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A predictive model for an effective maintenance of hospital critical systems

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Abstract

This paper presents a predictive model for the maintenance of critical systems in hospital facilities. The developed model is based on machine learning algorithms and data acquired from the Building Management System (BMS) and supported by the Computerized Maintenance Management System (CMMS). Support Vector Machine (SVM) and Prophet forecasting algorithms are used to assess the current condition of the system and to predict its future conditions. The model was applied to Air Handling Units (AHU) of the Heat Ventilation and Air Conditioning (HVAC) system of a hospital in Jordan. The AHU is considered one of the critical systems in the hospital as it is responsible for controlling the Indoor Air Quality(IAQ) of the building. The developed model achieved an acceptable accuracy in both current condition assessment and future condition prediction. The study has also highlighted the benefits of implementing the model to the hospital in terms of increasing the effectiveness of HVAC system operation and maintenance and cost reductions. The model is set to be integrated with advanced monitoring and maintenance technologies to optimize the performance of the hospital critical systems.

Keywords: Predictive Modeling; Predictive Maintenance; Artificial Intelligence; Air Handling Unit

1. Introduction

The maintenance of buildings is commonly regarded as an important part of Facility Management (FM) to maintain services, operations and make the building more sustainable. This also reduces the costs associated with maintenance and increases energy and environmental efficiency. According to Sacks et al.(2011), 65% of the building's operating cost is used for maintenance. Thus effective facility management requires an effective maintenance plan and strategy (Cheng et al., 2020).

Most facility managers undertake both corrective and preventive maintenance procedures. For corrective maintenance, procedures and actions are taken after the failure occurs which may usually lead to shutting down certain operations and systems in the building. This results in interruptions of services and increases the maintenance cost associated with repairing or replacing failed parts. On the other hand, in preventive maintenance (also called time-based maintenance/scheduled maintenance), the critical systems of the facility need to be inspected and repaired according to a planned schedule to prevent or reduce failures (Cheng et al., 2020). This may, however, involve unnecessary inspections which increase the operating expenses of the facility (Susto et al., 2015). According to Mobley (2002), one-third of maintenance expenses are caused by maintenance inspections and actions that are unnecessarily and improperly carried out.

To improve the building's operation and maintenance procedures, predictive maintenance (also known as condition-based maintenance) can tackle the challenge of balancing operational efficiency and maintenance costs. Predictive maintenance detects the uncontrolled failures and the performance degradation of a component's condition earlier before a failure happens (Mobley, 2002). This eventually leads to optimizing the service life of the equipment, minimizing maintenance inspections, and reducing the cost of material and labor (Carvalho et al., 2019).

Building Management System (BMS) is usually adopted to help facility managers monitor and control the technical systems in the facility by collecting massive sensor data from different building systems and monitoring their performance. Moreover, Computerized Maintenance Management System (CMMS) and Computerized Aided Facility Management (CAFM) are used to improve the efficiency of facility maintenance management systems.

The application of predictive maintenance is an effective strategy in complex buildings such as hospitals. Hospitals are complex buildings that depend on various, specialized and complicated systems to provide patients with healthcare services (Lavy and Shohet, 2009). As hospitals are non-stopping operating facilities, the efficiency of the hospital components is critical and their service failure may have serious consequences to patients' health human life (Mwanza and Mbohwa, 2015). One of these critical systems is the HVAC system. It plays a crucial role in delivering uninterrupted, high-performed healthcare services to the hospital's users. The mission of HVAC systems is to provide adequate ventilation, air conditioning, and good Indoor Air Quality (IAQ) to the building users (Au-Yong et al., 2014).

Based on Jardine et al. (2006), predictive maintenance for detection, diagnostic, and prognostic is mainly divided into three categories: model-based methods, artificial intelligence methods, and statistical methods. Data-driven methods that use artificial intelligence to predict the condition of the system are preferred for predictive maintenance (Zhang et al., 2019). This has become more common due to the increased availability of system data (Li et al., 2017). Such studies were limited to hospital HVAC systems. For example, Kukkonen (2018) developed a data-driven approach to condition-based maintenance of the AHU as an integral part of the HVAC system. The approach uses sensor data from the machine and applies fuzzy expert rules to detect faults. Cheng et al. (2020) applied Building Information Modeling (BIM) and the Internet-of-Things (IoT) technologies to build a data-driven predictive maintenance approach to predict the future condition of a chiller in an HVAC system using machine learning. Results showed that applying this approach can effectively predict the future conditions of the system..

This paper builds on the model developed by Cheng et al. (2020) to predict the future condition of an AHU. The AHU is one of the key components of HVAC systems in this hospital building as it controls the IAQ of the building. Support Vector Machine (SVM) and Prophet forecasting algorithms are used for current and future condition prediction of the AHU. The proposed method is based on real-time sensor data collected from the hospital BMS and will be integrated within the hospital's CMMS. Modeling predictive maintenance is expected to help facility managers perform maintenance procedures effectively and develop cost-effective maintenance plans based on the predicted conditions. This is expected to eventually reduce the overall cost of AHU maintenance and maintain a higher level of IAQ in the hospital building.

2. Literature review

Predictive maintenance is a condition-based maintenance plan that is adopted after a prediction process based on required analysis or known features and evaluation of significant parameters of the degradation of the item (European Committee for Standardization, 2017). As shown in Figure 1, predictive maintenance one type of preventive maintenance with prognostic ability, which can predict the Remaining Useful Life (RUL) of the system (that is, the period that the equipment will continue to function according to its design specifications) (Zio, 2013). The difference between predictive maintenance and traditional condition-based maintenance (preventive maintenance) is the use of data collected from monitored systems to find and analyze trends (Márquez, 2007).

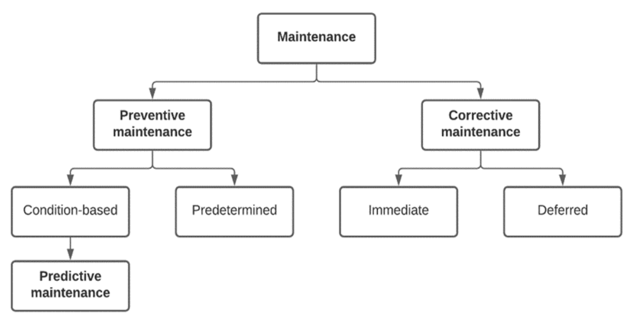


Figure 1. Maintenance types (European Committee for Standardization, 2017)

Multiple statistical and mathematical models can be used for predictive maintenance. In this case, a model that determines the relationship between the input variables and the output variable does not exist in advance. In fact, in the field of predictive maintenance for AHU, it is very difficult to adopt such a model due to the huge inherent variabilities among different systems such as (1) the age and operation modes of AHUs, (2) the operation set-up and environment (e.g., an AHU that operates in a closed high-temperature area is expected to perform poorly compared to the same AHU working in a healthier environment), (3) the different technologies and materials used in AHU, and (4) the existence of several hidden factors/variables that may affect the operation of the AHU. In addition, these models are of user-specific nature. That is, operators may consider different sets of variables to build their predictive model. This opens the door for a huge number of possible models due to variable change. Due to these challenges, machine learning presents itself as a potential solution to build efficient predictive models in the absence of such a reliable model. Carvalho et al. (2019) introduced a systematic literature review of the machine learning methods used for predictive maintenance. They mentioned that most machine-learning algorithms used to predict the condition of components include Support Vector Machine (SVM), Artificial Neural Networks (ANN), and K-means. Other algorithms are based on time-series data such as the Prophet forecasting model.

2.1. SVM and Prophet forecasting

The proposed model for predictive maintenance is based on SVM and Prophet forecasting algorithms. SVM is a number of supervised learning methods that analyze regression and recognize patterns (Carvalho et al., 2019). Because of its high level of accuracy, SVM is well- known machine learning method for executing classification and regression tasks (Sexton et al., 2017). It creates an n-dimensional hyperplane that ideally divides the data into n groups/classes (Carvalho et al., 2019). Its high precision in the separation of the different data classes allows for identifying the best point for separating data classes (Susto et al., 2013). Also, generally, it does not from overfitting when there is a clear indication of segregation between classes. The ability of SVM in condition prediction has been researched by (Cheng et al., 2020). They evaluated the performance of ANN and SVM in predicting the condition of chillers in the HVAC system and indicated there were particular advantages in predicting the chiller condition. Both methods are also dependent on the specific cases in the training and testing samples, the SVM outperformed the ANN as it is more sensitive to the values of the parameters. Therefore, SVM can be effectively used in predicting the current condition of AHU based on classifying sensor data.

Prophet forecasting is a robust machine learning model for time-series forecasting. Facebook has introduced this algorithm and opened it up to the public in 2017 (Hasan Shawon et al., 2020). According to Facebook, Prophet works best with time series that have strong seasonal effects (i.e., several seasons of historical data) and is robust to outliers and shifts in the trend (Aditya Satrio et al., 2021). These features fit the maintenance pattern of systems operating in facilities such as hospitals. However, no research was found in the reviewed literature on the Prophet's prediction of the future state of a critical facility system such as an HVAC system. Duc et al. (2019) used Prophet to predict the RUL of the four basic components of a passenger car, namely the engine, brake pads, springs, and tires. The results showed a good agreement with the model used for prediction.

2.2. Study objectives

In the literature review, the identified research gaps include that there is a need for research that works on data-driven predictive maintenance for AHU as a part of HVAC systems, need for research that focuses on utilizing BMS and CMMS for predictive maintenance, and need for research that applies machine learning algorithm for predicting the future condition of the HVAC system.

This study, therefore, proposed a model for data-driven predictive maintenance of critical facility systems. The model focuses on using BMS and CMMS to predict the future condition of AHU as a critical part of the HVAC system in the facility. The model utilizes SVM machine-learning algorithm for the assessment of AHU's current condition and Prophet forecasting method to predict the future condition of the AHU in a hospital in Jordan. AHU in HVAC systems is responsible for ventilating, controlling the air temperatures and the air quality of the hospital. The model monitors the condition of the AHU by collecting sensor data from BMS and CMMS in real-time. The collected data is used to assess the current condition of the AHU and the time-series of current conditions are used to predict future conditions. Model outcomes will help facility and maintenance managers perform immediate maintenance actions and prepare the maintenance plan for future periods (e.g., months). This includes ordering materials and tools in advance to conduct maintenance actions before failures occur. Expected benefits include increased efficiency of AHU of the hospital with more sustainable and improved indoor air quality. Benefits also include reduced maintenance costs by avoiding unnecessary costs associated with sudden repair or replacement and unnecessary inspections associated with traditional preventive maintenance.

3. Predictive maintenance model

This section details the methodology of modeling the predictive maintenance and the algorithms used for assessing the current condition and predicting the future condition of a critical system in a hospital facility. Figure 2 depicts the proposed model for predictive maintenance of the AHU in the HVAC system.

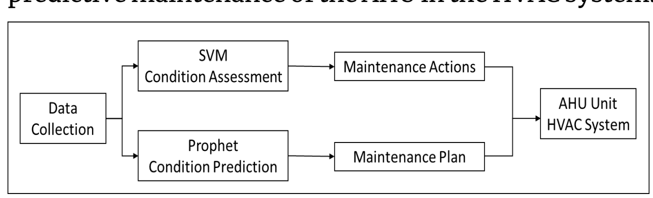


Figure 2. Model for HVAC predictive maintenance

3.1. Data collection

In this stage, component parameters related to predictive maintenance are identified and collected. The value of real-time sensor data is used to indicate the condition of the device. For effective predictive maintenance, Bansal et al. (2004) recommended collecting real-time data from a large number of sensors to include all machine parameters.

In this study, the data obtained from the AHU include sensor data such as temperature values, airflow, pressure, in addition to the unit's name and location. Sensor data are collected from field devices that measure and sense the field variables and send the signals to the Direct Digital Controller (DDC). The AHU has four types of sensors: temperature sensors, pressure sensors, CO_2 sensors, and airflow sensors. The DDC system then converts the sensor data into numeric information that can be displayed by the GUI and stored in the CMMS database. Figure 3 shows the data collection and display process.

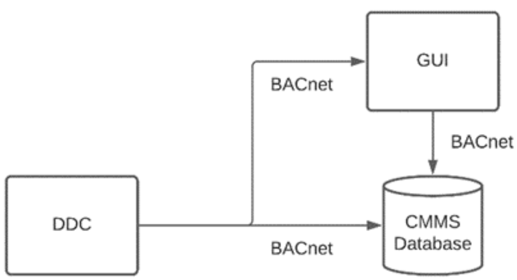


Figure 3. Sensor data collection and display process

As shown in Figure 3, DDC transmits sensor data through the Building Automation Control Network (BACnet) protocol. The protocol meets the communication needs of the systems such as HVAC systems, lighting control, access control, and fire detection control systems (American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 2020). The transmission process will be realized by a plug-in built-in and installed in the CMMS software to import and store data from the DDC. Thus, it is essential to map the imported data from the BMS to the CMMS system.

3.2. Current condition monitoring

Condition monitoring concerns the collection and analysis of relevant AHU parameters to determine whether the AHU's condition has changed compared to normal operating conditions (i.e., whether the AHU's condition has deteriorated). The key rule of condition monitoring is that if the sensor readings of an AHU or the current/future condition of the AHU reaches a certain point, an alarm or warning will be issued to indicate that the unit has/will have a problem. The maintenance staff will then check for potential failures and generate a maintenance work order to perform on-site maintenance and inspection of the AHU. The FM staff will check for potential failures based on previous experience of AHU failures. Figure 7 shows the condition monitoring process through Graphical User Interface (GUI).

As shown in Figure 4, condition monitoring directly monitors real-time sensor data and sends alerts in the event of a sudden failure. In such a case, a corrective maintenance procedure is followed. The prediction or assessment of the AHU condition is performed using CMMS. As shown in Figure 4, the SVM machine learning algorithm is used to predict and assess the current condition of the AHU based on a predetermined classification. It serves as decision support to maintenance staff by diagnosing and assessing the current condition of the AHU.

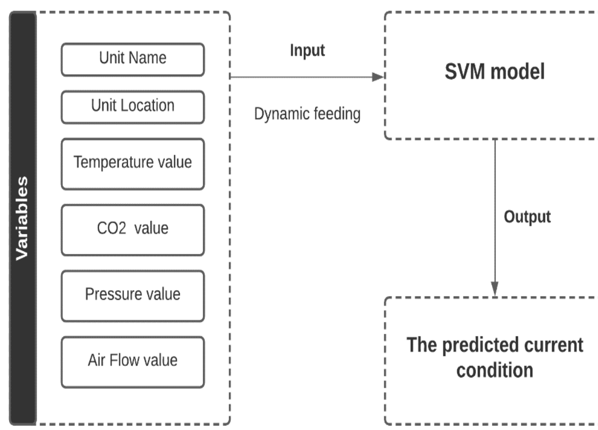


Figure 4. Condition monitoring and prediction

In this stage, the predictive maintenance procedure is followed for failures occur in the short-term. The SVM algorithm is used to classify obtained sensor readings stored in the CMMS database into classes scaled from (1-10) to predict the current condition using Python programming. The main parameters of the SVM model are the kernel type, which aids in defining the hyperplane mathematical equation. The C parameter helps in selecting the hyperplane margin. In this paper, the SVM model parameters were set 'linear' kernel type, C value of '100', and the other parameters were in default settings.

3.3. Future condition prediction

The purpose of this stage is to predict AHU failures that will occur in the long-term. This prognostic prediction of the future condition of the AHU is established based on the previous conditions generated from SVM and recorded in the CMMS database. The prediction of the future condition will help maintenance staff update maintenance plans, prepare reports for the tools and items needed for the maintenance plans, and facilitate the attainment of the required maintenance actions.

The Prophet forecasting algorithm is used to predict the future condition of the AHU. It is a machine learning model for time-series forecasting. The Prophet forecasting model is a simple additive regression model with three main components: piecewise trend, seasonality, and holiday effects (Taylor and Letham, 2018). The Prophet is robust to seasonality, outliers, missing values, and sudden changes in the time series forecasting.

The Prophet prediction model will obtain the recorded condition data stored in the Condition database to make predictions using Python programming. Figure 5 illustrates the AHU's future condition prediction process using the Prophet forecasting. The input to the prediction process is time-series of AHU's current obtained from the condition database. The output of this process is a condition index scaled from (1-10), that represents the future condition of the AHU at different time phases (e.g., 1 month, 3 months, etc.).

Figure 5. Future condition prediction process

3.4. Maintenance performing and planning

Based on the results of condition monitoring, maintenance is performed if the current action is needed. Typically, the maintenance staff will conduct an on-site inspection and assess the condition of the AHU. If the AHU needs maintenance, the FM staff will prepare the tools required for the maintenance operation (repair or replacement). The maintenance staff will also fill in the maintenance forms, the AHU checklist, and other relevant data (labor, cost, time, tools, and items) required for the maintenance operation. Afterward, the staff will update the CMMS database.

For effective condition prediction, the SVM algorithm is trained based on the continuously updated real-time sensor data and the previous condition records. Therefore, the parameters of the prediction models are adjusted according to the new conditions of the AHU. Thus, the predicted future condition will give insights into the future state of the AHU before it needs repairing. If the future condition is changed, the CMMS will send out an alert to notify the staff. Accordingly, the staff will then update their maintenance plans and prepare reports for the tools and items required to perform maintenance. This results in an effective maintenance plan that can enhance the condition of the AHU, reduce system failures, and mitigate maintenance costs associated with a sudden failure. Also, this helps the staff order and schedule the inventory of spare parts needed for maintenance ahead of time to avoid high costs associated with urgent replacement of parts.

4. Model application and preliminary results

To illustrate the functionality of the predictive maintenance model, it is applied to the AHU of the HVAC system for a hospital in Jordan. The HVAC is a system that provides adequate air circulation and ventilation for the building. Several building zones can be covered by the HVAC system. The main components of the HVAC system include Chillers, Pumps, and insulated steel pipes for water distribution, AHUs, Duct fans, Air terminal, Dampers for air distribution, Control systems, and Electrical distribution systems. The AHU connects the main heating/cooling system to different building zones.

The AHU is the main HVAC system component in the hospital. It is responsible for controlling the IAQ in different hospital zones by controlling the following parameters: temperature, humidity, air movement, and air quality. There are 42 AHUs serving the hospital. Four types of sensors are installed to monitor the AHU: (1) temperature sensors, (2) pressure sensors, (3) flow rate sensors, and (4) CO_2 sensors.

Figure 6 illustrates a typical AHU within the HVAC system. As shown in Figure 6, supply air is a combination of fresh air and recirculated air. The dampers are used to regulate the flow of air. The filters are used to purify the air. The cooled water from chillers and hot water from boilers are supplied to the AHU by pumps. The supply fan delivers the supplied air to each air conditioning zone. In addition, the return air is split into two streams by the return fan. One stream is the exhaust air outside the building, and the other is recycled air (Du et al., 2014).

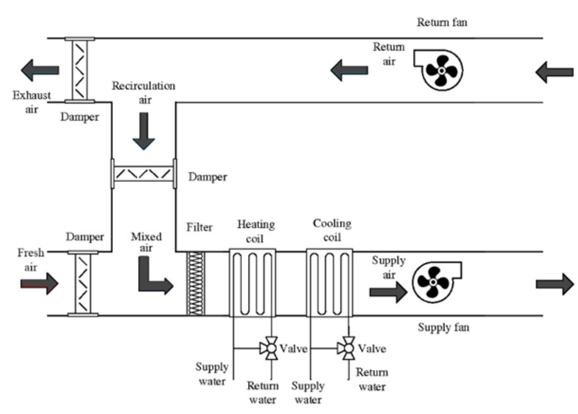


Figure 6. Schematic diagram of an AHU (Y. Yan et al., 2020)

The application of the predictive maintenance model shown in Figure 2 to the hospital AHU involves three stages: data collection, condition monitoring and prediction, and maintenance performing and planning.

For data collection, the sensor data of one AHU are collected and prepared for condition monitoring and prediction of the AHU. The temperature, pressure, airflow, and CO_2 values are collected from the field devices and processed in the Direct Digital Controller (DDC). For example, the setpoint value for temperature is 20°C and the actual temperature values increase or decrease based on the time of the day and season. The pattern of pressure is similar to the temperature. The setpoint value for the pressure is 750 Pascal. Airflow values have an inverse relationship with pressure values, the setpoint for airflow is 8000 liters/second when the pressure setpoint is 750 Pascal. CO_2 setpoint is 400 parts-per-million, high-temperature values affect CO_2 level.

The maintenance staff monitors the AHU condition through the Graphical User Interface (GUI). The goal is to directly monitor real-time sensor data and send an alert in the case of a sudden failure. Figure 7 shows how the AHU is visualized and monitored through the GUI in the hospital. It displays readings for all installed sensors, the unit's name, and location. Through the GUI, the maintenance staff can read the sensor reading and control the operation of the AHU. Each sensor reading (temperature, pressure, etc.) should not exceed a certain threshold and if any sensor reading exceeds it, the GUI will display a pop-up alarm to alert the staff. The staff will then check if there is a potential failure and generate a maintenance work order accordingly.

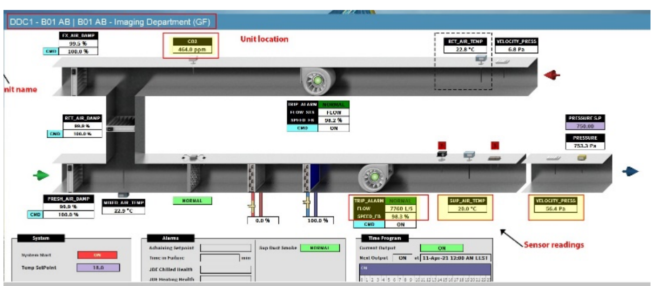


Figure 7. The GUI applied to the hospital

For condition prediction, the developed model uses the SVM algorithm to predict the current condition of AHU and Prophet forecasting to predict the future condition. The input for the Prophet forecasting model is the output of the SVM model which is stored in the condition database. The output of this process is the condition index scaled from (1-10) for different periods. Table 1 shows a sample of the predicted conditions of the AHU for the next four periods (3 months, 6 months, 9 months, and 1 year). In the developed model, the CMMS will monitor the output of the Prophet forecasting model. If there is any degradation between the previous output and the current one in a predefined value, the CMMS will then send out an alert to indicate this issue.

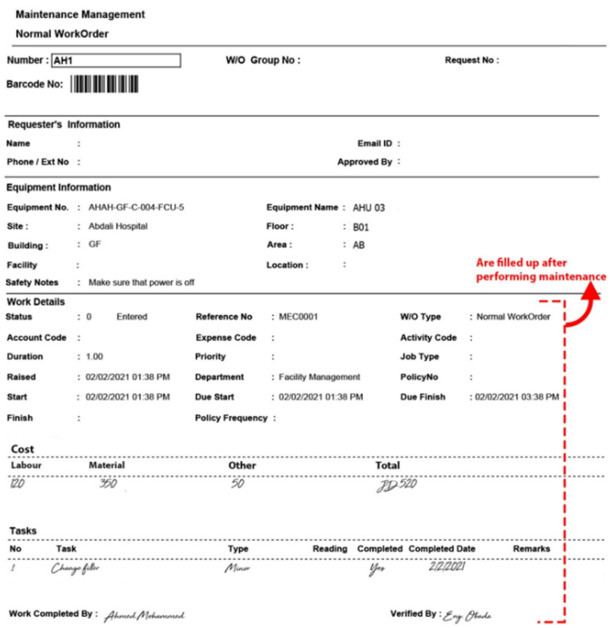
Table 1. The future predicted condition for the AHU for different time phases

HVAC System	Current condition	Predicted future condition			
		3 months	6 months	9 months	1 year
AHU	8.9	8.9	8.3	7.8	7.2

For maintenance performing and planning, a maintenance work order will be generated and the maintenance staff will conduct an on-site inspection of the AHU and evaluate its condition through a checklist prepared by the mechanical engineer. After that, if the AHU needs to be repaired, they will repair or replace the failed part. The maintenance staff will fill out the maintenance work order, which lists the tools, materials, and labor used, as well as the cost of performing the maintenance. The FM staff will then update the CMMS with these forms.

The maintenance staff will update the maintenance plans based on the output of future conditions predicted. For example, based on results in Table 1, the current condition of the AHU is 8.9, which indicates that the AHU needs minor improvements and maintenance. This status will remain the same for the next three months, so the staff should keep monitoring it to avoid any degradation in the condition. After 6 months, the condition of the AHU will decrease to 8.3. This indicates that the AHU is on a slight degradation status but it is still in a good condition and no major maintenance required. Monthly inspection will be appropriate for the AHU in the coming 6 months. However, the future condition will decrease by 0.5 in the next 9 months which suggests that obvious degradation exists and the staff should send an inspection work order to find the root cause of the degradation and repair it. If the staff only relied on the monthly inspections and did not perform any repairs, the condition will reach 7.2 one year later. This is a significant degradation and the facility manager should increase the frequency of regular inspection to twice a month to avoid any failures.

Overall, in the developed model, the CMMS will send alerts to maintenance staff to monitor the changes or degradation in the condition to prepare the tools and material in advance. The maintenance plan will be changed according to each predicted action. If the FM staff receive an alert of a sudden failure, a degradation in the current condition, or any specific repairs required based on the predicted future condition, then the FM staff will check whether there is a potential fault based on this alert and generate a maintenance work order from the CMMS. Figure 8 shows an example of an AHU maintenance work order generated by the CMMS used in the hospital. The maintenance work order contains request information, equipment information, and work details that will be filled out after the maintenance is performed.


Maintenance Management
Normal WorkOrder

Number : AH1 W/O Group No : Request No :
Barcode No:

Requester's Information
Name : Email ID :
Phone / Ext No : Approved By :

Equipment Information
Equipment No. : AHAH-GF-C-004-FCU-5 Equipment Name : AHU 03
Site : : Abdali Hospital Floor : : B01
Building : : GF Area : : AB
Facility : Location : :
Safety Notes : Make sure that power is off

Work Details
Status : 0 Entered Reference No : MEC0001 W/O Type : Normal WorkOrder
Account Code : Expense Code : Activity Code :
Duration : 1.00 Priority : Job Type :
Raised : 02/02/2021 01:38 PM Department : Facility Management PolicyNo :
Start : 02/02/2021 01:38 PM Due Start : 02/02/2021 01:38 PM Due Finish : 02/02/2021 03:38 PM
Finish : Policy Frequency :

Cost

Labour	Material	Other	Total
120	350	50	JD 520

Tasks

No	Task	Type	Reading	Completed	Completed Date	Remarks
1	Change filter	Minor		Yes	2/2/2021	

Work Completed By : Ahmed Mohammed Verified By : Eng. Obada

Figure 8. Maintenance work order for AHU

5. Conclusions

This paper presented a model for the predictive maintenance of a hospital AHU. The model consists of three stages; data collection, condition monitoring and prediction, and maintenance performing and planning. SVM and Prophet forecasting algorithms are used for condition short-term assessment and long-term prediction. Real-time sensor data is used to feed the SVM algorithm to assess the condition of the AHU and time-series data is used to feed the Prophet forecasting algorithm to predict its future condition. Reviewed literature revealed a need for predictive maintenance models that are applicable to critical systems of facilities, especially hospitals. The model was applied to an AHU unit in a hospital in Jordan. Preliminary results are encouraging in terms of accuracy and applicability.

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