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A NEW MAINTENANCE METHODOLOGY APPLIED TO A HVAC SYSTEM

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Abstract. *The heating, ventilation and air conditioning systems, also known as HVAC systems, are designed to supply quality air to confined interior spaces. Unfortunately, they often don't execute that function for which they were conceived properly. The cause for the eventual failure of these systems can be a project deficiency, an incorrect installation on site or an inadequate or sometimes forgotten maintenance. When that happens, the HVAC systems become a potential source of pollution, opposing to the purpose for which they were conceived, "to treat the air with quality". In this work, we characterized the functional, technical and physical aspects of an HVAC installation, responsible for the acclimatization of an office in the Orient Train Station, in Lisbon, Portugal. Also, the maintenance policies applied to the system up to the beginning of this study were analyzed. Due to the importance and the lack of knowledge about the air quality of the referred space, an evaluation and control diagnosis was made to the Indoor Air Quality (IAQ). Then, a work methodology was defined and the most important parameters to evaluate were identified. The system's data was collected and compared with standard values. After the characterization of the system parameters that influence the IAQ (physical, chemical and biological), a new strategy of preventive maintenance was applied, as the previous one was considered not good enough. The preliminary results of this new strategy are shown in this paper. Due to the complexity of this problem and the different opinions and sometimes the lack of knowledge that surrounds it, this work tries to bring to light the fundamental questions about the performance and maintenance of the HVAC systems and to catalyze the development of future works about this very important subject*

***Keywords**: HVAC, Indoor Air Quality, Maintenance*

1. Introduction

There are several factors that contribute to the air quality of a contained volume, as the one existing inside a room. These factors are associated to the air that comes from the outside, to the HVAC (Heating, Ventilation and Air Conditioned) equipments and to the interior environment by the type of construction, existing furniture, decoration, cleaning products and by the people that use that space.

The HVAC systems are supposed to provide quality air to the indoor spaces, satisfying the needs for comfort and salubrity of the air. But these systems can also be responsible for the pollution that can be found in these indoor spaces, because some of its components like filters, heating and cooling exchangers, humidifiers, the drain pans and the ducts can be a good environment for the proliferation and dissemination of biological contaminants, if they were not well designed and, above all, if they are not well maintained.

The concept of maintenance of HVAC systems is not a very precise one and in most cases the user tries to perform the maintenance job simply at what it seems to be the lowest price (Fitzner, 2001).

The main objectives of this work are:

- The physical, technical and functional characterization of a particular HVAC equipment and to establish a planed preventive maintenance system adopted to the technical characteristics and needs of the space where it is installed
- To develop this planed preventive maintenance system according to the data obtained by the system monitoring and technical and economical analysis, when granting the air quality to the confined space under study.

2. **Indoor air contamination**

The Indoor Air Quality (IAQ) can be affected by several factors and, as it mencioned, by the HVAC equipments themselves.

The sources of air pollution can be from exterior or interior origin. They can be classified as physical sources (dust and fibers), chemical sources (volatile organic products, ozone,…) and biological sources (virus, bacteria, fungus, mites).

The contaminants can be:

- Solid or gaseous particles
- Organic or inorganic contaminants
- Visible or not visible
- Toxic or not toxic
- Stable or instable
- Microscopic or macroscopic

On Table 1 it can be seen the origins, the sources and the types of contaminants that can affect the IAQ.

Table 1: Sources and types of contaminants for indoor air

Origin	Sources		Contaminants
Outdoor	Outdoor Air	Air	Several
		Ground	Radon, COV^s and Particles
HVAC Systems	Ventilation Systems	HVAC Equipments and Their Components	Micro-organisms, Particles, COV^s and $MCOV^s$
Indoor	Materials	Construction	COV^s, Particles and fibres
		Decoration	COV^s and Particles
	People and Their Activities	People	CO_2, Steam and Bioeffluents
		Convertion/use	NO_x, CO, CO_2, Steam and COV^s
		Energy	Particles
		Smoke	NO_x, CO, CO_2 ,Steam, COV^s and Nicotine
		Cleaning Products	COV^s

As it can be seen the HVAC equipments and their components can be an important source of contaminants, if they were not well designed and installed and if they are not properly maintained. For instance, it was reported (Fanger, 1988) that when the contaminants of fifteen office buildings were studied it was noticed that HVAC systems were responsible for 42% of the sensorial pollution (odor smell). To this kind of pollution could have contributed all the components of the system (filters, drain pans, ducts,…).

To improve the IAQ, the best is to control its quality at the origin, taking in consideration the fresh air that goes inside the room and the air that is recycled.

Several measures can be taken to assure that the indoor air has enough quality:

- The use of adequate filters and their regular control and cleaning.
- Cleaning of the air circulating system: pipes and ducts, drain pans and other equipments. These actions should be easy to perform.
- The interior air must be mixed with controlled fresh air

The filter's choice is very important. Its performance is measured by its efficiency, capacity for particle retention and power loss.

Table 2: Different types of filters

APLICATION	TYPE	CLASSIFICATION	
		EN779	EUROVENTE
Clean Rooms Sterilization Rooms Pharmaceutical Laboratories Electronic Plants Nuclear Plants	Absolute Filters	G1 G2 G3 G4	EU1 EU2 EU3 EU4
Informatics Rooms Industrial Painting Areas Chemical Industries	Intermediate Filters (high efficiency)	F5 to F9	EU5 to EU9
Public Areas Ventilation Pre-Filters for Absolute Filters Filters for Compressors	Pre-Filters (medium efficiency)	H10 to H14	EU10 to EU14

3. Physical and Functional Characterization of the Analyzed Installation

The installation that was the object of this study it is one that exists at the *Gare Intermodal de Lisboa* (better known by Orient Railway Station in Lisbon). It is an office space of about 350m^2. In this office space sixteen people work there everyday and the only ventilation is made by five Fan Coil systems, making part of a centralized system of four ducts and with a constant air flow. At Figure 1 one of these Fan Coil systems can be seen.

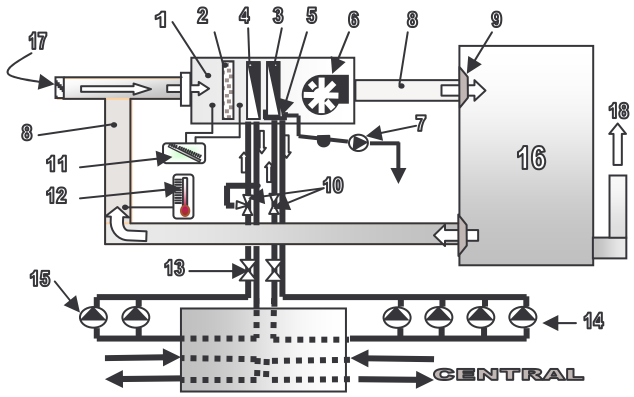

Figure 1: Fan Coil System

Air Circuit	Water Circuit	Condensate Circuit
Mixage camara (1)	Heat Exchanger (3)	Drain Pan (5)
Filter (2)	Cool Exchanger (4)	Condensate Removal Pan (7)
Fan (6)	Flow Valves (10)	
Ducts (8)	Balancing valves (13)	
Insufflation diffuser (9)	Chiller (14)	
Thermal Probe (12)	Boiler (15)	
Inlet air (17)		
Indoors Space (16)		

When the system was first installed, it was established a preventive maintenance plan, with different levels of interventions performed at every 300 h, 1800h and 2400h, as it can be seen in Table 3. This plan was established based in previous experiences in similar installations and by the manufacturer's suggestions. At this time, a risk analysis was not considered.

Table 3: Preventive Maintenance Planning and Scheduling

Time Interval (hours)	Maintenance Tasks
300	• Filter cleaning or replacement • Inspection of the condensed products pump • Float cleaning • Inspection of noises and/or leaks
1800	• Inspection of connections and insulations • Inspection of pipes of the condensed products circuit (clogged pipes) • Inspection of support structures
2400	• Inspection of the serpentines and cleaning if necessary • Test of actuators and valves • Inspection of the ventilator • Electrical measurements and control

This time scheduling was not fully carried out and as it can be seen in the next table, some corrective actions were necessary, especially in components that were not considered in the Preventive Maintenance Planning, like actuators, flow valves and temperature probes.

An analysis was made to these interventions and some Performance Indicators were calculated, as it can be seen in the Table 5. After analyzing this data, it was decided the maintenance actions taken were insufficient and that a new maintenance methodology was needed and also that the IAQ was not assured by the actions taken till this point.

Table 4: Dates and types of interventions. P – preventive; C – corrective; TBI – Time Between Interventions

TBI (Times Between Interventions – hours)															
Date	Machine 1			Machine 2			Machine 3			Machine 4			Machine 5		
	TBI	P	C	TBI	P	C	TBI	P	C	TBI	P	C	TBI	P	C
24-Abr-00	462	x		492	x		492	x		560	x		544	x	
1-Jun-00	527	x	x	534	x		530	x	x	521	x		501	x	
14-Jul-00	550	x		566	x	x	566	x		685	x		562	x	
7-Set-00	715	x	x	761	x		740	x		763	x		770	x	
13-Out-00	485	x		491	x		501	x		494	x		489	x	x
25-Out-00	152	x	x	143	x		419	x		444	x		156		x
15-Nov-00	276	x		275	x		411	x		320	x		284	x	
12-Dez-00	319	x		413		x	242	x		317	x	x	391	x	
8-Jan-01	306	x	x	195	x		484	x		377	x		252	x	
5-Fev-01	351	x		380	x		293	x		306	x		200	x	x
26-Fev-01	295	x		297	x		396	x		498	x		287	x	
12-Mar-01	191	x	x	284	x		188	x		291		x	295	x	
2-Abr-01	295	x		529	x		179		x	439	x		275	x	
30-Abr-01	355	x		351	x		378	x		339	x		192	x	x
28-Mai-01	359	x		357	x		185		x	404	x		172	x	
22-Jun-01	377	x	x	396	x		337	x		303	x		451	x	
23-Jul-01	390	x		280		x	518	x		285	x		197	x	
13-Ago-01	292	x		188	x		577	x		259	x	x	348	x	
3-Set-01	293	x		290	x		256	x		279	x		426	x	x
25-Set-01	297	x		255	x		312	x		340	x		277	x	
15-Out-01	239	x		376	x	x	131	x		364	x		407	x	
6-Nov-01	303	x		217	x		611	x	x	385	x		574		x
26-Nov-01	260	x		336	x		169	x		274	x		265	x	
26-Dez-01	381	x		312	x		320	x		345	x		294	x	
8-Jan-02	239	x		332	x		354	x		323	x		340	x	

Table 5: - Critical Componets Performance Indicators

Component	Working	N.º	Time	Failure	MTTR	MTBF	Ai (%)
	Hours.	**Failures**	**Maint.**	**Rate**			
Actuator Valve. 2 ways	25158	2	1.0	0.0000795	0.500	12579	99
Actuator Valve. 3 ways	19380	1	0.5	0.0000516	0.500	19380	99
Condensate Float	24796	6	3.3	0.0002420	0.550	4132	99
Condensate Removal Pump	24606	5	2.9	0.0002032	0.580	4921	99
Thermal Probe PT1000	44538	2	1.1	0.0000449	0.550	22269	99
Valve - 2 ways	24652	2	1.9	0.0000811	0.950	12326	99
Valve - 3 ways	19886	4	3.5	0.0002011	0.875	4971	99
Ventilator	44538	1	1.7	0.0000225	1.700	44538	99

$$MTBF = \frac{1}{\lambda}$$

$$\lambda = \frac{Nav}{\sum tFi}$$

$$MTBF = \frac{\sum tFi}{Nav}$$

$$MTTR = \sum TRi / Nav$$

Ai = Availability
MTTR = Mean Time To Repair
MTBF = Mean Time Between Failure
λ = Failure Rate
Nav = Number of Failures
tFi = Working Time

4. New Maintenance Methodology

To try to understand if the existing preventive maintenance could be improved, it was decided to implement a new methodology that consisted in monitoring several parameters of the indoor air at different points of the installation. The monitored points of the installation are shown in Figure 2. The type of monitoring can be seen in Table 6.

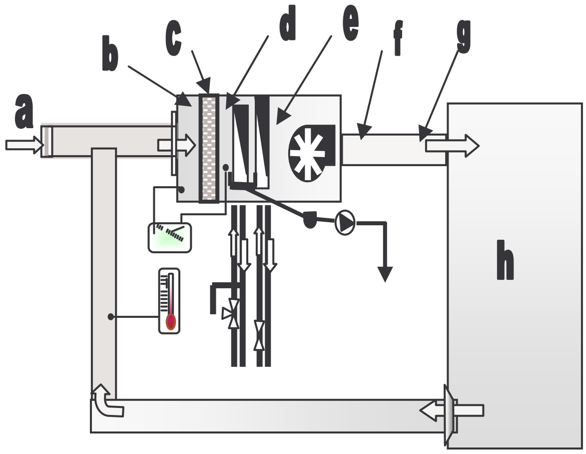

Figure 2: Points in the system where the air was monitored

The measured results were compared with existing standards, in our case the Brazilian Standard ANVISA – RE nº176 (200) and the ASHRAE Standard 62-1989R (Rev. 1990).

Table 6: Types of monitoring

Location		Measured Parameters	Type of Monitoring	What Was Monitored
a	Machine Room	Physical	Temperature Humidity and Dust	Air
			Caudal	New Air
		Chemical	CO; CO_2; NO; NO_x; NO_2; SO_2; $COVT^s$	Air
b	Before the Filter	Physical	Static Pressure	Air
		Biological	Microbiological	
c	Filter	Biological	Microbiological	Preceding Surface
				Posterior Surface
				Inside Filter
d	After the Filter	Physical	Static Pressure	Air
e	Before the Fan	Physical	Static Pressure	Air
f	After the Fan	Physical	Static Pressure	Air
g	Air Insufflation	Physical	Flow	Air
		Chemical	CO; CO_2; NO; NO_x; NO_2; SO_2; $COVT^s$	
		Biological	Microbiological	
h	Indoor Space	Physical	Temperature Humidity and Dust	Indoor Air
		Biological	Microbiological	

In Table 7 it is shown the results of the monitoring after about 3 500 hours (about 6 months) of the start of the equipment.

Analyzing these results and repeating the monitoring each 300 hours, it could be noticed that most of the tasks performed at every 300, 1800 and 2400 hours time intervals were not needed to be performed at such small time gaps. Instead, it was proposed new time intervals: 1 000, 3 000 and 6 000 hours, controlling also the IAQ. This was important especially for the replacement of filters, that were not replaced every 300 hours any more, as stated by the manufacturer, but only every 1 000 hours.

Table 7: Results of the monitoring action at ± 3 500 h
* Times for which the recommend final pressure drop has been found for each filter

Parameters	Monitored Element	Standard values	Measured Values	OK
Physical	Indoor temperature	Summer 23º a 26ºC Winter 20º a 22ºC	21.9º a 23.5ºC 21.5º a 22.5ºC	✔ ✔
	Relative humidity	Summer 40% a 65% Winter 35% a 65%	41% a 55%	✔
	Indoor air speed	0.025 a 0.25 m/s	0.01 a 0.16 m/s	✔
	New air flow	ASHRAE - 27m^{3}h for each people DL Nº118/98 – 35 m^3/h	527 m^3/h 37 m^3/h for each people	✔ ✔
	Pressure drop in the filter	Recommended final pressure drop 120Pa	110Pa - 3466h* 118Pa - 2540h* 118Pa - 2763h* 118Pa - 3040h* 120Pa - 3506h*	✔ ✔ ✔ ✔ ✔
Chemical	Total dust	≤ 80 μg/m^3	4 μg/m^3	✔
	CO_2	≤ 1000 ppm	1.009 x 10^{-3} ppm	✔
	COVT^s	300 – 1000 μg/m^3	0.45 mg/m^3 = 450 μg/m^3	✔
	CO	40000 ppm	0.0156 x 10^{-3} ppm	✔
	NO_2	320 μg/m^3	10.21 μg/m^3	✔
	SO_2	365 μg/m^3	2.27μg/m^3	✔
Biological	Air before the filter: Bacteria Fungus	750 UFC / m^3 In the Indoor Air	35 UFC / m^3 45 UFC / m^3	✔
	Air after the filter: Bacteria Fungus		80 UFC / m^3 135 UFC / m^3	✔
	Indoor Air: Bacteria Fungus		120 UFC / m^3 65 UFC / m^3	✔
	Preceding surface of the filter: Bacteria Fungus		99 UFC / Plate 242 UFC / Plate	
	Posterior surface of the filter: Bacteria Fungus		6 UFC / Plate 7 UFC / Plate	
	Filter after one month of use: Bacteria Fungus		21000 UFC / g 22000 UFC / g	
	Filter after six month of use: Bacteria Fungus		18000 UFC / g 8100 UFC / g	

5. System Risk Analysis

At this point it was decided to perform a risk analysis of the “Fan Coil” system and then to verify which components of the system present the highest RPN (Risk Priority Number). The RPN is defined as:

$$RPN = (SEV) X (OCC) X (DET)$$

Where: SEV = Severity level (1 to 10); OCC = Probability of occurrence of failure (1 to 10); DET = Detectability (1 to 10); RPN = Risk Priority Number (1 to 1000)

The RPN values are very important, because the items with the highest RPN numbers will be the ones that will get more attention from the maintenance staff to make improvements.

Another consequence was that about 5 000 € could be saved on the filters alone each year, even considering for the expense of the chemical and microbiological analysis (about 800 € each set of analysis).

To calculate the values of these parameters, FMEA (Failure Mode and Effect Analysis) was performed to the equipment. The results of this analysis are given in Table 8., where the RPN Number Classification means: a 1 rating is a failure that is highly unlikely and unimportant; ratings below 30 are considered as reasonable for typical applications; ratings above 100 means that there is a great possibility of failure; a 1000 rating implies that failure will happen, with hazardous and harmful, if no maintenance is performed.

According to these results and to the analysis of the system monitoring a new maintenance plan was proposed and implemented.

This maintenance planning was implemented and the IAQ is considered by the people working in the office to be better then before.

Table 8: FMEA and Risk analysis of the Fan Coil system

Components	Failure Modes	Failure Effects	Causes	Occurrence	Severity	Criticity	Ways of Failure Detection	Detectability	RPN	Maintenance Actions
Air Filters	Clogging	Energetic losses Flow reduction Contamination	Sediments in excess	6	7	42	Monitoring Visual	5	210	Cleaning or replacement
	Rupture	Deficient filtration Contamination	Wear Bad installation	3	5	15	Monitoring	5	75	Replacement
Heating and Cooling Exchangers	Bad Thermal Transmission	Energetic losses Contaminations	Crust Bad operation of regulation valve	3	5	15	Discomfort Monitoring	5	75	Cleaning
	Rupture	Equipment degradation Water spilling	Corrosion Bad connections	2	5	10	Visual	3	30	Repair Replacement
Drain Pan	Water Accumulation	Microorganisms	Deficient flow	3	7	21	Visual	4	84	Cleaning
	Corrosion	Equipment degradation Contaminations	Inadequate material Insufficient cleaning	2	6	12	Visual	5	60	Replacement Cleaning
Condensate removal pump	Malfunction	Water spilling	Energy loss Pump failure	4	5	20	Visual	5	100	Replacement
Condensed ball-float	Malfunction	Water spilling	Locked floater Failure in floater	5	5	25	Visual	5	125	Floater cleaning Replacement
Flow Valves	Malfunction	Missing water in serpentine	Actuator failure Valve failure	3	5	15	Discomfort	4	60	Repair
Actuators	Malfunction	Missing water in serpentine	Energy loss Failure Bad operation	4	5	20	Discomfort	4	80	Replacement Repair
Fans	Insufficient Flow	Insufficient insufflations Air contamination	Dirty turbine Closed gauge	2	7	14	Discomfort Monitoring	2	28	Cleaning To adjust
	Noise	Mechanical fatigue	Vibrations Unbalanced axes	2	5	10	Noise	3	30	To adjust fastenings Balancing
	Malfunction	No flow	Energy loss Motor failure Loose turbine	2	8	16	Discomfort	1	16	Electrical repair Repair
Thermal Probe	Malfunction	Temperature not controlled	Dirt Failure	4	6	24	Discomfort	2	48	Cleaning Repair
Pipes	Leaks	Waste/Gain of flow Energy Waste Pressure drop Insufficient IAQ	Mechanical malfunction Bad sealing Corrosion	2	5	10	Discomfort Monitoring	3	30	Repair
	Deficient isolating	Energy waste Condensations	Mechanical malfunction	3	4	12	Discomfort	2	24	Isolating repair
	Dirt accumulation	Contaminations	Bad filtering No cleaning	1	9	9	Discomfort	7	63	Cleaning

Table 9 – Risk Analysis and Maintenance Planning

Risk Analysis			Maintenance			
			Performance Ratios		Actions	
Component	Failure mode	RPN	MTBF (hours)	MTTR (hours)	Tasks	Intervals (hours)
Filter	Clogging	210			Cleaning / Replacement	1000
Ball-Float	Malfunction	125	4132	0,55	Cleaning / Replacement	
Pump	Malfunction	100	4921	0,58	Inspection	
Drain Pan	Water accumulation	84			Very draining	3000
Actuator	Malfunction	80	12579	0,50	Inspection	
Filter	Rupture	75			Visual inspection	
Heat Exchanger	Bad heat transmission	75			Cleaning	
Cool Exchanger	Bad Cool transmission	75			Cleaning	
Flow Valves	Malfunction	60	4971	0,88	Inspection	
Drain Pan	Corrosion	60			Inspection / Cleaning	
Ducts	Dirt sediments	54			Cleaning	
Thermal Probe	Malfunction	48	22269	0,55	Inspection	
Fan	Noise	30	44538	1,70	Noise inspection	
Heat Exchanger	Rupture	30			Visual inspection	
Ducts	Leaks	30			Visual inspection	
Fan	Insufficient flow	28	44538	1,70	Cleaning / Calibration	
Ducts	Damaged insulation	24			Inspection/Repair	
Fan	Malfunction	16	44538	1,70	Inspection/Repair	
Indoor Air	Contamination				Chemical analysis	6000
Filter / Indoor Air	Contamination				Microbiological analysis	
Motor Fan	To waste energy				Electrical measurements	

6. Conclusions

The maintenance of HVAC systems lacks a systematic approach about how to organize it. In the studied system, at the start the maintenance was organized following the suggestions of the equipment manufacturers and previous experiences on the maintenance of similar systems.

In this work, it was shown that this approach was not the most correct one, as: the IAQ monitoring was not good enough and the time intervals for the maintenance scheduling were too small and the actions taken during the interventions were insufficient.

With a new maintenance methodology it was possible to overcome these two shortcomings.

The advantages of this new maintenance methodology are: (a) physical, chemical and biological control; (b) better maintenance planning; (c) knowledge of the critical system components; (d) reduced maintenance costs; (e) indoor Air Quality can be guaranteed.

7. Acknowledgements

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10. Responsibility notice

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