# Operational Performance Comparison of Variable and Fixed Speed Chillers *at Duke University's Chilled Water Plant No. 2*

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# 1. Introduction

Duke Utility & Engineering Services (DUES), part of the broader Facilities Management Department, is responsible for managing Duke University's complex utility infrastructure, managing the purchase and operation of energy resources, and providing specialized engineering and technical support to construction projects, service contracts, and the University.[1] One such utility is the chilled water production and distribution system. The system produces chilled water at a target temperature of 40°F and pumps it through approximately 14 miles of pipes across the university's campus in order to serve various comfort and process cooling loads. Of the 47,000 Tons of total chilled water production capacity, approximately 42,000 Tons are located at two central chilled water plants, CCWP1 and CCWP2.[2] CCWP2 contains approximately 32,000 Tons of capacity distributed across nine centrifugal chillers, which are the focus of this study. CCWP2 also serves as the main hub for monitoring and control of the system. On a yearly basis, chillers in CCWP2 consume approximately 40,000,000 kWh of electricity, accounting for nearly ten percent of Duke University's total electricity consumption.[3]

Given the massive scale of the chilled water system, there are three important operations and planning challenges that DUES must continually address. First, the chilled water system serves a number of critical loads such as Duke University's hospitals and research centers, which makes reliability a top priority. Maintaining reliability alone can account for a significant portion of time and budgetary resources. Second and also related to reliability, careful load forecasting and capacity planning are required to ensure ample supply in the chilled water system. Load forecasting in particular can be very difficult given the fluctuating growth of university infrastructure and evolving building energy policies. Third, due to the scale of this system, advanced production and control technologies are needed to ensure both reliability and system efficiency. This requirement makes purchasing new technology a non-trivial decision involving careful consideration of potential costs, benefits, and technological capabilities.

An example that fully embodies these challenges and is also the focal point for the analysis in this report is the purchase and operation of variable speed chillers. In late 2009, DUES began to consider the additional purchase of variable speed drives (VSDs) for two centrifugal chillers it was planning to add to the CCWP2 facility. As part of the planning process, DUES estimated savings from the VSD upgrade would be approximately 1.4 million kWh per chiller per year. DUES projections for electricity costs and energy savings led them to anticipate a savings of $86K per

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[1] N.p.. Web. 27 Feb 2013. <http://fmd.duke.edu/utilities/index.php>.

[2] A refrigeration ton is equal to a heat extraction rate of 12,000 BTU per hour. "Course No. HV-4004: Overview of Chiller Compressors." *PDHengineer.com*. Decatur Professional Development, LLC. Web. 10 Feb 2013.

[3] Based on approximate total electricity consumption of 450,000,000 kWh per year. "Energy Sustainability Facts." *Sustainability.Duke.Edu*. Duke University Facilities Management, n.d. Web. 3 Feb 2013.

year per VSD upgrade.[4] In mid 2011, DUES decided to purchase, install and begin operating two variable speed (i.e. VSD-equipped) chillers in CCWP2.

Nearly two years into the project, DUES has seen significant efficiency improvements in the system. However, the precise amount of energy savings specifically from variable speed chillers and conditions under which the savings occur have not yet been studied in detail. While a generalized understanding and calculation of variable speed chiller energy savings may be relatively straightforward, it does not begin to answer more in-depth questions that could affect both individual chiller and plant-wide performance. The objective of this study is to evaluate the performance of variable and fixed speed chillers in their current production environment using operational data sets from multiple chillers. The study seeks to determine the actual contribution to efficiency and conditions for efficiency of both variable and fixed speed chillers. The analysis also develops performance prediction models for both types of chillers under various operating conditions and in doing so demonstrates that variable speed chillers have significantly outperformed initial energy savings estimates. Lastly, the results demonstrate that chiller performance and potential energy savings are relatively predictable under most operating conditions, helping to verify operators' current understanding of plant operation.

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[4] According to DUES planning estimate, the VSD upgrade is an additional $600K over the base price of a fixed speed chiller. Palumbo, Steven. "VFD Chiller Spreadsheet." Message to Andrew Myers. 28 02 2013. E-mail.

# 2. Background

There are four main types of power-consuming components in the chilled water system: chiller compressors, chilled and condenser water pumps, and cooling towers (Figure 1). This study is limited to the analysis of chiller compressor work, as it is by far the largest energy user accounting for over 70% of total plant electricity consumption.[5] Operation of other system components has been studied extensively in the refrigeration industry for many years and best practices have already been implemented at CCWP2. The analyses in this study therefore do not violate the constraints of current plant operation, which allows the scope of analysis to remain solely on chiller performance.

## 2.1 Chilled Water Production and the Vapor Compression Cycle

Figure 1 shows the primary components of centrifugal chillers and their relation to the cooling system as a whole. Centrifugal chillers work to reduce the temperature of return water in the load serving evaporator water loop by utilizing the vapor compression cycle.[6] The cycle "begins" with system return water entering the evaporator (at some flow rate $\dot{m}_e$) where heat is transferred between the initially warmer water and the cooler refrigerant also passing through the evaporator.[7] The compressor draws in the heated (vaporized) refrigerant from the evaporator in order to further heat and pressurize the refrigerant into a "hot gas". The superheated refrigerant then moves into the condenser where the cooler condenser water (at some flow rate $\dot{m}_c$) absorbs heat and causes liquid refrigerant condensate to develop, which is still at an elevated temperature and pressure. The liquid refrigerant condensate collects at the bottom of the condenser and then passes through a throttling device where the cycle repeats.[8] The throttling device is an important component of the chiller because it maintains the pressure differential between the high-pressure condenser and low-pressure evaporator sides of the

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[5] Based on CCWP2 total electricity consumption of approximately 60M kWh per year.

[6] Centrifugal compressors are dynamic machines that convert kinetic energy to static energy by using the rotating action of an impeller wheel to exert centrifugal force on a refrigerant. "Centrifugal Water Chillers: A Trane Air Conditioning Clinic." *NJATC.org*. American Standard Inc., n.d. Web. 25 Jan 2013.

[7] The chillers analyzed in this study operate using R-123 as the refrigerant.

[8] "Chilled Water Plant Design Guide." *EnergyDesignResources*. N.p., 01 12 2009. Web. 17 Mar 2013.

refrigeration system, as established by the compressor. This pressure difference is what allows the evaporator temperature ($T_{ei}$& $T_{eo}$) to be low enough for the refrigerant to absorb heat from the water being cooled and the condenser temperature ($T_{ci}$& $T_{co}$) to be high enough for the refrigerant to reject heat to water at varying temperatures.[9]

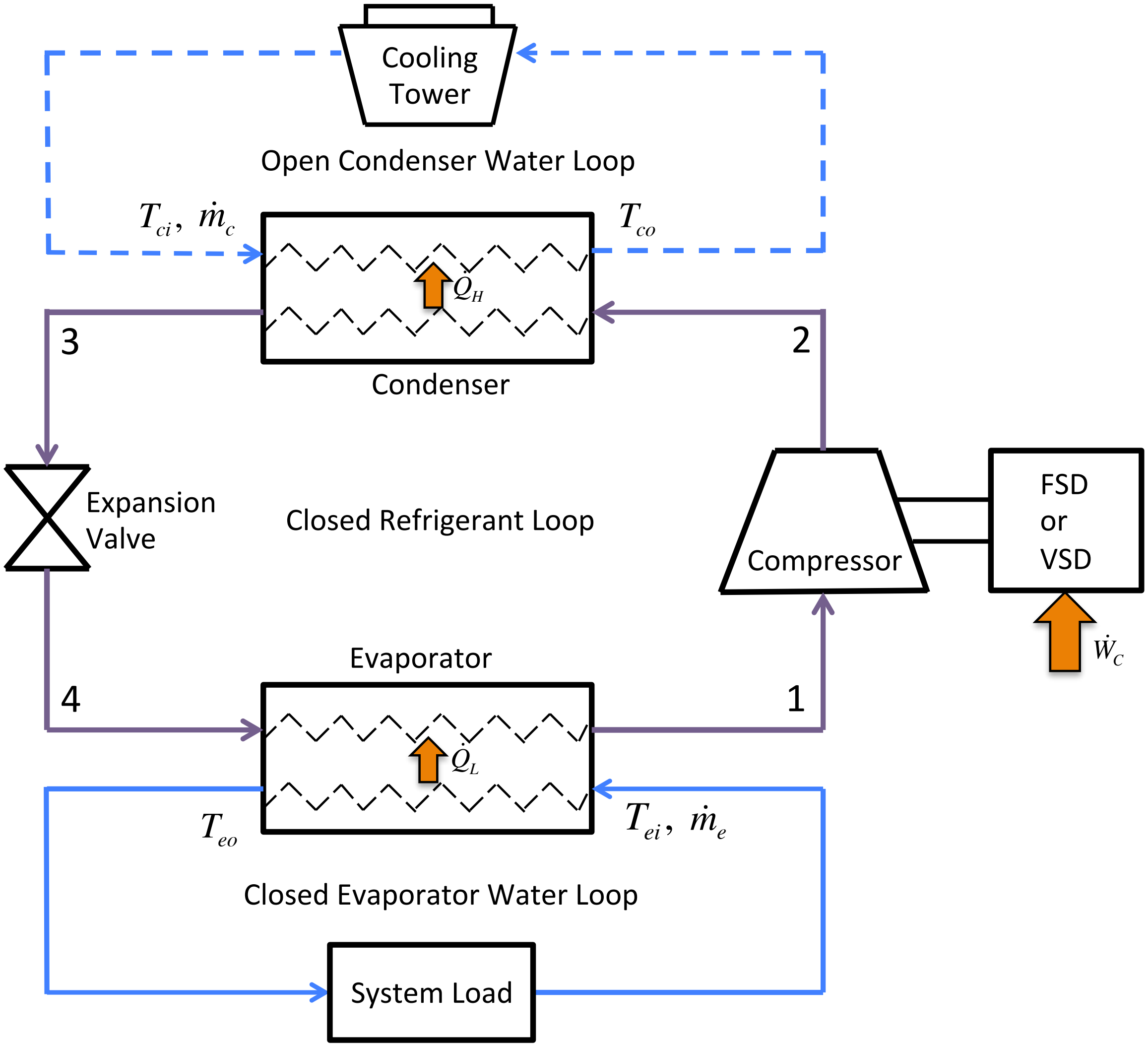

FIGURE 1. SCHEMATIC OF CENTRIFUGAL CHILLER SYSTEM.

## 2.2 Performance Factors Influencing Compressor Work Input

There are two key factors that impact chiller compressor performance, called "lift" and "load". Lift can be defined as the difference between the condenser and evaporator saturation temperatures.[10] Lift is essentially the temperature (or

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[9] Refer to source #6.

[10] Brasz, Joost, and Lee Tetu. "Variable-Speed Centrifugal Chiller Control for Variable Primary Flow (VPF) Applications." *International Compressor Engineering Conference, Purdue University School of Mechanical Engineering*. Purdue e-Pubs, Web. 17 Feb 2013.

pressure) gradient that must be overcome by the compressor in order to reject heat to the condenser water loop and cool the refrigerant to a temperature at or below that of the desired supply temperature at the evaporator outlet ($T_{eo}$). Lift can be further understood using the compressor work equation (Eqn. 1), where work is equivalent to the difference in enthalpy of the refrigerant at the compressor outlet and inlet (points 2 and 1 in Figure 1).

$$\dot{W}_C = \dot{m}(h_2 - h_1) \qquad \textit{(Eqn. 1)}$$

$$\Delta h = u_2 c_{\theta 2} - u_1 c_{\theta 1} \qquad \textit{(Eqn. 2)}$$

$\Delta h$ = change in enthalpy [J/kg]

$u_1$ = wheel speed at rotor inlet [m/s]

$c_{\theta 1}$ = tangential component of incoming flow [m/s]

$u_2$ = rotor speed at compressor exit [m/s]

$c_{\theta 2}$ = tangential velocity of flow exiting the rotor [m/s]

Equations 1 and 2 show that compressor work ($\dot{W}_C$) depends primarily on compressor speed and the tangential component of refrigerant flow through the compressor (Δh in equations 1 and 2).[11] Looking at lift from the perspective of the evaporator and condenser water loops, lift becomes smaller from a decrease in leaving condenser water temperature ($T_{co}$) or increase in leaving evaporator water temperature ($T_{eo}$), in which case fixed speed chillers are unable to reduce compressor speed and depend solely on inlet guide vanes (IGVs) to control Δh.[12] A variable speed chiller, however, is able to reduce speed and therefore power input when faced with low lift conditions. Lastly, the performance factor referred to as “load” is also related to lift and IGV control by the temperature differential of water through the evaporator. Load is discussed in more detail the next section on chiller load control.

### 2.3 Chiller Load Control

Load refers to the amount of tons a chiller is delivering at a given point in time and is explained by the relationship shown in Equation 3 where $c_p$ represents a conversion factor of 500, $\dot{m}_e$ is the flow rate of water through the evaporator, $T_{ei}$ is the temperature of water flowing into the evaporator and $T_{eo}$ is the temperature of water flowing out of the evaporator.[13]

$$Load\ [Tons] = c_p \dot{m}_e (T_{ei} - T_{eo}) / 12{,}000\, BTU \cdot hr\ /\ Ton \qquad (Eqn.\ 3)$$

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[11] Refer to source #10.

[12] Refer to source #8 for more information on IGVs.

[13] Nonnenmann, James. "Chilled Water Plant Pumping Schemes". Stanley Consultants, Inc. Web. 24 Feb 2013.

In order to determine load as a percentage of full rated operating capacity of a particular chiller (i.e. %load or %capacity), the amount of tons being output is divided by the rated tons of capacity as established by design specifications.[14] This effectively creates a proxy for measuring %capacity, while the actual range of possible operating capacities is limited by a number of factors including the minimum and maximum evaporator water flow rates and leaving evaporator water temperatures (Eqn. 3). As an example, given a hypothetically fixed water flow rate through the evaporator ($\dot{m}_e$) and fixed desired temperature of water leaving the evaporator ($T_{eo}$), only the changing temperature of water entering the evaporator ($T_{ei}$) will govern the maximum level of tonnage output that a chiller can achieve. In the case of CCWP2's variable-primary flow system, evaporator water flow rate will actually change over time, which adds further complexity to maintaining a specified level of output.[15]

## 3. Analysis & Methods

A review of the literature has not yet identified any analyses that attempt to compare variable and fixed speed chiller performance across their range of operating conditions and more specifically, their range of operating capacities. This study attempts to draw this comparison by carefully exploring the relationship between part load operation and chiller efficiency while systematically controlling for various operating conditions that also influence chiller performance (i.e. lift and load). The analysis begins with a very basic and generalized estimation of variable speed chiller energy savings, which takes into consideration various lift and load conditions. In order to control for lift, for example, a variable is chosen to represent lift and divided into partitions of smaller intervals of that variable. Depending on the depth of analysis, this partitioning method may be done for more than one "control variable" (explained in greater detail in Sections 3.2 & 3.3). Following the basic analysis, a simple linear regression method is used to create performance prediction models based on the relationship between percent operating capacity ($\%capacity$) and chiller performance ($kW/Ton$). Controlling for different operating conditions through the use of partitioned data subsets (i.e. combinations of control variables) is also an essential part of this method. The resulting performance prediction models for each unique subset are then used to estimate the energy savings from variable speed chillers, and the results are compared with those from the basic analysis.

### 3.1 Data Collection and Cleansing

The data sets used in this study come from chillers in operation at Duke University's Central Chilled Water Plant No. 2. The plant contains seven fixed and two variable speed drive chillers, which are used in various combinations and capacities to meet fluctuating system demand. DUES stores and analyzes a significant amount of

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[14] "AHRI Standard 550/590." *Air-Conditioning, Heating, and Refrigeration Institute*. AHRI, Web. 15 Jan 2013.

[15] Refer to source #13 for more information on variable-primary flow systems.

operational data that relates to nearly every aspect of plant wide performance. For the purposes of this study, water-side data proved to be most useful and readily available for analyzing chiller efficiency and developing performance prediction models. This is largely due to the direct relationship of water-side data with system demand and weather, both of which largely contribute to the variability in lift and load conditions, and only impact the refrigerant loop secondarily through the water loops. Important water-side measurements include condenser inlet and outlet water temperatures ($T_{ci}\ and\ T_{co}$), evaporator inlet and outlet water temperatures ($T_{ei}\ and\ T_{eo}$), condenser water flow rate ($\dot{m}_c$) and evaporator water flow rate ($\dot{m}_e$). Power input per capacity ($kW/Ton$) and percent operating capacity ($\%capacity$) are also used in the analyses.

Additionally, two different types of data sets were used in this study. First, full year sets of 15-minute interval data on each chiller were used to perform the basic savings estimations shown in Section 3.2. The second type of data set was used for development of chiller performance models and the related energy savings calculation. The second type contained approximately nine months of operational data spanning from July 2012 until March 2013 for each chiller. The reason a smaller data set was used is because certain measurements needed for an in-depth analysis had not been recorded prior to July 2012. Both types of data sets were also examined and cleansed to meet various range and cross-field constraints, as shown in Appendix A.

## 3.2 Basic Estimation of Variable Speed Chiller Energy Savings

The method for estimating variable speed chiller energy savings began by partitioning the data into eight bins by %capacity operation, ranging from 0-30%, 30-40%, 40-50% and so on until 100% operating capacity.[16] Next, the Excel Pivot Table tool was used to create summary data of each individual chiller's operational performance in the different capacity bins. The summary data includes average $kW/Ton$, average tons produced (load), and the number of fifteen-minute intervals in each operating capacity bin. Using summary data for two variable and two fixed speed chillers, a hypothetical "average" variable speed and "average" fixed speed chiller were created in order to generalize the energy usage comparison.[17] Using the actual operating hours and tonnage output of an "average" variable speed chiller in the plant, a predicted energy usage was calculated for a hypothetical fixed speed chiller (Equation 5). Energy savings are calculated as the difference between the hypothetical fixed speed chiller energy consumption and actual measured variable speed energy consumption (Equations 4 & 5). The results are shown in Table 1.

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[16] Centrifugal compressors allow roughly 30 to 100% capacity through vane control due to surge from low pressure through the compressor in the lower *%capacity* range. "Operation Maintenance Manual: Gear-Driven Centrifugal Water-Cooled Chillers with CH530 Controls." Trane. Web. 17 Mar 2013.

[17] Variable speed chiller Nos. 210, 211 and fixed speed chiller Nos. 22, 24 were chosen based on their comparable design and rated capacities.

$$VSD\ Avg\ \frac{kW}{Ton}\ x\ VSD\ Avg\ Tons\ x\ VSD\ OpHrs = [kWh]\ from\ actual\ VSD\ (Eqn. 4)$$

$$FSD\ Avg\ \frac{kW}{Ton}\ x\ VSD\ Avg\ Tons\ x\ VSD\ OpHrs = [kWh]\ from\ hypoth\ FSD\ (Eqn. 5)$$

TABLE 1. VARIABLE SPEED CHILLER ENERGY SAVINGS CONTROLLING FOR LOAD.

| % Capacity | FSD Avg kW/Ton | VSD Avg kW/Ton | VSD Avg Tons | VSD Hrs of Operation | Predicted FSD kWh | Measured VSD kWh |
|---|---|---|---|---|---|---|
| 0-30% | - | - | - | - | - | - |
| 30-40% | 0.54 | 0.34 | 1385 | 366 | 274,000 | 172,000 |
| 40-50% | 0.53 | 0.32 | 1681 | 1576 | 1,415,000 | 855,000 |
| 50-60% | 0.58 | 0.37 | 2029 | 2382 | 2,805,000 | 1,794,000 |
| 60-70% | 0.62 | 0.46 | 2397 | 1944 | 2,867,000 | 2,144,000 |
| 70-80% | 0.64 | 0.50 | 2749 | 1244 | 2,185,000 | 1,723,000 |
| 80-90% | 0.65 | 0.54 | 3091 | 336 | 672,000 | 564,000 |
| 90-100% | 0.58 | 0.55 | 3439 | 57 | 114,000 | 107,000 |
|  |  |  |  | Total kWh: | 10,332,000 | 7,359,000 |
|  |  |  |  | ***kWh Savings:** | **3,283,000** |  |

*Savings estimated for 1 VSD chiller for 1 year
*Extrapolating based on data set covering only 91% of full year

A general observation that can be made from Table 1 is that variable speed (VSD) $kW/Ton$ performance improves as $\%capacity$ decreases, which is to be expected from its compressor speed control capabilities. One should also expect the opposite trend for fixed speed chillers (FSD) due to their use of IGVs and lack of speed control, however, this trend cannot be immediately observed from Table 1. This is because both chillers also see an improvement in $kW/Ton$ performance in low lift conditions, which masks the results shown in Table 1. In order to account for the wide range of lift conditions, operational data was further partitioned by the temperature of water entering the condenser ($T_{ci}$).[18] One can observe from the results shown in Appendix B that after controlling for lift, fixed speed chiller performance does generally improve as $\%capacity$ moves closer to 100%.[19] The results in Table 2 were calculated using the tables shown in Appendix B by once again using the difference between Equations 4 and 5.

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[18] $T_{ci}$ is used in place of $T_{co}$ to control for lift based on the use of $T_{ci}$ in planning estimates. $T_{eo}$ is also assumed to remain constant around the target supply temperature of 40°F.

[19] Fixed speed chiller trends are not as conclusive as variable speed chillers, likely due to there being less operating data.

TABLE 2. VARIABLE SPEED CHILLER ENERGY SAVINGS CONTROLLING FOR LIFT AND LOAD.

| | kWh Savings from VSD by Condenser Inlet Water Temperature ($T_{ci}$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| % Capacity | 55 - 58 | 58 - 60 | 60 - 63 | 63 - 65 | 65 - 68 | 68 - 70 | 70 - 75 | 75 - 80 | 80 - 85 |
| 0 - 30% | - | - | - | - | - | - | - | - | - |
| 30 - 40% | 14,900 | 10,700 | 5,700 | 900 | 2,200 | 2,500 | 100 | - | - |
| 40 - 50% | 263,000 | 38,100 | 38,000 | 9,300 | 24,600 | 18,500 | 7,500 | - | - |
| 50 - 60% | 324,000 | 36,000 | 46,900 | 45,800 | 54,600 | 42,500 | 92,000 | 14,600 | - |
| 60 - 70% | 75,500 | 22,700 | 31,600 | 23,600 | 67,500 | 34,300 | 104,000 | 84,700 | 800 |
| 70 - 80% | 23,700 | 9,600 | 12,700 | 8,100 | 36,000 | 33,900 | 54,100 | 64,000 | 25,000 |
| 80 - 90% | - | 3,300 | 2,600 | 600 | 5,200 | 7,000 | 14,600 | 14,100 | 3,800 |
| 90 - 100% | - | (2,500) | 800 | - | - | (600) | - | (100) | 200 |
| kWh Savings: | 701,100 | 117,900 | 138,300 | 88,300 | 190,100 | 138,100 | 272,300 | 177,300 | 29,800 |
| ***Total Savings:** | **2,241,900** | *Savings estimated for 1 VSD chiller for 1 year and extrapolating based on data set covering 83% of full year | | | | | | | |

The results show that Table 1 seems to overestimate energy savings by not accounting for changing lift conditions, while Table 2 gives a more complete and lower estimate of energy savings.[20] Based on results from Table 2, variable speed chiller energy savings were approximately 60% higher than initial planning estimates. Section 3.3.3 will attempt to verify this finding but future analyses should also repeat this basic method as more data becomes available. Finally, it can be observed from the previous analyses that in order to improve accuracy of the energy savings calculation, control variables must be carefully selected and partitioned into smaller interval bins. In the next section, a method for selecting and partitioning additional control variables is developed and discussed. The method is also demonstrated to be useful for predicting chiller performance across its range of operating capacities.

## 3.3 Performance Prediction Models of Variable & Fixed Speed Chillers Under Various Operating Conditions

### 3.3.1 Model Formulation

In order to create additional control variable partitions, variables had to be carefully selected in order to account for key chiller performance factors without creating too small of data subsets (i.e. combinations of control variable partitions with N<25). Using the chiller performance principles discussed in Sections 2.1 - 2.3, four control variables were chosen largely based on their direct relationship with heat transfer in the compressor work equation ($T_{ci}$ , $T_{ei}$ , $\dot{m}_c$ , $\dot{m}_e$).[21] Percent operating capacity

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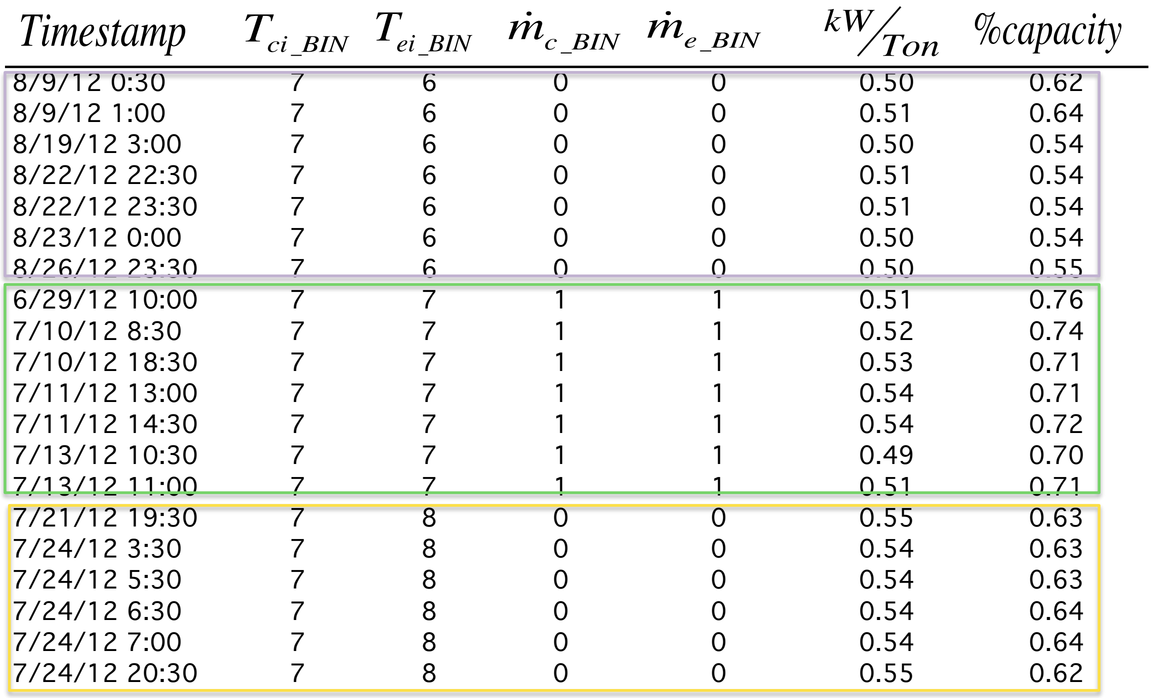
[20] In order to maintain consistency in the energy savings calculation, chiller Nos. 210, 211, 22, and 24 were chosen based on their comparable designs and rated capacities. However, the summarized performance of each chiller still varies due to differences in availability of operating data, which could introduce some error in the energy savings results.

[21] The temperature of evaporator outlet water ($T_{eo}$) and temperature of condenser outlet water ($T_{co}$) could have also been included but were *(continued on bottom of next page…)*

$(\%capacity)$ was then used as the main predictor of chiller performance $(kW/Ton)$.[22]

Using these chosen control variables, smaller data subsets were created by partitioning each control variable into smaller bins. Condenser inlet water temperature $(T_{ci})$ and evaporator inlet water temperature $(T_{ei})$ were both sorted least to greatest (i.e. coolest to warmest) and then partitioned into deciles. Condenser and evaporator flow rates $(\dot{m}_c$ & $\dot{m}_e)$ were also sorted least to greatest and partitioned by their respective medians into a "lower half" and "upper half". The number of partitioning bins was chosen somewhat arbitrarily by starting with the temperature variables and trying to create small enough bin ranges to simulate all types of lift conditions. The flow rate bins were then added by separating each variable only into two bins. This approach was initially used to get a first look at how the flow rates impact predictive model strength and also to again ensure there was sufficient data in each subset. Table 3 shows an example data table generated by this partitioning method. As shown, certain combinations of the $T_{ci}, T_{ei}, \dot{m}_c$ and $\dot{m}_e$ bins have multiple occurrences across the data set, thus creating data subsets representing unique combinations of operating conditions (example of 3 unique subsets shown by highlighted boxes).

TABLE 3. SAMPLE OF DATA SUBSETS.



| Timestamp | $T_{ci\_BIN}$ | $T_{ei\_BIN}$ | $\dot{m}_{c\_BIN}$ | $\dot{m}_{e\_BIN}$ | $kW/Ton$ | %capacity |
|---|---|---|---|---|---|---|
| 8/9/12 0:30 | 7 | 6 | 0 | 0 | 0.50 | 0.62 |
| 8/9/12 1:00 | 7 | 6 | 0 | 0 | 0.51 | 0.64 |
| 8/19/12 3:00 | 7 | 6 | 0 | 0 | 0.50 | 0.54 |
| 8/22/12 22:30 | 7 | 6 | 0 | 0 | 0.51 | 0.54 |
| 8/22/12 23:30 | 7 | 6 | 0 | 0 | 0.51 | 0.54 |
| 8/23/12 0:00 | 7 | 6 | 0 | 0 | 0.50 | 0.54 |
| 8/26/12 23:30 | 7 | 6 | 0 | 0 | 0.50 | 0.55 |
| 6/29/12 10:00 | 7 | 7 | 1 | 1 | 0.51 | 0.76 |
| 7/10/12 8:30 | 7 | 7 | 1 | 1 | 0.52 | 0.74 |
| 7/10/12 18:30 | 7 | 7 | 1 | 1 | 0.53 | 0.71 |
| 7/11/12 13:00 | 7 | 7 | 1 | 1 | 0.54 | 0.71 |
| 7/11/12 14:30 | 7 | 7 | 1 | 1 | 0.54 | 0.72 |
| 7/13/12 10:30 | 7 | 7 | 1 | 1 | 0.49 | 0.70 |
| 7/13/12 11:00 | 7 | 7 | 1 | 1 | 0.51 | 0.71 |
| 7/21/12 19:30 | 7 | 8 | 0 | 0 | 0.55 | 0.63 |
| 7/24/12 3:30 | 7 | 8 | 0 | 0 | 0.54 | 0.63 |
| 7/24/12 5:30 | 7 | 8 | 0 | 0 | 0.54 | 0.63 |
| 7/24/12 6:30 | 7 | 8 | 0 | 0 | 0.54 | 0.64 |
| 7/24/12 7:00 | 7 | 8 | 0 | 0 | 0.54 | 0.64 |
| 7/24/12 20:30 | 7 | 8 | 0 | 0 | 0.55 | 0.62 |

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left out to maintain large enough data subsets and because both are more of a result of chiller operation and not necessarily an independent operating condition.

[22] Appendix C contains a flow diagram that was created to understand the primary, secondary, and tertiary relationships between different available data points.

The benefit of these data subsets is that they make it possible to control for the effect of both water temperatures and flow rates on efficiency, while still exploring the relationship between $\%capacity$ and $kW/Ton$. In order to model the relationship between the predictor variable ($\%capacity$) and the response variable ($kW/Ton$) a regression model was created for each unique data subset. For example, using the data in subset [7, 6, 0, 0] from Table 3, one can regress $kW/Ton$ on $\%capacity$ in order to find if there is some linear relationship between the two variables. Since subset [7, 6, 0, 0] represents smaller intervals of each control variable we have effectively controlled for the influence those variables have on chiller performance. Table 4 provides performance prediction model results for a sample of the possible subsets for a single variable speed chiller, No. 211.[23]

TABLE 4. SAMPLE OF PERFORMANCE PREDICTION MODELS FOR CHILLER NO. 211

| $T_{ci\_BIN}$ | $T_{ei\_BIN}$ | $\dot{m}_{c\_BIN}$ | $\dot{m}_{e\_BIN}$ | $T_{ci,\min}$ | $T_{ci,\max}$ | $T_{ei,\min}$ | $T_{ei,\max}$ | $\dot{m}_{c,\min}$ | $\dot{m}_{c,\max}$ | $\dot{m}_{e,\min}$ | $\dot{m}_{e,\max}$ | $N$ | $R^2$ | Pvalue | $\beta$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 54.3 | 54.4 | 47.5 | 47.7 | 8081 | 8282 | 3719 | 4387 | 10 | 0.15 | 0.275 | 0.46 | 0.07 |
| 0 | 1 | 0 | 1 | 53.3 | 54.4 | 47.5 | 47.7 | 8034 | 8285 | 4469 | 7470 | 91 | 0.22 | 0.000 | 0.22 | 0.18 |
| 0 | 3 | 0 | 0 | 53.4 | 54.4 | 48 | 48.3 | 8041 | 8285 | 3866 | 4267 | 11 | 0.58 | 0.007 | 0.25 | 0.15 |
| 0 | 3 | 0 | 1 | 53.8 | 54.4 | 48 | 48.3 | 8060 | 8285 | 4436 | 5552 | 75 | 0.68 | 0.000 | 0.33 | 0.11 |
| 0 | 5 | 0 | 0 | 53.6 | 54.4 | 49.3 | 50.8 | 7997 | 8283 | 3233 | 4371 | 39 | 0.69 | 0.000 | 0.26 | 0.15 |
| 0 | 5 | 0 | 1 | 53.7 | 54.4 | 49.3 | 50.7 | 8057 | 8285 | 4436 | 6205 | 30 | 0.76 | 0.000 | 0.33 | 0.11 |
| 0 | 1 | 1 | 0 | 54.3 | 54.4 | 47.5 | 47.7 | 8298 | 8603 | 4119 | 4432 | 23 | 0.07 | 0.217 | 0.23 | 0.16 |
| 0 | 1 | 1 | 1 | 54 | 54.4 | 47.5 | 47.7 | 8287 | 8630 | 4433 | 7572 | 116 | 0.76 | 0.000 | 0.27 | 0.14 |
| 0 | 3 | 1 | 0 | 53.7 | 54.4 | 48 | 48.3 | 8290 | 8832 | 3744 | 4432 | 71 | 0.42 | 0.000 | 0.38 | 0.10 |
| 0 | 3 | 1 | 1 | 53.5 | 54.4 | 48 | 48.3 | 8289 | 8669 | 4433 | 5547 | 142 | 0.34 | 0.000 | 0.24 | 0.16 |
| 0 | 5 | 1 | 0 | 53.3 | 54.4 | 49.3 | 50.7 | 8287 | 8649 | 3230 | 4406 | 66 | 0.45 | 0.000 | 0.24 | 0.16 |
| 0 | 5 | 1 | 1 | 54 | 54.4 | 49.3 | 50.8 | 8291 | 8741 | 4448 | 5925 | 22 | 0.65 | 0.000 | 0.38 | 0.07 |
| 4 | 1 | 0 | 0 | 54.7 | 54.8 | 47.5 | 47.7 | 8245 | 8286 | 4079 | 4432 | 7 | 0.30 | 0.202 | 0.23 | 0.16 |
| 4 | 1 | 0 | 1 | 54.7 | 55.8 | 47.5 | 47.7 | 8027 | 8286 | 4485 | 7954 | 121 | 0.96 | 0.000 | 0.30 | 0.13 |
| 4 | 3 | 0 | 0 | 54.7 | 55.4 | 48 | 48.3 | 8085 | 8274 | 3711 | 4411 | 14 | 0.26 | 0.063 | 0.17 | 0.19 |
| 4 | 3 | 0 | 1 | 54.7 | 55.8 | 48 | 48.3 | 8074 | 8285 | 4448 | 7823 | 166 | 0.85 | 0.000 | 0.33 | 0.12 |
| 4 | 5 | 0 | 0 | 54.7 | 55.7 | 49.3 | 50.8 | 8050 | 8281 | 3053 | 4432 | 39 | 0.76 | 0.000 | 0.31 | 0.13 |
| 4 | 5 | 0 | 1 | 54.7 | 55.8 | 49.3 | 50.8 | 8027 | 8285 | 4445 | 7102 | 59 | 0.86 | 0.000 | 0.33 | 0.11 |
| 4 | 1 | 1 | 0 | 54.7 | 55.1 | 47.5 | 47.7 | 8315 | 8686 | 3921 | 4379 | 14 | 0.02 | 0.592 | -0.56 | 0.50 |
| 4 | 1 | 1 | 1 | 54.7 | 55.8 | 47.5 | 47.7 | 8287 | 8607 | 4466 | 7954 | 151 | 0.57 | 0.000 | 0.31 | 0.13 |
| 4 | 3 | 1 | 0 | 54.7 | 55.8 | 48 | 48.3 | 8293 | 8674 | 3704 | 4424 | 40 | 0.24 | 0.001 | 0.43 | 0.08 |
| 4 | 3 | 1 | 1 | 54.7 | 55.8 | 48 | 48.3 | 8287 | 8741 | 4435 | 6545 | 244 | 0.66 | 0.000 | 0.29 | 0.14 |
| 4 | 5 | 1 | 0 | 54.7 | 55.8 | 49.3 | 50.7 | 8288 | 8655 | 3050 | 4431 | 47 | 0.35 | 0.000 | 0.20 | 0.19 |
| 4 | 5 | 1 | 1 | 54.7 | 55.8 | 49.3 | 50.8 | 8289 | 8674 | 4507 | 6760 | 52 | 0.76 | 0.000 | 0.31 | 0.12 |
| 6 | 5 | 0 | 0 | 63 | 64.8 | 50 | 50.8 | 8205 | 8282 | 4187 | 4409 | 9 | 0.29 | 0.137 | 0.21 | 0.25 |
| 6 | 5 | 0 | 1 | 63 | 67.7 | 49.3 | 50.8 | 8166 | 8284 | 4460 | 7437 | 21 | 0.71 | 0.000 | 0.43 | 0.12 |
| 6 | 7 | 0 | 0 | 70.1 | 71.8 | 52.9 | 53.4 | 4778 | 7010 | 3103 | 3569 | 109 | 0.19 | 0.000 | 0.50 | 0.21 |
| 6 | 7 | 0 | 1 | 66.5 | 68.3 | 52.9 | 53.2 | 8240 | 8286 | 5366 | 5615 | 5 | 0.44 | 0.222 | -0.63 | 1.06 |
| 6 | 5 | 1 | 0 | 63 | 69.4 | 49.9 | 50.8 | 8299 | 8820 | 3192 | 4421 | 161 | 0.19 | 0.000 | 0.20 | 0.27 |
| 6 | 5 | 1 | 1 | 63 | 67.2 | 49.3 | 50.8 | 8289 | 8587 | 4433 | 6584 | 91 | 0.79 | 0.000 | 0.35 | 0.17 |
| 6 | 7 | 1 | 0 | 67.8 | 71.2 | 52.9 | 53.4 | 8447 | 8881 | 3697 | 4425 | 28 | 0.48 | 0.000 | 0.38 | 0.20 |
| 6 | 7 | 1 | 1 | 65.5 | 71.7 | 52.9 | 53.2 | 8344 | 8603 | 4462 | 5750 | 27 | 0.39 | 0.000 | 0.19 | 0.34 |
| 8 | 7 | 0 | 0 | 75.3 | 77.6 | 53.1 | 53.6 | 6721 | 7121 | 3321 | 4285 | 289 | 0.01 | 0.137 | 0.03 | 0.52 |
| 8 | 9 | 0 | 0 | 75.6 | 77.6 | 54.3 | 54.8 | 4762 | 7163 | 3523 | 4408 | 247 | 0.71 | 0.000 | 0.78 | 0.04 |
| 8 | 9 | 0 | 1 | 77.2 | 77.6 | 54.3 | 54.6 | 4754 | 4886 | 4454 | 4523 | 8 | 0.06 | 0.570 | 0.17 | 0.52 |
| 8 | 7 | 1 | 0 | 75.3 | 77.6 | 52.9 | 53.6 | 8448 | 8880 | 3668 | 4367 | 183 | 0.41 | 0.000 | 0.30 | 0.32 |
| 8 | 7 | 1 | 1 | 75.6 | 75.7 | 53.5 | 53.5 | 8770 | 8783 | 4769 | 5034 | 2 | - | - | - | - |
| 8 | 9 | 1 | 0 | 76.8 | 77.6 | 54.3 | 54.3 | 8519 | 8826 | 4136 | 4411 | 6 | 0.17 | 0.416 | 0.18 | 0.42 |
| 8 | 9 | 1 | 1 | 77.1 | 77.1 | 54.3 | 54.3 | 8735 | 8735 | 4628 | 4628 | 1 | - | - | - | - |

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[23] Sample set shown in Table 4 was generated by filtering out odd condenser temperature bins, even evaporator temperature bins, and all bins containing no data.

In total, chiller No. 211 data fell into 167 of the 400 possible subsets (i.e. combinations of control variable bins). Within those 167 subsets, 80% of the data was in a subset with N > 25 and regression results of $R^2 > 0.2$ and $P < 0.001$. In fact, much of the data fell in subsets with performance prediction models of N > 25 and $R^2 > 0.5$ (50%), $R^2 > 0.75$ (18%) and $R^2 > 0.9$ (9%), suggesting a somewhat predictable relationship between $kW/Ton$ and $\%capacity$ when controlling for the other influencing factors. Similar but not quite as strong of results were found for chiller No. 210, 22, and 24. For these chillers, approximately 50% of the data fell in subsets with performance prediction models of N > 25 and $R^2 > 0.2$. Chiller No. 210 is known to have issues with sediment build-up in its condenser pipes, causing irregular performance that could potentially have reduced predictability. Chiller Nos. 22 and 24 had significantly less operating data in the time period under question, which could also be a reason for reduced predictability. Sample performance prediction model results for chiller Nos. 210, 22, and 24 are given in Appendix D.

### 3.3.2 Model Validation

Based on the aforementioned factors influencing chiller performance (Sections 2.1 – 2.3) and the basic analysis findings (Section 3.2), some general observations can be used to validate the performance prediction modeling results. A closer look at the modeling results, which are summarized in Table 5, demonstrates that both variable speed (No. 211) and fixed speed (No. 22) chillers perform best in the lower end of condenser inlet water temperatures, as one would expect in low lift conditions.

TABLE 5: AVERAGE POWER INPUT PER CAPACITY AS LIFT INCREASES

|  | $T_{ci\_BIN}$ | Average VSD kW/Ton | Average FSD kW/Ton |
|---|---|---|---|
| *Coolest >* | 0 | 0.28 | 0.43 |
|  | 1 | 0.28 | 0.44 |
|  | 2 | 0.28 | 0.44 |
|  | 3 | 0.30 | 0.43 |
|  | 4 | 0.35 | 0.47 |
|  | 5 | 0.39 | 0.54 |
|  | 6 | 0.48 | 0.58 |
|  | 7 | 0.62 | 0.66 |
|  | 8 | 0.55 | 0.67 |
| *Warmest >* | 9 | 0.58 | 0.68 |

This relationship is also demonstrated in Figure 2, which provides the example of a variable and fixed speed chiller operating in two unique subsets, one representing low lift conditions and the other representing high lift conditions. Subset [0, 0, 1, 1] represents a condenser inlet temperature range of 53.8 to 54.4 °F, evaporator inlet temperature range of 46.8 to 47.4 °F, condenser flow rate in the upper half of its possible range, and also evaporator flow rate in the upper half of its possible range.

Subset [9, 8, 1, 1] then represents a condenser inlet temperature range of 78.3 to 80.6 °F, evaporator inlet temperature range of 54.0 to 54.3 °F, condenser flow rate in the upper half of its possible range, and also evaporator flow rate in the upper have of its possible range.

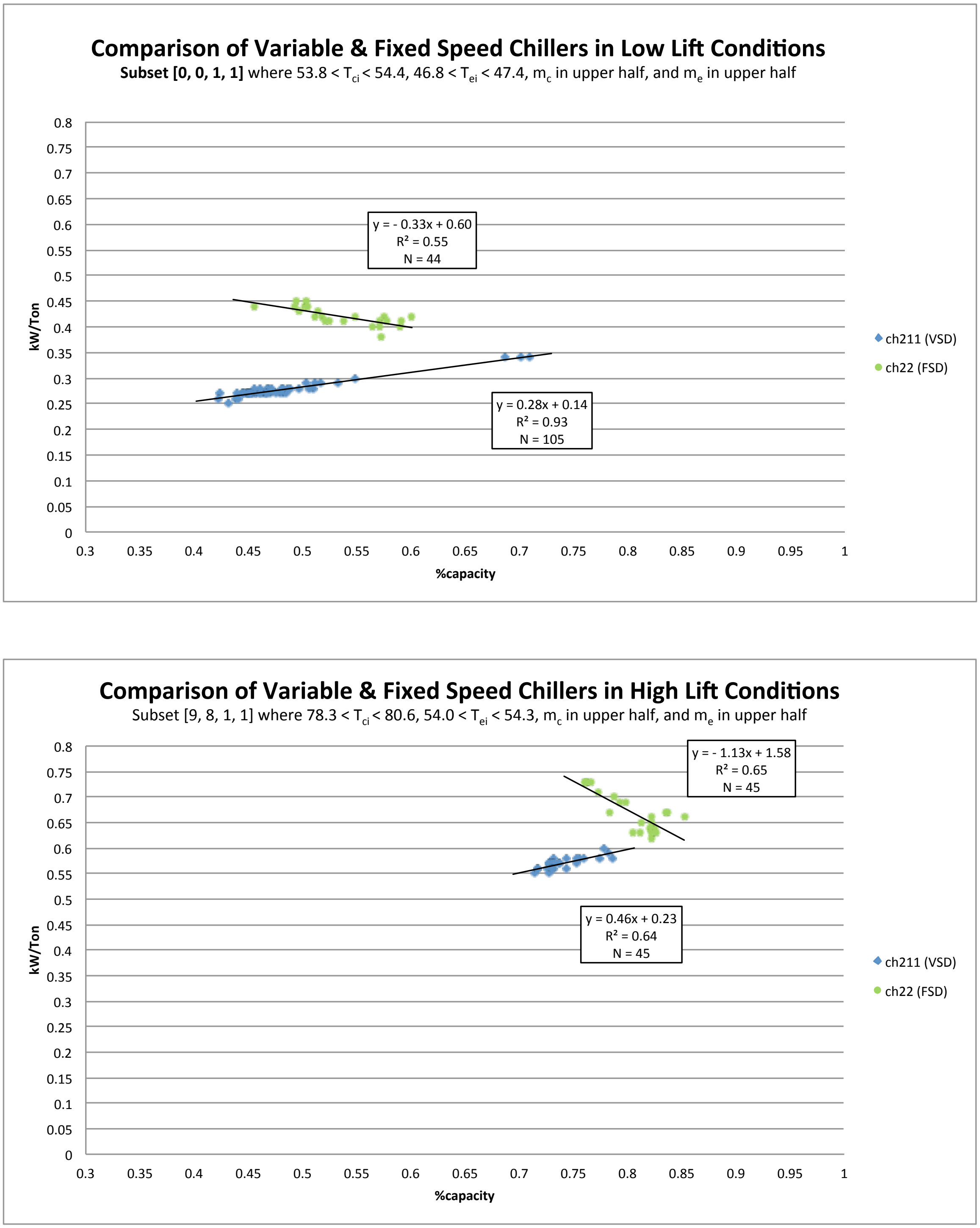

FIGURE 2. CHILLER NO. 211 (VSD) & CHILLER NO. 22 (FSD) COMBINED REGRESSION PLOTS UNDER LOW AND HIGH LIFT CONDITIONS

While Figure 2 only represents two of the total 167 subsets containing data, it still demonstrates that both fixed and variable speed chillers shift into a region of decreased performance or increased $kW/Ton$ as lift increases. It should also be noted that there is a lack of operating data in the high lift – low %capacity range and vice versa. This is partially because high lift conditions tend to correlate with high "system load" conditions, meaning that chillers have been running at higher $\%capacity$. However, this is also due to the fact that evaporator flow rate and evaporator leaving temperature set a limit on the range of attainable $\%capacity$, as was discussed in the end of Section 2.3.

A second model validating observation is that variable speed chiller performance improves as $\%capacity$ decreases and fixed speed chiller performance improves as $\%capacity$ increases. This can be verified with Figure 2 and also by taking a look at the sample of regression modeling results in Table 4 (see Appendix D for fixed speed chiller results). For each subset with $N > 25$ and $R^2 > 0.2$ the variable speed regression model is positively sloping, showing that $kW/Ton$ performance becomes worse with increased $\%capacity$. The results also show that fixed speed regression models are negatively sloping for each subset, demonstrating their lack of compressor speed control.

### 3.3.3 Energy Savings Estimation

In an attempt to validate the energy savings calculation in Section 3.2, one variable speed chiller and one fixed speed chiller were compared during the same time intervals. Using the bin ranges created for chiller No. 211, data was added for a closely sized fixed speed chiller, No. 22. Regression models were then developed within each subset for the fixed speed chiller. Using this combined data set, a hypothetical energy usage scenario was developed by inputting the operational data of chiller No. 211 ($\%capacity$) into the regression model ($kW/Ton = \beta * \%capacity + \alpha$) for chiller No. 22, resulting in a prediction of hypothetical fixed speed chiller $kW/Ton$ performance for each data point. By calculating the difference in energy consumption of the hypothetical fixed speed chiller and actual variable speed chiller (using similar methods to Section 3.2) we find an estimated energy savings of approximately 2.3M kWh per year per variable speed chiller, comparable to the findings in Section 3.2.[24]

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[24] Due to the fact that fixed speed chillers in CCWP2 were operated much less often than variable speed chillers over this time period, there is a significant reduction in operational data that is represented by a strong regression model for both the variable and fixed speed chiller (about 10% of the possible operating hours in a year). This is due to the fact that only a nine-month data set was used and the fixed speed chiller was only operational for about half of that time interval. In addition, some of the data was also cleaned for measurement errors. However, the data still seem to account for the wide range of potential operating conditions.

# 4. Results

## 4.1 Variable Speed Chiller Energy Savings

From the results in Sections 3.2 and 3.3.3, it has been determined that variable speed chiller energy savings are about 60% higher than initial planning estimates, at around 2.2M kWh per year per VSD. The equivalent yearly $CO_2$ reduction from operating the two variable speed chillers is equal to about 460 typical homes.[25] From environmental and utility planning perspectives this is definitely a great finding. Given Duke University's Climate Action Plan to be carbon neutral by 2024, a reduction of this size is a great first step. However, before upgrading all chillers with variable speed drives more detailed analyses will be needed to determine the actual incremental dollar value. Lastly, while this energy savings finding was confirmed through two unique analyses it should also be re-confirmed as more operational data becomes available in the future.

## 4.2 Fixed and Variable Speed Chiller Performance Prediction Models

This study also confirms that fixed and variable speed chiller performance can be modeled across a wide range of operating conditions. The study demonstrates the underlying functionality of fixed and variable speed chillers in two ways. First, it was demonstrated that both fixed and variable speed chiller performance improves as lift is reduced. Second, it was demonstrated that variable speed chiller performance improves as operating capacity is decreased, due to the ability to reduce compressor speed and therefore power input. It was also demonstrated that fixed speed chiller performance improves as operating capacity increases, due to the lack of compressor speed control and reliance on inlet guide vanes for control. The unique visualization of operational performance generated by this analysis will be very useful for plant operators trying to more clearly understand how their system should be operating.

# 5. Discussion

## 5.1 Model Refinement

According to the Lee, Liao, and Lu in their review of centrifugal chiller performance modeling methods, "Ideal empirical performance prediction models for water chillers must have the characteristics of high prediction accuracy, simple model training, small training data sets, good model suitability, and the ability to physically interpret the model regression coefficients."[26] While the models developed in this study meet these criteria, improvements and refinement in the modeling technique can still be made to improve prediction accuracy. One such adjustment could be to

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[25] According to the U.S. EPA Greenhouse Gas Equivalencies Calculator.

[26] Lee, Tzong-Shing, Ke-Yang Liao, and Wan-Chen Lu. "Evaluation of the suitability of empirically-based models for predicting energy performance of centrifugal water chillers with variable chilled water flow". Applied Energy, 30 12 2011. Web. 3 Mar 2013.

further remove a number of outliers in the low and high *%capacity* range. Looking through the regression results for each subset, there also appears to be a few potential measurement errors that reduce the strength of the otherwise close-fitting regression model in a handful of subsets (i.e. data points with much larger than average residuals from the least squares regression line). Lastly, it may also be found that additional control variables or further adjustment of control variable bin sizes will lead to more accurate predictions of performance.

## 5.2 Future Research Projects

This type of analysis or analyses similar to this one could also be very valuable for Duke University's other utilities, in particular the steam plant. Having a clearer understanding of any thermodynamic machine's performance under different operating conditions is extremely valuable for providing more effective and potentially more efficient utility services. Duke Utility & Engineering Services is eager to start new research projects with the potential to improve utility services. Interested students should follow up with DUES or myself with research ideas or to discuss existing research needs. Contact information is provided below.

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## 5.3 Acknowledgements

I would first like to thank Steve Palumbo, Casey Collins, Tom Young, and Dennis Woody from Duke Utility & Engineering Services for this opportunity and their assistance in understanding this multifaceted chilled water system. Steve and Casey were the two individuals with the vision to take on this project and I am thankful for being the person to receive that opportunity. Tom and Dennis were also instrumental in providing access and understanding to the extensive set of available chilled water plant data.

I would also like to thank my advisors Prof. Daniel Egger and Prof. Dalia Patiño-Echeverri for all their advice and expertise with complex modeling projects. Prof. Patiño-Echeverri's early advice for how to approach such a research question was instrumental in the success of the project. Prof. Egger's suggested modeling approach was then the key insight that made the analysis come to fruition. This project could not have been possible without their guidance and I am truly grateful for the opportunity to learn from these two gifted individuals.

Lastly, I would like to thank my friends Micah Johnson and Gustav Bernard for their assistance with writing the code that made this analysis happen, I couldn't have done it without them.

## Appendix A - Data Cleansing Methods

Range constraints:

- $0.05 < kW/Ton < 1$
- 40°F < $T_{ei}$ < 60°F
- 50°F < $T_{ci}$ < 100°F
- $\%Capacity$ > 35% (due to a high number of outliers in the lower range)

Cross-field constraints:

- $Load\ [Tons] \approx c_p \dot{m}_e (T_{ei} - T_{eo})/12{,}000\, BTU \cdot hr\ /\ Ton$
- $\Sigma\ Individual\ Chiller\ Loads = Total\ Plant\ Load$
- Measurements should not repeat for more than 20 consecutive 15-min time intervals, which may signify a string of measurement errors.

# Appendix B - Basic Savings Estimation Tables

*Chiller 210 (VSD)*

| $T_{ci}$ **(F)** | **55 - 58** | **58 - 60** | **60 - 63** | **63 - 65** | **65 - 68** | **68 - 70** | **70 - 75** | **75 - 80** | **80 - 85** |
|---|---|---|---|---|---|---|---|---|---|
| **% Capacity** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** | **210 Avg. kW/Ton** |
| 0 - 30% | - | - | - | - | - | - | - | - | - |
| 30 - 40% | 0.31 | 0.33 | 0.36 | 0.37 | 0.33 | 0.45 | - | - | - |
| 40 - 50% | 0.28 | 0.32 | 0.34 | 0.36 | 0.32 | 0.37 | 0.30 | - | - |
| 50 - 60% | 0.30 | 0.33 | 0.35 | 0.37 | 0.39 | 0.42 | 0.44 | 0.55 | - |
| 60 - 70% | 0.32 | 0.35 | 0.38 | 0.39 | 0.41 | 0.43 | 0.46 | 0.59 | 0.78 |
| 70 - 80% | 0.35 | 0.38 | 0.39 | 0.42 | 0.44 | 0.46 | 0.49 | 0.55 | 0.58 |
| 80 - 90% | 0.39 | 0.42 | 0.43 | 0.45 | 0.48 | 0.47 | 0.50 | 0.58 | 0.60 |
| 90 - 100% | 0.47 | 0.45 | 0.48 | 0.50 | 0.51 | 0.52 | 0.52 | 0.59 | 0.61 |

*Chiller 211 (VSD)*

| $T_{ci}$ **(F)** | **55 - 58** | **58 - 60** | **60 - 63** | **63 - 65** | **65 - 68** | **68 - 70** | **70 - 75** | **75 - 80** | **80 - 85** |
|---|---|---|---|---|---|---|---|---|---|
| **% Capacity** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** | **211 Avg. kW/Ton** |
| 0 - 30% | - | - | - | - | - | - | - | - | - |
| 30 - 40% | 0.33 | 0.35 | 0.35 | 0.38 | 0.40 | 0.49 | - | - | - |
| 40 - 50% | 0.30 | 0.36 | 0.37 | 0.39 | 0.42 | 0.45 | 0.46 | - | - |
| 50 - 60% | 0.32 | 0.38 | 0.38 | 0.40 | 0.43 | 0.46 | 0.49 | 0.52 | - |
| 60 - 70% | 0.35 | 0.40 | 0.42 | 0.43 | 0.45 | 0.47 | 0.51 | 0.55 | 0.60 |
| 70 - 80% | 0.39 | 0.43 | 0.45 | 0.46 | 0.48 | 0.50 | 0.55 | 0.60 | 0.62 |
| 80 - 90% | 0.45 | 0.48 | 0.51 | 0.52 | 0.53 | 0.53 | 0.54 | 0.64 | 0.65 |
| 90 - 100% | 0.52 | 0.56 | 0.55 | 0.62 | 0.59 | 0.58 | 0.61 | 0.65 | - |

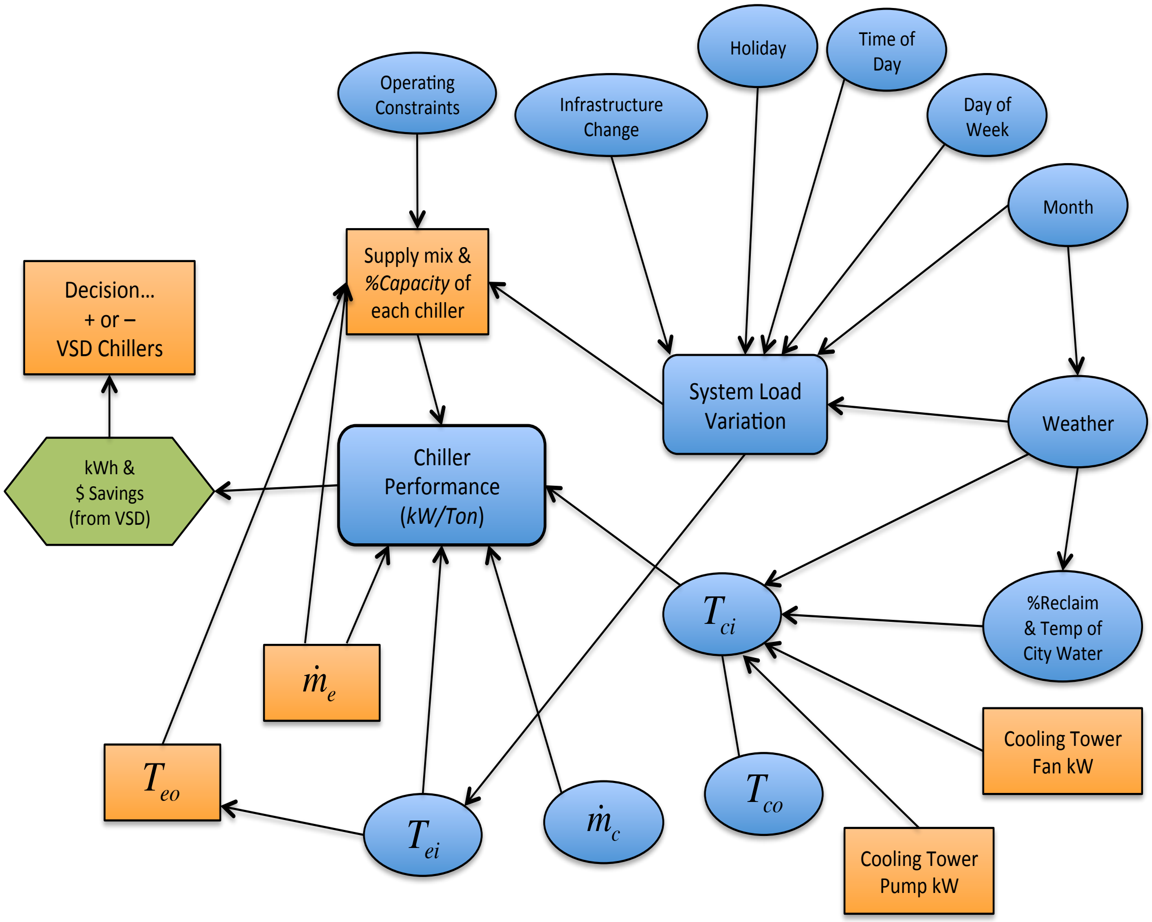
*Chiller 22 (FSD)*

| $T_{ci}$ **(F)** | **55 - 58** | **58 - 60** | **60 - 63** | **63 - 65** | **65 - 68** | **68 - 70** | **70 - 75** | **75 - 80** | **80 - 85** |
|---|---|---|---|---|---|---|---|---|---|
| **% Capacity** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** | **22 Avg. kW/Ton** |
| 0 - 30% | - | - | - | - | - | - | - | - | - |
| 30 - 40% | 0.51 | 0.50 | 0.55 | 0.58 | 0.51 | 0.56 | 0.51 | - | - |
| 40 - 50% | 0.48 | 0.49 | 0.53 | 0.55 | 0.53 | 0.51 | 0.49 | - | - |
| 50 - 60% | 0.46 | 0.46 | 0.49 | 0.53 | 0.53 | 0.56 | 0.57 | - | - |
| 60 - 70% | 0.46 | 0.46 | 0.49 | 0.51 | 0.53 | 0.54 | 0.59 | 0.62 | - |
| 70 - 80% | 0.47 | 0.46 | 0.47 | 0.51 | 0.54 | 0.55 | 0.59 | 0.63 | 0.69 |
| 80 - 90% | - | 0.49 | 0.51 | 0.51 | 0.54 | 0.55 | 0.60 | 0.64 | 0.67 |
| 90 - 100% | - | 0.50 | 0.53 | - | - | 0.52 | - | 0.61 | 0.63 |

*Chiller 24 (FSD)*

| $T_{ci}$ **(F)** | **55 - 58** | **58 - 60** | **60 - 63** | **63 - 65** | **65 - 68** | **68 - 70** | **70 - 75** | **75 - 80** | **80 - 85** |
|---|---|---|---|---|---|---|---|---|---|
| **% Capacity** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** | **24 Avg. kW/Ton** |
| 0 - 30% | - | - | - | - | - | - | - | - | - |
| 30 - 40% | - | 0.39 | 0.42 | 0.50 | 0.47 | 0.54 | 0.62 | - | - |
| 40 - 50% | 0.45 | 0.47 | 0.48 | 0.49 | 0.49 | 0.59 | 0.64 | - | - |
| 50 - 60% | 0.48 | 0.49 | 0.50 | 0.53 | 0.55 | 0.59 | 0.65 | 0.65 | - |
| 60 - 70% | 0.47 | 0.49 | 0.51 | 0.52 | 0.56 | 0.57 | 0.63 | 0.67 | 0.73 |
| 70 - 80% | 0.47 | 0.52 | 0.53 | 0.51 | 0.56 | 0.58 | 0.62 | 0.69 | 0.74 |
| 80 - 90% | - | 0.53 | - | - | - | 0.61 | 0.64 | 0.68 | - |
| 90 - 100% | - | - | - | - | - | - | - | - | - |

# Appendix C - Flow Diagram Used For Control Variable Selection



**Rectangular figures represent decision variables, rounded figures represent probabilistic variables, and the hexagon represents a measured benefit.*

# Appendix D - Performance Prediction Model Sample Results

*Chiller 210*

| $T_{ci\_BIN}$ | $T_{ei\_BIN}$ | $\dot{m}_{c\_BIN}$ | $\dot{m}_{e\_BIN}$ | $T_{ci,\min}$ | $T_{ci,\max}$ | $T_{ei,\min}$ | $T_{ei,\max}$ | $\dot{m}_{c,\min}$ | $\dot{m}_{c,\max}$ | $\dot{m}_{e,\min}$ | $\dot{m}_{e,\max}$ | $N$ | $R^2$ | Pvalue | $\beta$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 54.7 | 54.7 | 47.6 | 47.7 | 8937 | 9259 | 3982 | 4484 | 19 | 0.02 | 0.617 | -0.05 | 0.30 |
| 0 | 1 | 0 | 1 | 54.3 | 54.7 | 47.6 | 47.7 | 8873 | 9290 | 4537 | 5493 | 88 | 0.01 | 0.301 | -0.07 | 0.30 |
| 0 | 3 | 0 | 0 | 53.7 | 54.7 | 48.1 | 48.5 | 8654 | 9289 | 3627 | 4491 | 59 | 0.01 | 0.408 | -0.08 | 0.30 |
| 0 | 3 | 0 | 1 | 52.6 | 54.7 | 48.1 | 48.5 | 8734 | 9290 | 4498 | 5717 | 138 | 0.03 | 0.043 | -0.07 | 0.32 |
| 0 | 5 | 0 | 0 | 53.7 | 54.7 | 49.8 | 51.1 | 8712 | 9287 | 3380 | 4492 | 39 | 0.35 | 0.000 | 0.28 | 0.15 |
| 0 | 5 | 0 | 1 | 54.2 | 54.7 | 49.8 | 50.8 | 8792 | 9246 | 4586 | 6141 | 19 | 0.58 | 0.000 | 0.41 | 0.05 |
| 0 | 1 | 1 | 0 | 54.4 | 54.7 | 47.6 | 47.7 | 9295 | 9758 | 4052 | 4483 | 31 | 0.07 | 0.161 | 0.64 | -0.02 |
| 0 | 1 | 1 | 1 | 54.2 | 54.7 | 47.6 | 47.7 | 9294 | 9892 | 4499 | 5743 | 142 | 0.05 | 0.006 | -0.21 | 0.37 |
| 0 | 3 | 1 | 0 | 53.9 | 54.7 | 48.1 | 48.5 | 9293 | 9839 | 3803 | 4462 | 90 | 0.09 | 0.005 | -0.58 | 0.52 |
| 0 | 3 | 1 | 1 | 53.1 | 54.7 | 48.1 | 48.5 | 9293 | 9863 | 4498 | 7809 | 201 | 0.04 | 0.006 | -0.17 | 0.37 |
| 0 | 5 | 1 | 0 | 54.3 | 54.7 | 49.8 | 50.7 | 9296 | 9697 | 3377 | 4486 | 23 | 0.16 | 0.062 | 0.18 | 0.18 |
| 0 | 5 | 1 | 1 | 54.5 | 54.7 | 49.8 | 50.7 | 9329 | 9743 | 4547 | 6365 | 13 | 0.81 | 0.000 | 0.42 | 0.04 |
| 4 | 1 | 0 | 0 | 55.1 | 55.1 | 47.7 | 47.7 | 9289 | 9289 | 4277 | 4277 | 1 | - | - | - | - |
| 4 | 1 | 0 | 1 | 55.1 | 57.3 | 47.6 | 47.7 | 9106 | 9285 | 4685 | 5589 | 31 | 0.01 | 0.602 | -0.09 | 0.33 |
| 4 | 3 | 0 | 0 | 55.1 | 56.9 | 48.1 | 48.5 | 7336 | 9278 | 3879 | 4397 | 12 | 0.31 | 0.062 | 0.52 | 0.05 |
| 4 | 3 | 0 | 1 | 55.1 | 57.7 | 48.1 | 48.5 | 8712 | 9290 | 4499 | 6590 | 131 | 0.04 | 0.018 | 0.08 | 0.25 |
| 4 | 5 | 0 | 0 | 55.1 | 57.9 | 49.8 | 51.2 | 8787 | 9290 | 3143 | 4457 | 51 | 0.49 | 0.000 | 0.32 | 0.14 |
| 4 | 5 | 0 | 1 | 55.1 | 57.9 | 49.8 | 51.2 | 8703 | 9291 | 4517 | 6904 | 79 | 0.60 | 0.000 | 0.36 | 0.10 |
| 4 | 1 | 1 | 0 | 55.1 | 55.1 | 47.6 | 47.6 | 9665 | 9665 | 4235 | 4235 | 1 | - | - | - | - |
| 4 | 1 | 1 | 1 | 55.1 | 57.3 | 47.6 | 47.7 | 9298 | 9834 | 4552 | 5760 | 48 | 0.16 | 0.004 | -0.46 | 0.53 |
| 4 | 3 | 1 | 0 | 55.1 | 57.2 | 48.1 | 48.5 | 9302 | 9782 | 3692 | 4474 | 44 | 0.15 | 0.010 | 0.39 | 0.08 |
| 4 | 3 | 1 | 1 | 55.1 | 57.9 | 48.1 | 48.5 | 9293 | 11069 | 4533 | 7826 | 190 | 0.09 | 0.000 | 0.15 | 0.21 |
| 4 | 5 | 1 | 0 | 55.1 | 57.9 | 49.8 | 51.1 | 9308 | 9833 | 2997 | 4476 | 86 | 0.64 | 0.000 | 0.30 | 0.13 |
| 4 | 5 | 1 | 1 | 55.1 | 57.9 | 49.8 | 51.2 | 9293 | 9873 | 4574 | 7024 | 97 | 0.82 | 0.000 | 0.38 | 0.07 |
| 6 | 5 | 0 | 0 | 64.6 | 67.9 | 50.1 | 51.2 | 7592 | 9290 | 2960 | 4489 | 37 | 0.10 | 0.061 | 0.08 | 0.32 |
| 6 | 5 | 0 | 1 | 64.6 | 69 | 50 | 51.2 | 8858 | 9290 | 4516 | 6153 | 47 | 0.68 | 0.000 | 0.47 | 0.10 |
| 6 | 7 | 0 | 0 | 69.8 | 70.8 | 52.8 | 52.9 | 7607 | 7742 | 3163 | 3463 | 7 | 0.38 | 0.139 | -0.23 | 0.54 |
| 6 | 7 | 0 | 1 | 65 | 68.9 | 52.8 | 53.2 | 8986 | 9249 | 4541 | 5786 | 16 | 0.94 | 0.000 | 0.41 | 0.15 |
| 6 | 5 | 1 | 0 | 64.6 | 68.3 | 50.1 | 51.2 | 9293 | 9939 | 2953 | 4490 | 208 | 0.22 | 0.000 | 0.13 | 0.29 |
| 6 | 5 | 1 | 1 | 64.6 | 69.3 | 49.9 | 51.2 | 9294 | 9516 | 4499 | 6254 | 55 | 0.40 | 0.000 | 0.24 | 0.24 |
| 6 | 7 | 1 | 0 | 65.6 | 70.8 | 52.8 | 53.3 | 9456 | 12312 | 3165 | 4472 | 122 | 0.12 | 0.000 | 0.15 | 0.32 |
| 6 | 7 | 1 | 1 | 68.3 | 70.8 | 52.8 | 53.4 | 9632 | 9921 | 4499 | 5173 | 32 | 0.29 | 0.000 | 0.39 | 0.16 |
| 8 | 7 | 0 | 0 | 75.1 | 77.6 | 53.2 | 53.6 | 5277 | 7976 | 3520 | 4387 | 290 | 0.02 | 0.024 | 0.07 | 0.44 |
| 8 | 9 | 0 | 0 | 76.7 | 77.6 | 54.4 | 54.7 | 5334 | 8075 | 3538 | 4477 | 49 | 0.51 | 0.000 | 0.48 | 0.19 |
| 8 | 9 | 0 | 1 | 77.1 | 77.6 | 54.4 | 54.4 | 5349 | 7958 | 4540 | 4553 | 3 | 0.99 | 0.046 | 5.12 | -3.44 |
| 8 | 7 | 1 | 0 | 75.1 | 77.4 | 53 | 53.6 | 9838 | 10118 | 4052 | 4421 | 27 | 0.20 | 0.000 | 0.28 | 0.29 |
| 8 | 9 | 1 | 0 | 76.1 | 77.6 | 54.4 | 54.9 | 9632 | 10079 | 4157 | 4493 | 112 | 0.20 | 0.000 | 0.30 | 0.28 |
| 8 | 9 | 1 | 1 | 75.9 | 77.6 | 54.4 | 55.2 | 9638 | 10103 | 4499 | 5273 | 57 | 0.65 | 0.000 | 0.51 | 0.10 |

***Chiller 22***

| $T_{ci\_BIN}$ | $T_{ei\_BIN}$ | $\dot{m}_{c\_BIN}$ | $\dot{m}_{e\_BIN}$ | $T_{ci,\min}$ | $T_{ci,\max}$ | $T_{ei,\min}$ | $T_{ei,\max}$ | $\dot{m}_{c,\min}$ | $\dot{m}_{c,\max}$ | $\dot{m}_{e,\min}$ | $\dot{m}_{e,\max}$ | $N$ | $R^2$ | *Pvalue* | $\beta$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 52.76 | 54.06 | 48.3 | 49.3 | 5007 | 5664 | 3493 | 4189 | 81 | 0.62 | 0.000 | -0.54 | 0.72 |
| 0 | 1 | 0 | 1 | 52.62 | 53.93 | 48.9 | 49.2 | 5285 | 5552 | 4344 | 4664 | 5 | 0.24 | 0.399 | -0.32 | 0.63 |
| 0 | 3 | 0 | 0 | 53.08 | 53.64 | 51 | 51.2 | 3775 | 4172 | 3604 | 3613 | 2 | - | - | - | - |
| 0 | 3 | 0 | 1 | 53.45 | 54.06 | 51 | 51.3 | 5146 | 5785 | 4486 | 5699 | 12 | 0.37 | 0.035 | -0.13 | 0.55 |
| 0 | 1 | 1 | 0 | 51.68 | 54.07 | 48.3 | 49.3 | 6997 | 8141 | 3605 | 4279 | 159 | 0.66 | 0.000 | -0.57 | 0.72 |
| 0 | 1 | 1 | 1 | 50.52 | 54.07 | 48.3 | 49.3 | 6404 | 10182 | 4286 | 6356 | 353 | 0.15 | 0.000 | -0.14 | 0.52 |
| 0 | 3 | 1 | 1 | 53.18 | 54.07 | 51.1 | 51.6 | 7709 | 7991 | 6608 | 7507 | 7 | 0.85 | 0.003 | -0.94 | 1.32 |
| 2 | 1 | 0 | 0 | 56.46 | 60.17 | 48.9 | 49.3 | 4059 | 5786 | 3042 | 4227 | 35 | 0.29 | 0.001 | -0.30 | 0.63 |
| 2 | 1 | 0 | 1 | 57.09 | 58.66 | 48.4 | 49.2 | 3851 | 5180 | 4388 | 5170 | 2 | - | - | - | - |
| 2 | 3 | 0 | 0 | 57.5 | 61.51 | 51 | 51.9 | 4324 | 5807 | 2881 | 4283 | 124 | 0.32 | 0.000 | -0.22 | 0.61 |
| 2 | 3 | 0 | 1 | 58.41 | 61.36 | 51 | 51.6 | 4965 | 5660 | 4325 | 5067 | 6 | 0.64 | 0.054 | -0.32 | 0.75 |
| 2 | 5 | 0 | 0 | 57.62 | 61.04 | 52.8 | 52.9 | 5136 | 5694 | 3225 | 4258 | 6 | 0.90 | 0.004 | -0.29 | 0.68 |
| 2 | 1 | 1 | 0 | 56.46 | 60.98 | 48.3 | 49.3 | 5846 | 9646 | 3312 | 4273 | 114 | 0.44 | 0.000 | -0.60 | 0.78 |
| 2 | 1 | 1 | 1 | 56.52 | 61.52 | 48.3 | 49.3 | 7147 | 7809 | 4293 | 6868 | 106 | 0.07 | 0.008 | -0.10 | 0.55 |
| 2 | 3 | 1 | 0 | 56.62 | 61.43 | 51 | 51.9 | 5835 | 7911 | 2905 | 4273 | 32 | 0.04 | 0.246 | -0.11 | 0.54 |
| 2 | 3 | 1 | 1 | 56.69 | 61.44 | 51 | 51.9 | 5817 | 9026 | 4299 | 8449 | 40 | 0.32 | 0.000 | 0.14 | 0.42 |
| 2 | 5 | 1 | 0 | 58.83 | 60.93 | 52.8 | 53.1 | 7147 | 7351 | 4110 | 4274 | 7 | 0.00 | 0.994 | 0.00 | 0.51 |
| 2 | 5 | 1 | 1 | 60.88 | 61.39 | 52.8 | 53.1 | 6964 | 7381 | 4296 | 4470 | 9 | 0.34 | 0.102 | -0.38 | 0.78 |
| 4 | 3 | 0 | 0 | 65.77 | 70.06 | 51 | 51.9 | 4331 | 5759 | 2606 | 4273 | 294 | 0.23 | 0.000 | -0.26 | 0.70 |
| 4 | 3 | 0 | 1 | 65.78 | 70.17 | 51.1 | 51.9 | 5084 | 5770 | 4289 | 5302 | 64 | 0.47 | 0.000 | -0.48 | 0.88 |
| 4 | 5 | 0 | 0 | 65.79 | 70.21 | 52.8 | 53.3 | 4546 | 5792 | 3149 | 4273 | 162 | 0.31 | 0.000 | -0.26 | 0.71 |
| 4 | 5 | 0 | 1 | 66.87 | 70.21 | 52.8 | 53.1 | 5142 | 5799 | 4284 | 5076 | 19 | 0.36 | 0.007 | -0.64 | 1.02 |
| 4 | 3 | 1 | 1 | 65.79 | 69.04 | 51.3 | 51.9 | 5812 | 7999 | 4495 | 5073 | 18 | 0.27 | 0.029 | -0.39 | 0.84 |
| 4 | 5 | 1 | 0 | 66.35 | 70.08 | 52.9 | 53.2 | 5814 | 15829 | 3596 | 4269 | 6 | 0.23 | 0.333 | -0.41 | 0.85 |
| 4 | 5 | 1 | 1 | 66.16 | 70.21 | 52.8 | 53.3 | 5819 | 7782 | 4313 | 4933 | 46 | 0.47 | 0.000 | -0.40 | 0.86 |
| 6 | 5 | 0 | 0 | 73.52 | 75.47 | 52.8 | 53.3 | 4865 | 5781 | 3429 | 4278 | 324 | 0.11 | 0.000 | -0.16 | 0.71 |
| 6 | 5 | 0 | 1 | 73.6 | 75.38 | 52.8 | 53.3 | 5007 | 5771 | 4287 | 4744 | 36 | 0.06 | 0.137 | -0.18 | 0.74 |
| 6 | 7 | 0 | 0 | 73.52 | 75.47 | 53.8 | 54.1 | 5110 | 5766 | 3810 | 4282 | 303 | 0.41 | 0.000 | -0.48 | 0.96 |
| 6 | 7 | 0 | 1 | 73.54 | 75.47 | 53.8 | 54.1 | 5180 | 5802 | 4285 | 4750 | 84 | 0.42 | 0.000 | -0.63 | 1.10 |
| 6 | 5 | 1 | 0 | 73.71 | 74.67 | 52.9 | 53.3 | 6059 | 6371 | 4097 | 4228 | 2 | - | - | - | - |
| 6 | 5 | 1 | 1 | 73.68 | 74.59 | 53 | 53.3 | 6254 | 7744 | 4579 | 5210 | 14 | 0.20 | 0.105 | -0.17 | 0.76 |
| 6 | 7 | 1 | 0 | 73.76 | 75.47 | 53.8 | 54.1 | 5819 | 11287 | 3937 | 4282 | 12 | 0.65 | 0.001 | -0.55 | 1.02 |
| 6 | 7 | 1 | 1 | 73.64 | 75.45 | 53.8 | 54.1 | 5836 | 8342 | 4288 | 5069 | 76 | 0.30 | 0.000 | -0.49 | 0.99 |
| 8 | 5 | 0 | 1 | 77.65 | 77.65 | 53.3 | 53.3 | 5575 | 5575 | 4393 | 4393 | 1 | - | - | - | - |
| 8 | 7 | 0 | 0 | 77.27 | 79.13 | 53.8 | 54.1 | 5074 | 5737 | 3971 | 4275 | 104 | 0.40 | 0.000 | -0.51 | 1.02 |
| 8 | 7 | 0 | 1 | 77.3 | 79.36 | 53.8 | 54.1 | 5319 | 5807 | 4285 | 4551 | 36 | 0.68 | 0.000 | -0.74 | 1.22 |
| 8 | 9 | 0 | 0 | 77.29 | 78.88 | 54.6 | 54.9 | 5553 | 5786 | 3973 | 4258 | 6 | 0.52 | 0.107 | 0.46 | 0.27 |
| 8 | 9 | 0 | 1 | 79.35 | 79.35 | 54.9 | 54.9 | 5790 | 5790 | 4344 | 4344 | 1 | - | - | - | - |
| 8 | 7 | 1 | 0 | 77.37 | 79.23 | 53.8 | 54.1 | 5835 | 17266 | 3991 | 4260 | 7 | 0.01 | 0.814 | -0.13 | 0.74 |
| 8 | 7 | 1 | 1 | 77.27 | 79.38 | 53.8 | 54.1 | 5820 | 8125 | 4291 | 5387 | 177 | 0.349 | 0.000 | -0.375 | 0.955 |
| 8 | 9 | 1 | 0 | 77.3 | 79.37 | 54.6 | 54.9 | 5816 | 17849 | 3842 | 4282 | 74 | 0.213 | 0.000 | -0.430 | 0.970 |
| 8 | 9 | 1 | 1 | 77.29 | 79.39 | 54.6 | 55.3 | 5830 | 10275 | 4286 | 5470 | 383 | 0.089 | 0.000 | -0.147 | 0.776 |

*Chiller 24*

| $T_{ci\_BIN}$ | $T_{ei\_BIN}$ | $\dot{m}_{c\_BIN}$ | $\dot{m}_{e\_BIN}$ | $T_{ci,\min}$ | $T_{ci,\max}$ | $T_{ei,\min}$ | $T_{ei,\max}$ | $\dot{m}_{c,\min}$ | $\dot{m}_{c,\max}$ | $\dot{m}_{e,\min}$ | $\dot{m}_{e,\max}$ | $N$ | $R^2$ | Pvalue | $\beta$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 52.25 | 54.46 | 48.4 | 50.6 | 6 | 5034 | 2884 | 3831 | 57 | 0.38 | 0.000 | -0.48 | 0.73 |
| 0 | 1 | 0 | 1 | 51.67 | 54.48 | 48.3 | 50.6 | 5 | 5039 | 3841 | 5504 | 86 | 0.07 | 0.015 | -0.14 | 0.57 |
| 0 | 3 | 0 | 1 | 54.02 | 54.21 | 51.8 | 52 | 3280 | 4477 | 3998 | 4418 | 4 | 0.32 | 0.436 | -0.99 | 1.18 |
| 0 | 1 | 1 | 0 | 52.41 | 54.48 | 48.3 | 50.4 | 5109 | 20019 | 3025 | 3835 | 68 | 0.10 | 0.007 | -0.24 | 0.61 |
| 0 | 1 | 1 | 1 | 51.72 | 54.51 | 48.3 | 50.6 | 5107 | 20019 | 3837 | 5627 | 262 | 0.23 | 0.000 | -0.20 | 0.59 |
| 0 | 3 | 1 | 1 | 53.97 | 54.23 | 51.8 | 52 | 14120 | 19241 | 4338 | 4475 | 4 | 0.97 | 0.017 | -0.64 | 0.94 |
| 2 | 1 | 0 | 0 | 59.74 | 63.67 | 49.3 | 50.6 | 5 | 5071 | 2683 | 3826 | 104 | 0.30 | 0.000 | -0.43 | 0.75 |
| 2 | 1 | 0 | 1 | 59.83 | 63.99 | 48.3 | 50.6 | 5 | 5066 | 3839 | 6351 | 33 | 0.00 | 0.744 | -0.03 | 0.56 |
| 2 | 3 | 0 | 0 | 59.87 | 65.13 | 51.8 | 52.6 | 5 | 5039 | 2668 | 3835 | 50 | 0.46 | 0.000 | -0.29 | 0.73 |
| 2 | 3 | 0 | 1 | 59.76 | 65.14 | 51.8 | 52.6 | 6 | 5061 | 3838 | 5723 | 58 | 0.32 | 0.000 | -0.33 | 0.78 |
| 2 | 5 | 0 | 0 | 64.9 | 64.9 | 53.3 | 53.3 | 6 | 6 | 3335 | 3335 | 1 | - | - | - | - |
| 2 | 1 | 1 | 0 | 59.74 | 64.46 | 49.5 | 50.6 | 5087 | 20017 | 2558 | 3825 | 85 | 0.30 | 0.000 | -0.33 | 0.70 |
| 2 | 1 | 1 | 1 | 59.8 | 64.25 | 48.3 | 50.6 | 5092 | 19916 | 3866 | 7184 | 48 | 0.03 | 0.242 | 0.07 | 0.50 |
| 2 | 3 | 1 | 0 | 61.98 | 65.14 | 51.8 | 52.6 | 5086 | 20017 | 2950 | 3835 | 31 | 0.51 | 0.000 | -0.40 | 0.79 |
| 2 | 3 | 1 | 1 | 59.99 | 65.01 | 51.8 | 52.6 | 5087 | 19974 | 3856 | 5180 | 53 | 0.05 | 0.122 | -0.10 | 0.62 |
| 2 | 5 | 1 | 1 | 64.21 | 64.21 | 53.3 | 53.3 | 7169 | 7169 | 5080 | 5080 | 1 | - | - | - | - |
| 4 | 3 | 0 | 0 | 69.36 | 72.82 | 51.8 | 52.6 | 5 | 5070 | 2806 | 3760 | 106 | 0.43 | 0.000 | -0.32 | 0.79 |
| 4 | 3 | 0 | 1 | 69.34 | 72.45 | 52 | 52.6 | 5 | 5065 | 3891 | 5458 | 54 | 0.03 | 0.204 | -0.10 | 0.68 |
| 4 | 5 | 0 | 0 | 69.53 | 72.82 | 53.3 | 53.6 | 5 | 5059 | 2979 | 3835 | 98 | 0.25 | 0.000 | -0.32 | 0.82 |
| 4 | 5 | 0 | 1 | 69.67 | 72.71 | 53.3 | 53.6 | 5 | 4995 | 3852 | 4945 | 58 | 0.18 | 0.001 | -0.21 | 0.77 |
| 4 | 7 | 0 | 0 | 72.83 | 72.83 | 54 | 54 | 3752 | 3752 | 3387 | 3387 | 1 | - | - | - | - |
| 4 | 3 | 1 | 0 | 69.34 | 72.77 | 52 | 52.6 | 5075 | 18599 | 2803 | 3831 | 87 | 0.47 | 0.000 | -0.27 | 0.77 |
| 4 | 3 | 1 | 1 | 69.35 | 71.8 | 52 | 52.6 | 5091 | 13837 | 3853 | 4966 | 52 | 0.12 | 0.011 | -0.20 | 0.74 |
| 4 | 5 | 1 | 0 | 69.35 | 72.84 | 53.3 | 53.6 | 5072 | 20015 | 3004 | 3832 | 89 | 0.13 | 0.001 | -0.22 | 0.76 |
| 4 | 5 | 1 | 1 | 69.97 | 72.67 | 53.3 | 53.6 | 5231 | 15152 | 3870 | 4984 | 44 | 0.04 | 0.202 | -0.12 | 0.72 |
| 6 | 3 | 0 | 0 | 75.92 | 76.12 | 52.3 | 52.3 | 3274 | 4030 | 3636 | 3794 | 2 | - | - | - | - |
| 6 | 3 | 0 | 1 | 76.12 | 76.12 | 52.3 | 52.3 | 1426 | 1426 | 3941 | 3941 | 1 | - | - | - | - |
| 6 | 5 | 0 | 0 | 74.89 | 76.43 | 53.3 | 53.6 | 5 | 5070 | 3112 | 3831 | 177 | 0.03 | 0.029 | -0.06 | 0.69 |
| 6 | 5 | 0 | 1 | 74.92 | 76.45 | 53.3 | 53.6 | 5 | 5049 | 3838 | 4491 | 19 | 0.11 | 0.157 | 0.14 | 0.54 |
| 6 | 7 | 0 | 0 | 74.89 | 76.45 | 54 | 54.3 | 4 | 5071 | 3156 | 3816 | 175 | 0.64 | 0.000 | -0.69 | 1.10 |
| 6 | 7 | 0 | 1 | 74.92 | 76.45 | 54 | 54.3 | 5 | 4995 | 3839 | 4666 | 73 | 0.20 | 0.000 | -0.30 | 0.86 |
| 6 | 9 | 0 | 1 | 75.73 | 76.12 | 54.8 | 54.9 | 6 | 6 | 4783 | 4915 | 2 | - | - | - | - |
| 6 | 3 | 1 | 0 | 76.42 | 76.43 | 52 | 52.5 | 5537 | 7452 | 3553 | 3638 | 2 | - | - | - | - |
| 6 | 3 | 1 | 1 | 75.83 | 75.83 | 52.2 | 52.2 | 6456 | 6456 | 3937 | 3937 | 1 | - | - | - | - |
| 6 | 5 | 1 | 0 | 74.89 | 76.4 | 53.3 | 53.6 | 5076 | 17410 | 3055 | 3832 | 111 | 0.05 | 0.014 | -0.09 | 0.71 |
| 6 | 5 | 1 | 1 | 75 | 76.42 | 53.3 | 53.6 | 5081 | 19946 | 3844 | 4873 | 21 | 0.17 | 0.061 | -0.22 | 0.79 |
| 6 | 7 | 1 | 0 | 74.89 | 76.45 | 54 | 54.3 | 5085 | 19700 | 3196 | 3835 | 142 | 0.64 | 0.000 | -0.66 | 1.08 |
| 6 | 7 | 1 | 1 | 74.93 | 76.44 | 54 | 54.3 | 5370 | 20017 | 3836 | 4585 | 37 | 0.17 | 0.012 | -0.25 | 0.84 |
| 8 | 5 | 0 | 1 | 78.17 | 78.31 | 53.6 | 53.6 | 5 | 2195 | 3993 | 4065 | 3 | 0.97 | 0.104 | -0.43 | 1.01 |
| 8 | 7 | 0 | 0 | 78.08 | 79.96 | 54 | 54.3 | 4 | 4849 | 3293 | 3835 | 118 | 0.033 | 0.050 | -0.12 | 0.76 |
| 8 | 7 | 0 | 1 | 78.08 | 79.98 | 54 | 54.3 | 5 | 4837 | 3836 | 4411 | 91 | 0.084 | 0.005 | -0.16 | 0.81 |
| 8 | 9 | 0 | 0 | 78.14 | 79.99 | 54.8 | 55.2 | 4 | 4721 | 3459 | 3835 | 59 | 0.735 | 0.000 | -1.00 | 1.39 |
| 8 | 9 | 0 | 1 | 78.31 | 79.97 | 54.8 | 55.3 | 5 | 5044 | 3841 | 6328 | 98 | 0.134 | 0.000 | -0.22 | 0.85 |
| 8 | 5 | 1 | 1 | 78.61 | 78.61 | 53.6 | 53.6 | 5587 | 5587 | 3959 | 3959 | 1 | - | - | - | - |
| 8 | 7 | 1 | 0 | 78.08 | 79.95 | 54 | 54.3 | 5075 | 19949 | 3350 | 3832 | 47 | 0.005 | 0.653 | -0.05 | 0.72 |
| 8 | 7 | 1 | 1 | 78.08 | 80 | 54 | 54.3 | 5205 | 20016 | 3841 | 4984 | 70 | 0.100 | 0.008 | -0.16 | 0.80 |
| 8 | 9 | 1 | 0 | 78.2 | 79.98 | 54.8 | 55.4 | 5076 | 19924 | 3347 | 3835 | 34 | 0.631 | 0.000 | -0.92 | 1.34 |
| 8 | 9 | 1 | 1 | 78.08 | 80.01 | 54.8 | 55.3 | 5249 | 20017 | 3836 | 4894 | 122 | 0.229 | 0.000 | -0.29 | 0.91 |

**It should be noted that there are some measurement errors in condenser water flow rate for chiller No. 24 which could impact the effectiveness of the partitioning method.*