An Optimal Maintenance Scheduler

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ABSTRACT

A simplified sub-optimal service scheduling technique is presented that estimates the time between service tasks necessary to minimize the lifetime operating costs of HVAC&R equipment. The technique is simpler to implement in the field than the optimal solution, but still provides near optimal performance. The technique is described and its performance is compared to three benchmarks for determining when to service fouled evaporator and condenser coils in air-to-air air conditioning equipment. The simplified method is always within 2% of the optimal solution for the demonstration system. The performance is always as good as or better than comfort-based (minimal) and regular (annual) service schedules. Field implementation issues and the detection of multiple simultaneous faults are discussed.

1 INTRODUCTION

Rossi & Braun [1994] have shown that there is potential for reducing operating costs and improving reliability of HVAC&R equipment through optimal scheduling for cleaning fouled heat exchangers. However, implementing optimal service scheduling requires perfect knowledge of the future, complex optimization algorithms, and perfect sensors. Therefore, there is a need for a more practical scheduling technique capable of achieving most of the savings and that considers the practical limitations inherent in field applications. This paper describes and evaluates a sub-optimal scheduler that requires no knowledge of the future and has modest computational requirements.

2 SUB-OPTIMAL MAINTENANCE SCHEDULER

The goal of an optimal maintenance scheduler should be to minimize the total lifetime operating costs of a system. When only considering energy and service costs, the time averaged lifetime operating costs for mechanical equipment is given by

$$J_0 = \frac{1}{T_l}\int_0^{T_l} (\text{Energy cost } + \text{ Service cost})\, dt \tag{1}$$

where T_l is the equipment lifetime. Assuming constant energy costs (C_e) and service costs (C_s)

$$J_0 = \frac{1}{T_l}\int_0^{T_l} C_e P(\bar{x}(t), \bar{f}) + C_s \delta(t - \tau_i)\, dt \tag{2}$$

where $P(\bar{x}(t), \bar{f})$ is the power consumption of the equipment, $\delta(t - \tau_i)$ is the Dirac delta or impulse function, and $\{\tau_1, \tau_2, ..., \tau_N\}$ are the times of each service event. Power consumption is a function of external driving forces ($\bar{x}(t)$) (e.g. ambient drybulb and return air wetbulb and drybulb for air-to-air heat pumps) and the degradation states of system components ($\bar{f}$). The degradation states ($\bar{f}$) are either directly measured or estimated from measurements and uniquely indicate the condition of system components which are degrading over time. This concept is useful for tracking slow performance degradations, such as wear and fouling, in mechanical components. For example, the pressure drop across a filter or an estimation of the overall conductance of a heat exchanger (UA) can be used to define $\bar{f}$ for tracking the effect of heat exchanger fouling. It is important that $\bar{f}$ be selected such that each component f_i is only sensitive to the degradation of one component and is not sensitive to $\bar{x}(t)$. For simplicity, only one degrading component will be considered (i.e. $\bar{f} = f$). The concept can then be extended to consider multiple simultaneous faults.

Equation (2) can be rewritten by summing separate integrals over each service period

$$J_0 = \frac{1}{T_l}\left[\sum_{i=1}^{N}\int_{\tau_i}^{\tau_i+1} C_e P(\bar{x}(t), f))dt + NC_s\right] \tag{3}$$

where N is the number of service tasks performed during the lifetime of the equipment. The minimization of equation (3) is simplified by fixing the time between service tasks ($t_0 \equiv \tau_{i+1} - \tau_i,\ \forall\ 1 \leq i \leq N$), hence creating a new cost function

$$J_1 = \frac{N}{T_l}\left[\int_0^{t_0} C_e P(\bar{x}(t), f)\, dt + C_s\right] = \frac{1}{t_0}\left[\int_0^{t_0} C_e P(\bar{x}(t), f)\, dt + C_s\right] \tag{4}$$

where $T_l = Nt_0$. If J_0 were independent of $\bar{x}(t)$, and f always had the same time dependence after service, then the assumption of a fixed service interval would be exact (i.e. $J_1 = J_0$). However, since this is not the case, the assumption of a fixed service interval improves when seasonal effects on power consumption are reduced by subtracting the power consumed when no performance degradation occurs. Define f^* as f immediately after service and create another new cost function $J_2 = J_1 - K(t_0)$, where

$$K(t_0) = \frac{1}{t_0}\int_0^{t_0} C_e P(\bar{x}(t), f^*)\, dt \tag{5}$$

and

$$J_2 = \frac{1}{t_0}\left[\int_0^{t_0} C_e\left[P(\bar{x}(t), f) - P(\bar{x}(t), f^*)\right] dt + C_s\right] \tag{6}$$

The integral portion of equation (6) is the extra money spent on energy due to the degrading component and C_s is the service cost required to repair it. The minimum of J_2 is used as an approximation to the minimum of J_0. This approximation is less accurate when $\bar{x}(t)$ changes appreciably from one service cycle to the next. This will happen for service intervals (t_0) of 1 month, since cycles occurring in May, June, and July will have significantly different ambient conditions. However, performance will be good when $t_0 \geq 1$ year because each service cycle experiences similar weather conditions. It will be shown later, that subtracting the power consumption with no fouling also provides a mechanism for considering multiple simultaneous faults.

The cost function J_2 can be minimized by determining where its derivative is zero, providing the following solution:

$$\int_0^{t_0} g(t)\, dt + C_s = t_0 \cdot g(t_0) \tag{7}$$

where

$$g(t) = C_e\left[P(\bar{x}(t), f) - P(\bar{x}(t), f^*)\right] \tag{8}$$

This is guaranteed to be a minimum when g is an increasing function. Equation (7) can then be used to generate a classification rule used to decide when to perform service

$$C_s + \int_0^{t_0} g(t)\,dt - t_0 \cdot g(t_0) \underset{\omega_2}{\overset{\omega_1}{\lessgtr}} 0 \tag{9}$$

where ω_1 is the class "do service" and ω_2 is the class "no service". The time between service tasks (t_0) is determined by equation (9) and is defined as the time when the left hand side (LHS) makes a transition from a positive to a negative quantity. The integrator is initially set to zero in equation (9). All terms in (9) are positive and therefore the LHS is initially positive. As time progresses, the integral quantity grows until the LHS becomes negative, thereby indicating that service should be performed. After service is performed the integrator is reset and the cycle begins again. The evaluation of this rule is based on information acquired since the last service only and requires no forecasting of the future. These features make the maintenance scheduler easy to implement.

3 SIMULATION RESULTS

A simulation environment for evaluating service scheduling methods has been previously described [Rossi & Braun 1994]. A TRNSYS [Klein et al. 1990] simulation of an office building in Nashville, TN, USA with a 20 ton air-to-air vapor compression cooling plant was used to demonstrate the performance of different service scheduling techniques. Optimal, regular, and comfort schedules were compared. The optimal schedule performs service to minimize annual operating costs. The regular schedule performs service at regular intervals (once each year in this case) and may supplement additional service, for short fouling times, to maintain comfort. Finally, the comfort schedule is the minimum service schedule required to maintain comfort in the conditioned space.

Fig. 1 shows the performance of the simplified scheduler compared to previously obtained results. The simplified schedule is also constrained to maintain comfort (i.e. service will be done if comfort can not be maintained before rule (9) is fired). The abscissa is the characteristic fouling time (t_f) defined as the fan run-time required to to completely foul (no flow) the heat exchangers. The unit has a run-time of one month per year with no fouling and run-time increases with increasing fouling. The ordinate is the additional annual operating costs (energy and service) due to fouling normalized by the minimum cost (energy only, no fouling). See Rossi & Braun [1994] for details of the simulation conditions. Solutions are shown for evaporator and condenser fouling and for a plant with little (PLF_{max} = 0.94) and more (PLF_{max} = 0.57) extra cooling capacity. Maximum part load fraction (PLF_{max}) is defined as the PLF of the plant during maximum cooling load with no fouling. For this system (with on/off control), PLF_{max} is the fraction of the hour that the unit is running at the peak of the hottest summer day and with unfouled heat exchangers.

When optimal service decisions are based on comfort (fig. 1a, evaporator fouling with little extra capacity), the simplified maintenance scheduler provides the correct solution. In cases where there is potential to save money by doing more service than the minimum (figs. 1b-1d), the simplified solution is controlled by the comfort constraint for short fouling times and approaches the optimal for larger

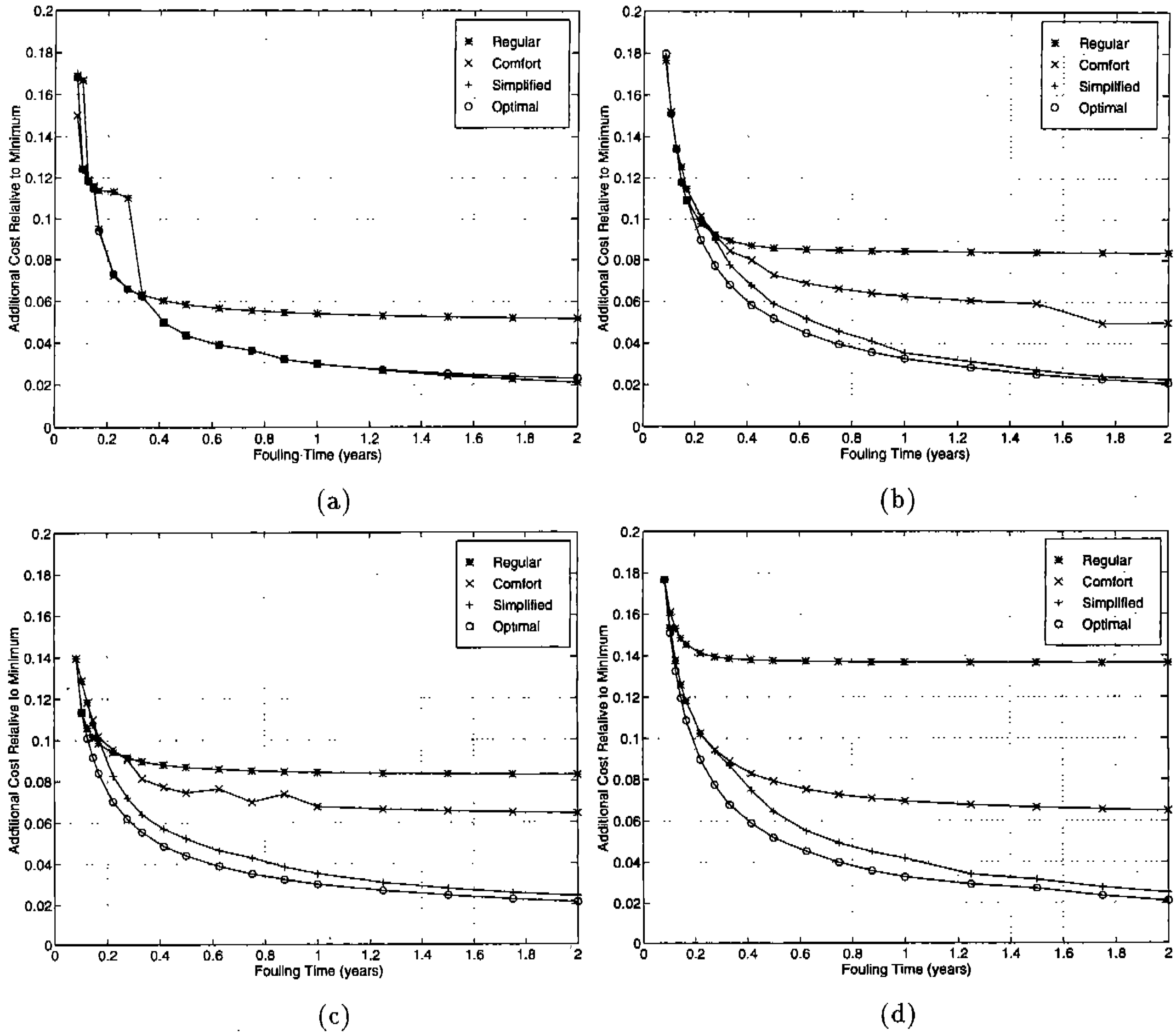

Figure 1: Additional annual operating costs (actual cost - minimum cost) normalized by the minimum operating cost (energy only, no fouling) vs. characteristic fouling time (t_f) for (a) evaporator fouling $PLF_{max} = 0.94$, (b) condenser fouling $PLF_{max} = 0.94$, (c) evaporator fouling $PLF_{max} = 0.57$, and (d) condenser fouling $PLF_{max} = 0.57$. The minimum costs are \$1206.65 for $PLF_{max} = 0.94$ and \$735.76 for $PLF_{max} = 0.57$.

fouling times. The results show that the simplified solution works better for longer fouling times, when the clock time between service tasks becomes considerably greater than one year. Under these conditions, the periodic service schedule becomes a better approximation to the true optimal solution because each service cycle experiences similar seasonal effects. The cost of the simplified schedule is always within 2% of the cost of the optimal schedule and provides more savings (compared with the regular schedule) with increasing fouling time with a maximum of 11% at $t_f = 2$ years for condenser fouling (fig. 1d).

4 IMPLEMENTATION

In the previous section, the simplified service scheduler was evaluated given perfect knowledge of the system. In an actual implementation, the function $P(\bar{x}(t), f^*)$ needs to be learned from observations and decisions should be evaluated statistically to reduce the errors introduced by noisy measurements. This section considers these important issues.

Evaluation of the simplified scheduler can be easily done with a small micro-controller attached to an air conditioner or refrigeration device in the field. The costs of service and energy need to be entered as parameters to the program. The required measurements are power consumption, call for cooling, driving functions (e.g. ambient and return air temperature and humidity), and the degradation state(s) (e.g. ΔP). The call for cooling can be used as a comfort indicator as well as determining when the unit is running. Power consumption can be simplified by predetermining power factor as a function of rms current and perhaps assuming that the voltage is its nominal value. This reduces the power consumption measurement to a simple rms current measurement and possibly a rms voltage measurement.

A model is required for determining $P(\bar{x}(t), f^*)$. For a unitary air-to-air heat pump, the inputs can be ambient drybulb and return air drybulb and wetbulb. One approach is to use a black box model that can be learned from measurements in the field for a retrofit, or preprogrammed in the factory for new systems. In the case of a retrofit, there may be a good opportunity to learn this relationship in the field because there are fouling mechanisms that are less active for a long time after service and then accelerate after a critical amount of fouling accumulates.

The heat exchangers should be new or well cleaned upon installation of the maintenance scheduler. Consider the simplified decision rule defined by equation (9). The integrator is reset to zero. For a retrofit, a learning period is required after service in order to generate a model for $P(\bar{x}(t), f^*)$. During the learning period, $P(\bar{x}(t), f) = P(\bar{x}(t), f^*)$ and the integrand is zero. After f changes significantly, the learning period stops. Note that the integrand is non zero for $f \neq f^*$ only when the unit is running. $g(t_0)$ can be evaluated by averaging over one day to reduce the effect of the diurnal variations of $g(t)$. The service/no-service decision can be made once each day. Service will eventually occur either by the firing of rule (9) or by the comfort constraint indicated by the call for cooling not being satisfied for a sufficiently long period. After service is performed, the integrator is reset and the cycle starts over.

5 MULTIPLE SIMULTANEOUS FAULTS

The simplified service scheduler can be extended to consider multiple simultaneous faults. Consider the case where two performance degradations are developing at the same time. Define f_1 and

f_2 as the fault states for the first and second degrading components respectively (e.g. evaporator and condenser fouling). There are three rules that must be evaluated, along with the comfort constraint, to determine when to do service. They are given by

$$C_{si} + \int_0^{t_0} g_i(t)\,dt - t_0 \cdot g_i(t_0) \underset{\omega_2}{\overset{\omega_1}{\lessgtr}} 0 \tag{10}$$

for i=1,2, and 3. C_{s1} is the cost of servicing component 1 only and

$$g_1(t) = C_e\left[P(\bar{x}(t), f_1, f_2) - P(\bar{x}(t), f_1^*, f_2)\right]. \tag{11}$$

C_{s2} is the cost of servicing component 2 only and

$$g_2(t) = C_e\left[P(\bar{x}(t), f_1, f_2) - P(\bar{x}(t), f_1, f_2^*)\right]. \tag{12}$$

Finally, C_{s3} is the cost of servicing components 1 & 2 together and

$$g_3(t) = C_e\left[P(\bar{x}(t), f_1, f_2) - P(\bar{x}(t), f_1^*, f_2^*)\right]. \tag{13}$$

In many cases, it may be possible to service both performance degradations at the same time for less money than both separately. Service is done when the first of these four rules fires.

6 CONCLUSION

A practical sub-optimal service scheduling technique has been described that estimates the best time to perform maintenance on HVAC&R equipment to minimize lifetime operating costs. Simulation results on a 20 ton air conditioner in an office building indicate that the method is always within 2% of the optimal solution. For short fouling times, optimal service times are controlled by the comfort constraint. Additional savings are possible by doing more service (than the minimum) for longer fouling times. Issues concerning implementation and the detection of multiple simultaneous faults are discussed. Laboratory testing is the next step in the development and validation of this technique.

References

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