Energy Research Journal

Original Research Paper

Developing an Integrated Method for Optimal Design of Chilled Water Plants in HVAC Systems

[1]Nabil Nassif, [2]Nihal Al Raees, [2]Fouad Al Rifaie and [3]Taher Abu-Lebdeh

[1]*Department of Civil and Architectural Engineering, University of Cincinnati, Cincinnati, USA*
[2]*Department of Civil and Architectural Engineering,*
North Carolina A and T State University, Greensboro, USA
[3]*Department of Civil, Architectural and Environmental Engineering,*
North Carolina A and T State Univesity, United States

Article history
Received: 26-02-2018
Revised: 15-03-2018
Accepted: 21-03-2018

Corresponding Author:
Nabil Nassif
Civil and Architectural Engineering, University of Cincinnati, Cincinnati, USA
Email: nassifnl@uc.edu

Abstract: Buildings account for a large portion of energy use in the US. Many those buildings have equipped with central plants to produce chilled water supplied to central air handling units. The chilled water plant design can have a significant impact on building energy uses and costs. In this paper, an integrated method for optimal design of chilled water plants is developed in order to minimize life cycle cost. The method integrates an optimization procedure with models that perform detailed cooling load analysis, pump head and energy calculations and life cycle cost analysis. The pump heads are determined by friction and fitting equations with specified flow parameters. The energy calculations are achieved by using chiller, pump and fan models. Genetic algorithm GA is used to solve the constrained optimization problem. The optimal design variables are the condenser and chilled water piping sizes, the condenser and chilled water temperature differences and the chilled water supply temperature. The method is evaluated using an existing building on different climate zone locations. The evaluation results show this integrated method can achieve better results than traditional process. The saving in life cycle cost could be up to 8% depending on locations and project specifications.

Keywords: HVAC Systems, Chillers, Chilled Water, Optimization, Central Pant

Introduction

As Buildings account for a large portion of total US energy use. According to US Energy Information Administration EIA (EIA) buildings consume 72% of the electricity produced and 55% of its natural gas. Buildings also account for approximately 48% of the energy consumed in the US at a rate of $350+ billion per year, which is more than the amount of energy used by industry and transportation. Heating and cooling systems account for almost 55% of energy consumption, while lights and appliances consume 35% of the energy used in society. This energy trend shows the need to develop advanced building energy saving methods. Most large commercial buildings are equipped with central plants that produce chilled and hot water to central air handling units AHUs or/and terminal units. A significant part of building energy operation and installation costs is related to the central plants such as chillers, pumps, cooling towers if installed and boilers. How to design chilled water plants will have a significant impact on building energy use and costs. Thus, an optimal design method can provide a cost-effective way to reduce operating energy cost, initial cost and/or life cycle cost.

Several investigations in the past few years have described methods for minimizing energy costs associated with building energy systems' operation (ASHRAE, 2015; 2016; Kusiak *et al*., 2011; Nassif, 2012). Many studies discussed the optimal operation and control of chilled water plant to reduce operation cost (Gao *et al*., 2016; Ma and Wang, 2011; Schwedler, 2012; Lee and Cheng, 2012; Mua *et al*., 2017). For instance, Gao *et al*. (2016) proposes pump speed control strategy for avoiding low temperature difference delta-T syndrome in chilled water systems of high-rise buildings. Ma and Wang introduce optimal control of central chiller plants using adaptive models combined with genetic algorithm optimization methods. Schwedler presents condenser water-side system saving opportunities through optimal flow rate and control.

For chilled water central plant design, most common method is rules-of thumb or by using the water temperature difference of 10°F (Taylor, 2011; Taylor and McGuire, 2008). Many studies (Taylor and McGuire 2008; Taylor, 2011; ASHRAE 90.1 2013; Cheng *et al*., 2016; Fang *et al*., 2017; Nassif *et al*., 2017) propose various ways to design central plant that includes water temperature difference and piping size. Table 6.5.4.6 of ASHRAE Standard 90.1 recommends primary pipe 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 to determine the water temperature difference and chilled water piping size. This tool, which is 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. To address the limitations in the current methods, an integrated design optimization method is proposed, which combines hourly/or sub-hourly cooling performance calculations, energy and head calculations and optimization algorithm. The method 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 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 friction and fitting equations with given flow parameters. To perform those calculations, the hourly or sub-hourly cooling loads and AHU airflow rates need to be obtained from any available energy simulation software and then be exported to the proposed design method. Although there are 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). An existing office building located in Greensboro NC is used in this study. Other locations are also considered for proposed method evaluations and cost saving calculations.

Modeling

The proposed design method integrates modeling technique with optimization solver. The model performs head and energy calculations to estimate the operating, initial and life cycle costs with different chilled water plant design variables. Using the cooling loads and AHU airflow rates (obtained from building energy simulation software), it calculates the total annual energy use as a sum of hourly energy uses of AHU fans, chillers, cooling tower fans and pumps. Fig. 1 shows a schematic of the model with its input requirements and output variables. The model combines water side and airside containing component models such as chiller, pumps, piping head, cooling tower and secondary system fans. The cooling tower model is derived from energy plus simulation tool (EnergyPlus, 2017) to determine the fan power as a function of condenser load/water supply temperature and outdoor air conditions. The electric chiller model is used based on DOE-2 chiller model since it is relatively accurate and easy to calibrate using manufacturer or field measured data (EnergyPlus, 2017; Hydeman *et al*., 2002). The chiller model runs each hour to calculate the chiller power as a function of given hourly cooling loads. The annual chiller energy use is then calculated as a sum of hourly energy power.

The water side pump head calculations including piping, all fittings, valves and devices are achieved by using fitting and friction equations (Darcy equation). The friction factor f is calculated by solving Colebrook equation. The water flow rate is determined each hour, utilizing the design option of chilled water temperature difference and given hourly cooling loads. The pump power is then determined by the calculated total pressure and the calculated water flow rate. Similar scenario is done for condenser water loop. The annual power is then determined as a sum of hourly pump energy uses. In air side, the actual total static pressure and then fan power are calculated (given hourly airflow rate). This process repeats for other air handling units AHUs. The total fan power is calculated as a sum of hourly energy uses for all given AHUs.

As shown in Fig. 1, four different input files are needed. The main inputs are the design variables that will be generated by the optimization algorithm discussed below to select the one yielding the minimum life cycle cost. Other important inputs are the hourly weather conditions, hourly cooling loads, hourly air flow rates over each cooling coil (through each AHU fan) that all can be obtained from any energy simulation software. The model output are hourly energy consumption and operating cost for fans, pumps and chillers, total energy and life cycle costs.

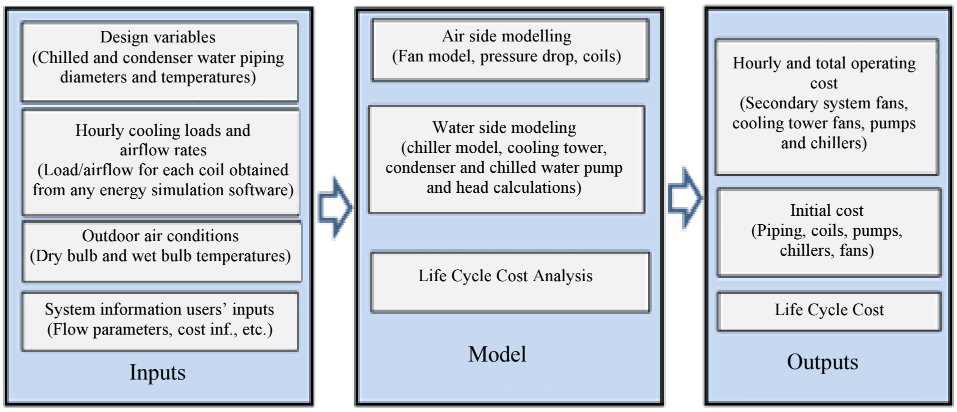


Fig. 1: A schematic of the model with its input and output variables

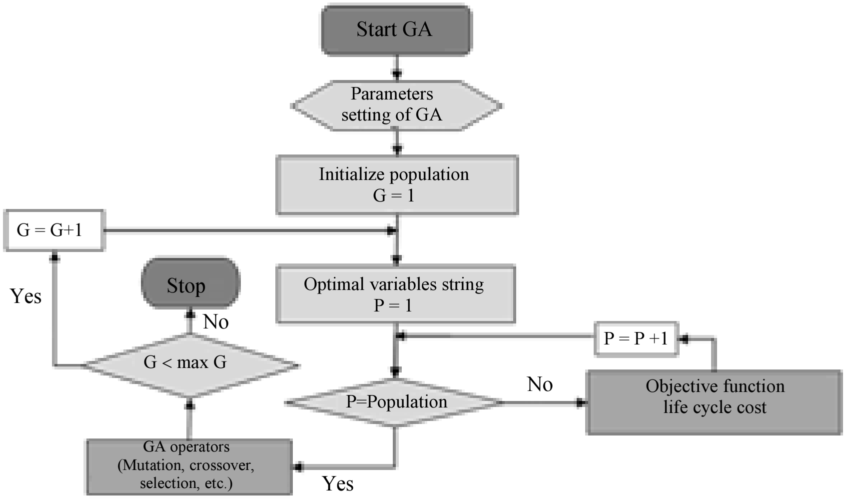


Fig. 2: Flow chart of genetic algorithm for the proposed optimization method

Optimization

To optimize the central plant design, an optimization method is integrated into the model as shown in Fig. 1. The proposed design method determines optimal design variables to minimize the life cycle cost that includes capital and operating costs. The problem variables are chilled water supply temperature, chilled and condenser water piping sizes (diameters) and chilled and condenser water temperature differences. The constraints address restrictions on the operation and size of the chilled water central plant. They cover design variable upper and lower limits, such as condenser and chilled water temperature differences, chilled water supply temperature and maximum and minimum pipe diameters. Other constraint is related to the fluid velocity as presented in ASHRAE standard 90.1 Table 6.5.4.6. The optimization method genetic algorithm is used to solve the central design optimization problem. The genetic algorithm is a optimization method for solving both unconstrained and constrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm GA modifies a population of individual solutions. Figure 2 shows GA flow chart for the proposed design method. At each step, the GA selects randomly individuals from the current population to be parents and takes them to produce the children for the next generation. Over successive generations, the population evolves toward an optimal design solution. The GA starts with a random generation of the initial design solutions (initial population) and ends with the optimal design solutions (optimal design variables). The problem variables represent an individual solution in the population. The objective function (life cycle cost) for each individual in the first generation is calculated. The second generation is identified using GA operations on individuals such as crossover, mutation

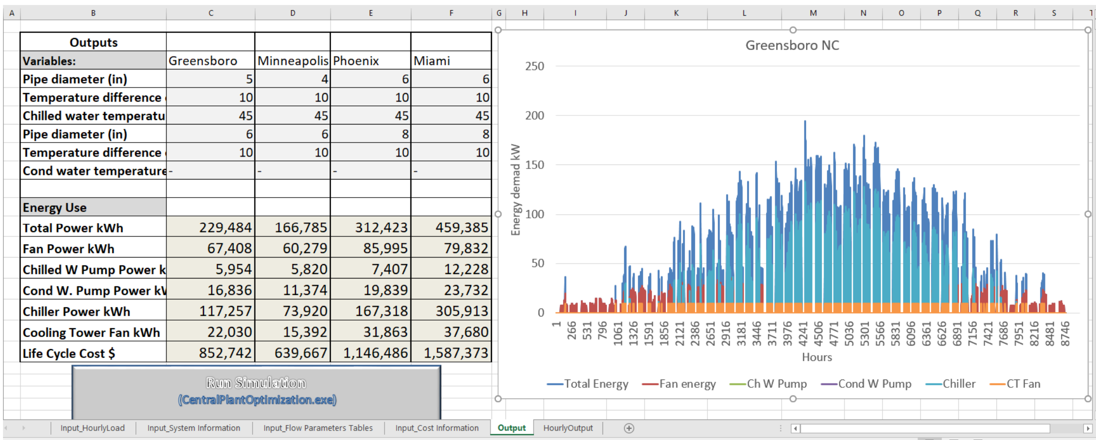
DOI: 10.3844/erjsp.2018.96.107

and selection. The minimum life cycle cost (highest fitness) have a better chance to survive. The fitness 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.

The optimization design method including the modeling technique and GA genetic algorithm is developed in Matlab environment so that the program can read the outdoor air conditions, hourly cooling loads and airflow rates, utility cost structure, system parameters, equipment cost from excel worksheets as user's input files and then send the results back into the same/or other excel sheet as user's output file. The hourly cooling loads, airflow rates and outdoor air conditions are collected from the detailed building energy simulation software eQuest and then are exported into the user's input file. A simple version of this design optimization method is shown in Fig. 3. This can run directly ('Run Simulation' bottom) from Microsoft Excel worksheet but in this case, the Matlab program script should be compiled as excel add-in.

Results

An existing three-story, 88,000 ft^2 office building located in Greensboro NC is used for method evaluation and cost saving estimation. The building is conditioned by a typical chilled water central plant with two water-cooled chillers supplied chilled water to six Air Handling Units (AHUs). Detailed information on the condenser and chilled water central plant such piping lengths, pipe roughness, number of fitting, etc. are collected. The building is first modeled by the building energy simulation software eQuest (eQUEST Version 3.65) to generate hourly cooling loads and required airflow rates for each AHU (which are then exported into the input file of the proposed design method). In this study, the chilled water primary-only variable flow rate configuration is used but the process can also apply for other configurations. The condenser water loop consists of two cooling towers and two constant-speed condenser pumps. The evaluation is done for four different locations: Greensboro NC, Minneapolis, Phoenix and Miami. The baseline design option (non-optimal design) is assumed to have condenser and chilled water temperature differences of 10°F (5.5°C) and chilled water supply temperature of 45°F (7.2°C). The baseline condenser and chilled piping sizes are selected from Table 6.5.4.6 of the ASHRAE standard 90.1 as a function of design maximum water flow rates and operating hours per year. The maximum water flow rates are estimated using the cooling loads for each location obtained from eQuest and baseline temperature difference. The maximum flow rates are 544, 506, 562 and 598 gpm (34.3 l/s, 31.9 l/s, 35.5 l/s, 37.7 l/s) and the operating hours are 2000, 1260, 2760 and 3526, for Greensboro, Minneapolis, Phoenix, Miami, respectively. The baseline conditions for different locations are shown in Fig. 3. From the Table 6.5.4.6, the baseline chilled water pipe diameter is 5 in (12.7 cm) for Greensboro, 4 in (10.16 cm) for Minneapolis and 6 in (15.2 cm) for Phoenix and Miami and the baseline condenser water pipe diameter is 6 in (15.2 cm) for Greensboro and Minneapolis and 8 in (20.32 cm) for Phoenix and Miami. The model shown in Fig. 1 runs for the baseline conditions and all investigated locations. Figure 3 shows a screenshot of baseline conditions and energy and cost results taken from the proposed worksheet design method. Condenser water temperature is not optimized. The graphic in this figure shows total and component-level hourly energy uses.



Outputs				
Variables:	Greensboro	Minneapolis	Phoenix	Miami
Pipe diameter (in)	5	4	6	6
Temperature difference	10	10	10	10
Chilled water temperatu	45	45	45	45
Pipe diameter (in)	6	6	8	8
Temperature difference	10	10	10	10
Cond water temperature	-	-	-	-
Energy Use				
Total Power kWh	229,484	166,785	312,423	459,385
Fan Power kWh	67,408	60,279	85,995	79,832
Chilled W Pump Power k	5,954	5,820	7,407	12,228
Cond W. Pump Power kV	16,836	11,374	19,839	23,732
Chiller Power kWh	117,257	73,920	167,318	305,913
Cooling Tower Fan kWh	22,030	15,392	31,863	37,680
Life Cycle Cost $	852,742	639,667	1,146,486	1,587,373

Fig. 3: Screenshot of baseline conditions and results taken from the proposed Excel-based design optimization method

Figure 4 shows total and component-level annual energy consumptions for all investigated locations. It includes six AHU fans, two chilled water pumps, two condenser water pumps, two chillers and two cooling tower fans. For the same building, it is obvious that the energy consumptions in Miami is highest among other locations.

To get insight into the variable relations and validate the optimization algorithm used, detailed parametric studies are performed. The proposed model (as shown in Fig. 1) runs for different design options and all investigated locations. The resulted energy consumptions in kWh are illustrated in Fig. 5-8. In those figures, one variable is varied and others are kept constant at baseline conditions. The size of chilled or condenser water pipe has great effect on condenser water pump (CW pump) or chilled water pump (CHW pump) energy uses. For all locations, increasing water pipe diameters leads to lower water flow rates required to meet the same loads and then lower water pumping and thereby total energy uses. The chiller and total energy uses reduce with higher chilled water supply temperature. When the chilled water temperature difference increases, the fan pressure and fan energy use rise due to a greater coil area required and elevated coil rows.

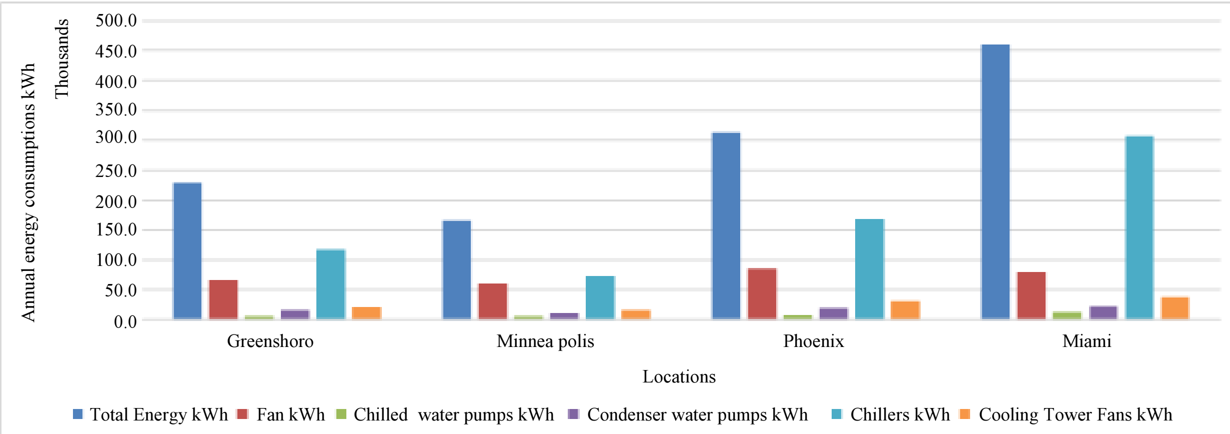


Fig. 4: Total and component-level annual energy consumptions

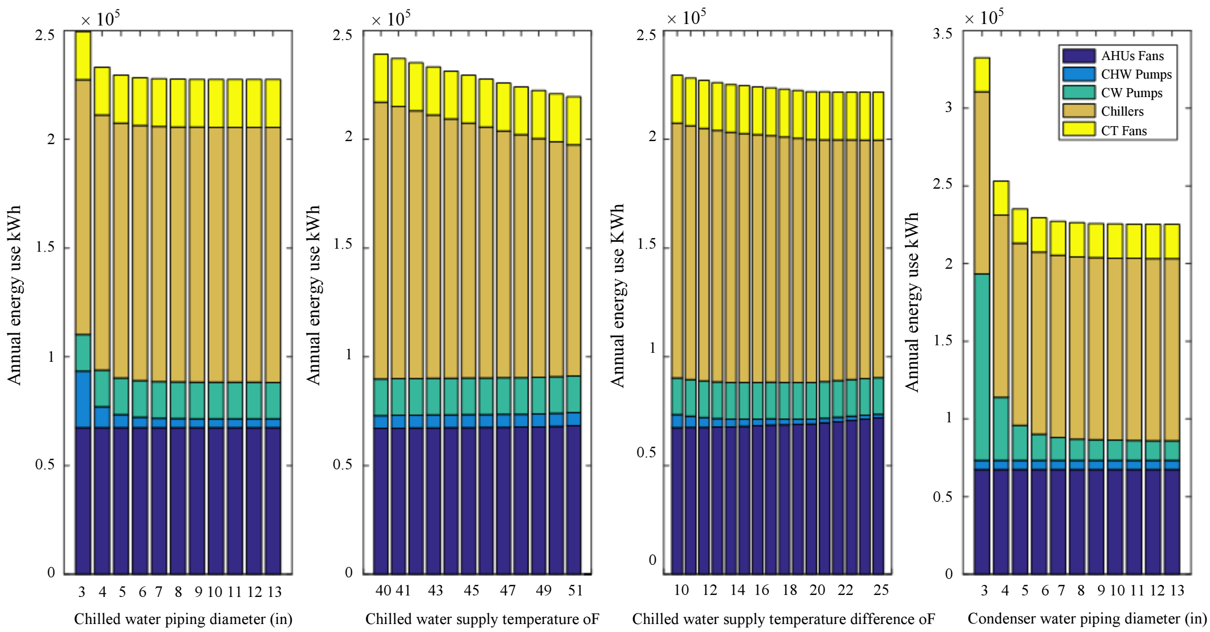


Fig. 5: Annual energy consumption in kWh for various design variables (Greensboro)

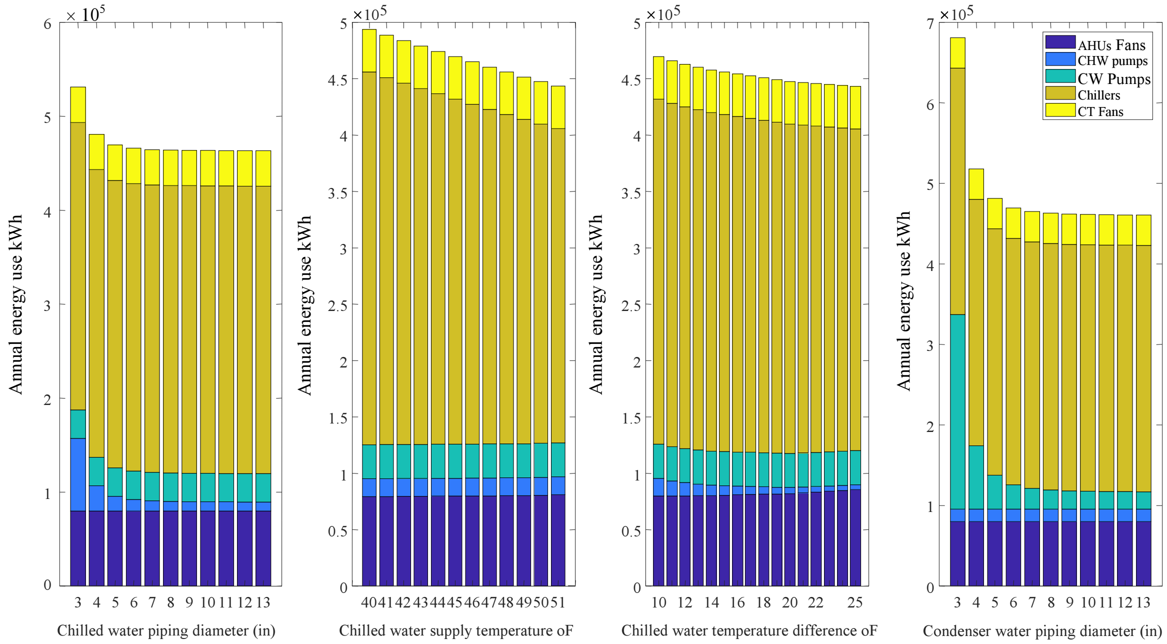


Fig. 6: Annual energy consumption in kWh for various design variables (Miami)

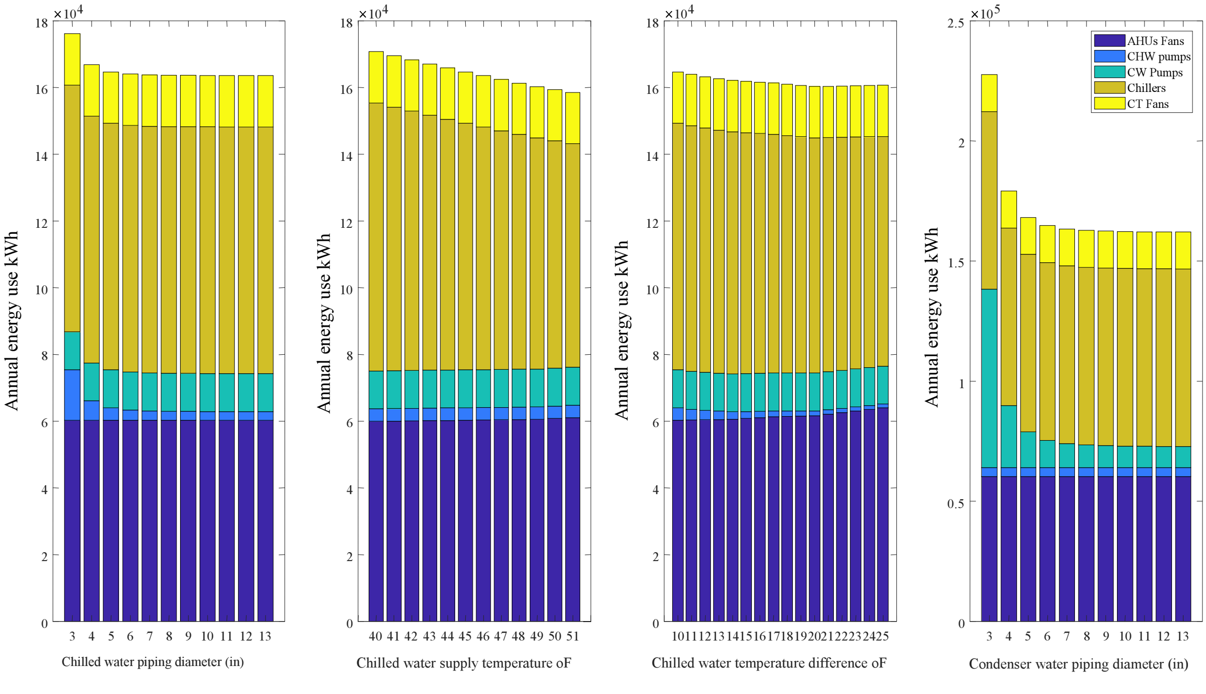


Fig. 7: Annual energy consumption in kWh for various design variables (Minneapolis)

To assess better those different design options, a life-cycle cost is addressed. The costs of coils, piping and fittings are taken from (Means, 2014; Taylor, 2016). The costs of coils, piping, fittings are only considered. The costs of pumps, chillers and cooling towers vary slightly with different pipe size and temperature difference design options, they are not considered in the analysis. However, as shown in Fig. 3, those costs can be included by modifying the input file (called Input_Cost Information). All costs and any other input information can be changed by replacing the defaults values in the input worksheets (Input_System Information, Input_Cost Information and Input_Flow Paramters). Figure 9 and 10 show the resulted life cycle costs for various chilled and condenser water temperature difference and piping sizes (Greensboro).

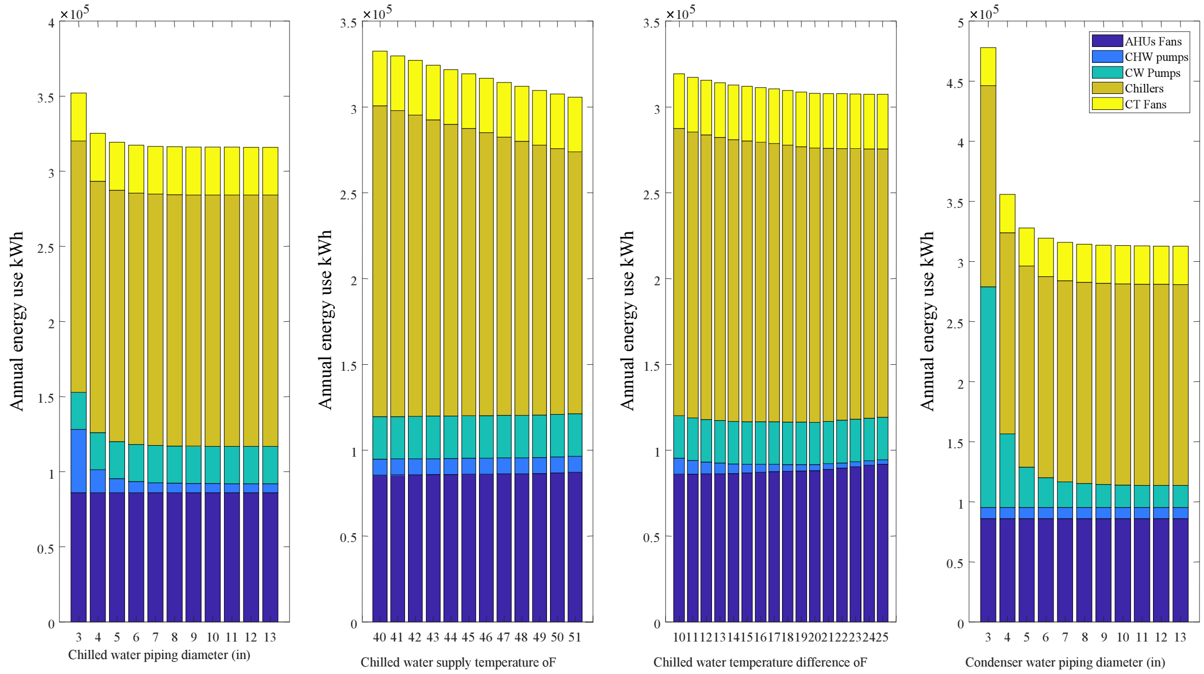


Fig. 8: Annual energy consumption in kWh for various design variables (Phoenix)

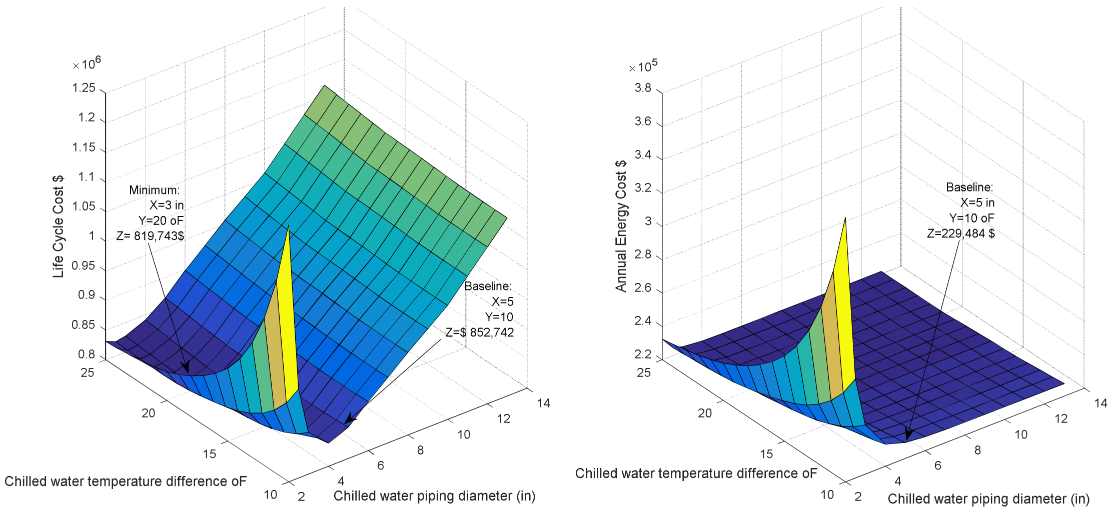


Fig. 9: Annual energy operation and life cycle costs for various chilled water temperature difference and piping sizes (Greensboro)

Figure 11 shows annual energy operation and life cycle costs for various chiller water temperature difference and pipe diameters (Miami, Phoenix and Minneapolis). Other variables are kept at baseline conditions. As shown in Fig. 9, larger pipe diameter leads to lower energy consumption but higher life cycle cost due to elevated piping cost. For Greensboro, the lowest energy consumption occurs at the largest considered diameter of 13 in (33 cm) but the minimum life cycle cost occurs at the pipe diameter of 3 in (7.6 cm). The minimum cycle costs for other locations and for chilled water side (condenser water side temperature difference and pipe diameter are kept at baseline conditions) are shown in Fig. 11. Of course, depending on the initial and energy costs, building locations and system parameters such as number of fitting and valves, number of coils, the length of piping, etc., the results may vary. A low initial cost of piping system makes the design option with minimum life cycle cost have higher pipe diameters. When chilled water temperature difference increases, the energy consumption reduces, mainly pump energy use.

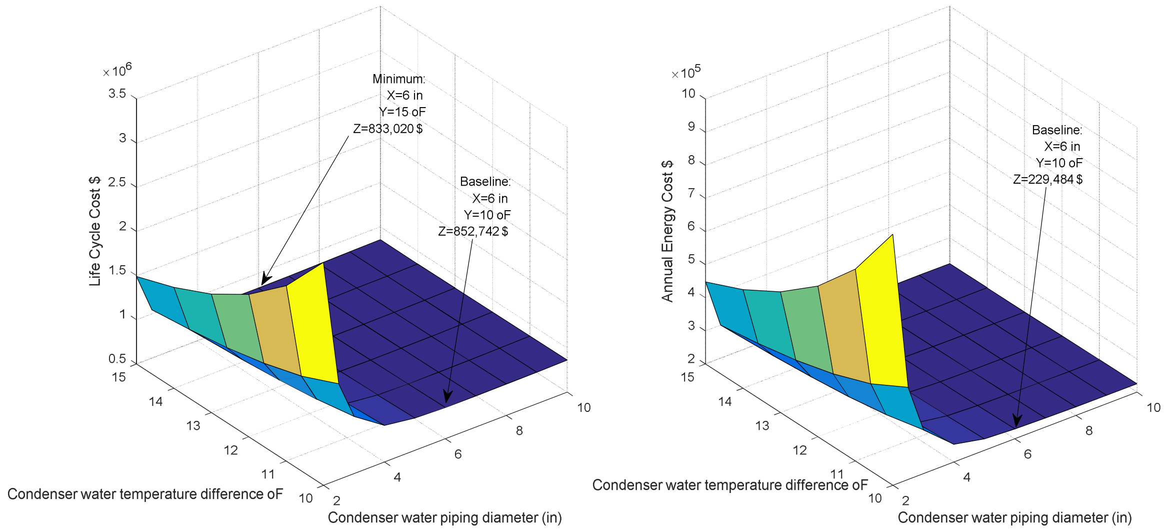


Fig. 10: Annual energy operation and life cycle costs for various condenser water temperature difference and piping sizes (Greensboro)

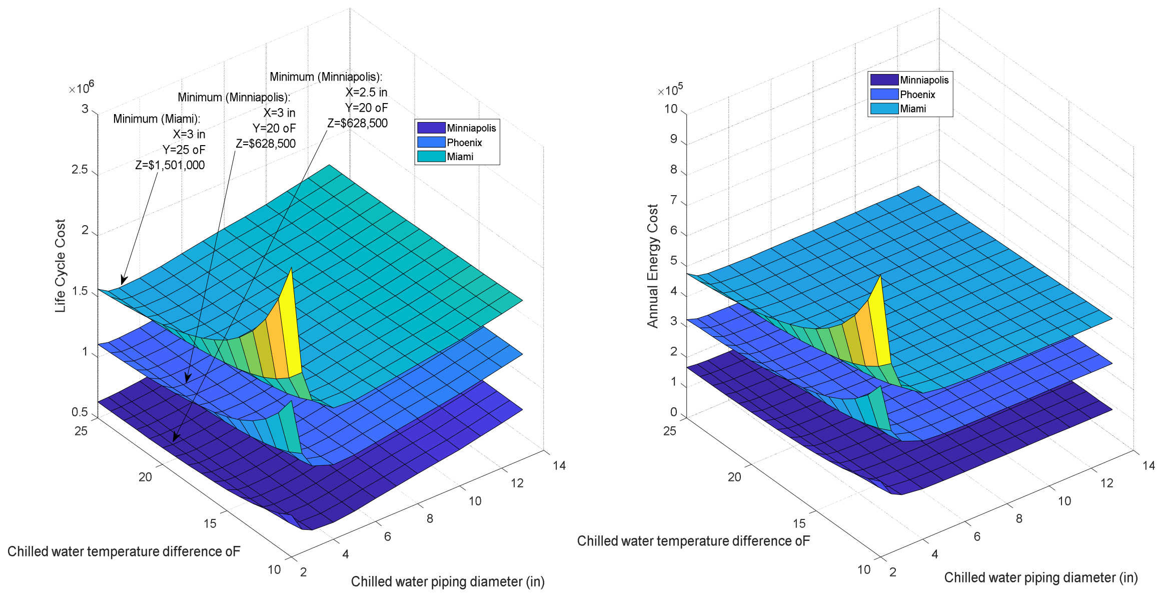


Fig. 11: Annual energy operation and life cycle costs for various chiller water temperature difference and piping sizes (Miami, Phoenix and Minneapolis)

This reduction in pump energy is usually larger than the slight increase in fan energy due to higher fan pressure drop. Looking at the life cycle cost, an increase of temperature difference rises the coil cost that could exceed the energy cost saving from pumps. The lowest energy cost happens at largest considered chilled water temperature difference of 25°F (13.8°C) but the minimum life cycle cost occurs at chilled water temperature difference of 20°F (11.1°C). The same scenario was found for other locations.

Regarding condenser water-side design variables, the condenser water temperature difference has no effect on either cooling coil cost or AHUs fan energy but has a slight 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 lowest energy consumption and lowest life cycle cost both occur at the condenser water temperature difference of 15°F (8.3°C). Both condenser water flow rate and pump energy reduce with elevated condenser water pipe diameter. Comparing to chilled water piping system, the cost of condenser water piping system increases at a lower rate with elevated diameters. This is due to the fact that the investigated chilled water piping system is larger in length and number of fittings/valves than the condenser piping system.

Using the data available from the parametric runs, the optimization algorithm (genetic algorithm GA) can be evaluated. First, the GA is tested to identify only two optimal variables: chilled water pipe diameter and temperature difference. The other variables are kept constant at baseline conditions. The GA finds the optimal solution yielding the minimum life cycle cost. The obtained optimal solution by GA matches exactly the solution found from the parametric studies and depicted in Fig. 9 (minimum: diameter X = 3 in, temperature difference Y = 20 oF, life cycle cost Z = $819,743). The GA reaches to that solution with a population of 30 and less than 40 generations. Second, the chilled water supply temperature is added to the optimization. The GA with a population of 40 and generations of 50 finds the optimal solution that is the same one obtained from the parametric studies. Third, the optimization algorithm is tested for only condenser water-side design variables (condenser water temperature difference and pipe diameter). The GA with a population of 30 and less than 30 generations finds the optimal solution that is the same one obtained from the parametric studies and depicted in Fig. 10 (minimum: diameter X = 6 in, temperature difference Y = 15°F, life cycle cost Z = $833,020). Finally, all five variables are included in the optimization, the GA runs with a population of 50 to find the optimal solution. Figure 12 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. The optimal and no-optimal (baseline) life cycle cost results are shown in Fig. 13 for all locations. The cost savings vary 4% to 8% depending on the location. The maximum cost saving of 8% is obtained for Phoenix and the minimum cost saving of 4% is obtained for Minneapolis. One of reason of saving variation is due to the different baseline pipe diameter values selected form ASHRAE standard 90.1 table with different locations (different maximum flow rate and operating hours).

Several constraints are considered. The maximum condenser water temperature difference is limited to 15°F (8.3°C) to lower the error from not considering the change of cooling tower cost as a function of condenser water temperature difference. The results show that the optimal condenser water temperature difference for all investigated locations stays at the maximum limit of 15°F (8.3°C) to lower condenser water pumping energy. The maximum chilled water temperature difference is limited to 25°F (13.8°C). The resulted optimal chilled water temperature differences vary slightly with locations and they are 20, 21, 21 and 20°F (11.1, 11.6, 11.6, 11.1°C) for Greensboro, Minneapolis, Phoenix and Miami, respectively. This is due to the trade-off between the operating pumping cost and fan energy costs (coil cost as well). Again, an increase in the chilled water temperature difference leads to lower flow rate and pump power but this requires a greater coil surface and more rows. There are also constraints on minimum and maximum fluid velocities. For Greensboro, Minneapolis, Phoenix and Miami, the optimal search for the diameters starts from 2, 2.5, 3 in (5, 6.35, 7.62 cm) and up to 15 in (38.1 cm). The optimal values for chilled water diameters are 3, 2.5, 3 and 4 in (7.62, 6.35, 7.62, 10.16 cm).

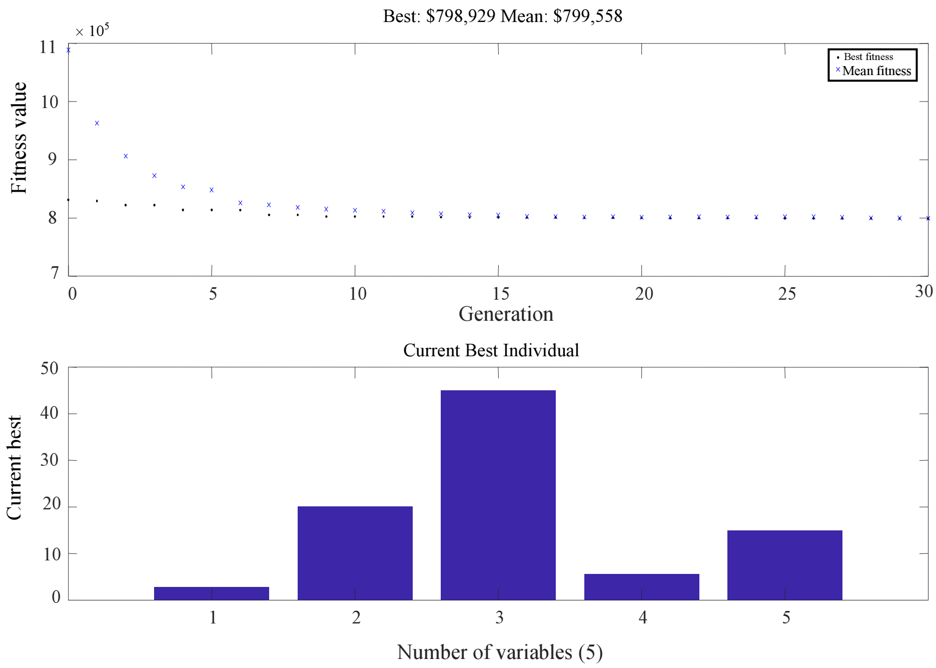


Fig. 12: GA performance with generations (fitness or life cycle cost vs. generations) for Greensboro

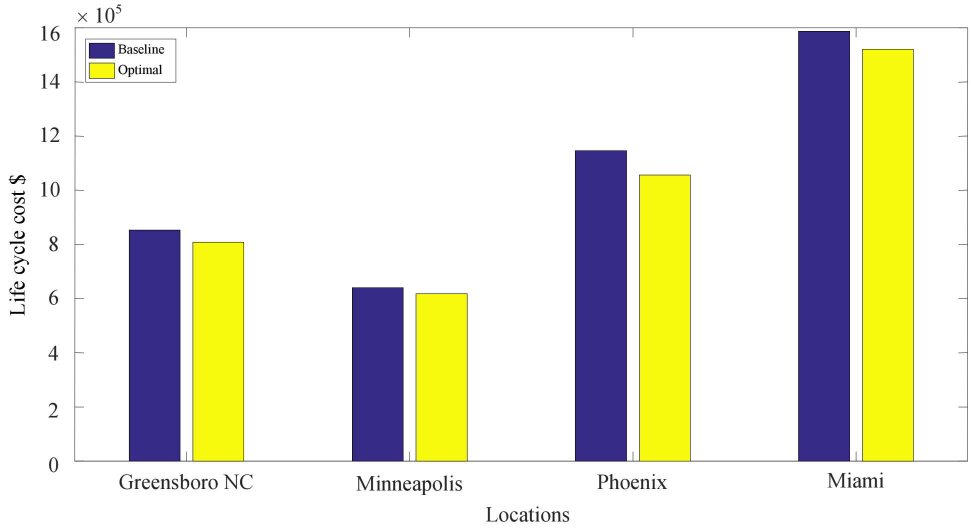


Fig. 13: Optimal and non-optimal life cycle costs for various locations

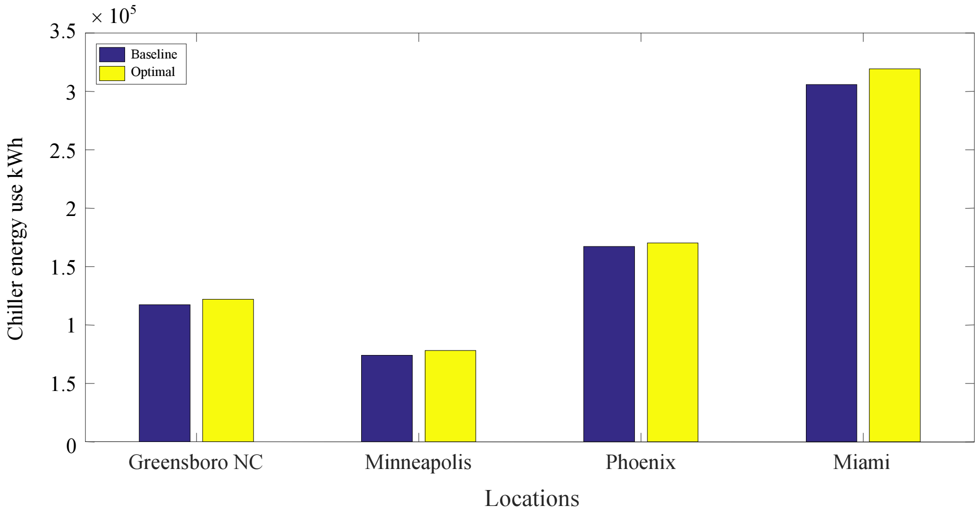


Fig. 14: Optimal and non-optimal chiller energy uses for various locations

The optimal values for condenser water are 4, 4, 5 and 6 in (10.16, 10.16, 12.7, 15.24 cm). Due to higher chilled water temperature differences and then lower flow rates, the diameters are relatively small comparing to the baseline conditions. There is a trade-off between piping installation cost and pump operating energy cost. Increasing the piping system cost leads to lower sizes of the pipe diameters. The range of chilled water supply temperature considered is 40 to 50°F (4.4 to 10 °C). The increase of chilled water temperature improves the chiller efficiency, but this causes a warmer coil and possible humidity problem mainly with elevated chilled water temperature difference. To maintain supply air temperature at for instance 55°F (12.7°C), a large coil with more rows is needed. The resulted optimal chilled water supply temperatures are 42, 42, 43, 42°F (5.5°C, 5.5°C, 6.1°C, 5.5°C) for Greensboro, Minneapolis, Phoenix and Miami, respectively. As the chilled water temperature for the baseline is 45°F (7.2°C), the chiller energy use for all optimal cases are higher than the baseline as shown in Fig 14. With chiller modern technology, the current chiller efficiency may relatively be less sensitive for the change of chilled water supply temperature. By using the actual manufacturers' data (instead of default values) in the chiller model, the penalty form using a lower chilled water temperature may be less than what discussed in this paper and thereby the actual savings in the life cycle cost will be higher than what are presented in Fig 14.

Conclusion

The design variables such as chilled and condenser water temperature differences, chilled water supply temperature and piping sizes were optimized by using the proposed design optimization method. This method integrates an optimization procedure with models that perform detailed cooling load analysis, pump head calculation, energy calculations and life cycle cost analysis. The method is evaluated on an existing 88,000 ft^2 office building located in Greensboro NC. Detailed parametric studies were performed to identify the effect of design variables on central plant system and component-level energy use and cost. Elevated chilled or condenser water temperature difference leads to reduce pump energy. However, the elevated chilled water temperature difference requires to install larger sizes of coils with more rows and thereby higher fan energy use that may exceed the energy cost saving from pumps. There is a trade-off between the pumping energy 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 pump operating energy cost and piping installation cost. To find the optimal design variables, the life cycle cost was considered. The optimization was conducted to determine the minimum life cycle cost and associated energy and cost savings were estimated for various locations. The life cycle cost savings found to be within 4-8%, depending on the project locations. The saving could be even higher if efficient chiller at lower chilled water supply 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.

Acknowledgement

The authors gratefully acknowledge the support of the U.S. Department of Commerce, National Institute of Standards and Technology for funding this project

Author's Contributions

Dr. Al Raees and Dr. Al Rifaie performed laboratory and computational experiments and conducted data analysis of the research. Dr. Nassif and Dr. Abu-Lebdeh provided the research topic and guided the research development, experimental plan and data analysis.

Ethics

References

ASHRAE, Standard 90.1-2013. Energy standard for buildings except low-rise residential buildings. American Society Heating, Refrigerating, Air-Conditioning Engineers, Inc.

ASHRAE, 2015. ASHRAE Handbook-Applications.1st Edn., American Society of Heating Refrigeration and Air Conditioning Engineers, Inc, Atlanta.

ASHRAE, 2016. ASHRAE Handbook-Systems. 1st Edn., American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., Atlanta.

Cheng, Q., S. Wang and C. Yan, 2016. Robust optimal design of chilled water systems in buildings with quantified uncertainty and reliability for minimized life-cycle cost. Energy Build., 126: 159-169.

eQuest Version 3.65. QUick energy simulation tool, eQUEST Version 3.65. http://www.doe2.com/equest/

EIA. US Energy Information Administration. www.eia.gov.

EnergyPlus, 2017. EnergyPlus™ version 8.8.0 documentation: Engineering reference. US. Department of Energy.

Fang, X., J. Xinqiao, Z. Du, Y. Wang and W. Shi, 2017. Evaluation of the design of chilled water system based on the optimal operation performance of equipments. Applied Thermal Eng., 113: 435-448. DOI: 10.1016/j.applthermaleng.2016.11.053

Gao, D., S. Wang and K. Shan, 2016. In-situ implementation and evaluation of an online robust pump speed control strategy for avoiding low delta-T syndrome in complex chilled water systems of high-rise buildings. Applied Energy, 171: 541-554

Goldberg, D.E., 1989. Genetic Algorithms in Search, Optimization and Machine Learning. 1st Edn., Addison-Wesley, Reading.

Hydeman, M., N. Webb, P. Sreedharan and S. Blanc, 2002. Development and testing of a reformulated regression-based electric chiller model. ASHRAE Trans., 105: 1118-27.

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

Lee, K.P. and T.A. Cheng, 2012. A simulation–optimization approach for energy efficiency of chilled water system. Energy Build., 54: 290-296

Ma, Z. and S. Wang, 2011. Supervisory and optimal control of central chiller plants using simplified adaptive models and genetic algorithm. Applied Energy, 88: 198-211

Means, 2014. RSMeans Mechanical Cost Data. 1st Edn., 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: 58-66.

Mua, B., Y. Lib, J.M. Housec and T.I. Salsburyc, 2017. Real-time optimization of a chilled water plant with parallel chillers based on extremum seeking control. Applied Energy, 208: 766-781. DOI: 10.1016/j.apenergy.2017.09.072

Nassif, N., S. Kajl and R. Sabourin, 2005. Optimization of HVAC control system strategy using two-objective genetic algorithm. HVAC&R Res., 11: 459-486.

Nassif, N., 2012. Modeling and optimization of HVAC systems using artificial intelligence approaches. ASHRAE Trans., 118: 133-140.

Nassif, N., N. AlRaees and F. AlRifaie, 2017. Optimizing the design of chilled water plants for commercial building energy systems. ASHRAE Trans., 123: 64-71.

Schwedler, M., 2012. Condenser water system savings: Optimizing flow rates and control. Engineers Newsletter, 41-3: 1-8.

Taylor, S.T., 2016. EDR cool-tools pipe size optimization spreadsheet v2.0.6.

Taylor, S.T., 2012. Optimizing design and control of chilled water part 4: Chiller and cooling tower selection. ASHRAE J., 3: 60-70.

Taylor, S.T., 2011. Optimizing design and control of chilled water part 3: Pipe sizing and optimizing ΔT. ASHRAE J., 12: 22-34.

Taylor, S.T. and M. McGuire, 2008. Sizing pipe using life-cycle costs. ASHRAE J., 11: 24-32.