Reducing Operating Costs with Optimal Maintenance Scheduling

T. M. Rossi
Purdue University

J. E. Braun
Purdue University

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Todd M. Rossi and James E. Braun

Ray W. Herrick Laboratories, Purdue University
West Lafayette, IN 47907-1077, USA.

ABSTRACT

The potential benefits of optimal service scheduling for cleaning heat exchangers based on minimizing operating costs are explored. A demonstration is performed on a simulated 20 ton air-to-air vapor compression air conditioner. The costs of regular service schedules (indicative of current practice), minimal schedules needed to maintain comfort, and the optimal schedules are compared. Generally, the minimum comfort schedules have costs between the regular and optimal schedules. The comfort schedules cost as much as 4.2% more than the optimal, the difference increasing with increasing fouling time. Regular (annual) service was as much as 11.7% more expensive than optimal for the range of conditions tested. Results are shown for evaporator and condenser fouling and for two different cooling capacity to building load ratios.

1 INTRODUCTION

Automated fault detection and diagnosis has the potential to reduce down time and operating costs in HVAC&R equipment. There are a large variety of techniques that compare observations with model predictions to detect and diagnose abnormal behavior. In a general sense, these techniques generate residuals representing the difference between observed and expected performance. Classifiers then operate on the residuals and return decisions indicating when the equipment is malfunctioning and its cause(s). The most challenging aspect of classifier design is determining the boundaries between various classes (e.g. fault/no fault). There are well established techniques derived from statistical pattern recognition applications for determining the optimal boundaries based on minimizing the probability of making erroneous decisions (Bayes classifier). These methods determine thresholds based on the statistical properties of training data.

There are two types of malfunctions: hard faults and performance degradations. Hard faults are sudden and abrupt changes such as motor failures and broken belts. They are relatively easy to classify because it is simple to find a residual for which the fault and no fault classes are well separated. Performance degradations are malfunctions that become progressively worse in a continuous sense (e.g. heat exchanger fouling). In this case, it becomes difficult to define when the malfunction is bad enough to justify the repair expense. It is possible to define four criteria for servicing performance degradations in HVAC&R equipment: (1) economics, (2) comfort or refrigeration requirements, (3) equipment safety, and (4) environmental hazard. The economic criteria prescribes service when it reduces or minimizes overall lifetime operating costs. The comfort criteria calls for service when design objectives are not satisfied. The equipment safety criteria detects operating states that wear expensive components prematurely (e.g. liquid entering a reciprocating compressor). Finally, the environmental hazard criteria searches for malfunctions that pollute or harm the environment (e.g. refrigerant leaks).

It is the goal of this paper to investigate optimal maintenance scheduling for cleaning evaporator coils (or changing filters) and condenser coils based on an economic criteria. The optimal maintenance schedule minimizes overall lifetime operating costs including energy, service, and downtime (not considered here). The main points considered in this paper are: (1) the potential financial benefits of optimal decision making vs. current state of the art (e.g. regular service schedules), and (2) the conditions for which service is based on an economic rather than comfort criteria. These insights are obtained by operating an optimal decision maker on a simulated building.

2 OPTIMAL SOLUTION

The optimal service schedule is obtained by minimizing the time averaged combined cost of service and energy over the lifetime of the equipment.

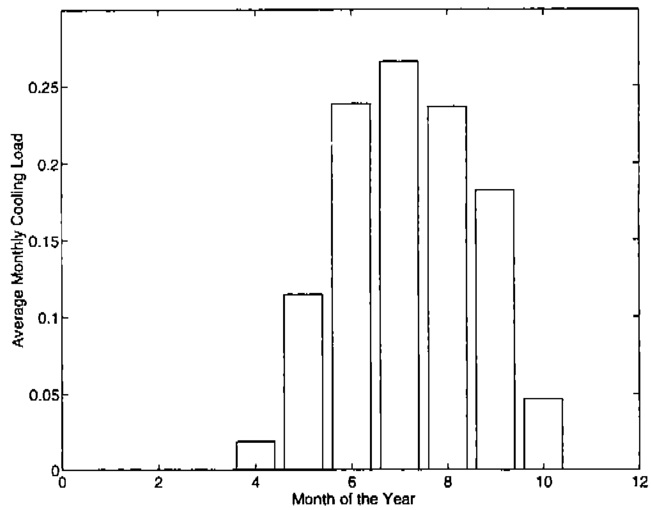
$$J = \frac{1}{T_l}\int_0^{T_l} (\text{Energy cost } + \text{ Service cost})\, dt$$

where T_l is the equipment lifetime. When service is performed too often, excess service costs increase J, and when service is too infrequent excess energy costs control J. Assume that there exists a periodic service schedule (allowing simple extrapolation for $T_l \to \infty$) that minimizes J and that the costs of energy and service are constants. Therefore,

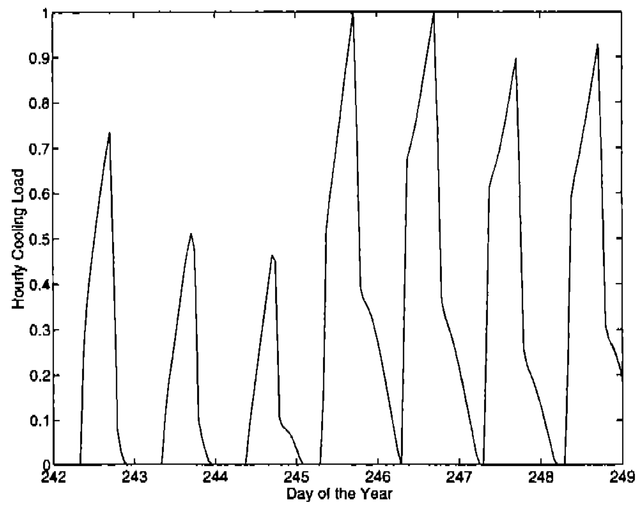
$$\begin{aligned} J &= \frac{1}{T}\int_0^T C_e P(\bar{x}(t), f(t_{on}, t_f)) + C_s \sum_{i=1}^{N} \delta(t-\tau_i) dt \\ &= \frac{1}{T}\left[\sum_{i=1}^{N} \int_{\tau_i}^{\tau_i+1} C_e P(\bar{x}(t), f(t_{on}, t_f)) dt + N C_s\right] \end{aligned} \tag{1}$$

where T is the period of the service cycle, C_e is the cost of energy, C_s is the cost of service, τ is the set of times, $\{\tau_1,\ \tau_2, \ldots.., \ \tau_N\}$, that each of N service tasks are performed, P is the instantaneous power consumption of the equipment, $\bar{x}(t)$ represents the driving functions controlling power consumption including ambient and return air temperature and humidity, f is the state of fouling of the heat exchangers, $t_{on} \equiv \phi t - \tau_i$ (where $\phi \equiv 0/1$ (fan off/on)) is the fan run-time since last cleaning, t_f is the characteristic fouling time of the heat exchangers, and $\delta(t-\tau_i)$ is the Dirac delta or impulse function.

A building model defines the driving functions $\bar{x}(t)$, a fouling model determines the fouling schedule $f(t_{on},\ t_f)$, and a steady state vapor compression refrigeration cycle model defines $P(\bar{x}(t), f(t_{on}, t_f))$ each of which are described in the next section. The goal of the optimization algorithm is to determine, for given C_s/C_e and t_f, the values of T, N, and $\{\tau_1,\ \tau_2, \ldots..,\ \tau_N\}$ (defining the service schedule) that minimizes J subject to a comfort constraint. The problem is simplified by only allowing service at fixed time intervals (e.g. one month). Dynamic programming [Bellman 1957] is then used to determine the times to perform service that minimizes the cost function.



(a)



(b)

Figure 1: Cooling load schedule for demonstration building (normalized by the peak load): (a) Average monthly cooling load, (b) hourly cooling load for one week surrounding the peak load day.

3 CONDITIONS OF DEMONSTRATION

Building cooling requirements were determined using a TRNSYS simulation [Klein et al. 1990] of a three zone office building in Nashville, TN, USA. The simulation considered detailed features including real typical meteorological year (TMY) weather data [Hall, Prairie, Anderson & Boes 1978], coupling to the ambient (temperature and humidity), internal and solar gains, building mass, weekday and weekend occupancy schedules, and night setback control. The cooling load for every hour of a typical year was provided by the simulation. Fig. 1 shows the average monthly cooling load for one year and the hourly cooling load for a one week period surrounding the peak cooling load day.

The building was cooled by an air-to-air vapor compression air conditioning system using on/off control. A detailed physical model was used to predict the performance of a commonly available commercial air conditioning system. It determined the power consumption and cooling capacity based on outdoor drybulb, indoor wetbulb, evaporator filter fouling state, and condenser fouling state. For simplicity, fouling was modeled only as an obstruction to air flow across the coils (a better assumption for dirty filters than fouled coils). The state of fouling was defined as the ratio of the air mass flow rate to the value for a clean coil. (0=completely obstructed and 1=no obstruction or clean). A simulation was run over an uniformly spaced four dimensional grid of the independent variables, $0°\text{C} \leq T_{out} \leq 45°\text{C}$ (outside drybulb), $13°\text{C} \leq T_{in} \leq 36.5°\text{C}$ (inside wetbulb), $2.0\,\text{kg}\,\text{s}^{-1}\,\text{m}^{-2} \leq G_{out} \leq 7.0\,\text{kg}\,\text{s}^{-1}\,\text{m}^{-2}$ (outside air mass flux), $0.4\,\text{kg}\,\text{s}^{-1}\text{m}^{-2} \leq G_{in} \leq 2.0\,\text{kg}\,\text{s}^{-1}\,\text{m}^{-2}$ (inside air mass flux), and then the results were inserted into a four dimensional linear lookup table for power consumption and capacity. The lookup table was then used by the optimal scheduling program to determine the amount of energy used to support the prescribed cooling load under the specified conditions and fouling states.

For simplicity, fouling was modeled as a linear function of fan run-time. It increased from 0, after cleaning, to 1 in a characteristic time t_f. The fans ran only during a call for cooling. An artificially large cost penalty was assigned for operation of the unit for fouling beyond the maximum considered by the air conditioner model (0.75 for the evaporator and 0.71 for the condenser) and when there was not enough capacity to meet the required load. The minimum fan run-time, which would occur if there were no fouling, was one month per year. As capacity decreased with fouling, added run-time was required to meet the load.

4 RESULTS

Fig. 2 shows the additional costs (service + energy) associated with fouling normalized by the minimum cost (energy only, no fouling) vs. the characteristic fouling time for evaporator and condenser fouling. The results are shown for two different cooling capacity to building load ratios defined by the part load fraction at maximum cooling load with no fouling (PLF_{max}). For $PLF_{max} = 0.94$, the minimum cost is \$1206.65 and there is less extra capacity than for $PLF_{max} = 0.57$ where the minimum cost is \$735.76. The nominal capacity of the unit is 20 tons, $C_e = 0.10\$/kWh$, $C_s = \$100$ for condenser cleaning, and $C_s = \$60$ for evaporator cleaning or filter changing. In the regular service schedule, evaporators and condensers are serviced annually. For short fouling times, regular service may be supplemented when required to maintain comfort. The comfort schedule shows the operating costs when the minimum service required to maintain comfort is performed.

Consider the effects of evaporator fouling. When the air conditioner has little extra cooling capacity (fig. 2a), the optimal and comfort solutions are the same. This indicates that evaporator fouling has a large impact on cooling capacity. When there is extra capacity (fig. 2c), less service is required to maintain comfort and there is potential to save money through additional service at the correct times as indicated by the optimal schedule. In the case of condenser fouling, the difference between the comfort and optimal solutions is not sensitive to available capacity (fig. 2b & fig. 2d). When condensers foul, capacity does not degrade appreciably, but head pressure rises, thereby driving up cost. In general, the optimal and comfort curves are asymptotically approaching zero as the fouling time increases because the additional costs associated with fouling are going to zero. The regular schedule is approaching the normalized annual service cost that is wasted when there is no fouling. For short fouling times, all three curves come together because service is controlled by the comfort constraint. Regular service is excessive for most fouling rates and can be as high as 11.7% above the optimal for $t_f = 2.0$ years in fig. 2d. This may indicate that regular schedules are chosen conservatively to counteract the reality that service is done less frequently than advised. The comfort schedule performs better than the regular schedule in most cases, with a maximum of 4.2% above the optimal for $t_f = 2.0$ years in fig. 2d. This suggests that simple comfort control of service may provide adequate performance for a simple fault detection system. Small irregularities of the data are caused by numerical limitations including limited cycle lengths and segment sizes.

Fig. 3 shows the annual cost savings for optimal service scheduling as compared with regular schedules vs. fouling time for different service costs and for $PLF_{max} = 0.69$. To provide a reference point, the annual operating cost with no fouling is \$882.91. For condenser fouling, the minimum savings occurs at t_f=1.5 months. Zero potential savings means that annual service is optimal for this fouling time. As the fouling time increases, annual service is too much and there is savings associated with doing less service. In the limit as $t_f \rightarrow \infty$, the savings approach the money spent on service in one year. As the fouling time decreases, the regular schedule is no longer capable of maintaining comfort; supplemental service is added, hence, driving up costs. The trends for evaporator fouling are similar.

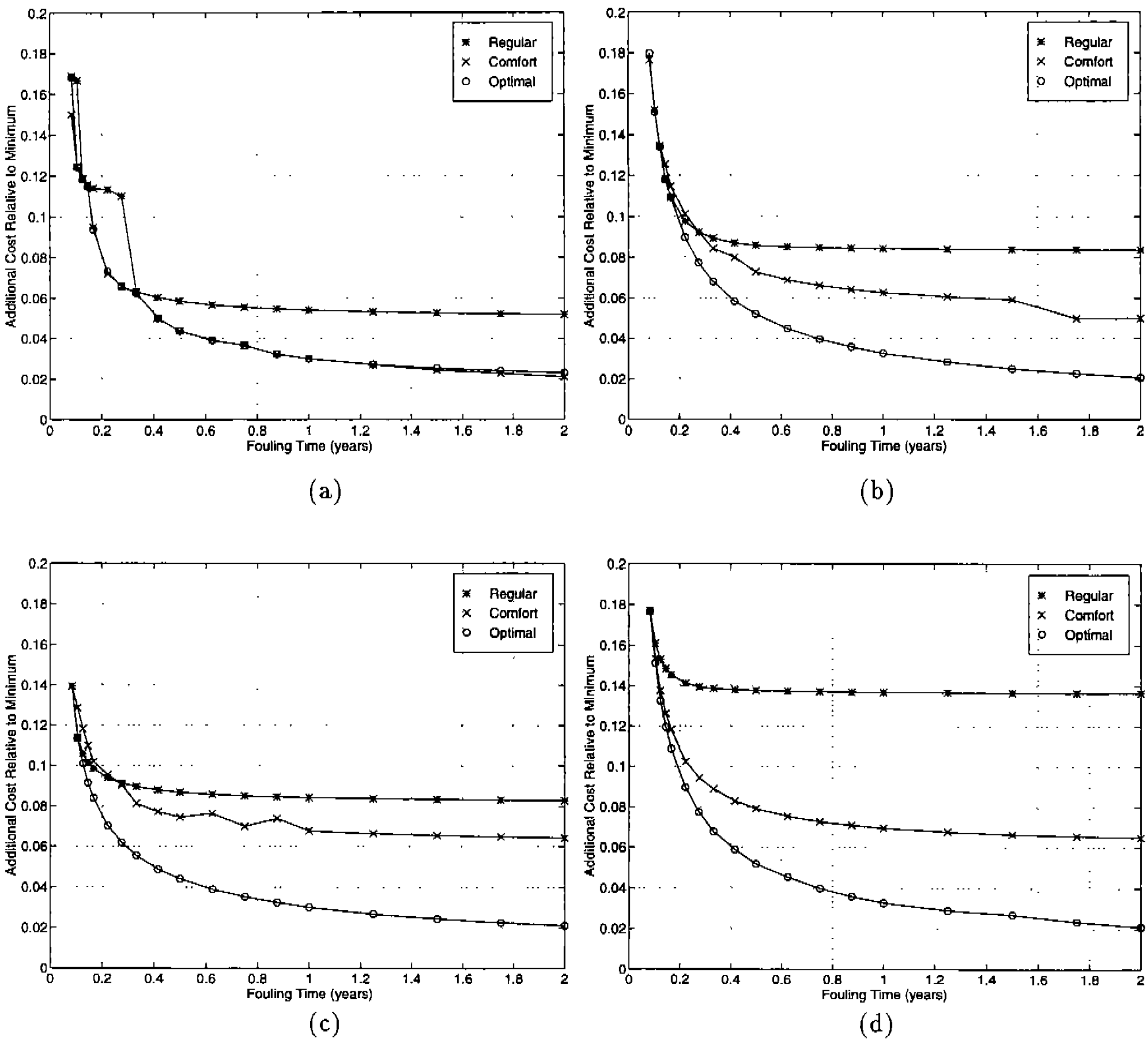
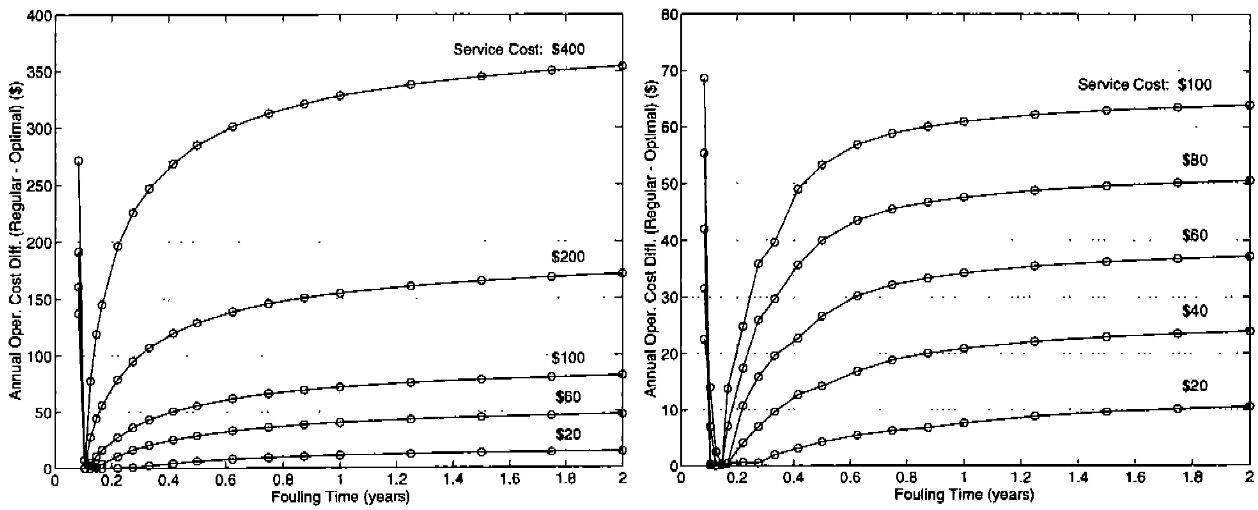


Figure 2: Additional annual operating cost (actual cost - minimum cost) normalized by the minimum operating cost (energy only, no fouling) vs. characteristic fouling time (t_f) for (a) evaporator fouling $PLF_{max} = 0.94$, (b) condenser fouling $PLF_{max} = 0.94$, (c) evaporator fouling $PLF_{max} = 0.57$, and (d) condenser fouling $PLF_{max} = 0.57$. The minimum costs are \$1206.65 for $PLF_{max} = 0.94$ and \$735.76 for $PLF_{max} = 0.57$.



(a) (b)

Figure 3: Difference in annual operating cost between optimal service and regular service schedules for (a) condenser fouling and (b) evaporator fouling.

5 CONCLUSIONS

The benefits of optimal service scheduling for cleaning heat exchanges based on minimizing operating costs has been considered. Annual savings of up to 11.7% were shown when compared with regular service schedules. This figure was sensitive to the choice of regular schedule, and since, for most of the fouling times considered, regular service was excessive, a more frequent regular schedule (e.g. quarterly) would indicate greater savings potential for these fouling times. Costs have also been compared to the minimum service schedule required to maintain comfort and the difference is never greater than 4.2% for the conditions studied. These results suggest that basing condenser and evaporator service on comfort requirements works better than regular service, and therefore may be a possible strategy for a simple fault detection system. However, additional cost savings are possible if a practical method for minimizing costs in the field can be developed.

References

Bellman, R. E. [1957]. *Dynamic Programming,* Princeton University Press, Princeton, New Jersey.

Hall, I., Prairie, R., Anderson, H. & Boes, E. [1978]. Generation of a typical meteorological year, *Proc. of 1978 Annual Meeting, American Section of ISES, Denver* 2(2): 669.

Klein, S. A. et al. [1990]. *TRNSYS A transient system simulation program,* 13.1 edn, Solar Energy Laboratory, University of Wisconsin - Madison, Madison, WI.