

HIERARCHY RANKING TECHNIQUE: A DECISION-MAKING METHOD TO PRIORITIZE CONSTRUCTION DEFECTS IN ONSHORE WIND TURBINE FOUNDATIONS

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ABSTRACT

This study introduces the Hierarchy Ranking Technique (HRT), a multi-criteria decision-making methodology developed to evaluate and prioritize the resolution of construction defects in onshore wind turbine foundations. The proposed technique establishes a structured prioritization strategy by considering factors such as urgency, seriousness, growth potential, time required for resolution, and associated costs. Employing data collected from an actual onshore wind farm, we applied the HRT to enhance decision-making in the resolution of construction defects of wind turbine foundations, by pinpointing, categorizing, and hierarchically ranking the mentioned defects. The findings demonstrate the effectiveness of the HRT in supporting decision-making processes, by assessing and ranking construction defects, thereby enabling stakeholders to systematically prioritize interventions, efficiently allocate resources, and effectively formulate maintenance strategies and mitigation plans.

KEYWORDS. Prioritization Method. Construction Defects. Wind Farms.

Paper topics in order of PRIORITY:

ADM – Métodos Multicritério para Ajuda de Tomada de Decisão

EN&OG – PO na Área de Energia, Óleo e Gás

POI – PO na Indústria

1. Introduction

Wind energy has increasingly become a dominant source of clean and renewable power generation, augmenting the demand for wind farm construction. In 2021, a notable addition of 72.5 GW to the global onshore wind capacity was observed, bringing the cumulative onshore wind capacity to a substantial 780 GW. This translates to the installation of tens of thousands of new wind turbines [Mathern et al. 2022, Global Wind Energy Council 2022, Nogueira 2023].

As cited in [Nogueira 2023], wind farm construction involves the assembly and installation of large wind turbine towers, a key component of its infrastructure. Such elements demand appropriate structural detailing and careful building procedures; thus, many works have approached the design and construction of wind turbines. For example, in [Paredes et al. 2011], researchers performed numerical simulations of wind turbine towers. In [Wymore 2015], a survey of commercial and research turbine health monitoring systems was conducted, analyzing their current state and associated challenges. The work in [Msigwa 2022] reviews the impacts of wind energy generation on the environmental, economic, and social aspects of sustainability and mitigation strategies. Moreover, [Nogueira 2023] proposed the use of the Urgency, Seriousness, and Growth (USG) Method in the assessment of construction defects in foundations for wind turbines.

One of the most critical components in wind farm construction, as explained in [Nogueira 2023], is the foundation of the turbine towers. Particular concerns include potential problems in the concrete used in the foundations, which can lead to structural failures, environmental degradation, and safety risks. In this context, studies have highlighted issues in foundation concrete, including those related to strength, durability, and cracking. For instance, [Cunha 2015] found that the use of recycled aggregates in concrete mixtures can reduce strength and durability, potentially compromising the safety and longevity of wind turbine foundations. Authors in [Wang 2017] identified issues related to the cracking of concrete used in wind turbine foundations, compromising structural integrity and increasing the risk of failure. Furthermore, as mentioned in [Cazacliu 2014], the use of certain types of cement in wind turbine foundations, such as high-alumina cement, has been linked to environmental issues like the release of heavy metals into surrounding ecosystems. Other studies, according to [Khalil 2018], have highlighted issues related to the potential for groundwater contamination during the construction and operation of wind turbine foundations.

As mentioned in [Nogueira 2023, Braga 2019], the USG Method, originally presented in [Kepner 1981], emerges as a potent tool for the construction process. However, this method, while helpful in ranking construction defect resolutions, does not account for parameters such as time and cost associated with resolving these defects. Therefore, this work proposes a new prioritization method, the Hierarchy Ranking Technique (HRT), based on the USG method, which is applicable to the assessment and hierarchical categorization of construction defects. The HRT incorporates time and cost variables to complement the considerations of urgency, seriousness, and growth potential of defects proposed in the USG Method. To illustrate potential applications of the technique, we analyzed a case study of tower foundation construction at an onshore wind farm in Brazil, using compiled and critically assessed data.

2. Methods

2.1. Construction Defects

As defined in [Nogueira 2023], we use "defect" as a broad term in this study, encompassing anomalies or nonconformities tied to the durability and functionality of foundations; those defects might arise from design errors, construction failures, or material deficiencies.

In this paper, we analyzed failures resulting from the construction process of a wind turbine foundation with nonconformities following the execution phase. The most frequently observed defects in this case study included cracks, footprints, exposed wire with rust marks, concrete segregation, and insufficient concrete cover (e.g., concrete honeycombs). Figure 1 provides a schematic of the primary types and the respective locations of concrete construction defects in the wind turbine foundations.

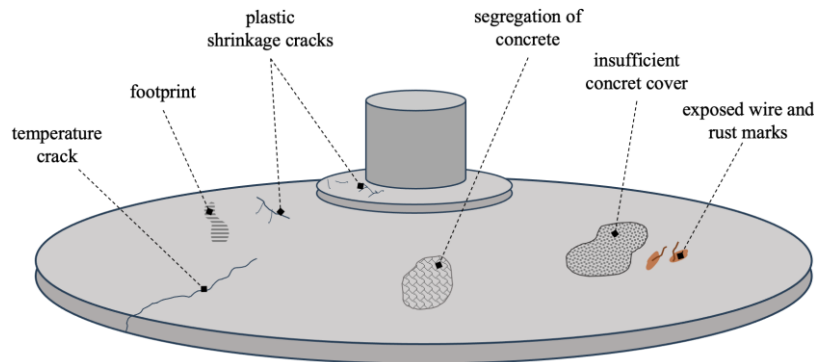


Figure 1: Schematic of main types of concrete defects on wind turbine foundations. Elaborated from [Nogueira 2023].

2.2 USG Method

As explained in [Nogueira 2023, Braga 2019, Kepner 1981], the Urgency, Seriousness and Growth (USG) Method is employed for problem prioritization. This methodological approach provides a structured framework for evaluating and ranking construction-related issues based on three distinct problems assessing criteria, namely urgency, seriousness, and growth. To evaluate the magnitude of each of the three USG criteria, we apply a scoring range, defined according to the defects' degrees, as presented in Table 1. In a construction site, defect scores are determined through inspection, relying on the professional judgment of construction professionals rather than on quantitatively precise criteria for measurement.

Table 1 – Evaluation and Scores of Urgency, Seriousness, and Growth Tendency in USG Method

Degree and Score			
Growth Tendency Degree	Seriousness Degree	Urgency Degree	Score
Quick growth	Extremely serious	Extremely urgent	5
Short-term growth	Very serious	Very urgent	4
Medium-term growth	Serious	Urgent	3
Long-term growth	Less serious	Less urgent	2
No growth trend	Non-serious	Non-urgent	1

After computing the USG scores, the total score T_s is obtained by using Equation 1, in which U_s , S_s , and G_s represent the urgency, seriousness and growth respectively.

$$T_s = U_s + S_s + G_s \quad (1)$$

An example of a USG total score computation is presented in Table 2. Additional details of defects, such as their location, may be included to complement their description – as in column 3 of Table 2.

Table 2 – Example of USG Total Score Computation

Tower Number	Defect characterization		USG METHOD			
	Description	Location	Us	Ss	Gs	Ts
1	Exposed Wire	Top	1	2	2	5
	Concrete Segregation	Base	4	3	4	11
	Cracks	Base	3	3	3	9
	Concrete Honeycombs	Top	4	3	3	10
	Footprints	Base	1	1	1	3

2.3. Hierarchy Ranking Technique

Despite USG's applicability in ranking construction defect resolutions, it does not consider the respective times and costs. We then propose a new method, the Hierarchy Ranking Technique (HRT), which incorporates time and cost variables and thus complements the considerations of urgency, seriousness, and growth potential of defects proposed in the USG Method. It is, therefore, a more robust method for the assessment and hierarchical categorization of construction defects.

2.3.1 – Parameter Scores

The parameters of the HRT are the problem-assessing criteria for the defects, and all of them follow a score range from 1 to 5; Urgency, Seriousness, and Growth are treated similarly to the USG Method. For Time and Cost, instead of using absolute values, we adopted a scoring range from 1 to 5, similar to those used for other parameters. Table 3 presents the scores for each parameter of the HRT.

Table 3 – Scores for Each Parameter of the HRT

Degree and Score					
Growth Tendency Degree	Seriousness Degree	Urgency Degree	Time	Cost	Score
Quick growth	Extremely serious	Extremely urgent	5 hour	\$50	5
Short-term growth	Very serious	Very urgent	4 hours	\$100	4
Medium-term growth	Serious	Urgent	3 hours	\$200	3
Long-term growth	Less serious	Less urgent	2 hours	\$400	2
No growth tendency	Non-serious	Non-urgent	1 hour	\$800	1

Values of Time and Cost have been considered within a range from 1 to 5 only to facilitate the illustration of the method; however, they may be adopted as absolute values without lower or

upper limits. For example, Time for a given defect could be 5 seconds (e.g. cleaning, watering a block) or 3 days (e.g. demolishing and rebuilding a footing); Cost could be input similarly.

2.3.2 – Pseudo Algorithm

HRT's code is based on The Shortest Job Next (SJN) algorithm, a well-known method in computer science - particularly in the context of operating systems - used by CPU schedulers to select the next job to be executed. In other words, SJN, also known as Shortest Job First (SJF), is a scheduling algorithm. The principle behind it is to choose the process with the shortest execution time, allowing it to run next. This approach minimizes the average waiting time for all processes in the queue.

In this work, we propose the combination of SJN and USG Method factors in order to establish an order of construction defect resolution. Moreover, we have added the cost associated with the defect resolution as a ranking parameter. Therefore, the HRT code takes into consideration not only time, but also cost and urgency, seriousness and the growth tendency of each wind turbine foundation construction defect.

The pseudo-code for the HRT is presented in Figure 2, with input and processing details highlighted. The DataFrame output refers to the order in which problems should be solved - that is the priority ranking for construction defects resolution.

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Algorithm: Hierarchy Ranking Technique

Input: List of processes with attributes (process_id, time_required,
urgency_factor, seriousness_factor, growth_factor, time_factor,
cost_factor)

1. Initialize the number of processes (n).
2. Create arrays for time, waiting_time, and HRT factors (urgency,
seriousness, growth, time and cost) of length n.
3. Set total_waiting_time to zero. Prepare an empty list for output
data (data).

4. Extract the required time and HRT factors from each process, store
them in their respective arrays.

5. Sort the processes in descending order of urgency, seriousness, and
growth factors. In case of a tie, sort by required time in ascending
order.

6. For each process in the sorted list, compute the waiting time,
accumulate it in total_waiting_time.

7. Construct a DataFrame from the sorted list, including each process's
attributes.

8. Return the constructed DataFrame

End of Algorithm

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Figure 2: Pseudo-code for the HRT

2.1.3 – HRT Usage

To illustrate potential applications of the HRT, we analyzed data from the foundation of a wind turbine tower at an onshore wind farm in Brazil. The construction site comprises a total of 9 towers; however, we focused on a single one to fully demonstrate the process of how the method should be employed.

First, we investigated the types of construction defects recorded in the inspection reports of Quality Management System for the tower foundation – a total of 5 defects were considered. Next, we assigned scores for urgency, seriousness, growth, cost and time of each defect. Finally, we ran the HRT code to obtain the order in which problems should be solved. The input for HRT code is presented in Table 4.

Table 4 – Input for the HRT code

Defect Label	Description	Urgency	Seriousness	Growth	Cost	Time
EW	Exposed Wire	1	2	1	1	2
CS	Concrete Segregation	4	3	3	2	3
CR	Cracks	3	3	4	4	4
CH	Concrete Honeycombs	4	3	4	4	4
FP	Footprints	1	1	1	1	1

3. Results

After running the HRT code with data from Table 4, we obtained the result shown in Table 5, which describes the priority ranking for construction defects resolution.

Table 5 – HRT result: defect resolution order

Resolution Order	Defect Label	Description
1st	CH	Concrete Honeycombs
2nd	CS	Concrete Segregation
3rd	CR	Cracks
4th	EW	Exposed Wire
5th	FP	Footprints

According to the results, Concrete Honeycombs should be addressed first, despite not being the quickest task to complete. Similarly, Footprints are ranked fifth, even though they have the smallest associated resolution time.

These results highlight the predominant influence of USG factors on the order in which defects should be tackled; for instance, the high scores for urgency and growth of Concrete Segregation helped secure its second rank in priority, despite its relatively low time and cost of resolution.

However, if Time and Cost are not considered, additional management challenges could arise, such as budget and workforce scheduling issues. For this reason, Cracks have been ranked third, even with relatively low urgency and seriousness.

4. Final Considerations

In this work, we presented the Hierarchy Ranking Technique (HRT), a decision-making methodology designed to evaluate and prioritize construction defect resolution in wind turbine foundations. The technique is based on the consideration of Time and Cost as input parameters to complement the traditional USG Method's approach. We selected the main types of construction defects of a specific wind farm in Brazil whose tower foundations were under construction. After cataloguing them, we established a priority order by applying the HRT, thus demonstrating the potential of this tool to prioritize problem resolution - that is, to determine which problem should be solved first by considering their urgency, seriousness, growth tendency, as well as associated costs and times. The ranking result allows construction managers to decide which defect should be tackled first, consequently, facilitating efficient allocation of resources, mitigation plans, and maintenance procedures.

Further works need to be carried out to investigate how HRT can be implemented for different applications, such as to provide the sequence of towers to be resolved, that is, among the set of towers under construction in a specific phase, which one should the workforce be directed to first. Adaptations and tests can also be performed to evaluate the application of HRT to decide if a single defect should be prioritized in all towers in sequence; for example, if the concrete honeycombs of all towers should be solved first and if so, which tower should be tackled first.

Moreover, future works need to be performed to calibrate the score ranges for Time and Cost, or even to decide if they should be considered as absolute values with no specific cap.

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