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# Reliability Assessment of Wind Turbines

*Mai F.M. Ayoub*

## Abstract

There are a wide variety of wind turbines types. The selection of a wind turbine type, the site of wind turbines fields erection and the maintenance scheme are basic parameters which should be carefully considered for optimum performance and reliable operation and power output. Many techniques had been developed and refined to represent and study the wind turbines complex system in order to make their operation safe, reliable and maintainable. In the present work, emphasis will be given to reliability block diagram quantitative technique to assess the reliability of wind turbines systems. This entails the application of reliability theories on wind turbines individually and wind turbines fields as a whole to ensure maximum utilization of available wind power. Specially devised computer software has been performed and applied on exemplary wind turbine field. The proposed computer program has shown to be helpful if adopted in assessing wind turbine fields giving indications of their reliability.

**Keywords:** wind turbines, wind farms, reliability, availability, maintenance

## 1. Introduction

Wind power projects have been developed rapidly in the last two decades due to the increase in fossil-fuel prices. Hence, energy policies have been created for renewable energy research and technical development. Wind power has been developed and became a new fast-growing industry to compete the existing fossil-fueled power plants [1]. Wind turbines have reached nowadays sizes of 8 MW [2] and wind farms are planned at a size of up to 1020 MW. Hence, large arrays of turbines, known as wind farms, become an increasingly important source of renewable energy and are used to reduce dependence on fossil fuels and protecting the environment [3].

The efficiency and the life time of any wind power project depends largely on the operation and maintenance function. This means that it is a primary aim for any manufacturer or investor is to have wind turbines with a very high level of reliability [3]. System reliability is defined as “the probability that the system will perform its intended function for a certain period of time under stated conditions”. This requires critical considerations to enable us to decide on the quality and frequency of maintenance required by keeping records of failure [4].

Classical reliability analysis techniques use parameters derived from actual test data in models to evaluate the performance of system or components. The analysis is based on the time-to-failure data of the component, either under use conditions or from accelerated life tests. Hence, a system (a collection of components, subsystems and/or assemblies) is designed in order to achieve desired function with acceptable

performance and reliability”. Therefore, the type of these components, their quantities, qualities, the manner in which they are arranged in the system and the relationship between these components would affect overall reliability of the system. This reliability relationship is usually expressed by using logical diagrams, such as Reliability Block Diagram (RBD) and/or Fault Trees [5]. The main objective of a reliability study would be to provide information as a basis for decision [6]. So, the results provided by the study of reliability does not tell us exactly what is a decision that we must take, but guide us towards optimum solution. For example, it can be useful in the study of reliability fields, risk analysis, optimization of operations and maintenance. Risk analysis is a way to identify the causes and consequences of failure events. In this case measuring the availability of the device will be more appropriated than reliability, as the availability of a repairable device is defined as: “The proportion of time, during the intended service time, that the device is present or ready for service.”

This chapter presents reliability calculation method as software that calculates the reliability of any system with any number of parallel and serial components. This method applied to reliability-based approach to select appropriate wind turbine types for a wind farm considering site-specific wind speed patterns.

## **2. Reliability analysis techniques**

The challenge in complex systems is the problem of analyzing and predicting how reliable they are. These complex systems goal is always to make them safer and more reliable. In order to do this we have to identify the parts that contribute most of the risks involved with their use. Many techniques have been developed and refined in order to more accurately represent these complex systems. Both qualitative and quantitative methods have been developed to analyze complex systems, some are used more widely than others, while some are developed primarily for one specific application, but all techniques have their advantages and disadvantages [7].

### **2.1 Qualitative techniques**

Qualitative reliability analysis methods have been used to identify all possible system failures, and risks of each failure. The most widely used qualitative method is failure modes and effects analysis (FMEA), sometimes also known as failure modes, effects and criticality analysis (FMECA). These are methodologies designed to identify potential failure modes for a product or process, to assess the risk of failures and rank issues in terms of importance and identify the corrective actions. This is generally done by identifying certain characteristics: how each of these parts may fail, what can the result in these failures, what are the possible effects of these failures, how failures can be discovered, and what provisions are provided to compensate for this design failure [7].

FMEA can be completed either on an existing system or during the design phase, and applied at different stages meets different objectives. When done during the design phase, it can help choose design alternatives with high safety and reliability. It can also help develop test planning, which can provide a basis for any quantitative reliability analysis to be performed.

### **2.2 Quantitative techniques**

There are several methods of quantitative reliability analysis techniques, with various theories behind them. The three that are most widely used are fault tree

analysis (FTA), reliability block diagrams (RBD), and Markov analysis (MA). Each method of these three methods is the best for different cases. Quantitative analysis depends on the data of how a system works, often gained from previously completed qualitative assessments, and apply information about failure rates, probabilities, characteristics, and so on to this data in order to learn more about subsystems or the system as a whole. Then, based on the method of analysis used, the result is a form of system failure data and can be used to perform a range of tasks, most notably identifying the largest contributors to risk in the system in order to improve them and thereby reduce the risk to the system [7].

These main quantitative reliability techniques can be summarized as follows:

#### 2.2.1 Fault tree

The fault tree shows all possible combinations of failure events that may cause a specific system failure. Fault trees are created by deductively thinking about the cause of failure. Component failures and other events are combined by logical operations “AND” ( $\cap$ ) and “OR” ( $\cup$ ) to provide a logical description of the failure [8].

#### 2.2.2 Reliability block diagram

The reliability block diagram shows how the performance of components or subsystems allows to meet the function of a specific system. These diagrams facilitate the calculation of reliability indicators and illustrate the role of redundancy [9].

#### 2.2.3 Markov analysis

For any given system, the Markov model consists of a list of possible states of the system, possible transition paths between those states, and the parameters of the rate of such transitions. In reliability analysis, transitions usually consist of failures and repairs. When a Markov model is graphically represented, each state is usually depicted as a “bubble,” where arrows indicate paths between states [10].

### 3. Wind turbines reliability and life time

The selection of components to describe the main system is not just an arbitrary choice; it is a choice of what is useful in practice and where available data can be found. The choice of which component should be used to model the entire system should be chosen based on functional and available information (Reliability performance and maintenance – a survey of failures in wind power systems).

As regards wind turbines life time, changes in reliability with increasing operational life can provide indicators of life expectancy and the amount of maintenance required. Reliability can be expressed in the failure rate. The principle of evolution is well-known as bathtub curve: sign of early failures in the beginning of the process followed generally by a longer period of random failures, with a fixed rate statistically, until it starts increasing with age process (Failure - wear out) because of the accumulation of wear and tear [11].

However, the actual total age of a turbine, naturally, differs depending on various technical systems for wind turbines, the loads, the environmental conditions, maintenance plans for each turbine, the operating conditions and labor skills.

#### 4. Reliability computational technique using reliability block diagrams (RBD)

Block diagrams can also be used to describe the relation between components and system definition. When used in this fashion, the block diagram is referred to as the Reliability Block Diagram (RBD). A reliability block diagram is a graphical representation of system components and how they relate to reliability (connected). (Note: One can also think of RBD as a logical scheme of the system based on its characteristics. It should also be noted that this may differ from how the components are actually connected).

After determining the properties of each block in the system, the blocks can then be connected reliably to create a system block reliability diagram. RBD provides a visual representation of the way the blocks are arranged in terms of reliability. This diagram shows the effect of component success or failure on system success or failure.

For example, if all components in a system must succeed in order for the system to succeed, the components will be arranged by reliability in series. If one of the components must succeed for the system to succeed, then these two components are ranked in reliability in parallel.

This order of reliability of the components is directly related to the mathematical description derived from the system. The mathematical description of the system is the key to determining the system reliability. Actually, the reliability of the system is that mathematical description (obtained using probabilistic methods) which determines the reliability of the system in terms of components reliabilities. The result is an analytical expression describing system reliability as a function of time based on the reliability functions of its components.

##### 4.1 Series systems

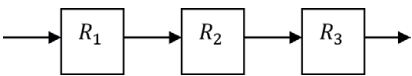
In a series system **Figure 1**, the reliability of the system is the probability that component 1 succeeds and component 2 succeeds and all of the other components in the system succeed. So all components must succeed for the system to succeed. Then, the system reliability will be given by:

$$R_s = P(X_1 \cap X_2 \cap \dots \cap X_n) \tag{1}$$

where:

- $R_s$  is the reliability of the system.
- $X_i$  is the event of component  $i$  being operational.
- $P(X_i)$  is probability that component  $i$  is operational.

In the case where the failure of a component affects the failure rates of other components (i.e. the life distribution characteristics of the other components



**Figure 1.**  
*Simple series systems.*



change when one component fails), then the conditional probabilities in equation above must be considered.

However, in the case of independent components, equation above becomes:

$$R_s = R(X_1, X_2, X_3, \dots, X_n) = P(X_1)P(X_2)P(X_3)\dots P(X_n)$$

$$= \prod_{i=1}^n P(X_i) \quad (2)$$

Or, in terms of individual component reliability

$$R_s = \prod_{i=1}^n R_i \quad (3)$$

In other words, for a pure series system, the system reliability is equal to the product the reliabilities of its constituent components.

## 4.2 Parallel systems

In a simple parallel system, as shown in the figure below, at least one unit must succeed for the system to succeed. Parallel units are also referred to as redundant units. Redundancy is a very important aspect of system design and reliability as redundancy is one of several ways to improve system reliability.

The probability of failure, or unreliability, for a system that has statistically independent parallel components **Figure 2** is the probability of failure of component 1, failure of component 2 and failure of all other components of the system. So in a parallel system, all  $n$  components must fail until the system fails. In other words, if component 1 succeeds, component 2 succeeds, or any component  $n$  succeeds, the system will succeed. The system's unreliability (failure rate) is then given by:

$$Q_s = P(X_1 \cap X_2 \cap \dots \cap X_n) \quad (4)$$

where:

- $Q_s$  is the unreliability of the system
- $X_i$  is the event of failure of unit  $i$
- $P(X_i)$  is probability of failure unit  $i$

In the case where component failure affects failure rates of other components, conditional probabilities must be considered as the above equation. However, in the case of independent components, the above equation becomes:

$$Q_s = P(X_1)P(X_2)P(X_3)\dots P(X_n) = \prod_{i=1}^n P(X_i) \quad (5)$$

Or, in terms of component unreliability:

$$Q_s = \prod_{i=1}^n Q_i \quad (6)$$

Observe the variation with the series system, where the reliability of the system was the product of components reliabilities; whereas the parallel system has the overall system unreliability as a product of component unreliability (failure rates).

The reliability of the parallel system is then given by:

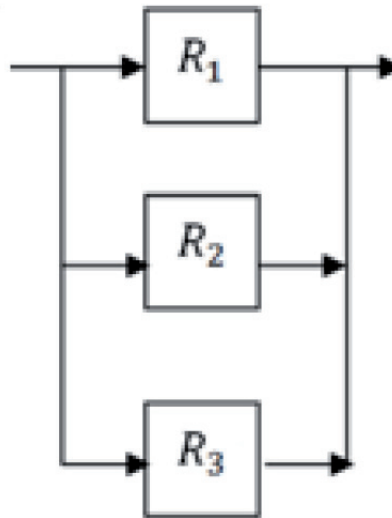
$$R_s = 1 - Q_s = 1 - (Q_1 * Q_2 * ... * Q_n) = 1 - [(1 - R_1) * (1 - R_2) * ... * (1 - R_n)]$$

$$R_s = 1 - \prod_{i=1}^n (1 - R_i) \quad (7)$$

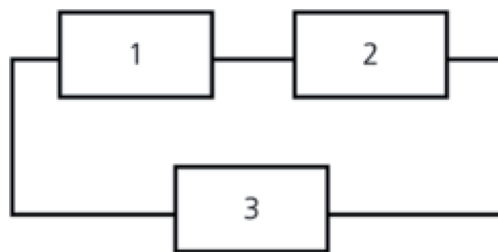
In a series system, the least reliable component has the biggest effect on the reliability of the system. However, the component with the highest reliability in a parallel system has the biggest effect on the system's reliability, since the most reliable component is the one that will most likely fail last. This is a very important property of the parallel configuration, specifically in the selection, design and improvement of systems.

### 4.3 Combined series and parallel systems

While many smaller systems can be accurately represented by a simple series or parallel configuration, there may be larger systems that include both parallel and series configurations in the overall system. These systems can be analyzed by calculating the reliability of the individual series and parallel segments and then integrating them in an appropriate manner. This methodology is illustrated in **Figure 3**.



**Figure 2.**  
*Simple parallel system.*



**Figure 3.**  
*Combination of series and parallel.*

First, the reliability of the series segment consisting of components 1 and 2 is calculated:

$$R_{1,2} = R_1 \cdot R_2 \tag{8}$$

The reliability of the overall system is then calculated by treating component 1 and component 2 as one component with reliability connected in parallel with component 3. Therefore:

$$R_s = 1 - [(1 - R_{1,2}) * (1 - R_3)] \tag{9}$$

5. Reliability assessment and calculation software

Advanced reliability assessment and distribution reliability analysis provides engineers with an efficient and effective tool for estimating the performance of power systems. Using flexible input parameters, results can be quickly obtained for both radial and looped systems. Powerful calculation techniques allow engineers to choose the depth of system design and the associated results.

Reliability software is a technique by which one can draw conclusion about the behavior of the system and its failure rate based on back history or manufacturer given reliability of the components and/or subsystems. There is a lot of reliability

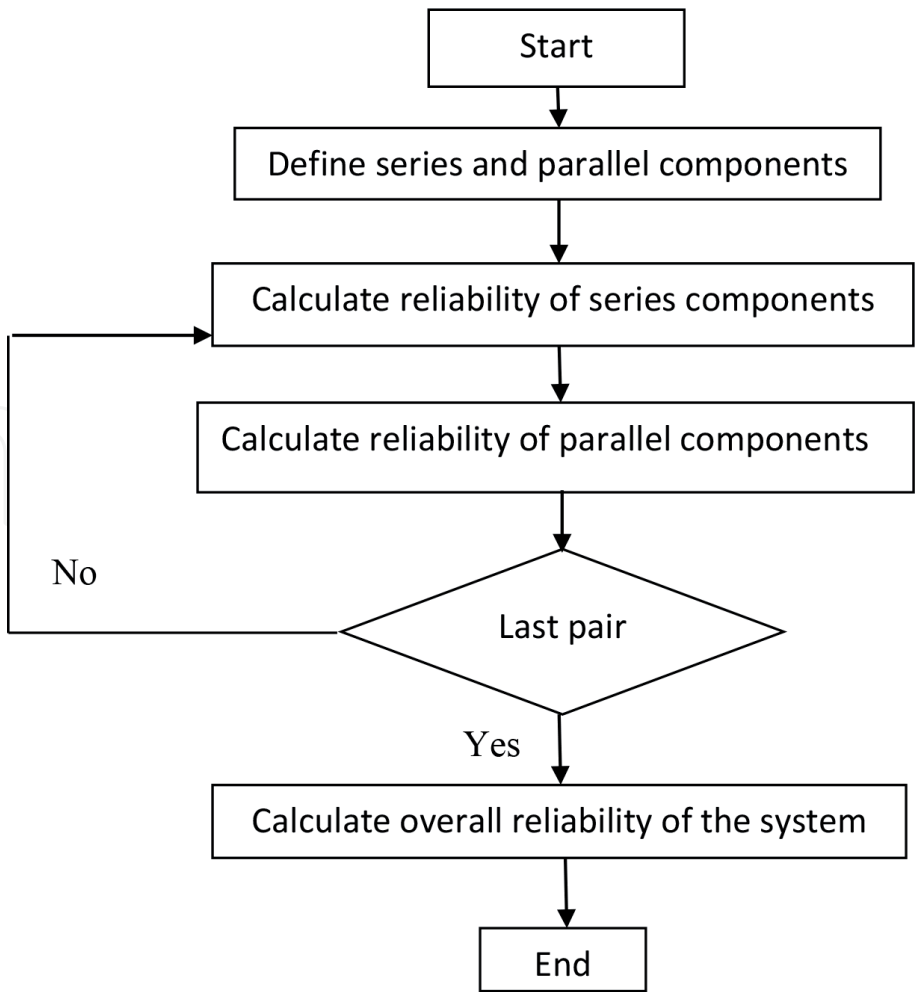


Figure 4.  
Reliability calculations program’s flow chart.



software in the market; however, the present proposed software represents an endeavor towards devising a computerized simple interactive technique for reliability assessment. The software was programmed using “Visual Basic 6” to develop general reliability calculations software which is suitable for solving any system in simple steps to understand and use.

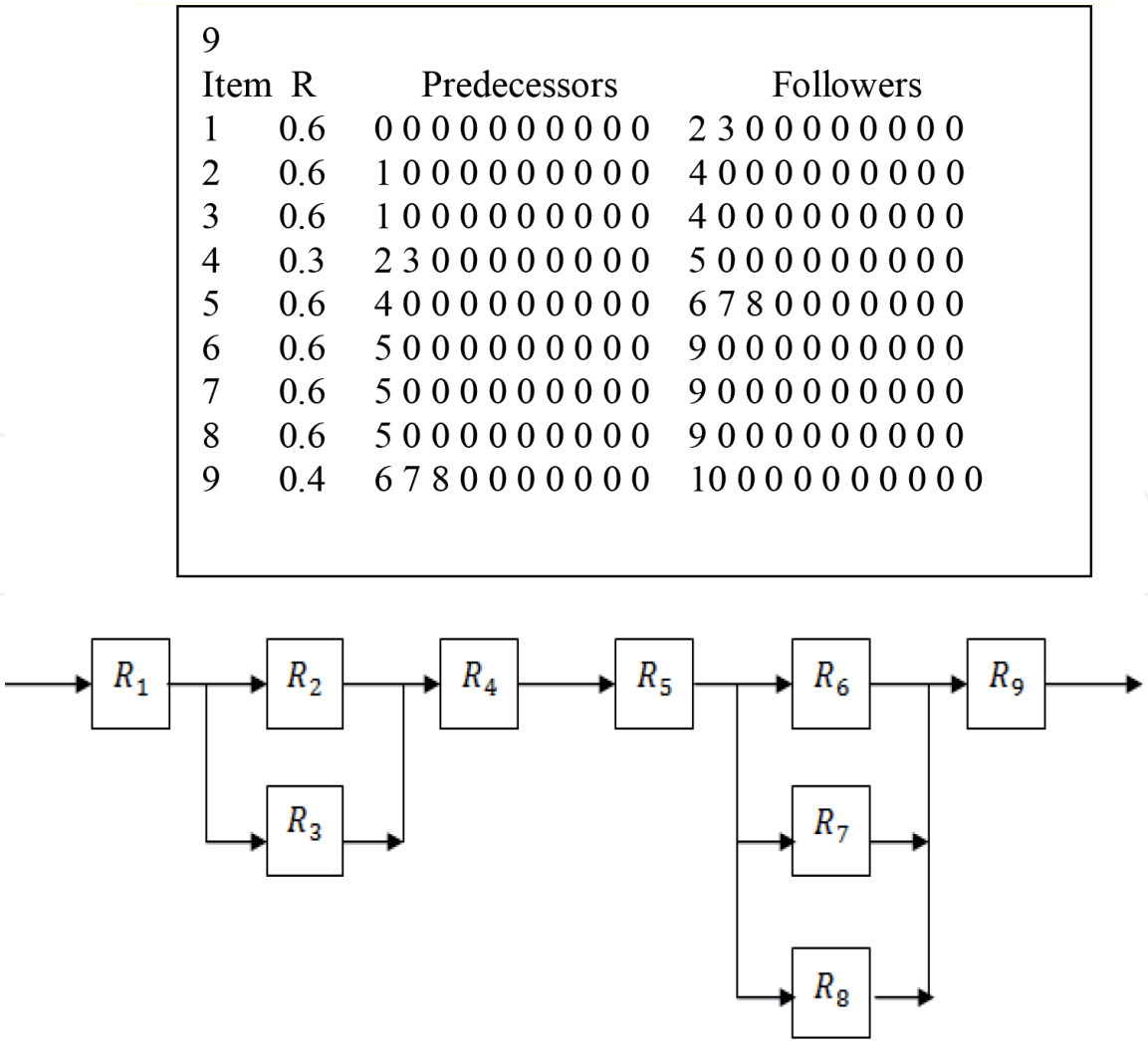
5.1 Program description

The present program deals with the reliability calculations of any system-with any number of components- connected in parallel and/or in series based on its back history.

**Figure 4.** present a generalized flow chart of the first version (reliability calculation software), the second version (reliability-based selection of wind turbines) will be discussed later as shown in Section 6.1.

5.2 Program inputs

Program inputs are the reliability block diagram data represented at a text file (.txt) contains the number of components (items) in the top, then the component number, its reliability and its location on the RBD is defined by predecessors and followers as shown in **Figure 5**.



**Figure 5.** Program’s input reliability block diagram example.

5.3 Program outputs

Program output is the resultant value of the overall reliability of the system.

6. Reliability-based selection of wind turbines software

This application represents reliability/availability-based approach to select appropriate wind turbine types for a wind farm considering site-specific wind speed patterns.

Assuming a constant failure rate, reliability prediction using the exponential distribution, would be most appropriate. If  $\lambda$  is the failure rate and  $t$  is the time, then the reliability  $R(t)$  can be determined by [12]:

$$R(t) = e^{-\lambda \cdot t} \tag{10}$$

The mathematical description of the system is the key to the determination of the reliability of the system. In fact, the system’s reliability function is that mathematical description (obtained using probabilistic methods) and it defines the system reliability in terms of the component reliabilities. The result is an analytical expression that describes the reliability of the system as a function of time based on the reliability functions of its components. In the case of the wind turbine all components are in series as shown in **Figure 6** and the overall reliability of the system,  $R_s$ , can be determined as follows [13]:

$$R_s = R(X_1, X_2, X_3, \dots, X_n) = P(X_1)P(X_2)P(X_3) \dots P(X_n) \tag{11}$$

where  $P(X_n)$  is .. Component reliability.

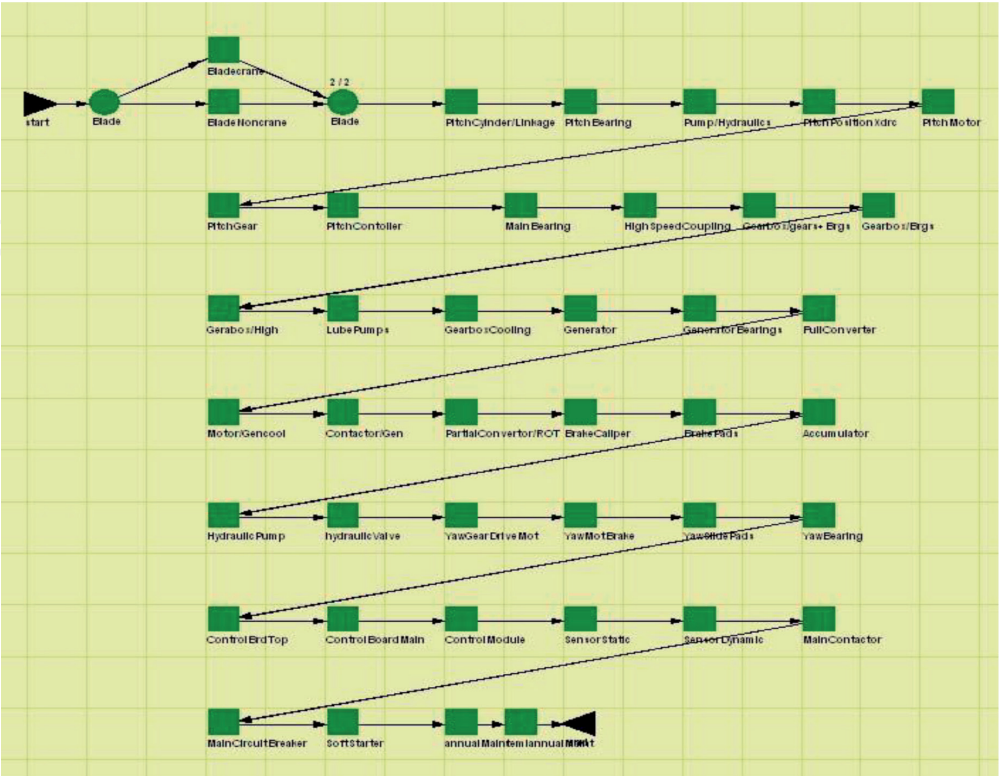
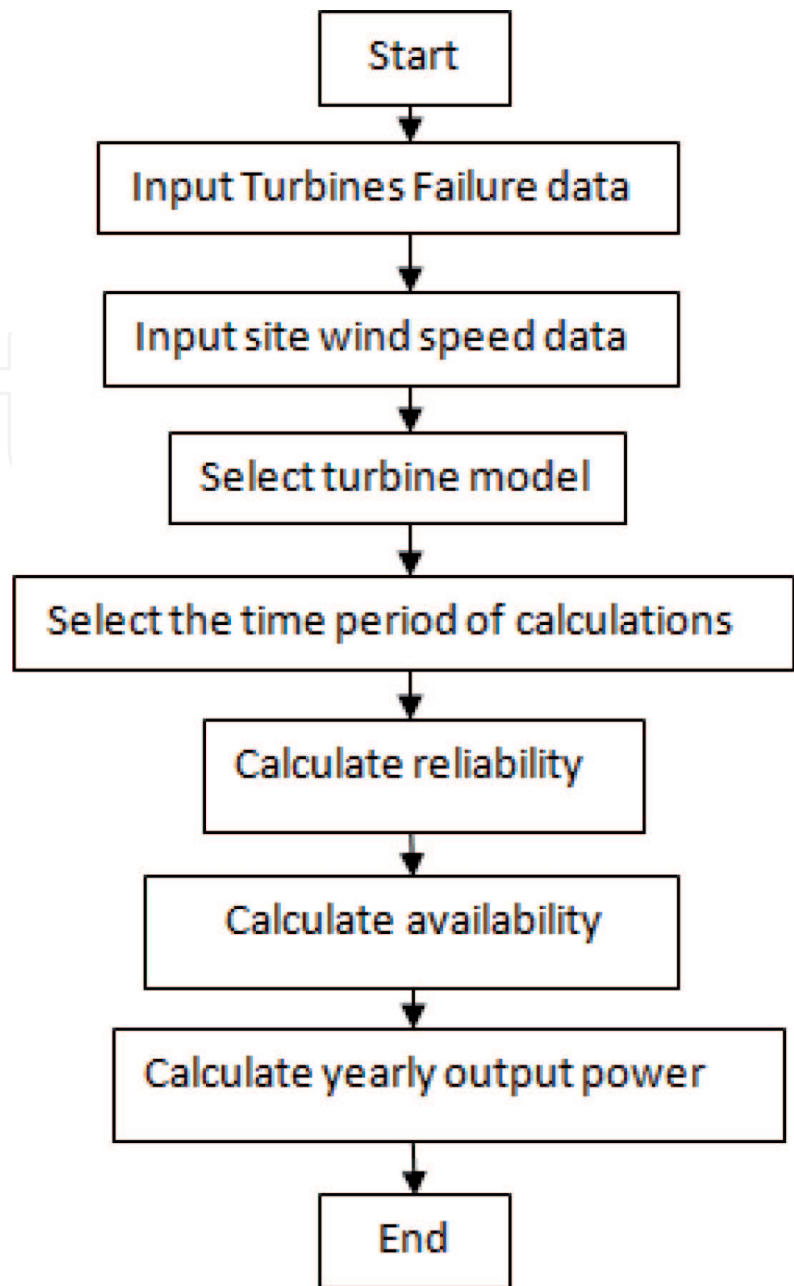


Figure 6.  
Wind turbine reliability block diagram [14].



**Figure 7.**  
*Reliability/availability based selection of wind turbines. Program's flow chart.*

### 6.1 Program description

This program used to build a module for WT selection based on reliability and availability according to each turbine's components back history and the site's wind availability. **Figure 7** presents a generalized flow chart of the (reliability based selection of wind turbines).

### 6.2 Program inputs

Program have three inputs first is the turbines failure data represented at a text file (.txt) which contains historical data for both of failure rate/year and mean time to repair in days for each subsystem in the turbine. The second input file contains all turbine's data (number of turbines, turbine's name, Height, Rated Power, wind speeds, Reliability File and Photo File if available). The third input file contains average hourly wind speeds for each site in the study all over the year.

### 6.3 Program outputs

Program outputs are the followings: site's wind availability all over a year represented as a histogram, wind turbine's reliability and availability for the chosen period of time, and also the yearly output power for the selected turbine in the selected specific site.

Both of version one, "Reliability Calculations software", and version two, "Reliability/Availability Based Selection of Wind Turbines", was tested and compared with the traditional calculation methods. The software has advantage over the analytical approaches since version one can calculate the reliability of any complex system, whatever its components number where or how this components were connected, with a very high speed and perfectly with no need for professional user. This advantage minimized error opportunities and saves lot of work and time. The second version was used to build a module for wind turbines selection based on reliability and availability and was capable of differentiating between different wind turbines systems based on reliability and availability criterion. It was very useful to graph results and understand the effect of reliability of the components with the wind availability of the site on the power output of the turbine. Those graphs also can help the investors to choose the most suitable turbine for the selected site in order to maximize production and minimize operation and maintenance costs. Accordingly the aims of the current study have been satisfactorily fulfilled.

## 7. Conclusions


The implementation of the reliability/availability calculations software will be very useful for understanding and preparing maintenance schedules. The developed methodology can give the user a proper selection of wind turbines fields according to the back history of wind turbine components and site specifications.

### Author details

Mai F.M. Ayoub  
Mechanical Engineering Department, National Research Centre, Cairo, Egypt

\*Address all correspondence to: [maifayez.mf86@gmail.com](mailto:maifayez.mf86@gmail.com)

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