Maintenance cost optimization in condition based maintenance: a case study for critical facilities

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Abstract— **The increasing availability required to industrial plants and the limited budget often existing to assure it, require a careful formulation of maintenance optimization models. This need is primary for process plants, for which minimization of stops and maximization of their availability, are essential for ensuring targeted production and, therefore, profitability. In this context, the choice of the maintenance strategy is hence fundamental, depending on the system features and then on the effectiveness of the strategy. To evaluate the maintenance activities expected costs, it is necessary to implement appropriate technical and economic models, in order to represent the different types of maintenance types adopted. The aim of this study is to evaluate the technical and economic feasibility of condition based maintenance techniques for a service facility of a process plants. For this aim, the study was done for a HVAC system of a pharmaceutical laboratory. Three different kinds of maintenance strategies (corrective, time based and condition based) were considered, referring to three important equipment of the laboratory. For each system, the evaluation of the average cost of each maintenance strategy was done, so as to identify the most affordable one. Finally, we considered the cost-effectiveness of the implementation of a reliability continuous monitoring system, through the installation of an up-to-date supervision structure. The paper offers an example of an economic model for the maintenance of a HVAC service system, presenting an original evaluation of continuous monitoring economics. Moreover, in this study, the newest monitoring technologies were considered, up to date and improved from the latest studies. This paper is directed to facility service and process plant managers.**

Keyword-CBM, HVAC system, maintenance optimization models.

I. INTRODUCTION

HVAC (Heating, Ventilation and Air Conditioning) systems are usually designed to ensure thermal comfort conditions (temperature, ventilation and humidity) inside a public building or an industrial plant. These systems become critical when they are organically incorporated into more complex process plants, in which it is necessary to have well-specified air requirements needed by the production cycle. In the chemical and pharmaceutical industry, there are many examples of companies in which the HVAC systems are playing an enabling role for the productivity of the department in which they are inserted. These industries, in fact, have, some laboratories in which tricky production phases take place. The laboratories require the retention of stringent internal environmental conditions and the careful control of ventilation, to prevent the proliferation of bacteria, viruses and other harmful microorganisms. A lot of laboratories areas must keep sterility conditions, which is achieved also thanks to the correct operation of the thermal ventilation plant and to the moisture control. For chemical and pharmaceutical companies, moreover, the exact control of the temperature and humidity conditions is an important parameter for the certification of the production process.

In such companies, therefore, it is essential to ensure high values of availability for service facilities, including HVAC systems, in order to minimize the costs of plant downtime that would result from a failure of such systems. In these kinds of industries, in fact, faults of air conditioning systems can cause stopping of the work process and even throwing away some of the produced goods[1]. In addition, any stops would involve considerable time of non-production related to the restoration of optimal temperature and humidity conditions. Such reversals may be definitely costly and complex for the company, especially for the need to "rehabilitate" the production process.

For all these reasons, the proper maintenance of an HVAC system is critical both when it would become uncertified for the production process, both in different contexts, such as in the case of commercial buildings, in which thermal comfort is economically significant.

The analysis presented in this paper is based on technical and economic optimization of maintenance operations, carried out on three representative elements of an air conditioning system of a pharmaceutical laboratory. Specifically, they are the supply fan of the Air Handling Unit (AHU), the associated filters, and fire dampers in duct air inlet were considered. These components are critical since they aren't redundant and their failure causes the overall system unavailability.

For each of the three elements, the following elements were analysed: operation; failure modes; maintenance activities; monitoring activities implemented and implementable. For the air treatment unit fan, for example, a vibrational analysis is the most used monitoring activity.

The second phase of the analysis is about the identification of alternative maintenance management modes. For each mode, in order to identify the best one, a cost analysis was developed, considering both short and long-term costs. The main aim was figuring out if it could be appropriate to extend Condition Based Maintenance (CBM) policies to guarantee availability and cost effectiveness.

This type of analysis cannot be considered definitive, because of the speed of technological progress and the birth of new technologies with more affordable costs. For this reason, this analysis requires frequent updating. The remainder of this paper is organized as follows: section 2 shows the main maintenance model used, and in section 3 the case study is presented. Section 4 describes the experimental results and the last one presents a discussion of the results and the main conclusions.

II. METHODS

Reliability [2] [3] [4] [5], safety [6] [7] and maintenance management [8] [9] [4] are some of the most interesting issues of international scientific research and have been deeply analysed by the authors. In particular, the planning of maintenance activities is one of the core elements in the design of a production system [10] [11] [12]. The production process, in fact, flows regularly if the different systems are available when required by the production plan. All the maintenance operations, for this reason, have to be organized and scheduled so that they can be planned in time according to the production plan. Despite the planning phase, such schedule cannot remain the same over time because any unplanned emergency maintenance action causes its modification [13]. Anyway, it is still important to have a basic maintenance activity schedule, mainly to coordinate production with the planned maintenance stops. In this regard, the choice of when carrying out a scheduled maintenance operation can be done according to different approaches. One is the Reliability Centred Maintenance (RCM) [14][15][16][17]. It is a technique for developing a program of preventive maintenance (PM) activities [15], which was born in aircraft industry and later spread in all the other sectors. The main goal of RCM is to decrease maintenance costs, removing all the PM activities that are unnecessary. While in the most cases the maintenance decisions derive by legislation, recommendations from manufactures and company standards, RCM focuses on the failures and functional degradation of the system considered: system reliability is the focus of the maintenance planning. RCM may be implemented through some steps [15]: after the selection of the specific system, a functional failure analysis in developed to identify the potential system failure modes, according to one of the many classification of failure modes [18] presented in literature. Then the critical items are selected and, with the data collected over time, a FMECA analysis is fulfilled. The next steps are the selection of the appropriate maintenance actions and, finally, the determination of preventive maintenance intervals. The choice of the maintenance type to adopt for a specific system is one of the more difficult tasks, since there is not an unique clear rule to help. RCM considers the main failure modes emerging from the FMECA as the basis for the selection of the maintenance type. The main plight is to understand whether a PM activity is favourable or it would be better to replace an item after its failure with a corrective maintenance action (CM). The maintenance activities can be classified according to the grouping proposed by UNI 13306 [19], which identifies, among others, the corrective maintenance actions and the preventive ones. Preventive maintenance can be carried out in accordance with specific time intervals (without specific condition investigation) or considering the real condition of the system: in the first case we call it predetermined maintenance, otherwise it's called condition based maintenance (CBM).

CBM [20][21][22] is a type of maintenance policy that considers the current real state of system degradation. It is nowadays widely used in industrial environments because there are many measurable degradation parameters that can be properly monitored. The different monitoring techniques allow keeping under control the operating parameters that are the most significant for the system degradation , in order to identify the most appropriate time for the execution of maintenance activities.

The choice of the best maintenance type is far from trivial. RCM faces this problem considering a lot of data, such as design data, functioning data and, above all, reliability ones. These are necessary to describe the failure process and to have all the information required in the maintenance activities decision phase, not only for the choice of the maintenance type to perform, but also for the optimization of time between PM actions.

The evaluation of the necessary reliability parameters of a specific system can be made empirically, if a lot of functioning data are available. In this case, assuming that we have many failure data concerning different time intervals (numbers of failed and survived components in each interval time), the reference formulas are the following:

$$\mathrm{f(t)} = \frac{\#\text{failures}}{\#\text{total failures} * \Delta t} \quad (1)$$
$$\mathrm{F(t)} = \sum \mathrm{f(t)} \quad (2)$$
$$\mathrm{R(t)} = 1 - \mathrm{F(t)} \quad (3)$$
$$\lambda(\mathrm{t}) = \frac{\#\text{failures}}{\#\text{survived} * \Delta t} \quad (4)$$

$\mathrm{R(t)}$ is the reliability function, $\lambda(\mathrm{t})$ is the failure rate, $\mathrm{f(t)}$ is the failure density function and $\mathrm{F(t)}$ is the failure distribution function.

All these parameters are used in the maintenance optimization models, which are a good basis both for the choice between PM and CM, and to select the optimal interval time for the preventive maintenance activities.

A lot of maintenance optimization models have been studied and published in the literature [23], [24], [25], [26], [27]. They are based on some hypothesis related, for example, to the kind of maintenance (perfect, imperfect, minimal), to the failure distribution functions, and so on. There is not a best general model, but rather each real case may find one that is more appropriate.

In this paper some technical-economic models are considered, related to CM, PM and CBM. They are based on some mathematical formulations, taking into account the main cost and time items related to each maintenance policy.

The main cost and time items related to the maintenance activities are as follows:

TABLE I
Main costs and times of maintenance activities

Symbol	Description
C_{LP}	Lost productivity hourly cost
C_L	Hourly labour cost
C_M	Material cost
t_d	Time of diagnosis
t_a	Time required for maintenance service activation
t_r	Repair time
t_{rs}	Time for reactivation of production
t_q	Time for system retrain after the unplanned shutdown

These allow us to evaluate the total cost related to each maintenance type. For CM we have:

$$C_c = C_{LP} * \left(t_d + t_a + t_r + t_{rs} + t_q\right) + C_L * t_r + C_M \quad (5)$$

While for PM the total cost is obtained with the following formulation:

$$C_p = C_{LP} * (t_r + t_{rs}) + C_L * t_r + C_M \quad (6)$$

For CBM, it is also necessary to know the cost of an inspection C_i, the expected number of inspections i, the visibility time v (that is the time for which the inspection is significant) and the error level P_e.

The economic advantage of each maintenance type is evaluated considering its average unit cost $c(\tau)$.

The reference formulas are set out below:

$$c(\tau)_{CM} = \frac{C_c}{MTTF} \quad (7)$$
$$c(\tau)_{PM} = \frac{C_p * R(\tau) + C_c * F(\tau)}{MTBM} \quad (8)$$
$$c(\tau)_{CBM} = \frac{C_i * i + C_c * P_e + C_p * (1 - P_e)}{MTTF} \quad (9)$$

Each maintenance type has cost and time items that mainly affect on its average unit cost. For The CM model, the main critical parameter is t_q, time to retrain system after its unscheduled stop. C_M is the cost that increase considerably the average cost for PM. With preventive maintenance, in fact, the component is replaced whatever its eventual residual life. In the CBM model, finally, the main costs are related to inspection activities.

Before applying these models to select the more suitable maintenance type, some observations must be made. In particular PM is a valid alternative to the CM, two conditions must occur:

1) The overall cost of PM is lower than the total cost of CM (otherwise it should always be waited for the occurrence of the fault);

2) The failure rate of component decreases: in the case of constant failure rate, in particular, the occurrence of a fault is modelled as a Poissonian event as (negative exponential model). Since the phenomenon is memory-

less, the probability of having a failure in a generic interval D_t is independent on the time in which it is calculated, but it depends only on the size instead of that interval. It is understandable, therefore, that a preventive intervention would not bring virtually any advantage in terms of availability but would only cause additional maintenance costs.

III. CASE STUDY

The optimization models presented in the previous section have been applied to a particular case study, specifically to a pharmaceutical laboratory. This is a research centre of a pharmaceutical production plant, where a lot of activities are carried out: quality control, new product development, pharmaceutical and medical research and so on. The desired air conditions in the laboratory are assured by an HVAC system that include multiple stages of heating and cooling capacity [28]: when demand is low, the lowest capacity power is operated, while with demand rise, higher capacity stages are deployed.

An HVAC system consists of many components that function together in a well-coordinated mode. Typically, it contains an indoor unit such as a fan coil, and outdoor unit such as an heat pump and a thermostat. A lot of subsystems, like filters, humidifiers and ventilators are present too [29].

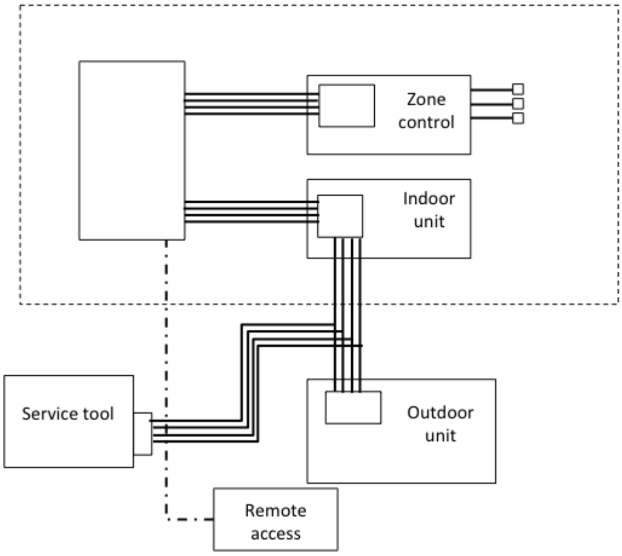

Fig. 1. General schematic view of an HVAC

In this paper, three specific component of the HVAC system were considered: the supply fan of AHU, the associated filters and the fire dampers in duct air inlet.

AHU is a cluster of devices for conveying the conditioned air to the several plant areas. It is able to recirculate internal air and with a precise mixing process with pure air, it can assure optimal internal conditions. This practice allows both air replacement and reduction of energy consumption with the partial resumption of the air that had been previously treated.

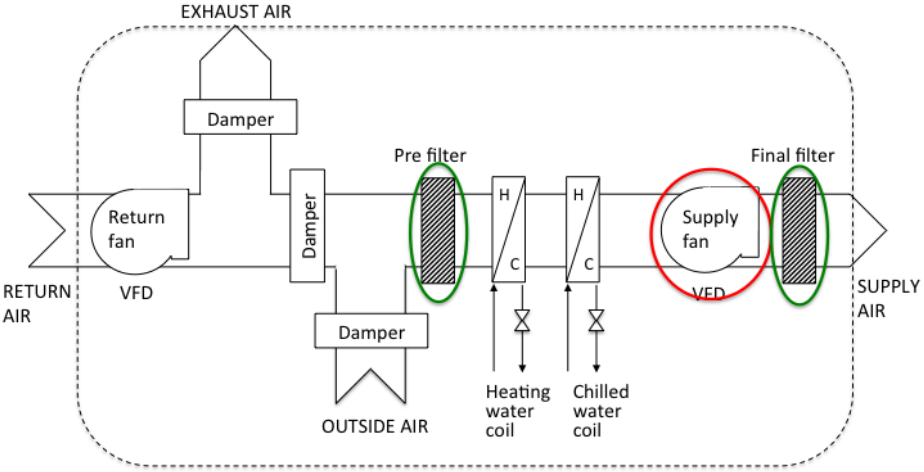

Fig. 2. Typical Air Handling Unit system layout

An AHU is a metal box with fans, cooling and heating elements, valves, filters, etc. It is connected with air ducts for the air distribution, conveying it into the whole building and then extracting it back to the AHU itself. Filters are essential in the AHU since they remove contaminants from air, mainly solid particles like dust, pollen, and bacteria. Filters can be made with different materials: the most used are fibres such as cotton.

In an air conditioning system, also fire dampers are present: they are installed in the air ducts through fire walls and have the function of preventing the spreading of flames, smoke and hot gases through ducts.

IV. RESULTS

In the study, the main reliability parameters of the components of the HVAC system considered, were evaluated. This was possible thanks to real failure data, gathered during 1200 hours of plant operation. These were the available data: expanding the observation period or increasing the sample taken as a reference for the empirical calculation of the reliability parameters, could improve the analysis presented in this paper. In the absence of more data, however, it seemed consistently better to use such information, rather than relying on anonymous and less significant generalist databases.

Table 4.1 shows the failure data for the filters of the air-handling unit: from these real data, fault functions were evaluated. The same was done for the other two components analysed here.

TABLE II
Example of reliability parameters evaluation for filters of the air-handling unit.

Hours	**# faults**	**# survived**	$\mathbf{f(t)}$	$\mathbf{F(t)}$	$\mathbf{R(t)}$	$\boldsymbol{\lambda}\mathbf{(t)}$
0 – 1500	1	50	0,000013	0,02	0,98	0,000013
1500 – 3000	7	49	0,000093	0,16	0,84	0,000095
3000 – 4500	3	42	0,000040	0,22	0,78	0,000048
4500 – 6000	8	39	0,000107	0,38	0,62	0,000137
6000 – 7500	15	31	0,000200	0,68	0,32	0,000323
7500 – 9000	10	16	0,000133	0,88	0,12	0,000417
9000 – 10500	6	6	0,000080	1,00	0,00	0,000667
10500 – 12000	0	0	0,000000	1,00	0,00	-

The next step was the evaluation of the total cost for CM, PM and CBM for the three elements of the HVAC system considered. Even these parameters derived from real cost and time information.

TABLE III
Global cost for CM, PM and CBM for the three elements.

HVAC element	**Cc**	**Cp**
Filters of AHU	€ 10.850	€ 1.328
Air handling AHU	€ 14.838	€ 3.040
Fire dampers in duct air inlet	€ 11.211	€ 1.061

Finally the average unit cost related to CM, PM and CBM activities were evaluated.

The application of (8) to estimate the cost associated to preventive maintenance activities, is linked to the choice of the preventive maintenance time interval: the best one is that has the lowest average cost. As an example, in table 4.3 it is presented the method for the AHU filters.

TABLE IV
$\boldsymbol{c(\tau)_{PM}}$ evaluation for the AHU filters.

Hours	**# faults**	**# survived**	$\mathbf{f(t)}$	$\mathbf{F(t)}$	$\mathbf{R(t)}$	$\boldsymbol{\lambda}\mathbf{(t)}$	**Interval PM** $\boldsymbol{\tau}$	**MTBM**	$\mathbf{c(\tau)_{PM}}$
0 – 1500	1	50	0,000013	0,02	0,98	0,000013	1500	1485	1,02
1500 – 3000	7	49	0,000093	0,16	0,84	0,000095	3000	2850	1,00
3000 – 4500	3	42	0,000040	0,22	0,78	0,000048	4500	4065	0,84
4500 – 6000	8	39	0,000107	0,38	0,62	0,000137	6000	5115	0,97
6000 – 7500	15	31	0,000200	0,68	0,32	0,000323	7500	5820	1,34
7500 – 9000	10	16	0,000133	0,88	0,12	0,000417	9000	6150	1,58
9000 – 10500	6	6	0,000080	1,00	0,00	0,000667	10500	6240	1,74
10500 – 12000	0	0	0,000000	1,00	0,00	-	12000	6240	1,74

As visible in the previous table, for the AHU element the best time interval for preventive maintenance is 4500 hours: to this maintenance interval is related the lowest average unit cost.

Table 4.4 shows results of $c(\tau)$ for the three maintenance policies for each element of the HVAC system.

TABLE V
$c(\tau)_{PM}$ evaluation for the AHU filters.

Element of the HVAC system	$c(\tau)_{CM}$	$c(\tau)_{PM}$	$c(\tau)_{CBM}$
AHU filters	€ 1,74	€ 0,84	€ 0,33
AHU supply fan	€ 2,63	€ 1,53	€ 1,05
Fire dampers in duct air inlet	€ 1,65	€ 0,80	€ 0,20

V. DISCUSSION AND CONCLUSIONS

The results showed in table 4.4 highlight that, for the elements considered in this study, CM is the less cheap maintenance type because of times and costs due to unscheduled stops.

Cyclical maintenance is not favourable since the useful lifetime of each component could not be exploited completely. When PM is a potential maintenance choice, it is anyway important to resort to an optimization process like the one presented in this study, in order to identify the best PM interval time. In fact, if this phase is skipped, for example in business cases in which there is not an engineering maintenance service, it is likely to run the risk of choosing wrong time intervals for the preventive maintenance activities. When an extremely improper time interval is chosen, PM may even be worse than CM (even though the failure rates are increasing).

If a component has a critical availability, if $\lambda(t)$ increases and if condition based maintenance activities can be adopted efficiently, it is appropriate to deal with a detailed analysis of technical and economic feasibility. In the present work, as showed in table 4.4, CBM is always eligible, being the type of maintenance that is associated with the lower average unit cost.

The convenience of adopting CBM depends greatly on the relationship between technology and fault, that is to say on the availability of an efficiency technology for detecting weak signals, premonitory of a fault.

A further advanced mode of performing condition-based maintenance, not analysed in this report, is the one that provides continuous monitoring (in real time). This kind of CBM requires a detailed evaluation through specific cost models. Costs related to real time CBM, in fact, are strictly dependent on costs for the supervision system installation. The possible scenarios are various and they consider whether there is a supervision system already installed. If it has to be installed ex novo, the scale economies play an important role, because the fixed costs must be apportioned to all the points of measure. This subdivision will be more advantageous when the number of measurement points is greater, if compared to the case of a smaller number of points.

REFERENCES

[1] J. Berka and K. Macek, “Effective maintenance of stochastic systems via dynamic programming.”

[2] G. Racioppi, G. Monaci, C. Michelassi, D. Saccardi, O. Borgia, and F. De Carlo, “Availability assessment for a gas plant,” *Pet. Technol. Q.*, vol. 13, no. 2 SUPPL., pp. 33–37, 2008.

[3] J. D. Campbell, A. K. Jardine, and J. McGlynn, *Asset Management Excellence: Optimizing Equipment Life-cycle Decisions*. CRC Press, 2011.

[4] O. Borgia, F. De Carlo, and M. Tucci, “Imperfect maintenance modelling by dynamic object oriented Bayesian networks,” *Int. J. Eng. Technol.*, vol. 5, no. 5, 2013.

[5] J. van Iwaarden and T. van der Wiele, “The effects of increasing product variety and shortening product life cycles on the use of quality management systems,” *Int. J. Qual. Reliab. Manag.*, vol. 29, no. 5, pp. 470–500, 2012.

[6] F. De Carlo, O. Borgia, and M. Tucci, “Risk-based inspections enhanced with Bayesian networks,” *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.*, vol. 225, no. 3, pp. 375–386, 2011.

[7] A. Silvestri, F. De Felice, and A. Petrillo, “Multi-criteria risk analysis to improve safety in manufacturing systems,” *Int. J. Prod. Res.*, vol. 50, no. 17, pp. 4806–4821, 2012.

[8] F. De Carlo, M. Tucci, and O. Borgia, “Conception of a prototype to validate a maintenance expert system,” *Int. J. Eng. Technol.*, vol. 5, no. 5, 2013.

[9] F. T. Chan and A. Prakash, “Maintenance policy selection in manufacturing firms using the fuzzy MCDM approach,” *Int. J. Prod. Res.*, vol. 50, no. 23, pp. 7044–7056, 2012.

[10] F. De Carlo, O. Borgia, and M. Tucci, “Accelerated degradation tests for reliability estimation of a new product: a case study for washing machines,” *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.*, 2014.

[11] B. M. Worrall and B. Mert, “Application of dynamic scheduling rules in maintenance planning and scheduling,” *Int. J. Prod. Res.*, vol. 18, no. 1, pp. 57–71, 1980.

[12] F. De Carlo, “Manufacturing nonconformities management through conditional probabilities,” *Int. J. Eng. Technol.*, vol. 5, no. 5, 2013.

[13] O. Borgia, F. De Carlo, M. Tucci, and N. Fanciullacci, “Service demand forecasting through the systemability model: a case study.,” *Int. J. Eng. Technol.*, vol. 5, no. 5, 2013.

[14] J. Moubray, *RCM II: reliability-centered maintenance*. Industrial Press Inc., 2001.

[15] M. Rausand, “Reliability centered maintenance,” *Reliab. Eng. Syst. Saf.*, vol. 60, no. 2, pp. 121–132, 1998.

[16] F. S. Nowlan and H. F. Heap, “Reliability-centered maintenance,” DTIC Document, 1978.

[17] A. M. Smith, *Reliability-centered maintenance*. McGraw-Hill New York, 1993.

[18] M. Rausand and K. Øien, “The basic concepts of failure analysis,” *Reliab. Eng. Syst. Saf.*, vol. 53, no. 1, pp. 73–83, 1996.

[19] *UNI EN 13306, Maintenance—Terminology*. 2003.

[20] B. A. Ellis, “Condition Based Maintenance,” 2008.

[21] A. K. S. Jardine, D. Lin, and D. Banjevic, “A review on machinery diagnostics and prognostics implementing condition-based maintenance,” *Mech. Syst. Signal Process.*, vol. 20, no. 7, pp. 1483–1510, Oct. 2006.

[22] A. G. Starr, “A structured approach to the selection of condition based maintenance,” in *Factory 2000-The Technology Exploitation Process, Fifth International Conference on (Conf. Publ. No. 435)*, 1997, pp. 131–138.

[23] W. P. Pierskalla and J. A. Voelker, “A survey of maintenance models: the control and surveillance of deteriorating systems,” *Nav. Res. Logist. Q.*, vol. 23, no. 3, pp. 353–388, 1976.
[24] C. Valdez-Flores and R. M. Feldman, “A survey of preventive maintenance models for stochastically deteriorating single-unit systems,” *Nav. Res. Logist. Nrl*, vol. 36, no. 4, pp. 419–446, 1989.
[25] D. I. Cho and M. Parlar, “A survey of maintenance models for multi-unit systems,” *Eur. J. Oper. Res.*, vol. 51, no. 1, pp. 1–23, 1991.
[26] R. Dekker, “Applications of maintenance optimization models: a review and analysis,” *Reliab. Eng. Syst. Saf.*, vol. 51, no. 3, pp. 229–240, 1996.
[27] J. Vatn, P. Hokstad, and L. Bodsberg, “An overall model for maintenance optimization,” *Reliab. Eng. Syst. Saf.*, vol. 51, no. 3, pp. 241–257, 1996.
[28] W. F. Van Ostrand, R. K. Shah, and others, “Failure mode for HVAC system,” 7,216,016May-2007.
[29] A. Handbook, “HVAC systems and equipment,” *Am. Soc. Heat. Refrig. Air Cond. Eng. Atlanta Ga*, 1996.