing the risk of delays in maintenance activities due to unavailability of parts and minimizing potential production losses.

MI_3: Intensification of plant flexibility: enhancing the flexibility of the plant operations can improve the adaptability and responsiveness of the water supply system to changing demands and operational requirements, leading to more efficient maintenance planning and execution.

MI_4: Availability of a back-up water storage: having a back-up water storage system can provide a buffer during maintenance activities or water supply disruptions, ensuring uninterrupted water availability to meet production needs and prevent operational disruptions.

MI_5: Implementing a tele-surveillance system: implementing a tele-surveillance system can enable remote monitoring and diagnostics of the water supply system, allowing for early detection of potential issues and proactive maintenance interventions, reducing downtime and improving overall system performance.

Data processing and statistical analysis have been performed by using R software Team (2022), in particular by using the `igraph` package Csardi and Nepusz (2006).

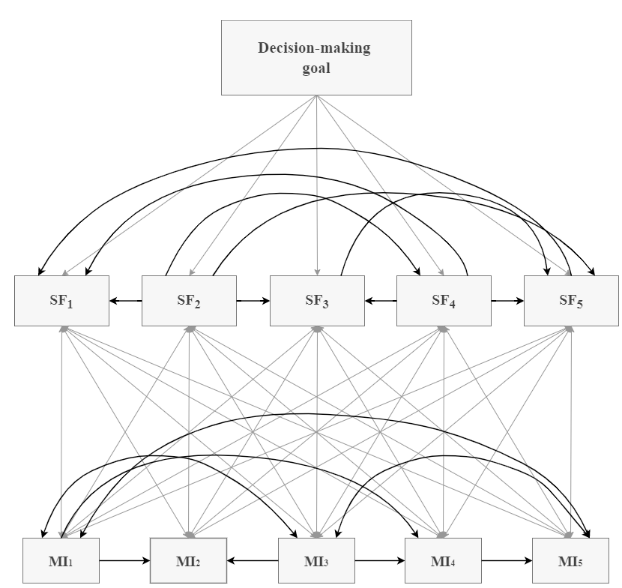

Fig. 2. Hierarchical decision structure illustrating interdependence relationships (Carpitella et al., 2022)

Fig. 3 reports the final scores associated to criteria and alternatives by iterating the PageRank algorithm. Notice that the scores are identical to those obtained in Carpitella et al. (2022), demonstrating as the most influential criterion is SF_1 (availability rate) and the maintenance intervention to be carried out with priority is MI_5 (implementing a tele-surveillance system). This of course is valid in adherence to the input data reported in Fig. 1.

SF1	SF2	SF3	SF4	SF5	MI1	MI2	MI3	MI4	MI5
0.16	0.05	0.07	0.08	0.08	0.13	0.06	0.10	0.04	0.20

Fig. 3. PageRank scores

5. CONCLUSIONS

In this study, we compared the PageRank algorithm with the ANP for prioritizing maintenance activities in industrial water distribution systems. Our findings revealed that the PageRank algorithm offers several strengths over ANP, including lower computational complexity and scalability, while achieving exactly the same results. The PageRank algorithm, originally designed for web page ranking, provides a scalable and objective approach for analyzing complex systems, making it a promising alternative for decision-making in the field of maintenance management. Furthermore, we used a case study developed in our previous research that applied ANP as input data for comparison. This allowed us to showcase the comparable performance of the PageRank algorithm with the ANP in the context of sustainability-related problems involving water distribution systems feeding manufacturing industries.

However, it is important to acknowledge a limitation of the paper, which lies in the presence of only one case study to compare results. To address this limitation and further enhance the paper's findings, our future work will focus on extending the research by simulating multiple scenarios through additional case studies. By incorporating a wider range of cases, we aim to improve the modeling, estimation, and control aspects of maintenance interventions, providing a more comprehensive understanding of sustainable practices in complex systems.

In addition to the strengths of the PageRank algorithm, there are further potential lines for developments. For instance, further research can explore the applicability of the PageRank algorithm in other domains beyond water distribution systems, such as transportation systems, energy grids, and supply chain management. Additionally, the integration of other criteria could be considered to enhance the decision-making process. The analysis of preference data in the form of rankings could be extended and analyzed in a Bayesian framework, particularly when considering individual preferences from multiple technical managers rather than relying solely on a single general manager. By incorporating the preferences of various technical managers, a more comprehensive and diverse range of perspectives can be captured. Within the Bayesian framework, this extension allows for a more robust and probabilistic analysis of rankings.

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