



LCOE Optimization based on Reliability and corrective Maintenance for Wind Energy Systems

Bouadi Mohamed^{1*}, Rachid Meziane²

¹University of Saida University – Dr. Moulay Tahar, Saida Algeria

* **Corresponding Author Email:** mohamed.bouadi@univ-saida.dz - **ORCID:** 0000-0002-5247-7851

²Electrotechnical Engineering Laboratory, University of Saida University – Dr. Moulay Tahar, Saida Algeria

Email: meziane22@yahoo.fr - **ORCID:** 0000-0002-5247-7800

Article Info:

DOI: 10.22399/ijcesen.4165

Received : 02 June 2025

Accepted : 25 September 2025

Keywords

LCOE,
Corrective Maintenance,
Reliability,
Optimization,
Availability,
LCA.

Abstract:

This work presents an approach to minimizing the Levelized Cost of Energy (LCOE) for wind power systems integrated reliability and a corrective maintenance. League Championship Algorithm (LCA) is a metaheuristic Used for optimization. It considers decision variables such as capacity factor (FC), system availability (A), corrective maintenance (C_{cm}). Based on the results obtained; assist operation and maintenance managers know the types of maintenance contracts in order to avoid wasting money the optimal availability obtained from the LCOE model. This study is the subject of a real case, which is the Kabertanne wind farm, located in the W. Adrar who counts 12 wind power turbines, type G.52- 850 kW. The results obtained show a final optimized LCOE of 0.02324 \$/kWh, with a corrective maintenance cost of \$64645 per year and an availability of 0.87.

1. Introduction

The excessive release of greenhouse gases emitted by conventional production systems caused an environmental degradation stems. These are considered the main of climate change over the past sixty years. One of the major challenges in the electricity production sector is to meet the growing demand while preserving the natural context. Currently, reducing pollution is a significant issue that mobilizes many countries. The solution found to address this issue is to move towards renewable energies. In this perspective, the wind source is one of the sources that has seen the greatest growth in the field of renewable energy. Wind farm system is an exciting renewables energies sources, on all the plans. Wind turbines are now part of our landscape and which are developing at high speed. The expansion recent accelerated of wind farms is synonymous of a set of techno-economic constraints and ecological emit. The extraordinary increase in the costs of these installations from the manufacturing phase to the disposal phase in recent years has directly influenced this trend of expansion in wind energy projects, whether large or a small wind farm [3]. Generally, the production system is

subject to failures, especially for wind systems, the frequency of which often increases with the non-compliance of preventive maintenance periods for various components and the variation in production rate. To remain competitive, a maintenance task management strategy must be developed to minimize the impact of shutdowns on the overall system performance. For this purpose, maintenance actions are necessary to maintain or restore the plant to a desired operational level. However, Maintenance costs represent an important part of the total cost, during the lifetime of a wind turbine. This taking in particular, failures and the means of transport which are dedicated to the personnel. To assess the cost and in order to reduce the cost of maintenance, some systems remote command, control and intervention systems have been used to monitor the status of certain components continuously. The financial cost which therefore represents an economic impact accompanying, the life cycle of wind turbines is one of the main issues that needs to be optimized. The life cycle cost analysis which can be a necessary tool to estimate the expenses of the successive stages and to optimize the maintenance cost with studies of levelized cost of the generated electricity LCOE.

2. Development of wind systems on the international politics

Environmental degradation stems from an excessive release of greenhouse gases emitted by conventional production systems. These greenhouse gases are considered the main cause of climate change over the past sixty years [1]. One of the major challenges in the electricity production sector is to meet the growing demand while preserving the natural context. Currently, reducing pollution is a significant issue that mobilizes many countries. The solution found by the majority of countries to address this issue is to move towards renewable energies. Among the proposed solutions, the installation of wind systems has experienced significant growth in recent years [2]. On all the plans; Wind turbines are now part of our landscape and which are developing at high speed. The expansion recent accelerated of wind farms is synonymous of a set of techno-economic constraints and ecological emit. wind energie holds a prominent place With the installed capacity worldwide increasing [1]. After a slowdown in 2013, the wind industry set a new record for annual installations in 2014 [3]. Globally, 51,477 MW of new wind capacity was added in 2014. The record figure represents a 44% increase in the annual market, and is a solid sign of the industry's recovery after a difficult period. Total cumulative installations stood at 369,553 MW at the end of 2014 [4]. Global wind power has experienced strong growth in recent years, surpassing 1.13 TW of cumulative installed capacity by the end of 2024 [5]. In 2024 alone, the world added approximately 117 GW of new wind capacity, setting a new record but still falling short of the annual pace required to meet the 2030 renewable energy goals [5], [6]. Onshore wind remains dominant, with around 109 GW installed in 2024, while offshore wind accounted for roughly 8 GW of the annual additions [7]. Despite this, offshore wind including emerging floating wind technology is steadily gaining attention as a key component of future expansion [8].

China continues to lead global development, contributing about 79.8 GW of new installations in 2024, far surpassing other markets such as the United States (~4.1 GW) and European leaders like Germany [8]. However, to align with the United Nations target of tripling renewable capacity by 2030, the Global Wind Energy Council (GWEC) estimates that annual wind installations must reach roughly 320 GW [8].

Key technical trends include the repowering of aging onshore wind farms, the deployment of larger

offshore turbines, and the integration of artificial intelligence for optimizing wind farm layouts and operations [9]. Grid integration challenges, particularly voltage and frequency stability, remain critical as the share of variable renewable energy sources grows [9].

As is the case in our country Algeria, where the energy transition holds a significant position in the national energy program.

3 Case of Algeria

In Algeria, the integration of renewable energies as new sources of energy, alongside conventional energies, aims to move towards a national energy mix that preserves fossil resources and diversifies production sectors [1]. Electricity is also a master in driving the national economy with the global dynamics of sustainable development (technological monitoring). In 2009, fossil fuels represented a share of 99.2% of electricity production. Since 2010 [3], Algeria is committed to promoting and developing a renewable energy strategy within its borders. On February 3, 2011, the national program for the development of renewable energies, for the period 2011-2030 approved by the government such as Plan, which produce 40% of total electricity generation by 2030 [11]. Wind power is the second only to solar, where is expected to extinguish more than 5MW of electricity national production. This significant transition of the country towards renewable energies is due to its location geographic and its surface, where Algeria has extensive reserves of renewable energies. To assess the importance of wind at a given location, it is sufficient to determine the weighted annual arithmetic mean speed, calculated over a minimum sampling period of 10 years. [12] This value provides an order of magnitude for the wind speed at a specific site. Moreover, wind speeds vary significantly depending on the season, the time of day, and the year. This variability must be characterized, as it enables the appropriate sizing of wind systems in accordance with energy requirements, which themselves vary across seasons, days, and years.

4 The Wind Map and Seasonal Mean Wind Speed of, Algeria

The wind map of Algeria, estimated at 10 m above ground level. The obtained annual mean wind speeds range from 2 to 6.5 m/s. [11] It can be observed that, with the exception of the coastal regions (excluding Bejaia and Oran), the Tassili area, and Beni Abbès, the average wind speed exceeds 3 m/s. The central region of Algeria is characterized by wind speeds varying between 3 and 4 m/s, which increase progressively toward the

southwest. The maximum is recorded in the Adrar region, with an average value of 6.5 m/s[12].

However, several microclimates exist where wind speeds exceed 5 m/s, such as in the Tindouf and Oran regions.

In Algeria the summer and spring are windier than the rest of the year. All established atlases highlight the southwestern region, namely Adrar, Timimoune, and In Salah, as the windiest zone, with the exception of the winter atlas, which identifies the microclimate of Tiaret as presenting the highest wind speeds [11].

5 Literature review

Several studies have been conducted to analyze the discounted cost of electricity over the lifetime of the plant, these works used the LCOE study:

For nuclear power plants; Gao and al. [13] proposed a method for calculating the LCOE, accounting for all co-procedures of nuclear installations. Lucheroni et al. [14] suggested a comprehensive stochastic model of LCOE applied to a nuclear power plant. Mondol and al. [15] highlighted that gas quantity is considered the main factor in LCOE calculations for fossil fuel power plants.

For photovoltaic and thermal solar systems, Sens and al. [16] provided insights into the evolution of LCOE up to 2050. Tamas Kerekes and al. [2] presented the calculation of the optimal configuration of large PV plants, such that the levelized cost of the generated electricity (LCOE) is minimized.

Jésus and al. [17] studied climatic and aerodynamic influences on the levelized cost of offshore wind turbines, Hou and al. [18] proposed a predictive end-of-life strategy that reduces LCOE by 10.43%. Tahtah, and al. [19] studied the technical, economic and environmental constraints of wind farm emissions on life cycle cost optimization to achieve energy cost equilibrium.

The studies suggesting maintenance cost optimization that;

S.K. Tiwari and al. [20] developed a preventive maintenance model for manufacturing industry based on delay-time analysis to reduce the downtime and cost of maintenance activities. Z Otsmani [21] and al applied in here work an methodology to determine the best inspection period for preventive maintenance of a serial parallel systems, they it adopted for an electrical unit of a natural gas liquefaction in Algeria.

Allal Anis [3] proposed an approach of multi-agents simulation for an optimization of

maintenance cost us to find best set of wind turbines to maintain in the same tour.

Boufala and al [22] developed an algorithm to generate an optimal sequence of maintenance actions for hybrid wind -gas power system working with the desired level of availability during its lifetime with minimal maintenance cost rate.

6 Maintenance

Maintenance activity is constantly evolving to ensure the proper functioning of systems as well as the safety of people and property while preserving the environment. This activity of maintenance is based on maintenance [23], renovation and improvement and takes into account the double constraint of performance and reduced cost [24]. It is a set of actions that enable the preservation or restoration of an asset to a specified state or given conditions of operational safety, in order to fulfill a required function (AFNOR Standard X60-010) [25].

Maintenance can be preventive or corrective.

6.2.1 Corrective maintenance

The set of activities carried out after the failure of the asset or the degradation of its function to enable it to perform a required function [3], at least temporarily: these activities include the localization of the failure and its diagnosis, the restoration with or without modification, and the verification of proper functioning (AFNOR Standard X60-010) [25].

6.2.2 Preventive maintenance

The set of actions aimed at reducing the probability of failure or degradation of a good or a rendered service (AFNOR Standard X60-010) [23].

6.2.3 Reliability

the standard definition can be used it “Ability of an item to perform a required function under given conditions for a given time interval” [24].

6.2.4 Availability

“Ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided” [25].

6.2.5 Downtime

“Time interval throughout which an item is in a down state” [25]

6.3 Maintenance of wind systems

Maintenance and servicing plan for wind power plants is established annually. This plan is developed in collaboration with various partners (project owners; contracting companies; subcontractors, etc.). [24] These strategies are generally adopted after the contractual period has

expired to continue maintaining the turbines; Wind turbines are often purchased with a 2 to 5 year contract, which includes warranties, and corrective and preventive maintenance strategies[26].

6.3.1 Preventive maintenance of wind turbines

Preventive maintenance actions are planned to include routine checks, tests and servicing. The tasks are designed to determine whether major maintenance work is required, so that corrective maintenance can be kept to a minimum. complete maintenance of wind turbines is often carried out twice a year. This biannual maintenance is carried out using a checklist to verify the condition of the wind turbines and update the record Checklists are specific to the turbine, and activities include checking the gearbox and hydraulic system oil levels, inspecting for oil leaks, inspecting the cables running down the tower and their support systems, observing the turbine during operation to check for unusual vibrations, inspecting the brake disc, and inspecting the emergency evacuation equipment. Other activities include checking fastener security (e.g. blade attachment, gearbox retainer, tower base bolt), high-speed shaft alignment, brake adjustment and pad wear, nacelle and brake performance, bearing lubrication, cable termination security, pitch calibration, oil filters, etc.

6.3.2 Corrective maintenance of wind turbines

Corrective maintenance of wind turbines includes tasks carried out in response to component wear, human error, design faults and operational factors such as overvoltage, excessive vibration, low gearbox oil pressure, yaw error, pitch error, premature brake activation, synchronization failure, loss of grid connection, etc. Operators become aware of corrective tasks either during a routine inspection, or when the protection system shuts down the turbines in response to an incipient fault [26]

7 Life Cycle Cost Analysis

LCC concept can be expressed by a standard definition “Life cycle cost is all the costs generated during the life cycle of an item”. It takes into account each of the phases of the life cycle. The fundamental equation of LCC consists in estimating the global sum of the costs of each of the phases according to equation [2]:

$$LCC = C_{inv} + C_{cm} + C_{pm} + C_{pl} + C_{dem}$$

LCC is commonly adopted for cost saving for an investment and it implies calculation methods of total life time costs [19]. LCC could be describes e.g. as “A technique which enables comparative

cost assessment to be made over a specified period of time, taking into account all relevant economic factors both on terms of initial capital and future operational costs”. [24]

The use of LCC analysis is finalized to compare different investment options, calculated over a given period of time, where both initial and future costs have to be taken into account.

The fundamental idea of LCC is to estimate what an investment actually costs, where the initial investment cost has to be taken into account as well as costs related to the product’s whole lifetime.

Within this work the LCC analytic definition is:

$$LCC = C_{inv} + C_{cm} + C_{pm} + C_{pl} + C_{dem}$$

The economic parameters and the input data considered within this definition are the cost of investment (C_{inv}), the cost for corrective maintenance (C_{cm}), the cost for preventive maintenance (C_{pm}), the cost for production loss (C_{pl}) and the remainder value (C_{dem}).

7.1 Production losses

During the lifetime of a WT, failures could occur and they cause unplanned downtimes.

It’s possible to evaluate the cost for production losses as:

[1]

$$C_{pl} = N \cdot P \cdot C_f \cdot C_{el} \cdot (1 - A)$$

Where N is number of wind turbines, P is electric power generated, C_f : capacity factor, C_{el} is cost of electricity and A is the viability.

8 LCOE Optimization based on maintenance cost and Reability

LCOE is calculated as the ratio of the present value of the total life cycle costs, divided by the total energy produced over its lifetime period [1]. This LCOE function is defined as follows:

$$LCOE = \frac{\sum_{t=0}^t \frac{LCC}{(1+r)^t}}{\frac{E_{tot}}{(1+r)^t}}$$

$$LCOE = \frac{\sum_{t=0}^t \frac{C_{inv} + C_{cm} + C_{pm} + C_{pl} + C_{dem}}{(1+r)^t}}{\frac{E_{tot}}{(1+r)^t}}$$

Where C_{inv} is the capital cost for investment, C_{cm} is the corrective maintenance cost, C_{pm} is the preventive maintenance cost, C_{pl} is the cost for production loss, C_{dem} the remainder value cost, r

(%) is discount rate, t lifespan and E_{tot} is the total energy produced over its lifetime.

$$C_{pl} = N \cdot P \cdot C_f \cdot C_{el} \cdot (1 - A)$$

Where N is the number of wind turbines, P is electric power generated, C_f is the capacity factor, C_{el} is the cost of electricity [\$] and A is the availability.

$$E_{tot} = C_f \cdot P \cdot 8970 \cdot t$$

The proposed optimization procedure is to minimise LCOE function.

8.1 Case study

To demonstrate in this study, we consider the case off the wind farm 10.2 MW project installed in W. Adrar, Algeria [1]. This farm consists of 12 wind turbines of 0.85 MW[19].

8.2 Implementation of the optimization algorithm

In this work, we propose to use the new metaheuristic "League Champion" [19] to solve the cleaning cost optimization problem. This algorithm, abbreviated LCA, is a global optimization algorithm inspired by sports championships [27]. The LCA was implemented in the form of software developed using the MATLAB tool [2]. The pre-established design, technical and economic parameters of this plant are presented in Table 1. Table 2 summarizes the variables used in the optimization algorithm.

Table 1: Technical and economical parameters of the plant.

N	12
P	850 W
C _{el}	0.07
t	20 ans
C _{pm}	150000
C _{inv}	12*0.975
C _{pl}	790000

Table 2: Data variables.

C _{cm}	45000-85000
A	0.7-0.99
C _f %	0.2-0.5

7.4.2 Results: The Table 3 gathers the best obtained results.

Table 3: Economical values.

LCOE (\$ /kWh)	C _{cm} (\$)	A	C _f %
0.02324	64645	0.87	0.265

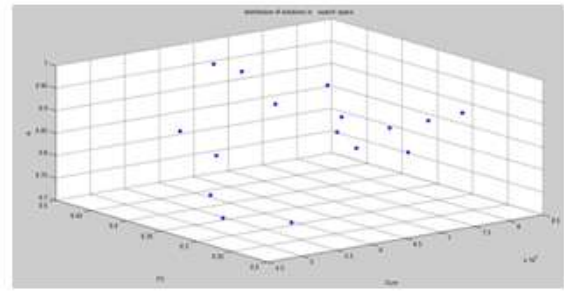


Fig. 1 : The objectif function convergence.

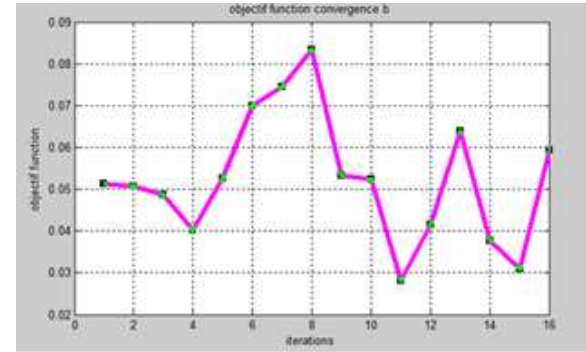


Figure 2: Distribution of solutions in the search space.

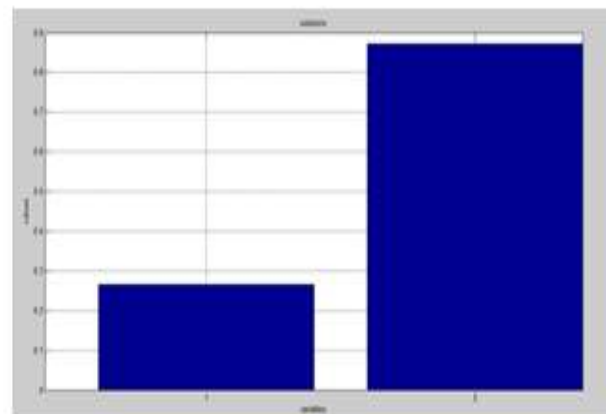


Figure 3: Found solutions.

8.2.1 Interpretation

The obtained results are very significant that the found LCOE value (0, 02324 \$ /KWH). In fact, A and C_{cm} have a proportional relationship (when A decreases, C_{cm} increases, and vice versa). 0.87 as the availability , 64645 \$ is the annual corrective maintenance cost. The value of the factor capacity is 0.265, typical of a good onshore site .The value of LCOE is very competitive even availability is very acceptable ,it can be improved by increasing of maintenance preventive ;which will increase LCOE.

9 Conclusion

In this work, The LCOE studies and the minimization of the maintenance cost during the operational life of the power plants of

KABERTENE have very significant results, i.e. $LCOE=0.02324$ \$/KWH. $A=0.87$ is the availability, $Cf=0.265$ is the capacity factor, finally $Ccm=64645$ \$ is the annual corrective maintenance cost of the plant. These results can be used for a diagnosis of WIND sites, using their own data.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

- [1] TAHTAH Abdelkarim « Evaluation de l'optimisation des cycles de vies des systèmes à énergies renouvelables » Thèse Doctorat 3ème Cycle ; Filière : Electrotechnique ; Spécialité : Réseaux électriques Université de Saida– Dr. Moulay Tahar; Décembre 2023.
- [2] Tamas Kerekes, Member, IEEE, Eftichis Koutroulis, Member, IEEE, Dezső S'era, Member, IEEE, Remus Teodorescu, Fellow, IEEE, and Markos Katsanevakis « An Optimization Method for Designing Large PV Plants ». IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 3, NO. 2, APRIL 2013.
- [3] ALLAL Anis « Conception et développement d'outil d'aide à la décision pour la gestion de la maintenance et la production dans le cadre des énergies renouvelables » Thèse Doctorat en Sciences ; Filière : Informatique ; Spécialité : Systèmes d'information et de connaissances (SIC) UNIVERSITE DJILLALI LIABES DE SIDI-BEL-ABBES le :30 /01/2022.
- [4] ATTIA MOUSSA « Contribution à l'étude et la commande des systèmes solaires et éoliennes » Thèse Doctorat en Sciences ; Filière : Mines ; Spécialité : Electromécanique minière UNIVERSITE LARBI TEBESSI DE TEBESSA le :22 /07/2022.
- [5] Global Wind Energy Council, Global Wind Report 2025, 2025.
- [6] “New wind capacity falls short despite reaching record, industry body says,” Reuters, Apr. 23, 2025.
- [7] World Wind Energy Association, WWEA Annual Report 2024: A Challenging Year for Windpower, Bonn, 2025.
- [8] M. O'Malley, H. Holttinen, N. Cutululis, T. K. Vrana et al., “Grand challenges of wind energy science – meeting the needs and services of the power system,” Wind Energy Science, vol. 9, no. 11, Nov. 2024.
- [9] J. A. Ribeiro, B. A. Ribeiro, F. Pimenta, S. M. O. Tavares, J. Zhang, F. Ahmed, “Offshore Wind Turbine Tower Design and Optimization: A Review and AI-Driven Future Directions,” arXiv, Feb. 2024.
- [10] Dr. DEKKICHE Mohammed Amine « MODELISATION ET SIMULATION D'UN SYSTEME HYBRIDE AUTONOME (PV /EOLIEENNE/DIESEL) POUR ALIMENTER UN SITE ISOLE A CHLEF, ALGERIE » Thèse doctorat Doctorat LMD en Génie mécanique ; Université Hassiba Benbouali de Chlef; le :09 /12/2017.
- [11] Rahmouni soumia « étude prospective de la transition énergétique et l'impact environnemental en Algérie » Thèse doctorat en sciences en Génie des procédés ; Université KASDI MERBAH OUARGLA; le :17 /01/2019.
- [12] KKEIRALLAH Mohamed « ETUDE D'UN SYSTEME EOLIEENNE INJECTE SUR LE RESEAU DE TRANSPORT DE L'ELECTRICITE » Mémoire de MASTER en PHYSIQUE ENERGETIQUE ; Université AHMED DRRARIA de ADRAR; le :26 /11/2014.
- [13] R. Gao, H. O. Nam, H. Jang, and W. I. Ko, « The economic competitiveness of promising nuclear energy system: A closer look at the input uncertainties in LCOE analysis » International Journal of Energy Research, vol. 43, pp. 3928-3958, 2019.
- [14] C. Lucheroni and C. Mari, « CO2 volatility impact on energy portfolio choice: A fully stochastic LCOE theory analysis » Applied Energy, vol. 190, pp. 278-290, 2017.
- [15] J. D. Mondol and C. Carr, « Techno-economic assessments of advanced Combined Cycle Gas Turbine (CCGT) technology for the new electricity market in the United Arab Emirates », Sustainable Energy Technologies and Assessments, vol. 19, pp. 160-172, 2017.
- [16] L. Sens, U. Neuling, and M. Kaltschmitt, "Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines–Development by 2050," Renewable Energy, vol. 185, pp. 525-537, 2022.
- [17] F. Jesus, Guanche, R., Losada, Í.J., "The impact of wind resource spatial variability on floating offshore wind farms finance," Wind Energy pp. 1131–1143, 2017.

- [18] P. Hou, Enevoldsen, P., Hu, W., Chen, C., Chen, Z, " Offshore wind farm repowering optimization," Applied Energy, pp. 834–844, 2017.
- [19] Abdelkarim Tahtah, Driss Raouti, Rachid Meziane, Lionel Vido « Life Cycle Cost Assesment and LCOE of 10.2MW wind farm»,
- [20] S.K. Tiwari¹, R.K. Singh, B. Kumar « Optimizing PM Intervals for Manufacturing Industries Using Delay-time Analysis and MOGA » Jordan Journal of Mechanical and Industrial Engineering, Volume 16, Number 3, June. 2022.
- [21] ZINZB OSTMANI, M.KHIAT; A. CHAKER «Minimisation du cout preventive periodique d'un systeme serrie parallele par l'algorithme génétique» 2011 ; Mediamira science ACTA ELECTROTEHNICA.
- [22] Boufala, and al. «Preventive Maintenance Strategy Based on RCM and CMS» IRSEC 2016.
- [23] Frédéric TOMALA « Cours de maintenance ».
- [24] GLORIA PUGLIA «Life cycle cost analysis on wind turbines ». Master of Science Thesis in Energetic engineering CHALMERS UNIVERSITY OF TECHNOLOGY Gothenburg, Sweden, 2013.
- [25] HARITZA CAMBLONG «Minimisation de l'impact des perturbations d'origine EOLIENNE dans la génération d'électricité par des aérogénérateurs à vitesse variable » Thèse Doctorat en automatique ; Ecole nationale superieur des arts et métiers; le : 18 /12/2013.
- [26] Maryem Bouzoubaa «Strategies de maintenance intégré à la production d'énergie dans un parc éolienne sous contrainte opérationnelles et environnementales ». thèse de doctorat UNIVERSITE DE LORRAINE, France, 2021.
- [27] Hussein Zadeh Kashan A. League championship algorithm: a new algorithm for numerical function optimization. In: Proceedings of the international conference of soft computing and pattern recognition. SoCPaR 2009. IEEE Computer Society; 2009. p. 43–8.