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# Application of Predictive Maintenance in Hospital Heating, Ventilation and Air Conditioning Facilities

Gonzalo Sánchez-Barroso [a], Justo García Sanz-Calcedo [a*]

[a] *University of Extremadura, Av. de Elvas s/n, Badajoz (06006), Spain*

**Abstract**

The variety of a hospital's users leads to different levels of requirements relating to indoor environmental conditions. The responsibility for generating these favourable conditions for the pathologies treated in the different areas of a hospital lies with heating, ventilating and air-conditioning (HVAC) system. They carry out the control of nosocomial infections. Consequently, establishing adequate maintenance plans for these facilities will have a high positive impact on economic and environmental management, on the one hand, and on people's health, on the other. The aim of this work is to analyse foreseeable information and results generated after applying condition-based maintenance (CBM) techniques. The Weibull distribution was used to model the distribution of equipment failures and the potential of the information obtained from applying the CBM methodology was highlighted. The results of this work represent an improvement in the working practise of the HVAC facilities hospital maintenance departments. They dispose of information to decide on investment in equipment taking into account maintenance costs. In addition, this allow analyse data to know current status of a piece of equipment or unit, thus establishing an optimized maintenance plan considering asset's remaining useful life and associated maintenance costs.

**Keywords:**

Maintenance;
Weibull;
HVAC;
Healthcare Engineering;
Hospital Projects.

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## 1- Introduction

Hospitals are inhabited by a multitude of people with a very variable state of health. Some pathologies require specific environmental needs in order to favor their improvement and/or avoid their transmission to medical personnel and other patients (nosocomial infections). Hospital heating, ventilating and air-conditioning (HVAC) installations are an effective tool in the fight against nosocomial infections [1], so providing adequate indoor environmental conditions in hospitals is intimately related to people's health.

Operating theatres, isolated rooms and other clean rooms, such as laboratories, are the air-conditioning facilities to be highlighted within a hospital. Other variables different from the thermohygrometric ones are used to define the specifications of the necessary air conditioning in these rooms. These are: overpressure of the room, microbiological load, velocity of the impulsion and surface of the diffuser, etc. These variables must be conjugated in such a way as to create an ultra-clean air movement pattern that favors the dragging and elimination of airborne bioparticles from the work field.

The maintenance of HVAC systems and their equipment has a special economic and environmental relevance, due to the fact that hospitals are energy-intensive buildings [2]. The demand for uninterrupted availability of equipment calls for more efficient maintenance plans. In addition, the Regulation on Thermal Installations of Buildings (RITE) requires the design of specific maintenance programs to ensure continuity in the expected performance of the installation [3].

* **CONTACT**: Jgsanz@unex.es

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The classic objectives of maintenance are efficiency, availability and durability [4]. Reliability-Centred Maintenance (RCM), also called preventive maintenance, is the broadest application for energy production equipment [5]. Statistical techniques are used for future failure detection based on historical results [6]. With this strategy, a maintenance action is carried out without maximizing the useful life of the replaced part. Condition-Based Maintenance (CBM), known as predictive maintenance, monitors relevant variables to empirically determine the percentage of service life consumed (and, consequently, the remaining one) [7]. In other words, its actions are subordinated to the current condition of the equipment to be maintained. The maintenance strategy implemented influences the satisfaction of the end user of the installations [8].

Currently, maintenance is in its fifth generation of development based on the concept of terotechnology. This concept seeks to achieve a holistic view of the impact of maintenance on the quality of the elements that make up the production process, and to continuously produce both technical and economic improvements [9].

Salah et *al.* (2018) proposed an approach to predictive maintenance of critical facilities in an optimized hospital through the application of Failure Mode and Effects Analysis (FMEA) [10]. They applied it to a 5,200 $m^2$ hospital and quantified savings of 6-16% in maintenance costs relative to existing preventive maintenance strategies.

García-Sanz-Calcedo and Gómez-Chaparro (2017) carried out a quantitative analysis of the impact of maintenance management on the energy consumption of a hospital [11]. They concluded that the maintenance strategy used in the facilities has a direct relationship with the hospital's energy consumption, allowing energy savings to be achieved without increasing investment in maintenance tasks.

Carnero and Gómez (2017) determined the optimal combination of policies for the maintenance of thermal energy production systems in hospitals [12]. For that purpose, they designed an innovative multi-criteria decision-making method using the MACBETH approach to ensure the highest quality of medical service. They concluded that the ideal maintenance strategy to serve the air conditioning installation is predictive maintenance, monitoring the vibration of the equipment.

Sezdi (2016) recommended the use of two different maintenance strategies for old and new devices at hospitals in developing countries [13]. Thus, older technology devices that applied only corrective maintenance will be included in maintenance like high-tech devices.

Badnjevic *et al.* (2017) presented the results of performance tests conducted on 50 mechanical ventilators and 50 infant incubators used in various public healthcare institutions in Bosnia and Herzegovina [14]. The results shown that 30% of the tested medical devices were not operating properly and should be serviced, recalibrated and/or removed from daily application.

Yang *et al.* (2018) proposed a failure mode and effects analysis method for common building HVAC equipment by exploring work-orders generated by building energy management systems using a data mining approach [15]. Satta et al. (2017) reviewed the taxonomies and main methodologies currently used for condition-based maintenance through a dissimilarity-based approach to predictive maintenance with application to HVAC systems [16].

Carretero-Ayuso *et al.* (2019) analyzed the recurrence of complaints related to design faults in HVAC installations of housing buildings [17]. The installations with the most faults were ventilation (45.83%), followed by heating (35.12%) and air conditioning (19.05%).

Weibull Distribution is one of the most widespread models used to describe failure time in component reliability analysis in complex systems [18]. By modifying the value of the shape coefficient, it accurately describes the model of faults that will occur in the different phases of the life of the components and allows them to be related to the bath curve [19]. Other authors also use different distributions to model faults in air conditioning systems, such as the Monte Carlo Distribution due to its randomness and independence between fault and inspection [20].

The aim of this work is to evaluate the factors related to the change from the current RCM (preventive maintenance) model to a CBM (predictive maintenance) approach that maximizes the useful life of the components of hospital air conditioning installations, optimizes the consumption of energy and economic resources and provides adequate indoor environmental conditions for people's health.

## 2- Methodology

The implementation of the CBM methodology as a focus for the maintenance of the hospital air conditioning facilities applies statistical techniques on the monitored performance data of the equipment and components of the system under study.

At the beginning, the random variable $T$ is defined, which represents the useful life of the component to be studied. A Survival (or Reliability) function, $R(t)$, is defined, which quantifies the probability that a component is running at the end of time *t*. Also defined is the Fault function, *F(t)*, which measures the probability that a component will fail in time *t*. The first follows a negative exponential function and both are complementary.

The random variable *T* has a function *F(t)* of cumulative distribution defined according to Equation 1:

$$F(t) = \mathrm{P}(T \leq t) \tag{1}$$

The Failure Density Function is derived from the Fault Function with respect to time. It is defined by Equation 2 and indicates failure probability per time unit:

$$f(t) = \frac{d}{dt}F(t) \tag{2}$$

The hazard function *λ(t)* represents the propensity for a component to fail at the next instant considering that up to the current one it has not failed. A formal definition can be reached following this reasoning which ends in Equation 4. Starting from the conditioned probability that a component fails in a time gap *s* after the instant *t*, shown in Equation 3.

$$P(t < T \leq T + s \,/\, T > t) = \frac{P(t < T \leq T + s)}{P(T > t)} = \frac{F(t+s) - F(t)}{R(t)} \tag{3}$$

By dividing this expression by the unit of time s, taking limits and establishing that s tends to 0, Equation 4 is obtained.

$$\lambda(t) = \lim_{s \to 0} \frac{1}{s} \cdot \frac{F(t+s) - F(t)}{R(t)} = \frac{f(t)}{R(t)} \tag{4}$$

Reliability is quantified through the Mean Time Between Failure (MTBF), which corresponds to the mathematical expectation of the random variable *t* (time of occurrence of a fault). This means that an operating device will inevitably suffer a fault at the instant *t* which is a priori unknown. The mathematical expression of MTBF is Equation 5 and the inverse of hazard rate $\lambda$.

$$MTBF = \sum_{n=0}^{n=i} \frac{TBF_i}{n} = \frac{1}{\lambda} \tag{5}$$

## 3- Results

The inclusion of Weibull Distribution in these fault analyses enables the maintenance of hospital HVAC facilities to be managed from a predictive perspective.

Predictive maintenance makes it possible to advance in the failure survival curve or reliability curve and to delay the maintenance inspection inherent to preventive maintenance, which stands at 36.8% reliability (characteristic life of the component) [21]. As the reliability curve is perfectly plotted after undertaking the implantation proposed here this is possible. This results in a reduction in the wastage of the component's useful life, as illustrated in Figure 1. Consequently, maintenance managers can decide the optimal moment of action on the component.

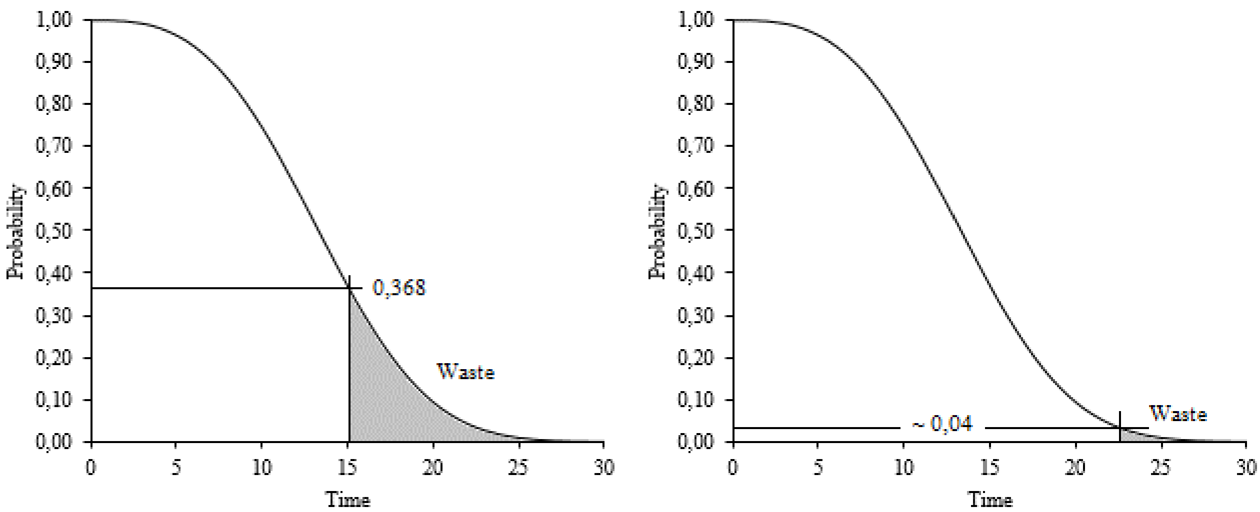


**Figure 1. Reduction of waste due to change of maintenance strategy.**

In this regard, particularizing failure density function (Equation 2) allows graphical visualize a very useful indicator in the decision making of investment in equipment. Representing in a graph when an equipment is most likely to fail, we have a quantitative parameter that supports our decision. Figure 2 shows the probability of failure distribution of two units.

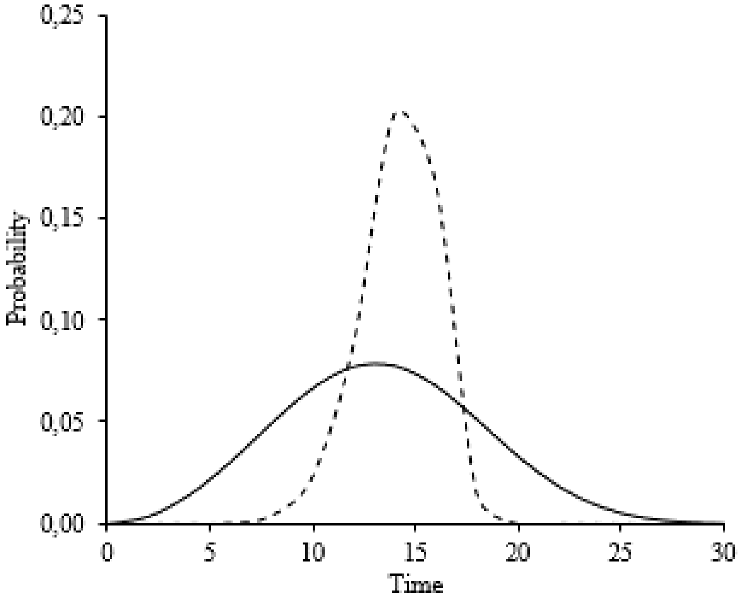


**Figure 2. PDF representation of two components of HVAC system.**

In the predictive maintenance inspection schedule, it is important to adjust the frequency. On the one hand, if they are carried out with a high frequency, the inspection costs are higher than the savings costs and, therefore, the savings opportunities represented by the prediction of failures are being underused. On the other hand, if its frequency is low, it is possible that the failure has already occurred, so that the investment in prediction is completely wasted and the company incurs its own corrective maintenance costs.

Three time periods are defined in which the inspection can be undertaken ($H_0$) with respect to the instant of time in which the fault occurs ($T_i$) as shown in Figure 3. In this way, there is zone B, called the fault zone. In this zone, imminent failures are discovered, which leads to inspection costs being incurred, but the benefits of the prediction are optimized. Zone A and zone C define a time period prior to the fault zone and after the fault, respectively, which should be avoided.

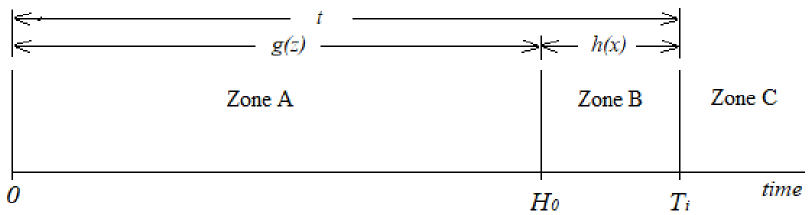


**Figure 3. Time ranges in which inspection can be performed.**

Where *h(x)* is the time before the fault occurs, when the inspection should be carried out. The time until a fault is discovered is function *g(z)*.

If the inspection takes place in zone A, inspection costs are incurred (A) and no savings are made; if it takes place in zone B, inspection costs are incurred, but the failure costs are saved (B); in zone C no inspection can be carried out since the system has already failed. The total saving per time unit (s) is obtained with Equation 6:

$$s = \frac{P(t < H_0)(-A) + P(H_0 < t < T_i)(B - A)}{P(t > T_i)M + P(t < T_i)T_i} \tag{6}$$

Where $P(t < H_0)$ is the probability that the inspection is carried out in zone A, $P(H_0 < t < Ti)$ is the probability that the inspection is carried out in zone B and $P(t > T_i)$ is the probability of occurrence of failure before the inspection is carried out.

In order to determine $T_i$ in such a way as to maximise savings per unit of time, a fault distribution is assumed in accordance with Weibull Distribution (with three parameters). According to this model, the reliability function is defined according to Equation 7 where $t_0$ is location parameter, $\alpha$ is scale parameter and $\beta$ is shape parameter.

$$R(t) = e^{-\left(\frac{t-t_0}{\alpha}\right)^{\beta}} \tag{7}$$

The calculation of these parameters is carried out from the analysis of the failure history by periods of time for the components of the system under study. Two kinds of methods can be used to calculate them: four analytical (least-squared, maximum likelihood estimation, moment estimation, and linear estimator) and a graphical (Allen Plait's paper). Least-squared methods method applies double logarithmic transformation of $F(t)$ for obtaining an analytical expression of $y = m \cdot x + b$ type, where $m$ is slope and $b$ is the cutting with the ordinate axis. After the x-y representation, the slope value $\beta$ of the linearized line is directly obtained and, from this, $\alpha$ is calculated.

There are two possible approaches to recording fault data. The first one consists of recording the number of failures that occur at regular intervals of time. Record the time from startup after a fault until a device fails again is the second one. Considering the spread of the latter, time between failures (TBF) is available. TBF of HVAC equipment and components is the only variable that must be recorded to trace the reliability curve of the studied system. The technical department's historical TBF data record must be sequenced in order to analyse it properly. They should be ordered in an increasing way and then use a non-parametric estimator "Median Range" that assigns a failure probability to a certain time interval which can be approximated by Equation 8:

$$RM = \frac{i - 0{,}3}{n + 0{,}4}; \quad i = 1, 2, \ldots, i, \ldots, n \tag{8}$$

Where: $i$ is the position of the record and $n$ is the total number records.

Deciding on the need to calculate the location parameter is the last step and, if so, estimating its value through numerical methods. Analyzing graphically the linearization obtained from which alpha and beta have been calculated is a subjective option to decide. Notwithstanding, an objective calculation premise consists of applying numerical methods to maximize the value of the coefficient of linear correlation, $R^2$.

Once the value of the parameters has been determined, it is possible to estimate the probability that a certain component will fail for a certain operating time and the guaranteed time of use with a certain level of reliability, and thus properly establish the maintenance plan.

## 4- Discussion

The growing degree of complexity of today's hospitals and their facilities demands a review of the building's life cycle management methodology. The scientific approach applied through the use of advanced statistical methods demonstrates excellent results in this regard [22].

The application of these innovative techniques will lead to savings in economic and energy costs, favouring an increase in the energy efficiency of hospital facilities. A project phase in which the architecture of the building and the equipment are studied with the aim of optimising energy consumption will provide excellent savings [23].

Using these techniques of mathematical and statistical analysis allows to have an objective vision of the current situation, having monitored data and precise forecasts based on them [24]. The representation of the failure density function is a quantitative graphic tool to choose a component or equipment. On the one hand, a stretched curve will represent a similar probability of failure occurrence for the whole time interval. On the other hand, an abrupt graph indicates increases in this probability but decreases the time it is most likely to occur. The latter represents adequate equipment since it allows for a range of time in which its surveillance should be intensified.

Failure survival curve represents the probability that a component will continue to function after $t$ time units. This result is presented initially, however, this graph is constructed as the last step in the implementation process. In order to do this it is necessary to have previously carried out an analysis of TBF as has been shown. Nevertheless, presenting it in this way enhances its comprehension.

The risk function is a measure of the component predisposition to fail, i.e. it represents the speed at which failures occur [25]. The three possible trends in its graphical representation indicates in which part of the bathtub curve the component is and allows taking actions accordingly. A fundamental difference exists between the risk function and the hazard rate. The first hosts an instantaneous component that is not available in the second, which indicates a constant value for the entire life of the component [26].

Controversy may arise in the choice of method of calculation of Weibull distribution parameters. There are reasons to decline the possibility of using other calculation methods in the implementation of this maintenance framework in hospital facilities. Mainly due to the mathematical difficulty involved and the successive steps and iterations necessary for the graphical method. In addition, all these methods only allow the estimation of the biparametric case. Nevertheless, least-squared method provides accurate results with acceptable computing power for maintenance managers in hospitals. Afterwards, location parameter can be easily estimated through numerical methods.

If the number of faults were available at each defined regular interval, plotting the reliability curve would be a direct procedure since the correlative sum of these data would provide the cumulative frequency. However, the usual practice of the maintenance team is to record the time in which the fault occurs (TBF) which requires a special statistical treatment.

Since three parameters define this model, a great flexibility in the representation of the failure mode of various HVAC systems is provided. An analysis of the values that Weibull's parameters can take is necessary. A special case that must be mentioned is that in which $t - t_0 = \alpha$ where the reliability value will be 36.8 % regardless of the shape parameter value.

Firstly, the location parameter usually takes a null value since it indicates the time origin of the data capture. The failure mode is simplified by being known as bi-parametric. Secondly, if it takes a negative value, it is recognized that the unit had problems prior to data collection. Finally, a positive value indicate that reliability is fully guaranteed until that moment in time.

Varying the scale parameter has the same effect on the probability density function as a change in the abscissa scale, hence its name. Maintaining the other parameters constant, decreasing the $\alpha$ value means narrowing the probability density function graph towards the coordinate origin, increasing its height. Increasing the alpha value supposes to stretch the probability density function graphic towards right, moving away from the coordinate origin, decreasing consequently its height.

## 5- Conclusion

In this work, how to approach the change of maintenance strategy of the hospital air conditioning installations has been exposed. In addition, the potential of the information provided by the predictive approach to maintenance complemented by the application of Weibull Distribution has been analysed. The Weibull distribution was used to model the distribution of equipment failures and the potential of the information obtained from applying the condition-based maintenance methodology was highlighted.

The results of this work are very useful for those responsible for the maintenance of facilities in healthcare buildings (hospitals, healthcare centres, etc.) as they will be able to make maintenance decisions based on empirical data. They dispose of information to decide on investment in equipment taking into account maintenance costs. In addition, they can analyse data to know current status of a piece of equipment or unit, thus establishing an optimized maintenance plan, considering asset's remaining useful life and associated maintenance costs.

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## 7- Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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