eSim 2018
«BUILDING SIMULATION TO SUPPORT BUILDING SUSTAINABILITY»
IBPSA Canada
The Canadian Chapter of the International Building Performance Simulation Association
Le chapitre canadien de International Building Performance Simulation Association

Development of Optimal Design Tool for Chilled Water Plants for Commercial Buildings

Nabil Nassif[1], Nihal AlRaees[2], Fouad AlRifaie[2]

[1] Associate Professor, University of Cincinnati, Cincinnati, Ohio, USA
[2] Graduate Student, University of North Carolina A&T State University, Greensboro, North Carolina, USA

Abstract: *This paper proposes a design tool for optimal design of chilled water plants for commercial buildings. The proposed tool integrating system models with a genetic algorithm optimization solver minimizes the life cycle cost by finding the design variables such as chilled water and condenser piping diameters, chilled and condenser water temperature differences, and chilled water supply temperature. The proposed modeling methods depend on detailed cooling load analysis and head and energy calculations. The method is tested on an existing three-story, eighty-eight thousand square foot building. A whole building energy simulation model is used to generate the hourly cooling loads and then the optimal design variables are found to minimize the life cycle cost. The testing results show this approach will achieve better results than rules-of-thumb or traditional design procedures. The life cycle cost saving could be up to 8% depending on project specifications and locations.*

Keywords: *HVAC System, Chilled Water System, Optimization, Piping Design*

INTRODUCTION

The operation and installation costs of chilled water central plant consist of a large amount of total building energy system costs. How to design chilled water plants will then have a very large impact on building energy use and costs. Most common design method is rules-of thumb by using the water temperature difference (Delta T) of 10°F (Taylor 2011; Taylor 2008). Many studies (Taylor and McGuire 2008; Taylor 2011; Taylor 2008; ASHRAE 90.1 2013) discusses various ways to design central plant that includes piping size and temperature difference Delta T. ASHRAE Standard 90.1 (table 6.5.4.6) recommends piping diameters as a function of maximum flow rates and number of hours. A design tool, called Cool-Tools Pipe Size Optimization Spreadsheet (Taylor 2016) was developed in order to determine the chilled water piping diameter and Delta T. This tool, similar to the table 6.5.4.6 of ASHRAE standard is simply based on the total number of operating hours not on detailed hourly cooling load analysis. In this paper, a design optimization tool is proposed, which combines hourly/or sub-hourly cooling performance calculations and optimization algorithm. The tool aims at minimizing the life cycle cost of chilled water plant by finding optimally both condenser water- and chilled water-side design variables such as chilled water and condenser piping sizes, chilled and condenser water temperature differences (Delta T), and chilled water supply temperature. The proposed design method depends on detailed hourly (or sub-hourly) cooling load analysis and head and energy calculations. The pump head calculations including piping, all fittings, valves, and devices are achieved by using the Darcy-Weisbach equation with given flow parameters. To perform those calculations, the hourly or sub-hourly cooling loads should be obtained from any available energy simulation software and then be exported to the proposed design tool. Although there may be many optimization methods that could be used for solving the optimization problem to minimize the life cycle cost, the genetic algorithm (GA) inspired by natural evolution (Goldberg 1989) is used. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The GA is successfully applied to a wide range of applications including HVAC system control and design (Nassif 2012; Kusiak et al. 2011; Mossolly et al. 2009; Nassif et al. 2005). The proposed tool is tested on an existing three-story, eighty-eight thousand square foot office building located in Greensboro NC. Other locations are also considered. Detailed parametric studies are first conducted and the design optimization is then followed with cost saving calculations.

MODELING AND OPTIMIZATION

The objective of modeling is to estimate the initial and operating energy costs with different chilled water plant design alternatives and different design variables. The model simulates the annual energy use as a sum of fan, chiller, and pump hourly or sub-hourly energy uses. Figure 1 shows a schematic of the model with its input and output variables. The model combines airside and water side component models such as chiller, cooling-tower, pumps, piping head, cooling tower and secondary system fans. The electric chiller is addressed using DOE-2 chiller model since it is relatively accurate and easy to calibrate using manufacture or field measured data (Hydeman and

ISBN 978-2-921145-88-6

Gillespie 2002). This chiller model calculates chiller energy use as a function of cooling load and condenser and chilled water supply temperatures. Cooling-tower model is derived from energy plus simulation tool to determine the fan power as a function of condenser load/water supply temperature and outdoor air conditions. While the fan/pump models are developed using the basic power calculation as function of flow and pressure drop. The pump head calculations including piping, all fittings, valves, and devices are achieved by using the Darcy-Weisbach equation with given flow parameters. As shown in Figure 1, the required inputs are hourly weather conditions and hourly cooling loads that can be obtained from any energy simulation software. Other input is information on system parameters such as equipment cost, piping length, pipe roughness, number of elbows/tees, design pressure across the chiller and AHUs, duct static pressure set point, etc. The model outputs are hourly energy consumption and operating cost for fans, pumps, and chillers, total energy and life cycle costs.

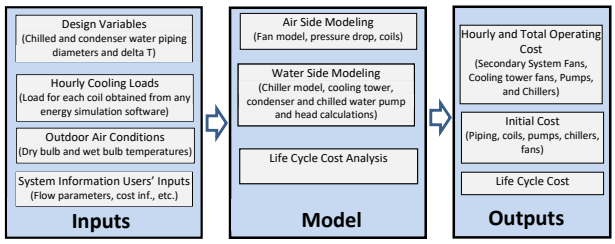

Figure 1: A schematic of the model with its input and output variables

To optimize the design of chilled water central plant, an optimization algorithm is developed and integrated into the model that was shown in Figure 1. The proposed optimization design tool determines optimal design variables to reduce life cycle cost. The life cycle cost includes operation and capital costs. The problem variables are (1) chilled water piping diameter, (2) chilled water temperature difference (Delta T), (3) chilled water supply temperature, (4) condenser water piping diameter, and (5) condenser water temperature difference (Delta T). The constraints are related to the restrictions on the size and operation of the central plant. They cover the lower and upper limits of design variables, such as the maximum and minimum piping diameters, delta T and chilled water temperature. Other constraint is connected to the fluid velocity as indicated in the Table 6.5.4.6 of the ASHRAE standard 90.1. The genetic algorithm is used to solve the optimization problem. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. Figure 2 shows the flow chart of GA for the proposed design optimization tool. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. The GA starts with a random generation of the initial population (initial solution) and ends with the optimal solutions including the optimal variables. The problem variables represent an individual solution in the population. The performance or objective function of each individual of the first generation is estimated. The second generation is generated using operations on individuals such as selection, crossover, and mutation, in which individuals with higher performance (fitness) have a greater chance to survive. The performance of each new individual is again evaluated. The process is repeated until the maximum number of generations is reached. In this study, the GA algorithm from the optimization tool available in MATLAB toolbox is used.

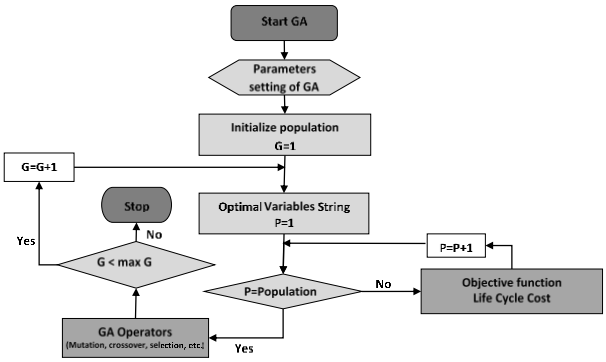

Figure 2: A schematic of the model with its input and output variables

The simulation models and optimization genetic algorithm are both developed and programmed in Matlab environment so that the program can read the hourly cooling loads, outdoor air conditions, equipment cost, system parameters, and utility cost structure from excel worksheets as user's input files and then write the results back into the same /or other excel sheet as user's output file. The hourly cooling loads and outdoor air conditions can be collected from any detailed building energy simulation software and then should be copied and paste into the user's input file. A simple version of this design optimization tool as shown in Figure 3 is to run the simulation directly ('Run Simulation' bottom) from Microsoft Excel worksheet but in this case, the Matlab program script should be compiled as excel add-in.

ISBN 978-2-921145-88-6

SYSTEM DESCRIPTION AND BASELINE

An existing three-story, eighty-eight thousand square foot office building is used. The building is conditioned by typical VAV systems, consisting of six air handling units (AHUs) and chilled water central plant with two water cooled chillers. Detailed information, particularly on chilled and condenser water central plant information such piping lengths, number of fitting, etc. are collected. The building was first modeled by the building energy simulation software eQuest (eQUEST Version 3.65) to generate hourly cooling loads for each AHU. The cooling loads are then exported to input file of the proposed design tool. The chilled water primary-only variable flow rate configuration with constant speed condenser pumps as shown in Figure 4 is used for this study even though the process can also apply for other configurations. For this analysis, the baseline or non-optimal design option is assumed as a follow. The chilled water and condenser water temperature difference of 10ºF (5.5ºC), and chilled water temperature of 45ºF (7.2ºC). The chilled and condenser piping sizes are selected from Table 6.5.4.6 of the ASHRAE standard 90.1based on design maximum flow rate. The model shown in Figure 1 is run for this baseline and four various ASHRAE Climate Zones, Greensboro NC (Zone 4A), Minneapolis (Zone 6A), Phoenix (Zone 2B), and Miami (Zone 1A). Figure 3 shows a screenshot of baseline conditions and energy and cost results taken from the proposed Excel-based design tool. Condenser water temperature is not optimized. The graphic in this figure shows the component-level hourly energy uses.

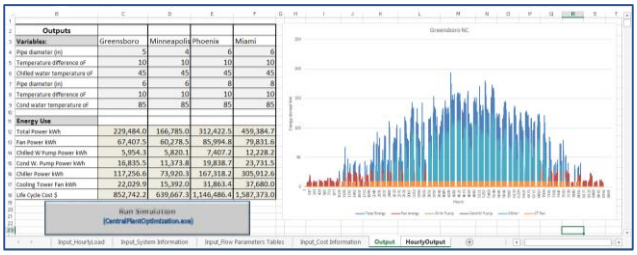

Figure 3: Screenshot of baseline conditions and results taken from the proposed Excel-based design tool

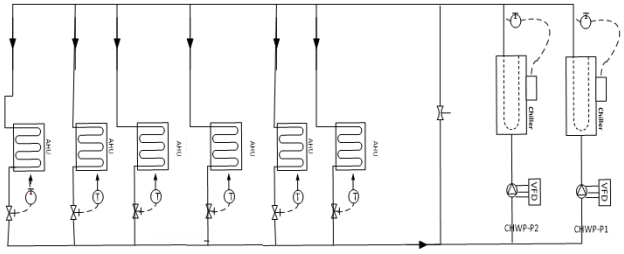

Figure 4. Variable flow primarily only piping configuration

DISCUSSION AND RESULT ANALYSIS

Parametric Studies

Parametric studies are first conducted to get insight into the variable relations and to validate the optimization results. The model as shown in Figure 1 is run for different design options and for Greensboro, NC. The hourly cooling loads are obtained for the energy simulation software eQuest. The costs of piping, fitting, and coil are from (Taylor 2016 and Means 2014). The cost of piping, fitting, coils are only considered. As the pumps, chillers, and cooling towers varies slightly, they are not considered in the analysis. However, those costs can be simply included by modifying the input file (called Input_Cost Information) as shown in Figure 3. All costs and any other input information can be changed by replacing the defaults values in the input worksheets (Input_Cost Information, Input_System Information, and Input_Flow Paramters).

Figures 5-8 shows the effect of chilled and condenser water pipe diameters on energy and life cycle costs for Greensboro, NC. In each of those figure, one variable is only varied and the others are kept constant at baseline conditions, which are the chilled water supply temperature of 45ºF (7.2ºC), the chilled water temperature difference of 10ºF (5.5ºC), the condenser water temperature difference of 10ºF (5.5ºC), the chilled water pipe diameter of 5 in (12.7 cm), and condenser water pipe diameter of 6 in (15.2 cm). Varying the chilled (or condenser) water diameter leads to a great change in the chilled pumps (CHW pumps) or the condenser pumps (CW pumps) energy uses. When water diameter increases, the pump energy and thereby total energy uses decrease due to lower friction in the pipe. Increasing the pipe diameters decreases energy consumption but increases the life cycle cost as the cost of piping system increases. For this particular project and for the location of Greensboro NC, the minimum energy consumption is at the highest considered pipe diameter of 13 in (33 cm) but the minimum life cycle cost is at the pipe diameter of 3 in (7.62 cm). Off course, depending on the current energy and initial costs, building locations, and system parameters such as the length of piping, number of fitting/valves, number of coils, etc., the results may vary. A low piping system initial cost moves the minimum life cycle cost to higher piping diameters.

In addition to pipe diameters, chilled water supply temperature (but not shown) and temperature difference changes were investigated (see figures 9-10). It is noticed that when the chilled water supply temperature increases, the chiller and then total energy uses drop. Increasing chilled water temperature difference leads a greater coil area and a higher number of coil rows that will add more

ISBN 978-2-921145-88-6

fan pressure and energy use. Increasing chilled water temperature difference reduces energy consumption, particularly pump energy use. This pump energy use reduction is usually higher than the slight increase of fan energy use due to higher fan pressure drop. Looking at the life cycle cost, the increase of temperature difference increases the cost of coils that could exceed the energy cost saving from pumps. The minimum energy cost occurs at highest considered temperature difference of 25°F but the minimum life cycle cost happens at temperature difference of 20°F (11.1°C)

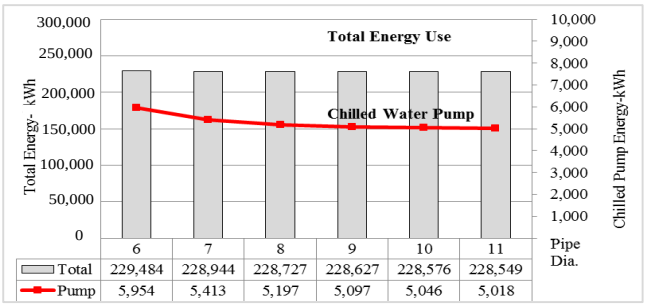

Figure 5: Effect of increasing chilled pipe diameter on system energy use

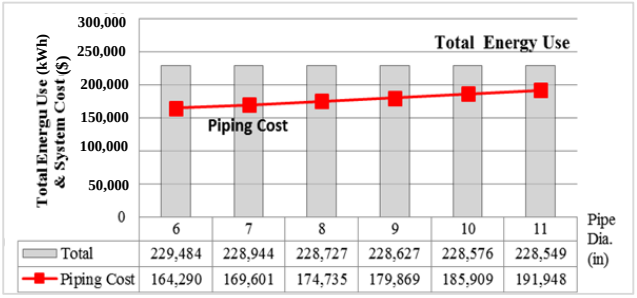

Figure 6: Effect of increasing chilled water pipe diameter on system initial cost

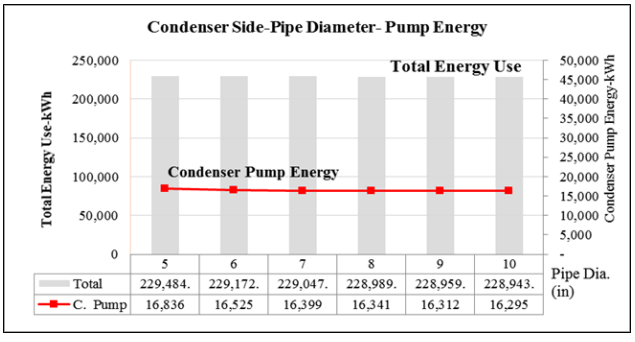

Figure 7: Effect of condenser water pipe diameter on system energy use

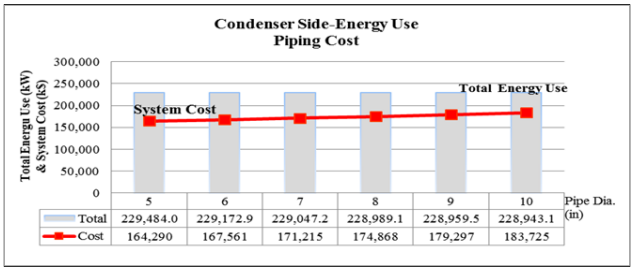

Figure 8: Effect of condenser side pipe diameter on piping initial cost

Examining the condenser water-side design variables, the temperature difference has no effect on either AHUs fan energy use or cooling coil cost but has a slightly effect on the operation of cooling tower fans and its associated cost. As the cooling tower cost was not included, the temperature difference is limited to a maximum value of 15°F (8.3°C). This is why the minimum energy consumption and minimum life cycle cost both happen at the temperature difference of 15°F (8.3°C). When the condenser water pipe diameter increases, the condenser water flow rate and then the pump energy use both drop but the condenser water piping system cost increases at a lower rate as comparing to chilled water piping system (For the investigated chilled water plant, the chilled water piping system is larger in length and number of fitting and valves than the condenser piping system).

Optimization Results

Using the available data from the parametric runs, the optimization algorithm GA can be tested for accuracy and to better set the GA parameters. First, the optimization algorithm is tested to find only two design variables (1) chilled water temperature difference and (2) chilled water pipe diameter. The other variables are kept constant at baseline conditions. The GA finds the optimal solution having the least life cycle cost. Figure 8 shows the resulted life cycle costs for various chilled water temperature difference and piping diameters. The optimal solution found by GA matches exactly the solution obtained from the parametric studies and shown in Figure 9 (minimum: X=4 in, Y=20 oF, Z=$819,743). The GA with a population of 30 converges quickly to that solution with less than 40 generations. Second, the chilled water supply temperature is added and optimized. The GA finds the optimal solution which is similar to the one obtained from the parametric studies with a population of 40 and generations of 50. Third, the optimization algorithm is then tested for only condenser water-side design variables (1) condenser water temperature difference and (2) condenser water pipe diameter. Figure 10 shows the resulted life cycle costs for various condenser water temperature difference and piping diameters. The GA finds the optimal solution, exactly

ISBN 978-2-921145-88-6

similar to the solution obtained from the parametric studies and shown in Figure 10 (minimum: X=6 in, Y=15 ºF, Z= $833,020). The GA with a population of 30 converges to that solution with less than 30 generations as shown . Finally, all five variables are optimized, the GA finds the optimal solution with a population of 50 to find the optimal solution. Figure 11 shows GA performance with generations (fitness or life cycle cost vs. generations) for Greensboro. Indeed, the GA finds the optimal solution with less than 30 generations. The minimum life cycle cost is $798,928.

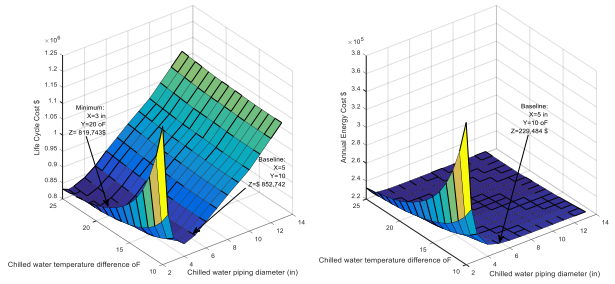

Figure 9: Annual energy operation and life cycle costs for various chilled water temperature difference and piping diameters (Greensboro).

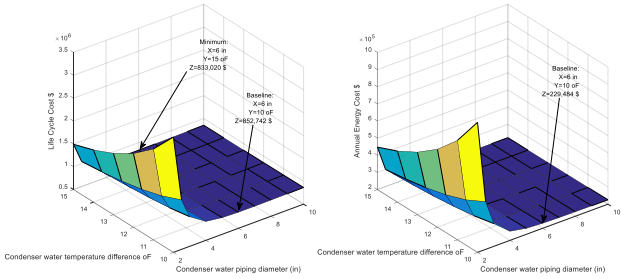

Figure 10: Annual energy operation and life cycle costs for various condenser water temperature difference and piping diameters (Greensboro).

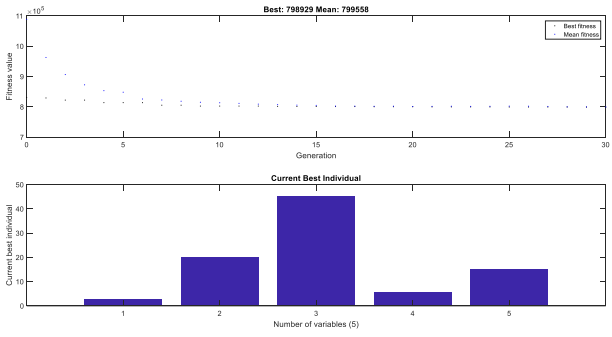

Figure 11: GA performance with generations (fitness or life cycle cost vs. generations) for Greensboro.

The optimal and baseline (non-optional) life cycle cost results are depicted in Figure 12 for four different locations.

The cost savings vary 4% to 8% depending on the location. The lowest saving of 4% is obtained for Minneapolis and the highest saving of 8% is obtained for Phoenix. The key reason of saving variation is related to the size of baseline pipe diameter selected form ASHRAE table, which is as a function of maximum flow rate and operating hours. For each location, the maximum flow rates and operating hours per year are estimated. The maximum flow rates (GPM) are 544, 506, 562, and 598 (34.3, 31.9, 35.5, 37.7 l/s) and the operating hours are 2000, 1260, 2760, and 3526, for locations Greensboro, Minneapolis, Phoenix, Miami, respectively. The baseline conditions for different locations are shown in Figure 3.

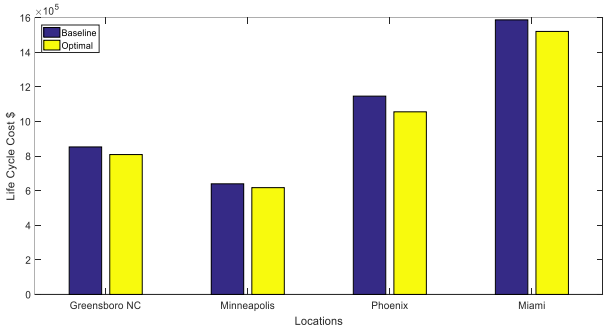

Figure 12: Optimal and non-optimal life cycle costs for various locations

CONCLUSION

The design variables such as condenser and chilled water delta T, piping diameters, and chilled water temperature were determined using a design tool proposed in this paper. The tool integrates head and energy cost calculations, GA optimization algorithm, and hourly or sub-hourly cooling loads obtained from any building energy simulation software. The method is tested on an existing three-story, eighty-eight thousand square foot office building located in Greensboro NC. Parametric studies were conducted to determine the effect of design variables on energy use and cost of each component of chilled water plant. Increasing chilled or condenser water delta T reduces pump energy use. However, the chilled water delta T causes an increase of fan energy use and the cost of coils that could exceed the energy cost saving from pumps. There is a trade-off between the operating pumping cost, fan energy cost, and coil cost. Increasing the pipe diameters decreases energy consumption but it increases the piping cost. Also, there is a trade-off between the pump operating energy cost and piping installation cost. To find the optimal design variables, the life cycle cost was considered. The optimization was performed to find the minimum life cycle cost and associated savings were calculated for various locations. The savings found to be within 4-8%, depending on the project locations. The saving could be even higher if higher efficiency chiller at lower chilled water supply

ISBN 978-2-921145-88-6

temperature is used. The amount of the saving depends on piping configurations, current energy and initial costs, building locations, and system parameters such as the length of piping, number of fitting/valves, number of coils, etc.

REFERENCES

ASHRAE Standard 90.1-2013. *Energy Standard for Buildings Except Low-Rise Residential Buildings.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

eQuest. **QU**ick **E**nergy **S**imulation **T**ool, eQUEST Version 3.65. http://www.doe2.com/equest/

Goldberg, D.E. 1989. Genetic Algorithms in Search, Optimization, and Machine Learning. Reading. Addison-Wesley.

Hydeman, M., N. Webb, P. Sreedharan, and S. Blanc. 2002. Development and Testing of a Reformulated Regression-Based Electric Chiller Model. *ASHRAE Transactions 105(2): 1118-27*.

Kusiak, A, F. Tang, G. Xu. 2011. Multi-objective optimization of HVAC system with an evolutionary computation algorithm. *Energy 36(5): 2440-2449*.

Means. 2014. RSMeans Mechanical Cost Data. Norwell, Mass.

Mossolly, M., K. Ghali and N. Ghaddar. 2009. Optimal control strategy for a multi-zone air conditioning system using a genetic algorithm. *Energy 34 (1): 58-66*.

Nassif, N., S. Kajl, and R. Sabourin. 2005. Optimization of HVAC Control System Strategy Using Two-Objective Genetic Algorithm. *HVAC&R Research 11(3): 459-486*.

Nassif, N. 2012. Modeling and Optimization of HVAC Systems Using Artificial Intelligence Approaches. *ASHRAE Transactions 118 (2): 133*

Taylor, S.T. (2016), EDR Cool-Tools Pipe Size Optimization Spreadsheet v2.0.6

Taylor, S. T. (2012). Optimizing Design & Control of Chilled Water Part 4: Chiller & Cooling Tower Selection. *ASHRAE Journal, 3, 60-70*.

Taylor, S. T. (2011). Optimizing Design & Control of Chilled Water Part 3: Pipe Sizing and Optimizing ΔT. *ASHRAE Journal, 12, 22-34*.

Taylor, S. T and McGuire, M. (2008). Sizing Pipe Using Life-Cycle Costs. *ASHRAE Journal, 11, 24-32*.

ISBN 978-2-921145-88-6