ETM
ENGINEERING & TECHNOLOGY MANAGEMENT

HVAC Optimization for Data Centers

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I. Abstract

THIS paper examines the optimization of Operating costs for High Performance Data Centers in the context of Operations Research. Operating costs are defined as the yearly Total Cost of Ownership as relates to the energy costs for Heating Ventilating and Air Conditioning (HVAC) system and hardware (server) costs. The energy cost of the Heating Ventilating and Air Conditioning Cooling Plant is by far the dominant cost.

The methodology of *ASHRAE TC 9.9: 2011 Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance*, was used as a guide. Various metrics such as power and reliability factors are used to determine optimal Data Center ambient operating temperatures. The concepts of Air and Water Economizers were also used to reduce Energy costs. Server characteristics were used to determine operating temperature constraints. Models were constructed to examine the effects of the metrics, economizer operation and equipment constraints [1].

This study found that maximizing the use of Economizer operation is the dominant factor in reducing yearly energy costs for Data Centers with a high density of servers and corresponding high density heat load. A secondary finding was that the Equipment characteristics used allowed a very broad band of environmental conditions. The modeling suggested that the optimal results could be obtained by maximizing economizer operation and maintaining as ambient temperatures as low as economizer operation allows, minimizing total costs of ownership. .

II. Introduction

Typical HVAC design utilizes a Chilled Water System for lager Data Centers, Make-up Air Handling and Recirculation Air Handlings systems. Current design is characterized by minimum outside air used for ventilation and low constant temperature ambient operating temperatures.

Cooled air is typically delivered via a raised floor supply air plenum to “cool” Aisles located between rows of Servers mounted in racks. The cooling air is then drawn through the Servers by fans integral to the servers. The heated air was then exhausted by the servers to common “Hot” Aisles. The heated air is allowed to rise to ceiling return air grilles to a ceiling return air plenum. The hot air from the ceiling plenum is then returned to the recirculation units for cooling. Conditioned make-up air is introduced to the Data Center Server space to provide ventilation and pressurization. Make-up air is returned from the space or allowed to “leak” or transfer to adjacent spaces dependent on the Engineers selection of equipment.

III. ASHREA Technical Committee 9.9 Thermal Guidelines for Data Processing Environments

ASHRAE Technical Committee 9.9 created *Thermal Guidelines for Data Processing Environments* in 2004, to establish guidelines for environmental parameters (operating conditions) within Data Center Server spaces. The original goals were to establish Environmental Design Standards that ensured Server Reliability that focused on upper and lower Temperature and Humidity requirements. A second edition was issued in 2008, which added emphasis on Power Utilization Efficiency (PUE) metrics that would result in lower annual HVAC energy costs for the owner / operator of the Data Center. Environmental conditions were also expanded in the second edition to reflect improvements in server technology and Data Center classes were defined [1].

The 3rd edition of "*Thermal Guidelines for Data Processing Environments*" has been issued in White Paper form as *ASHRAE TC 9.9 2011 Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance.* It adds emphasis on Economizer Operation and further expands metrics for optimizing HVAC energy cost, while maintaining reliability. It also further expands the Environmental Conditions to reflect improvements in server technology and establishes more classes of Data Center. Key elements of the 2011 White Paper include metrics, environmental conditions and economizer operation. Suggested metrics are given graphically by Figure 1 [1].

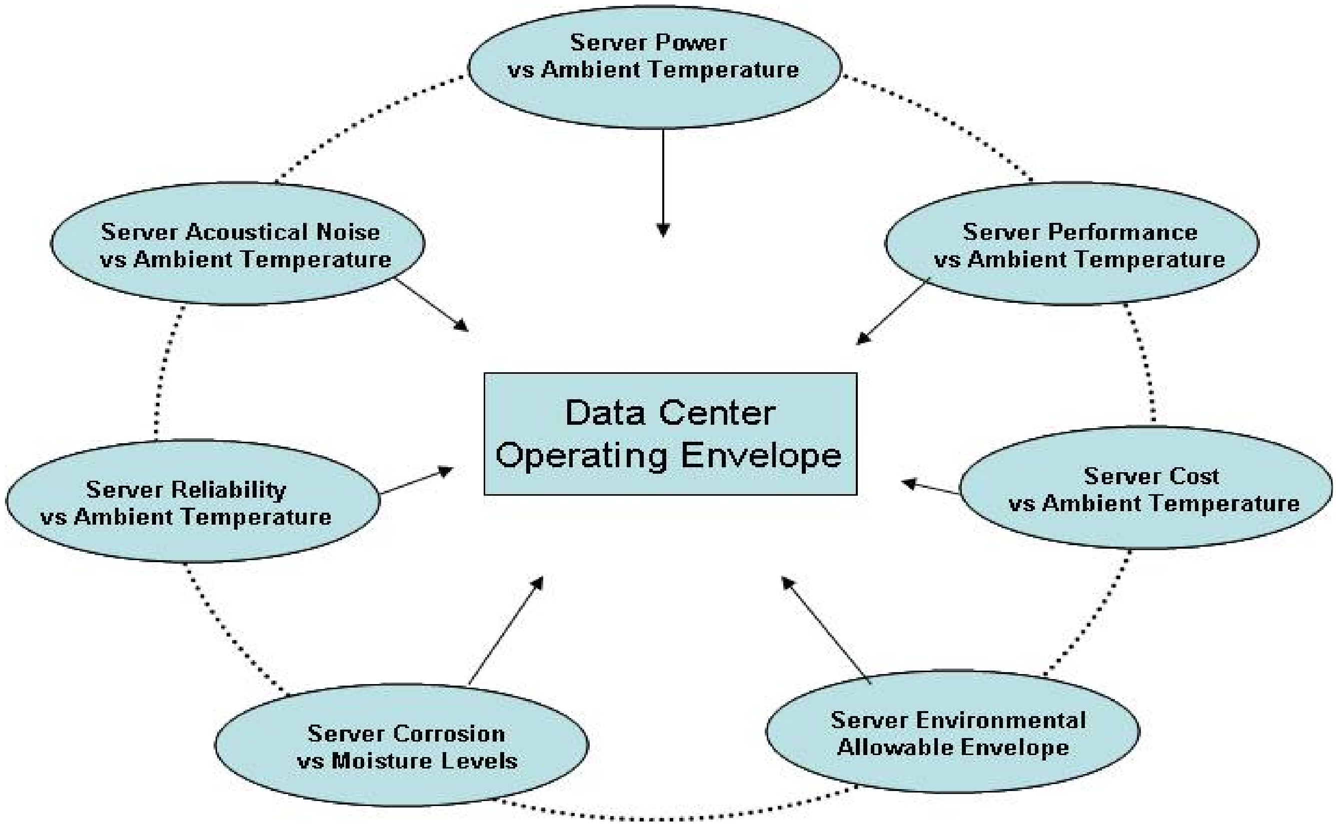
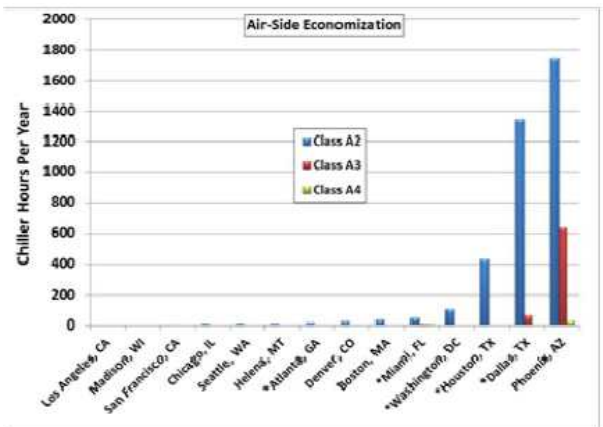


Figure 1: Server Metrics for Determining Data Center Operating Environmental Envelope

For the metrics given in Figure 1, the most significant are Server Power (consumption), Server Reliability and Server Environmental Allowable Envelope (Parameters) when determining Energy Costs. Server Acoustic Noise, Server Corrosion, Server Performance act as operating constraints (limits). Possible Air and Water Economizer Savings for selected cities are highlighted by Figures 2 & 3 [1].



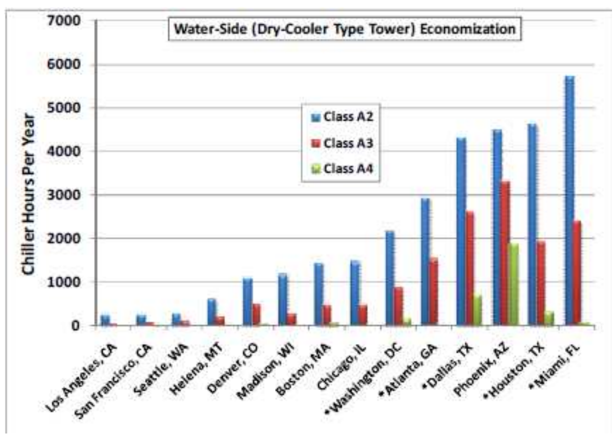


Figure 2: Number of hours per year of chiller operation required for air-side economization for selected US cities

Figure 3: Number of hours per year of chiller operation required for water-side dry-cooled tower economizer for selected US cities

Economizer operation allows the Chiller Cooling Plant to be bypassed. For an Air Economizer, Outside Ambient Air is used to cool the Data Center space and hot Return Air from the space is exhausted. A lower outside air temperatures a mix of cold Outside Air and Return Air is used to cool the space. Energy cost for Air Economizer is dependent on the required Fan energy cost. Substantial additional first cost may be required to configure the HVAC system for full economizer operation. The upper Air Economizer temperature and relative humidity are limited by Server environmental parameters.

Classes (a)	Equipment Environmental Specifications							
	Product Operations (b)(c)					Product Power Off (c) (d)		
	Dry-Bulb Temperature (˚C) (e) (g)	Humidity Range, non-Condensing (h) (i)	Maximum Dew Point (˚C)	Maximum Elevation (m)	Maximum Rate of Change(˚C/hr) (f)	Dry-Bulb Temperature (˚C)	Relative Humidity (%)	Maximum Dew Point (˚C)
Recommended (Applies to all A classes; individual data centers can choose to expand this range based upon the analysis described in this document)								
A1 to A4	18 to 27	5.5ºC DP to 60% RH and 15ºC DP						
Allowable								
A1	15 to 32	20% to 80% RH	17	3050	5/20	5 to 45	8 to 80	27
A2	10 to 35	20% to 80% RH	21	3050	5/20	5 to 45	8 to 80	27
A3	5 to 40	-12˚C DP & 8% RH to 85% RH	24	3050	5/20	5 to 45	8 to 85	27
A4	5 to 45	-12˚C DP & 8% RH to 90% RH	24	3050	5/20	5 to 45	8 to 90	27
B	5 to 35	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29
C	5 to 40	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29

Table 1: ASHRAE Thermal Guidelines

For a Water Economizer, Chilled Water Returning from the Air Handlers is cooled by a Heat Exchanger prior to its return to the Chiller Cooling Plant by the Cooling Tower Condenser Water. When the Outside Air Temperature is less than the Chilled Water Return Temperature seen during Chiller Plant operation, the Water Economizer may be used to bypass or supplement Chiller operation. Energy cost for Water Economizer is dependent on Pump energy cost and to a lesser extent, Cooling Tower Fan energy cost. The upper Water Economizer temperature is also limited by Server environmental parameters. Recommended Environmental Parameters are given by Table 1 [1].

IV. Modeling

A. *Modeling Objectives*

Analyze an A1 Data Center, seeking to minimize operating costs. The Methodology for the analysis is to utilize the techniques of *ASHRAE TC 9.9 2011 Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance*. Server Power and Server Reliability Metrics are to be modeled. HVAC Energy Costs to be modeled for Chiller Cooling Plant and Air Economizer Operation. Data Center Environmental Parameters are to be based on Manufacturer's Server Data.

B. *Methodology*

Model Construction Procedure

1. Create HVAC Energy Cost Equations based on Local Ambient Temperature for the Chiller Cooling Plant and for Economizer operation.
2. Modify HVAC Energy Cost Equation by creating and adding Server Power Metric.
3. Create Server Reliability Metric.
4. Create Total Cost of Ownership (TCO) Equation.
5. Evaluate TCO Equation for economizer and non-economizer operation to minimize TCO.

Input

For this study, input data was obtained from the M+W Group. Data from the MIT Green High Performance Computing Center (MGHPCC) project in Boston, Massachusetts were used [2][3]. The MGHPCC project is currently in the design phase.

Assumptions

- Data Center Cooling Airflow = Constant Volume = 554,000
- Chilled Water Supply Temperature = 65ºF
- Data Center Building Envelope Heat Gain and Loss is negligible.
- Server Heat Load is Constant at 70% Usage = 9400 kW

HVAC Energy Cost Equations

Total HVAC Energy is given by [4]:

$$E_{HVAC} = \left(P_{Cooling\ Plant} \times Hrs_{Tamb}\right) + \left(P_{Air\ Economizer} \times Hrs_{Tamb}\right)\ (kWh)$$

Where:

$$P_{Cooling\ Plant} = \left(\frac{Q_{Server\ Heat\ Load} \times Pf_{Power\ Factor}}{\eta_{HVAC\ System}}\right)\ (kW)$$

$$Q_{Server\ Heat\ Load} = \left(C_{usage} \times Q_{In\ Use}\right) + \left(1 - C_{usage}\right) \times Q_{Idle}$$

$$For\ C_{Usage} = Constant = 70\%,$$

$$Q_{Server\ Heat\ Load} = 9400\ kW$$

$$\eta_{HVAC\ System} = 0.33$$

And Air Economizer Power is given by [4]:

$$P_{Air\ Economizer} = \frac{V \times \Delta P}{6370 \times \eta_{Fan} \times \eta_{Motor}} = HP \times \frac{0.746\ kW}{1\ HP} = 368\ kW$$

Where:

$$V = Volumetric\ Airflow = 554{,}000\ cubic\ feet\ per\ minute\ (cfm)$$

$$\Delta P = Air\ Pressure\ Differential = Inches\ Water\ Gage = 4.0''\ w.g.$$

$$\eta_{Fan} = Fan\ Efficiency = 0.75$$

$$\eta_{Motor} = Motor\ Efficiency = 0.94$$

Server Power Metric

Server Power Factor of each server was calculated as a function of temperature [1][5]. We used data points from ASHRAE TC 9.9., on a chart which was plotted against different operating temperatures. Once plotted, using JMP software, we derived an equation where the power factor was a function of temperature. It fit the graph as seen in figure 4 [1].

$$Pf_{PowerFactor} = .00006(T_{Amb})^3 - .0038(T_{Amb})^2 + .0839(T_{Amb}) + .4$$

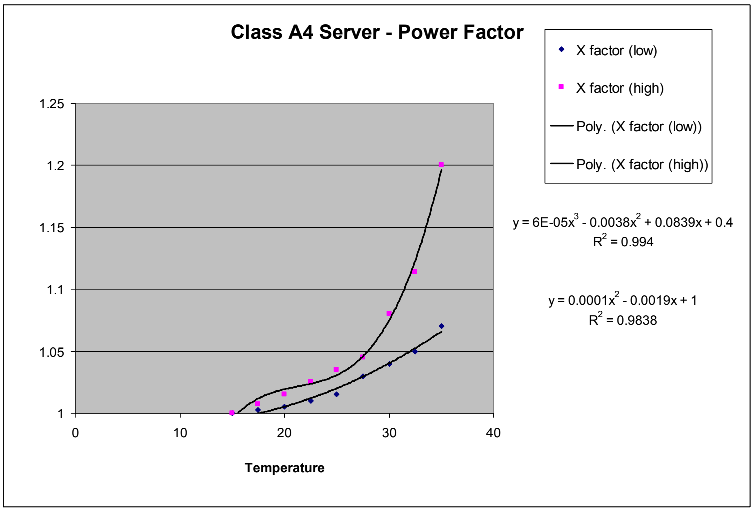


Figure 4: Power Factor as a function of temperature

Server Reliability Metric

Server Reliability and hardware cost was derived first by establishing a baseline. This baseline was taken from finding the average failure rate of servers over a given period of time. There was not conclusive data against the server we used; therefore we estimated the baseline at 7.8%. This estimate was taken from a study in Feb of 2007 and although not very accurate or specific to the type of hardware we are using, it was the best data we could find [6]. It was also very reasonable given other estimates which either exceeded or fell short of this.

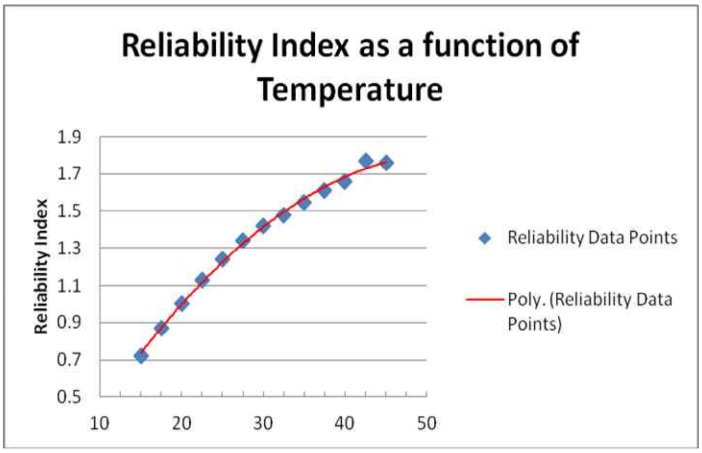


Figure 5: Reliability Index plotted using known data points

Once we found this baseline failure rate, we next had to derive a reliability index. According to the ASHRAE TC 9.9, there were several data points taken industry wide in which they assigned a reliability index to servers based on different operating temperatures of ambient air. We took these data points and plotted them. Then using JMP software, we derived an equation where the reliability index was a function of temperature. This equation closely fit the graph as seen in figure 5. It fit closely as reflected by the adjusted r squared of .996 which was also calculated by JMP. The equation derived is:

$$\text{Reliability Index} = .3872 + .034242 * T_{amb} + .0007369 * (T_{amb} - 30)^2$$

Total Cost of Ownership Equation

Total Cost of Ownership is given by a combination of HVAC and Hardware costs

$$\$_{TCO} = \$_{HVAC} + \$_{ServerLoad} + \$_{H/W}$$

Where:

$$\$_{HVAC} = E_{HVAC}(kWh) * UtilityCost(\$/kWh))$$

$$\$_{ServerEnergy} = Q_{ServerHeatLoad \times (Pf-1)} \times UtilityCost(\$/kWh)$$

$$\$_{H/W} = \$\text{Total Hardware Value} * 7.8\% * \text{Reliablity Index}$$

V. Building the Model

The goal of this model is to minimize the yearly operating costs related to energy and temperature. There are four factors that contribute to operating costs, and the key decision is the temperature to maintain by either running the cooling plant or economizer for each outside temperature level. The four operating factors are cooling plant energy, economizer energy, additional energy consumed by servers as temperatures increase (which is then implemented into the cooling plant energy costs), and server failure rates as the ambient temperature increases. The objective function is as follows:

$$Min: \sum_{t=15}^{T}\left(\left(X_t * C_{Cooling}\right)+\left(\left(1-X_t\right)*C_{Economizer}\right)+C_{ServerEnergy}+C_{HWamb}\right)$$

$$S.T.: \quad 15 \le amb \le 35$$

$$X_t = \begin{cases} 1\ if\ the\ cooling\ plant\ is\ turned\ on\ at\ outside\ temperature\ t \\ 0\ otherwise \end{cases}$$

$$P_{amb} = .00006 * T_{amb}^{\ 3} - .0038 * T_{amb}^{\ 2} + .0839 * T_{amb} + .394T$$

$$T_{amb} = \left(X_t * 15\right) + \left(\left(1-X_t\right)*t\right)$$

$$C_{Cooling} = C_{kWh} * H_t * ServerPowerLoad / .33$$

$$C_{Economizer} = C_{kWh} * H_t * 736$$

$$C_{ServerEnergy} = C_{kWh} * H_t\left(P_{amb} - 1\right) * ServerPowerLoad$$

$$C_{HW\,amb} = \left(R_{amb} * 7.8\%\right) * \left(\text{Total Hardware Cost}\right) * \left(H_t / 8759\right)$$

$$R_{amb} = 3872228 + .0342418 * T_{amb} - .0007369 * (T_{amb} - 30)^2$$

Where:

$t \equiv outs\text{ide air temperature}$

$\text{H}_\text{t} \equiv \text{Hours in a year operating at temperature t}$

$X_t \equiv decision\ boolean\ whether\ cooling\ plant\ is\ turned\ on\ or\ not$

$C_{Cooling} \equiv \cos t\ of\ running\ the\ cooling\ plant\ in\ one\ hour$

$P_{amb} \equiv power\ factor\ at\ a\ given\ ambient\ temperature$

$T_{amb} = \text{Indoor (ambient) air temperature}$

$C_{Economizer} \equiv \cos t\ of\ running\ the\ economizer\ in\ one\ hour$

$C_{Servers} \equiv \cos t\ of\ server\ energy\ at\ 15^\circ\ C$

$R_{amb} \equiv reliability\ index\ at\ a\ given\ ambient\ temperature$

$C_{HW\,amb} \equiv \cos t\ of\ server\ failures\ at\ a\ given\ ambient\ temperature$

$C_{kWh} \equiv \cos t\ per\ kWh\ is\ \$.088$

For an outside temperature t, X_t specifies whether the space will be cooled by the cooling plant or the economizer. Weather data was gathered from Air Force Manual AFM-89 [7], which lists the number of hours in a year for each outside air temperature. This model does not represent time linearly. Rather, all temperature points for a given year are specified, and then a tally is made for the number of hours in that year for each temperature point. For each given temperature, a decision is made whether it is optimal to run the cooling plant or the economizer.

Each hour, at a 15^o C baseline, total server power consumption is 9400 kW, based on 70% average server utilization [3]. Each server is rated at 1000 W max and 800 W idle [3]. The cooling system is 33% efficient [2], so it requires three times the energy to cool heat generated from servers. The cost to run the cooling system for one hour at 15^o C is \$2507. Since the center is well insulated, any potential heating of the building from the outside is negligible and doesn't need to be considered for cooling.

$$1000\ W/server * 20\ servers/rack * 500\ racks = 10000\ kW$$
$$800\ W/server * 20\ servers/rack * 500\ racks = 8000\ kW$$
$$.7 * \left(P_{\max} - P_{idle}\right) + P_{idle} = 9400\ kW$$
$$9400/.33 = 28485\ kW$$
$$28485 * .088 = 2507$$

If the economizer is selected instead of the cooling plant, the only energy consumed is that required to power the economizer fans. For the 32,500 ft^2 computing space [2], both intake and exhaust fans each require up to 368 kW per hour. The use of outside air is sufficient to displace all the heated air exhausted from the servers.

Using the economizer on days where outside temperatures exceeds 15^o C, causes the servers to consume more energy. ASHRAE Whitepaper TC 9.9 specifies a power factor function for temperatures between 15^o C and 35^o C. A best fit line (see model above) with R^2 of .9942 was generated in Excel, and the resulting (output – 1) is multiplied with the 15^o C base energy level to determine the cost of additional server energy. As temperatures approach 40^o C, servers consume nearly 25% more energy due to electrical leakage in silicon as well as increased fan use.

Temperatures also affect hardware reliability. According to a 2008 Google study [6], servers have an average failure rate of 7.8% at 20^o C. This figure improves as temperatures decrease until 15^o C, and the rates worsen as temperatures increase. In ASHRAE TC 9.9, a reliability index function was given, and this index multiplies the base 7.8% failure rate. JMP was used to generate a best fit line (see model above) with R^2 of .996. This model assumes a 100% replacement cost for failed equipment that generalizes factors such as repair costs, downtime costs, and warranty. Each temperature level failure cost is weighted according to its percent of yearly hours.

Spreadsheet Implementation

There are rows for each outside air temperature point, and each of these temperatures has a corresponding binary decision variable that switches between the cooling plant and the economizer. Only one binary variable can be chosen at each temperature point. If cooling plant is selected, then there are no economizer costs or additional server energy costs, and reliability is optimized. If economizer is selected, cooling plant costs are zeroed, and additional server energy and hardware failure costs increase according to temperature. Parameters can be altered such as hourly energy rates, server energy specs, number of servers, and racks.

Additional Considerations

This model only assumes parameters that represent the MGHPCC case. It is known that MGHPCC is under budget constraints and was not able to invest in additional capital upgrades. To make this model more general for MGHPCC and other computing centers, additional variables can be included. MGHPCC chose high-performance Dell R710 servers. Additional server types can be included with different cost, energy use, power factor, reliability index, and maximum temperature. There is also a \$600 per server power supply upgrade which cuts server energy use by 10%. Server performance degradation isn't considered in this model. As temperature increases, the number of computational operations performed decreases. In addition, for these servers, it was determined that they would not be able to operate with a temperature above 35 degrees C and at that outside air temperature the cooling tower must be used. Therefore Xt was set at 1 for all of those temperatures to ensure cooling plant use. Lastly, water economizers are a less expensive (yet more limited) alternative than air economizers. Binary decision variables could be added for these to determine if there are different results for different computing center configurations.

Verification and Validation

The initial goal for this model was to determine the ambient temperature at which the increased costs of hardware failure and increased server energy use due to high temperatures exceeded the cost of running the cooling plant. Our model accomplishes this implicitly by determining the optimal decision for each temperature point. At the completion of our model, we were informed that the conclusion that we drew was the same as MGHPCC and M+W.

Several iterations of debugging were needed to refine our logic. We ran into glitches related to our implementation of the power factor increasing server energy when the cooling plant was on, as well as issues with cooling equation parameters that yielded very expensive energy costs.

VI. RESULTS

A. Final Cost

Using solver to run the model, we find that in this situation, the lowest cost solution is to run the economizer and use outside air for cooling up to 35 degrees C (95 degrees F). At 35 degrees we then switch off the economizer and switch on the cooling tower to keep the building at 15 degrees C. This gave us a final operating cost of $6,209,822 to operate the economizer, the cooling tower, and replace hardware.

The use of the economizer up to 35 degrees C is driven by the low cost of using outside air in combination with the fans. Since the heat energy generated by the servers needs to be exchanged, using outside air is a low cost solution. The cost of the HVAC system is driven by the power required. If we use outside air for cooling, then we only need to use energy to power the fans to mechanically move the air across the servers to exchange the heat. If we were going to use the cooling tower, then we would have to use energy to both mechanically move the air, and also thermally cool the air through the use of the cooling tower. This requires more energy and thus is a higher cost solution.

One thing that was not discussed in the above model is the hardware cost. We estimated the hardware reliability baseline to be 7.8%. As discussed earlier, this was an estimate based on research. It was not an actual value. In addition the research is several years old and not necessarily correct. Since actual data would take years to derive however, and would be driven by a number of factors, 7.8% is a good number to start with. In addition it is very easy to modify that number and run the model with several different numbers.

Although there was a cost with hardware replacement based on temperature, as you increased the temperature and increased the hardware cost, it did not have enough effect to change the results (more on this later). Therefore for the model the primary cost drivers on the model were the high cost of the cooling tower vs. the low cost of using the economizers. It always made sense to use the economizers all the way to 35 degrees C and then have the cooling tower switch on.

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B. Decision Variables

One important thing to note, for our results, we had two decision variables at each temperature point. This gave us over 100 decision variables which were too many for solver to work on. Therefore we had to go through the model and let solver run incrementally over sections. This was far from ideal and meant that we had to do a lot of manual work to have solver find the best solution incrementally through the model. For example we would put in a solution which was within the constraints and then select a small portion of the decision variables and let solver find a solution among those variables (in that temperature range). Then we would freeze those and move on to the next temperature band.

A better way to do it in the future would have been to use a software solution which could handle more decision variables such as GLPK. Although programming our model on GLPK in this instance was not needed, further analysis of our model may justify programming GLPK. Manually manipulating our model also made the sensitivity analysis difficult but possible. Using GLPK would have simplified this task as well.

VII. SENSITIVITY ANALYSIS

A. Cooling costs

The first thing that stands out among the results is the switchover. In any cost situation, as the constraints are tightened, the cost of the system will increase. This case is no different. One of the primary constraints for our system is the hardware temperature operating constraint. The servers are not able to operate above 35 degrees C. This is a primary cost driver because when the outside air is above 35 degrees, the higher cost cooling towers have to be used.

For our model, if we were able to increase the operating limitations on the servers by 3.5 degrees to 38.5 degrees, the cost would decrease from the original model cost of $6,209,822 to 6,171,287 for a cost savings of $38,535. This means that there is a shadow price of approximately $11,010 per degree C that is increased on the server constraint.

$$\frac{\$38{,}535}{3.5\deg C}$$

This means that if you increase this constraint by 3.5 degrees and don't change anything else, you will get a cost savings of $11,010 per degree. Therefore, as you relax the server temperature limitation constraint, you also are able to decrease the cost of the system.

It should be noted that the amount of time that the model is run at each degree changes. Therefore the above shadow price is averaged over the entire 3.5 degree range and changes slightly at each point on the temperature scale.

B. Hardware Reliability

Another item to point out in the analysis is the use of the hardware failure rate and the effect of the model. Although the hardware reliability did not have a significant effect on the model, this was due to the low failure rate which we derived from data.

For the model, if we were modeling a different type of server which was more costly or had a higher failure rate, then it would have a large impact of the model and that would have significantly changed our decision variable.

If we run a sensitivity analysis, it will always be more economical to run the economizer with a low failure rate. This does not change until the baseline hardware failure rate is over 28%. At that point, it becomes more economical to use the cooling towers at higher operating temperatures, because then you are lowering the ambient air temperature to 15 degrees C. This improves the hardware failure rate to a point significant enough to justify using the cooling towers over the economizer.

This same holds true when the server cost increases. If the cost per server increases above $30,900 then it also has an impact on the model enough to start changing the decision variables. This is not a realistic situation for this model since this is a cost several times what a server normally costs, but it could have an impact on another datacenter with different parameters or cost variables.

Both of these situations, although not applicable in our model, are conceivable. Therefore there is evidence that although for our model it made sense to maximize the economizer, this may not always be the case.

VIII. CONCLUSION

The goal at the onset of this project was to explore the constraint interactions specified in ASHRAE TC 9.9. At what outside temperature will it no longer be economical to run an air economizer? In other words, when will the costs of hardware failures and additional server energy consumption exceed the costs of running a cooling plant? It is evident with the advances in server technology; many data centers will change their standard practice and operate at outside air temperature. The cost of running a cooling plant far exceeds the costs of hardware failures, at least with high end servers as analyzed in this study. However in doing our sensitivity analysis we did find that this may not always be the case.

Although for our model this did work, as hardware costs, hardware operating limitations, and hardware failure rates change, they could potentially change the decision variables. In addition, there were other cooling solutions that may have been a better fit or changed things in this model. For example if you had cooling solutions which operated at higher efficiencies, they could drive the decision variables in different directions. Therefore in future modeling it is important to emphasis that the model must be specific to the details of the data center.

APPENDIX A

FINAL MODEL RESULTS

Total Cost:	6,209,822
HVAC Cost:	62,667
Economizer Costs:	565,684
H/W Cost:	5,486,960

Economizer	
Number of Fans:	2
Hp of each Fan:	368

Type of Server:	Dell R610	Hypothetical A	Hypothetical B
Cost Per Server:	$8,400	$8,400	$8,400
Draw per Server (Watts)	1000	1004	1004
Server Utilization	0.7	0.7	0.7
Servers Per Rack:	20	20	20
Cost per Rack:	$168,000	$168,000	$168,000
Number of Racks	500	50	2000
Total Server Power Load (KW)	9400		
Total Material H/W Cost	$84,000,000	$8,400,000	$336,000,000

Utility Cost
$0.088 /kWh

HVAC Energy (Excel Equation)
((9400*D)/0.33)

Average Failure Rate per year 7.80%
Hours in a year: 8759

Outdoor Temp

Degrees			Cooling Plant			Air Economizer			Cooling/ECON		Servers			Ambient	Reliability	Failure	H/W Failure	Total	Cost Per
F	C	hrs/yr	On?	Energy	Cost	On? (1=yes)	Energy	Cost	Switch		PowFact	Energy	Cost	Deg C	Index	Rate	Cost	Cost	Hour
-8	-22.2	2	0	56,970	$0	1	1472	$130	1	1	1	0	$0	-22.2	0.74	5.7%	$1,100	$1,229.212	$614.61
-6	-21.1	1	0	28,485	$0	1	736	$65	1	1	1	0	$0	-21.1	0.74	5.7%	$550	$614.606	$614.61
-4	-20.0	1	0	28,485	$0	1	736	$65	1	1	1	0	$0	-20.0	0.74	5.7%	$550	$614.606	$614.61
-2	-18.9	3	0	85,455	$0	1	2208	$194	1	1	1	0	$0	-18.9	0.74	5.7%	$1,650	$1,843.818	$614.61
0	-17.8	5	0	142,424	$0	1	3680	$324	1	1	1	0	$0	-17.8	0.74	5.7%	$2,749	$3,073.029	$614.61
1	-17.2	3	0	85,455	$0	1	2208	$194	1	1	1	0	$0	-17.2	0.74	5.7%	$1,650	$1,843.818	$614.61
2	-16.7	1	0	28,485	$0	1	736	$65	1	1	1	0	$0	-16.7	0.74	5.7%	$550	$614.606	$614.61
3	-16.1	1	0	28,485	$0	1	736	$65	1	1	1	0	$0	-16.1	0.74	5.7%	$550	$614.606	$614.61
4	-15.6	4	0	113,939	$0	1	2944	$259	1	1	1	0	$0	-15.6	0.74	5.7%	$2,199	$2,458.423	$614.61
5	-15.0	5	0	142,424	$0	1	3680	$324	1	1	1	0	$0	-15.0	0.74	5.7%	$2,749	$3,073.029	$614.61
6	-14.4	1	0	28,485	$0	1	736	$65	1	1	1	0	$0	-14.4	0.74	5.7%	$550	$614.606	$614.61
7	-13.9	10	0	284,848	$0	1	7360	$648	1	1	1	0	$0	-13.9	0.74	5.7%	$5,498	$6,146.059	$614.61
8	-13.3	2	0	56,970	$0	1	1472	$130	1	1	1	0	$0	-13.3	0.74	5.7%	$1,100	$1,229.212	$614.61
9	-12.8	19	0	541,212	$0	1	13984	$1,231	1	1	1	0	$0	-12.8	0.74	5.7%	$10,447	$11,677.512	$614.61
10	-12.2	14	0	398,788	$0	1	10304	$907	1	1	1	0	$0	-12.2	0.74	5.7%	$7,698	$8,604.482	$614.61
11	-11.7	9	0	256,364	$0	1	6624	$583	1	1	1	0	$0	-11.7	0.74	5.7%	$4,949	$5,531.453	$614.61
12	-11.1	21	0	598,182	$0	1	15456	$1,360	1	1	1	0	$0	-11.1	0.74	5.7%	$11,547	$12,906.723	$614.61
13	-10.6	18	0	512,727	$0	1	13248	$1,166	1	1	1	0	$0	-10.6	0.74	5.7%	$9,897	$11,062.906	$614.61
14	-10.0	45	0	1,281,818	$0	1	33120	$2,915	1	1	1	0	$0	-10.0	0.74	5.7%	$24,743	$27,657.264	$614.61
15	-9.4	21	0	598,182	$0	1	15456	$1,360	1	1	1	0	$0	-9.4	0.74	5.7%	$11,547	$12,906.723	$614.61
16	-8.9	40	0	1,139,394	$0	1	29440	$2,591	1	1	1	0	$0	-8.9	0.74	5.7%	$21,994	$24,584.235	$614.61
17	-8.3	30	0	854,545	$0	1	22080	$1,943	1	1	1	0	$0	-8.3	0.74	5.7%	$16,495	$18,438.176	$614.61
18	-7.8	65	0	1,851,515	$0	1	47840	$4,210	1	1	1	0	$0	-7.8	0.74	5.7%	$35,739	$39,949.382	$614.61
19	-7.2	78	0	2,221,818	$0	1	57408	$5,052	1	1	1	0	$0	-7.2	0.74	5.7%	$42,887	$47,939.258	$614.61
20	-6.7	33	0	940,000	$0	1	24288	$2,137	1	1	1	0	$0	-6.7	0.74	5.7%	$18,145	$20,281.994	$614.61
21	-6.1	93	0	2,649,091	$0	1	68448	$6,023	1	1	1	0	$0	-6.1	0.74	5.7%	$51,135	$57,158.346	$614.61
22	-5.6	37	0	1,053,939	$0	1	27232	$2,396	1	1	1	0	$0	-5.6	0.74	5.7%	$20,344	$22,740.417	$614.61
23	-5.0	96	0	2,734,545	$0	1	70656	$6,218	1	1	1	0	$0	-5.0	0.74	5.7%	$52,784	$59,002.164	$614.61
24	-4.4	37	0	1,053,939	$0	1	27232	$2,396	1	1	1	0	$0	-4.4	0.74	5.7%	$20,344	$22,740.417	$614.61
25	-3.9	120	0	3,418,182	$0	1	88320	$7,772	1	1	1	0	$0	-3.9	0.74	5.7%	$65,981	$73,752.704	$614.61
26	-3.3	43	0	1,224,848	$0	1	31648	$2,785	1	1	1	0	$0	-3.3	0.74	5.7%	$23,643	$26,428.052	$614.61
27	-2.8	158	0	4,500,606	$0	1	116288	$10,233	1	1	1	0	$0	-2.8	0.74	5.7%	$86,874	$97,107.728	$614.61
28	-2.2	183	0	5,212,727	$0	1	134688	$11,853	1	1	1	0	$0	-2.2	0.74	5.7%	$100,620	$112,472.874	$614.61
29	-1.7	49	0	1,395,758	$0	1	36064	$3,174	1	1	1	0	$0	-1.7	0.74	5.7%	$26,942	$30,115.688	$614.61
30	-1.1	212	0	6,038,788	$0	1	156032	$13,731	1	1	1	0	$0	-1.1	0.74	5.7%	$116,566	$130,296.445	$614.61
31	-0.6	63	0	1,794,545	$0	1	46368	$4,080	1	1	1	0	$0	-0.6	0.74	5.7%	$34,640	$38,720.170	$614.61
32	0.0	239	0	6,807,879	$0	1	175904	$15,480	1	1	1	0	$0	0.0	0.74	5.7%	$131,411	$146,890.803	$614.61
33	0.6	78	0	2,221,818	$0	1	57408	$5,052	1	1	1	0	$0	0.6	0.74	5.7%	$42,887	$47,939.258	$614.61
34	1.1	321	0	9,143,636	$0	1	236256	$20,791	1	1	1	0	$0	1.1	0.74	5.7%	$176,498	$197,288.484	$614.61
35	1.7	95	0	2,706,061	$0	1	69920	$6,153	1	1	1	0	$0	1.7	0.74	5.7%	$52,235	$58,387.558	$614.61
36	2.2	311	0	8,858,788	$0	1	228896	$20,143	1	1	1	0	$0	2.2	0.74	5.7%	$171,000	$191,142.426	$614.61
37	2.8	276	0	7,861,818	$0	1	203136	$17,876	1	1	1	0	$0	2.8	0.74	5.7%	$151,755	$169,631.220	$614.61
38	3.3	72	0	2,050,909	$0	1	52992	$4,663	1	1	1	0	$0	3.3	0.74	5.7%	$39,588	$44,251.623	$614.61
39	3.9	240	0	6,836,364	$0	1	176640	$15,544	1	1	1	0	$0	3.9	0.74	5.7%	$131,961	$147,505.409	$614.61
40	4.4	44	0	1,253,333	$0	1	32384	$2,850	1	1	1	0	$0	4.4	0.74	5.7%	$24,193	$27,042.658	$614.61
41	5.0	192	0	5,469,091	$0	1	141312	$12,435	1	1	1	0	$0	5.0	0.74	5.7%	$105,569	$118,004.327	$614.61
42	5.6	41	0	1,167,879	$0	1	30176	$2,655	1	1	1	0	$0	5.6	0.74	5.7%	$22,543	$25,198.841	$614.61
43	6.1	208	0	5,924,848	$0	1	153088	$13,472	1	1	1	0	$0	6.1	0.74	5.7%	$114,366	$127,838.021	$614.61
44	6.7	52	0	1,481,212	$0	1	38272	$3,368	1	1	1	0	$0	6.7	0.74	5.7%	$28,592	$31,959.505	$614.61
45	7.2	196	0	5,583,030	$0	1	144256	$12,695	1	1	1	0	$0	7.2	0.74	5.7%	$107,768	$120,462.751	$614.61
46	7.8	234	0	6,665,455	$0	1	172224	$15,156	1	1	1	0	$0	7.8	0.74	5.7%	$128,662	$143,817.774	$614.61
47	8.3	53	0	1,509,697	$0	1	39008	$3,433	1	1	1	0	$0	8.3	0.74	5.7%	$29,141	$32,574.111	$614.61
48	8.9	204	0	5,810,909	$0	1	150144	$13,213	1	1	1	0	$0	8.9	0.74	5.7%	$112,167	$125,379.598	$614.61
49	9.4	50	0	1,424,242	$0	1	36800	$3,238	1	1	1	0	$0	9.4	0.74	5.7%	$27,492	$30,730.294	$614.61

Degrees			Cooling Plant			Air Economizer			Cooling/ECON		Servers			Ambient	Reliability	Failure	H/W Failure		Total	Cost Per
F	C	hrs/yr	On?	Energy	Cost	On? (1=yes)	Energy	Cost	Switch		PowFact	Energy	Cost	Deg C	Index	Rate	Cost		Cost	Hour
50	10.0	191	0	5,440,606	$0	1	140576	$12,371	1	1	1	0	$0	10.0	0.74	5.7%	$105,019		$117,389.721	$614.61
51	10.6	56	0	1,595,152	$0	1	41216	$3,627	1	1	1	0	$0	10.6	0.74	5.7%	$30,791		$34,417.929	$614.61
52	11.1	202	0	5,753,939	$0	1	148672	$13,083	1	1	1	0	$0	11.1	0.74	5.7%	$111,067		$124,150.386	$614.61
53	11.7	43	0	1,224,848	$0	1	31648	$2,785	1	1	1	0	$0	11.7	0.74	5.7%	$23,643		$26,428.052	$614.61
54	12.2	198	0	5,640,000	$0	1	145728	$12,824	1	1	1	0	$0	12.2	0.74	5.7%	$108,868		$121,691.962	$614.61
55	12.8	216	0	6,152,727	$0	1	158976	$13,990	1	1	1	0	$0	12.8	0.74	5.7%	$118,765		$132,754.868	$614.61
56	13.3	48	0	1,367,273	$0	1	35328	$3,109	1	1	1	0	$0	13.3	0.74	5.7%	$26,392		$29,501.082	$614.61
57	13.9	193	0	5,497,576	$0	1	142048	$12,500	1	1	1	0	$0	13.9	0.74	5.7%	$106,119		$118,618.933	$614.61
58	14.4	51	0	1,452,727	$0	1	37536	$3,303	1	1	1	0	$0	14.4	0.74	5.7%	$28,042		$31,344.899	$614.61
59	15.0	172	0	4,899,394	$0	1	126592	$11,140	1	1	1	0	$0	15.0	0.74	5.7%	$94,572		$105,712.210	$614.61
60	15.6	65	0	1,851,515	$0	1	47840	$4,210	1	1	1.00545	3,329	$293	15.6	0.74	5.8%	$36,056		$40,559.069	$623.99
61	16.1	212	0	6,038,788	$0	1	156032	$13,731	1	1	1.01028	20,486	$1,803	16.1	0.80	6.2%	$126,350		$141,883.726	$669.26
62	16.7	72	0	2,050,909	$0	1	52992	$4,663	1	1	1.01456	9,851	$867	16.7	0.83	6.4%	$44,536		$50,066.359	$695.37
63	17.2	230	0	6,551,515	$0	1	169280	$14,897	1	1	1.01834	39,646	$3,489	17.2	0.86	6.7%	$147,380		$165,765.732	$720.72
64	17.8	236	0	6,722,424	$0	1	173696	$15,285	1	1	1.02169	48,111	$4,234	17.8	0.89	6.9%	$156,390		$175,909.057	$745.38
65	18.3	76	0	2,164,848	$0	1	55936	$4,922	1	1	1.02467	17,622	$1,551	18.3	0.91	7.1%	$52,000		$58,473.451	$769.39
66	18.9	239	0	6,807,879	$0	1	175904	$15,480	1	1	1.02734	61,416	$5,405	18.9	0.94	7.4%	$168,596		$189,479.703	$792.80
67	19.4	105	0	2,990,909	$0	1	77280	$6,801	1	1	1.02976	29,374	$2,585	19.4	0.97	7.6%	$76,260		$85,645.579	$815.67
68	20.0	223	0	6,352,121	$0	1	164128	$14,443	1	1	1.032	67,078	$5,903	20.0	1.00	7.8%	$166,539		$186,884.885	$838.05
69	20.6	81	0	2,307,273	$0	1	59616	$5,246	1	1	1.03412	25,975	$2,286	20.6	1.03	8.0%	$62,127		$69,658.627	$859.98
70	21.1	182	0	5,184,242	$0	1	133952	$11,788	1	1	1.03617	61,877	$5,445	21.1	1.05	8.2%	$143,205		$160,437.728	$881.53
71	21.7	88	0	2,506,667	$0	1	64768	$5,700	1	1	1.03822	31,617	$2,782	21.7	1.08	8.4%	$70,958		$79,440.120	$902.73
72	22.2	169	0	4,813,939	$0	1	124384	$10,946	1	1	1.04034	64,080	$5,639	22.2	1.10	8.6%	$139,511		$156,095.514	$923.64
73	22.8	170	0	4,842,424	$0	1	125120	$11,011	1	1	1.04258	68,037	$5,987	22.8	1.13	8.8%	$143,536		$160,533.961	$944.32
74	23.3	45	0	1,281,818	$0	1	33120	$2,915	1	1	1.045	19,035	$1,675	23.3	1.15	9.0%	$38,827		$43,416.255	$964.81
75	23.9	136	0	3,873,939	$0	1	100096	$8,808	1	1	1.04767	60,942	$5,363	23.9	1.18	9.2%	$119,810		$133,981.474	$985.16
76	24.4	51	0	1,452,727	$0	1	37536	$3,303	1	1	1.05065	24,282	$2,137	24.4	1.20	9.4%	$45,837		$51,276.684	$1,005.43
77	25.0	115	0	3,275,758	$0	1	84640	$7,448	1	1	1.054	58,374	$5,137	25.0	1.22	9.6%	$105,366		$117,950.735	$1,025.66
78	25.6	42	0	1,196,364	$0	1	30912	$2,720	1	1	1.05778	22,812	$2,007	25.6	1.25	9.7%	$39,200		$43,928.183	$1,045.91
79	26.1	88	0	2,506,667	$0	1	64768	$5,700	1	1	1.06206	51,334	$4,517	26.1	1.27	9.9%	$83,611		$93,828.056	$1,066.23
80	26.7	22	0	626,667	$0	1	16192	$1,425	1	1	1.06689	13,833	$1,217	26.7	1.29	10.1%	$21,264		$23,906.652	$1,086.67
81	27.2	70	0	1,993,939	$0	1	51520	$4,534	1	1	1.07234	47,598	$4,189	27.2	1.31	10.2%	$68,787		$77,509.210	$1,107.27
82	27.8	43	0	1,224,848	$0	1	31648	$2,785	1	1	1.07847	31,716	$2,791	27.8	1.33	10.4%	$42,932		$48,508.484	$1,128.10
83	28.3	31	0	883,030	$0	1	22816	$2,008	1	1	1.08533	24,866	$2,188	28.3	1.36	10.6%	$31,429		$35,625.405	$1,149.21
84	28.9	33	0	940,000	$0	1	24288	$2,137	1	1	1.093	28,850	$2,539	28.9	1.38	10.7%	$33,955		$38,630.873	$1,170.63
85	29.4	23	0	655,152	$0	1	16928	$1,490	1	1	1.10154	21,953	$1,932	29.4	1.40	10.9%	$24,004		$27,425.959	$1,192.43
86	30.0	27	0	769,091	$0	1	19872	$1,749	1	1	1.111	28,172	$2,479	30.0	1.41	11.0%	$28,568		$32,795.796	$1,214.66
87	30.6	10	0	284,848	$0	1	7360	$648	1	1	1.12145	11,416	$1,005	30.6	1.43	11.2%	$10,721		$12,373.620	$1,237.36
88	31.1	12	0	341,818	$0	1	8832	$777	1	1	1.13295	14,996	$1,320	31.1	1.45	11.3%	$13,030		$15,127.112	$1,260.59
89	31.7	6	0	170,909	$0	1	4416	$389	1	1	1.14556	8,209	$722	31.7	1.47	11.5%	$6,595		$7,706.413	$1,284.40
90	32.2	11	0	313,333	$0	1	8096	$712	1	1	1.15934	16,475	$1,450	32.2	1.49	11.6%	$12,235		$14,397.257	$1,308.84
91	32.8	10	0	284,848	$0	1	7360	$648	1	1	1.17435	16,389	$1,442	32.8	1.50	11.7%	$11,250		$13,339.620	$1,333.96
92	33.3	2	0	56,970	$0	1	1472	$130	1	1	1.19067	3,585	$315	33.3	1.52	11.9%	$2,275		$2,719.629	$1,359.81
93	33.9	4	0	113,939	$0	1	2944	$259	1	1	1.20834	7,833	$689	33.9	1.54	12.0%	$4,597		$5,545.800	$1,386.45
94	34.4	6	0	170,909	$0	1	4416	$389	1	1	1.22743	12,827	$1,129	34.4	1.55	12.1%	$6,966		$8,483.518	$1,413.92
95	35.0	5	1	142,424	$12,533	0	3680	$0	1	1	1	0	$0	15.0	0.74	5.7%	$2,749		$15,282.523	$3,056.50
96	35.6	7	1	199,394	$17,547	0	5152	$0	1	1	1	0	$0	15.0	0.74	5.7%	$3,849		$21,395.532	$3,056.50
97	36.1	3	1	85,455	$7,520	0	2208	$0	1	1	1	0	$0	15.0	0.74	5.7%	$1,650		$9,169.514	$3,056.50
98	36.7	1	1	28,485	$2,507	0	736	$0	1	1	1	0	$0	15.0	0.74	5.7%	$550		$3,056.505	$3,056.50
99	37.2	3	1	85,455	$7,520	0	2208	$0	1	1	1	0	$0	15.0	0.74	5.7%	$1,650		$9,169.514	$3,056.50
100	37.8	5	1	142,424	$12,533	0	3680	$0	1	1	1	0	$0	15.0	0.74	5.7%	$2,749		$15,282.523	$3,056.50
101	38.3	1	1	28,485	$2,507	0	736	$0	1	1	1	0	$0	15.0	0.74	5.7%	$550		$3,056.505	$3,056.50
102	38.9	0	1	0	$0	0	0	$0	1	1	1	0	$0	15.0	0.74	5.7%	$0		$0.000	#DIV/0!
103	39.4	0	1	0	$0	0	0	$0	1	1	1	0	$0	15.0	0.74	5.7%	$0		$0.000	#DIV/0!
104	40.0	0	1	0	$0	0	0	$0	1	1	1	0	$0	15.0	0.74	5.7%	$0		$0.000	#DIV/0!
		8,759			**$62,667**			**$565,684**					**$94,512**				**$5,486,960**	Total:	**$6,209,822**	

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