ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA131

WASTE HEAT RECOVERY FOR THE LHC COOOLING TOWERS: CONTROL SYSTEM VALIDATION USING DIGITAL TWINS

B. Schofield*, M. O. Peljo, W. Booth, E. Blanco, CERN, Geneva, Switzerland

Abstract

In order to improve its energy utilization, CERN will deploy a Waste Heat Recovery (WHR) system at one of the surface sites of the Large Hadron Collider (LHC) which will provide heating power to a local municipality. To study the effects that the heat recovery plant will have on the cooling system, a 'digital twin' of the cooling plant was created in the simulation tool EcosimPro. The primary question of interest was whether the existing control system of the cooling plant would be capable of handling transients arising from a sudden shutdown of the heat recovery plant.

The simulation was connected via the communication protocol OPC Unified Architecture (OPC-UA) to a Programmable Logic Controller (PLC) implementing the cooling plant control system. This 'virtual commissioning' setup was used to study a number of scenarios representing different cooling loads, ambient temperature conditions, and heat recovery plant operating points. Upon completion of the investigation it was found that the current cooling plant control system will be sufficient to deal with the transients arising from a sudden stop of heat recovery plant operation. In addition, it was shown that an improvement in the controls could also enhance the energy savings of the cooling towers.

INTRODUCTION

To minimize the environmental impact of CERN's activities, an environmental commitment has been agreed on [1]. WHR has been identified as a key measure to increase the energy efficiency [2]. Preparations have started for installing WHR on the cooling sites, and the project is starting with a pilot at LHC point 8, providing heat from the primary cooling water for use by the nearby municipality of Ferney-Voltaire [2]. During the early design phase of the WHR plant, the question was raised as to whether the existing cooling plant and its associated control system would be capable of rejecting disturbances in the cooling water temperature caused by a failure of the WHR plant. The cooling towers supply primary cooling water to cryogenic refrigeration plants, which are critical for operation of the LHC. Transient events in the cooling plant could cause the secondary cooling circuits for the cryogenics to shut down, which would then halt the operation of the LHC. In order to investigate the effects that the WHR plant might have on the primary cooling water system, it was decided to use a virtual commissioning approach to verify the performance of the existing control system under a set of temperature transients caused by a sudden loss of the WHR.

VIRTUAL COMMISSIONING USING DIGITAL TWINS

The principle of virtual commissioning is to connect a production-ready control system implementation with a simulation model (a 'digital twin') of the process to be controlled. This practise allows engineers to detect errors earlier in the development process, and facilitates the final commissioning phase. Lee and Park [3] provide an overview of virtual commissioning as used in manufacturing processes. They identified that the main obstacle for wider application of virtual commissioning is the model building, which requires in-depth expertise, both in modeling and control engineering. Model validation is then a critical step in order to give credibility to the results. However, once a model has been developed, its usefulness does not end at the commissioning phase, as it may be used continuously for operator training, and evaluation of updates to control strategies. At CERN, a process simulation of cryogenic refrigeration plants of the LHC has been developed by Bradu, Gayet, and Niculescu [4]. The simulation model connects to the existing control and supervision systems, and is used extensively for operator training. Virtual commissioning has also been employed by Booth, Blanco Viñuela, Bradu, and Sourisseau [5] for the development of the heating, ventilation and air conditioning (HVAC) system of the Compact Muon Solenoid (CMS) experimental cavern.

In this paper, the development of a model of the primary cooling water plant at LHC Point 8 is presented. The model was implemented in EcosimPro, a multidomain modeling and simulation tool. The EcosimPro model was then connected to a PLC running a copy of the currently operational version of the cooling plant control system using OPC-UA, and a number of simulated scenarios identified by the process experts were evaluated.

MODELLING AND IDENTIFICATION OF EVAPORATIVE COOLING TOWERS

The focus of this work was the development of a mathematical model of the main element of the primary water cooling plant, namely the evaporative cooling towers. The primary water cooling plant at LHC point 8, known as Surface Fluid 8 (SF8), has five main cooling towers, as well as two backup towers. A schematic of the cooling plant is shown in Fig. 1. The five main towers receive the combined return water from three primary cooling circuits, and collect the cooled water in a common basin from where it is supplied to these three circuits. One of the circuits (corresponding to the cryogenics equipment) can be rerouted to the backup towers; however modelling of these towers was

* brad.schofield@cern.ch

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA131

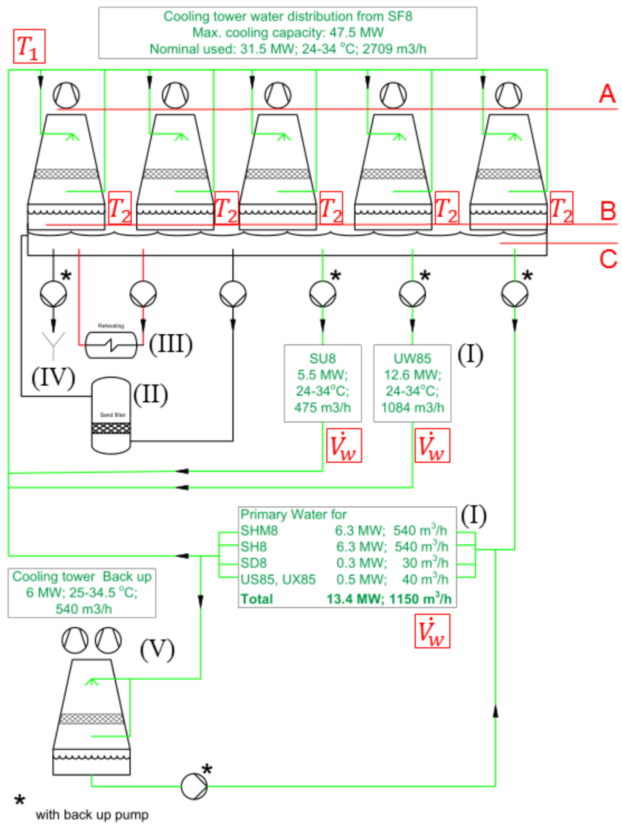

Figure 1: Cooling system at LHC point 8. The common basin collects cooled primary cooling water, from where the cooling water is distributed to clients.

not undertaken. The WHR plant is to be installed on the combined return line.

Although the five main towers are almost identical, there are some small differences between them. The intention with the modelling effort was to derive a common model structure which could be used for all towers, and then to parameterize each tower independently.

Heat transfer in evaporative cooling towers involves both convection at the air-water interface and heat absorption by the evaporating process water due to mass transfer. Evaporative cooling is very effective, due to the latent heat transfer during the phase transition from water to vapor. Latent heat transfer is the thermal energy transfer in a constant temperature process. The cooling water evaporation rate is only between 1-2 per cent, but it plays an important role in the heat dissipation. The losses from evaporation must be compensated by adding new process water. As a result of the evaporation, a theoretical minimum for the leaving cooling water temperature is the ambient wet-bulb temperature, and often temperatures less than ambient dry-bulb temperatures are reached.

The components of an evaporative cooling tower are illustrated in Fig. 2. They consist of, from top to bottom: a fan, drift eliminators, water spray, cooling tower fill, shower area and basin. The fan is powered by an electrical motor (in this case a Variable Frequency Drive (VFD)) and is used to increase the air flow in the tower to increase cooling capacity. Drift eliminator prevents the smallest mist escaping the cooling tower. The sprays are used to create small droplets in order to increase the convection and evaporation area, and to equally distribute the water across the cooling tower cross section. The cooling tower fill is used to slow down the water and increase time of contact and area with the counter flowing air. [6]

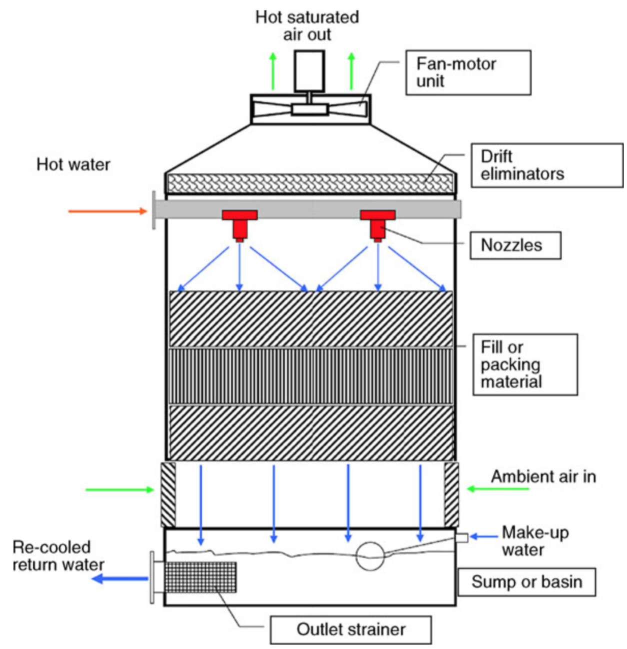

Figure 2: Mechanical draft counter flow evaporative cooling tower. Figure shows the components inside the cooling tower, which are needed to increase cooling capacity and prevent water from escaping the cooling tower.

Several calculation methods for modeling steady state operation of cooling towers exists in commercial products and the theory behind is often based on knowledge freely available in the literature. The most widely used methods to model steady operation points are the Merkel method and the Poppe method [6, 7]. Dynamic models capable of modeling transient events are more scarce and complex. However the modeling method presented by Jin [8] suited the requirements of this project and available data well. Jin, Cai, Lu, Lee, and Chiang [9] have published an article about a steady state model for control and optimization of HVAC-systems. Later Jin [8] revisited his previous work and extended the model and covered a validation study also for transient modeling.

Dynamic Modeling of Output Water Temperature

Jin, Cai, Lu, Lee, and Chiang [9] proposes that the heat dissipation rate Q can be calculated using a semi empirical model, a combination of physical modeling and empirical parameters. Physical properties of the model are based on the analogy between cooling tower and a heat exchanger.

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA131

The heat dissipation rate Q is calculated using the overall heat resistance R of the cooling tower:

$$Q = \frac{T_1 - T_{wb}}{R} \tag{1}$$

where T_1 is the entering cooling water temperature and T_{wb} is the ambient wet-bulb temperature. The overall heat resistance R consists of the heat resistance of the water side and the heat resistance of the air side:

$$R = R_w + R_a \tag{2}$$

The heat transfer at the water-air film can be considered as forced convection, and equations for calculating the heat resistances R_w, R_a as functions of air and water mass flows $\dot{m}_a$ and $\dot{m}_w$ can be expressed as [9]:

$$\frac{1}{R_w} = b_1 \dot{m}_w^l \tag{3}$$

$$\frac{1}{R_a} = b_2 \dot{m}_a^l \tag{4}$$

Substituting Eqs. (2), (3) and (4) into Eq. (1) a model for the heat dissipation rate Q is obtained:

$$Q = \frac{b_1 \dot{m}_w^l \cdot b_2 \dot{m}_a^l}{b_1 \dot{m}_w^l + b_2 \dot{m}_a^l}(T_1 - T_{wb}) = \frac{c_4 \dot{m}_w^l}{1 + c_3 \frac{\dot{m}_w}{\dot{m}_a}^l}(T_1 - T_{wb}) \tag{5}$$

where $c_4 = b_1$, $c_3 = \frac{b_1}{b_2}$ and l are the empirical parameters of the model.

Jin, Cai, Lu, Lee, and Chiang [9] experimentally validate, that the Eq. (5) can be used to estimate steady state heat dissipation rate of a counter flow evaporative cooling tower and thus the leaving cooling water temperature T_2. The model parameters c_3, c_4 and l are optimized against manufactures steady state cooling tower performance data, or real operational steady state data.

In a PhD thesis by Jin [8], the steady state model by Jin, Cai, Lu, Lee, and Chiang [9] is revisited and the model is further developed for dynamic modeling. Jin [8] proposes and validates that the Eqs. 6 and 7 can be used to dynamically model the rate of change of output water temperature T_2 over time.

$$\frac{dT_2}{dt} = c_1 \phi(t) \tag{6}$$

where,

$$\phi(t) = -\frac{\frac{c_4}{C_{pw}} \dot{m}_w^l(t)}{1 + c_3 \left[\frac{\dot{m}_w(t)}{\dot{m}_a(t)}\right]^l}[T_1(t) - T_{wb}(t)] - \dot{m}_w(t)[T_2(t) - T_1(t)] \tag{7}$$

where steady state parameters c_3, l, c_4 and dynamic parameter c_1 are optimized against operational data.

Parameter Identification and Model Validation

Historical operation data was used to parametrize and validate the model of the cooling towers at SF8. The data from various sensors linked in to the existing control system is continuously logged in to the LHC logging system, from where the data was queried. SF8 has sensors for cooling water input temperature T_1 and volumetric flow. The cooling water output temperature T_2 is measured with sensors submerged in each of the cooling tower basins. The ambient conditions where obtained from nearby temperature and humidity sensors. The air mass flow is estimated by a linear model identified for the fan speed signal under assumption that the output air is saturated and its temperature equals input cooling water temperature.

While the quality and availability of the data was good, the data needed to be combined and modified to correct form. An algorithm was developed in R programming language to detect steady operations points from time series data. The algorithm identifies time periods where the model input variables T_1, T_{wb}, $\dot{m}_w$, $\dot{m}_a$ and output variable T_2 are all steady and aggregates the values into steady operation points, an average of each variable over a steady time window. The steady state parameters were then optimized as non-linear multi variable least squares problem by the Levenberg-Mardquardt method, available in an open source R-library *minpack.lm*, which minimizes the offset for estimated output variable T_2. To gather data for identifying the dynamic parameter c_1, step response tests where carried out with the towers. R was used to solve the optimal parameter c_1 as a linear least squares problem.

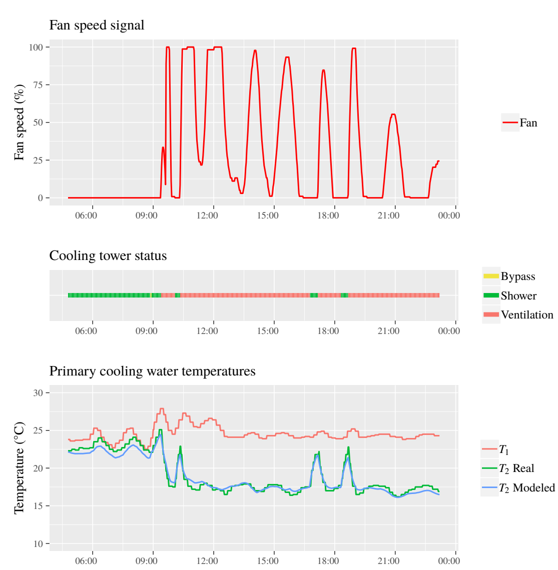

Figure 3: Validation plot ETR-880, rmse = 0.4905 °C, mean T_{wb} = 13.57 °C. The model captures the dynamics well with minor offset.

Transient events available in the historical data where used to cross validate the dynamic performance of the model. It was found that the model reproduces the dynamics in

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA131

output temperature T_2 very well with root mean squared error (RMSE) between 0.5 and 1.25 °C. Model estimation versus the real measured value is presented in Fig. 3. Further details of the model parameter identification and validation can be found in Peljo [10].

Model Implementation

The model structure in Eqs. (6) and (7) was implemented as a cooling tower component in EcosimPro. A complete model of the SF8 cooling plant was created by instantiating and parameterizing five of these tower components with the parameters obtained as above. Two parameter sets were used; one corresponding to a tower with slightly different fan geometry, and another for the remainder of the towers. A simple model of the basin was implemented, and the cooling clients and the WHR system were modeled as simple heat sources and sinks. The cooling tower component also implemented the different operational modes of the towers, which include bypass, when the return water is routed directly into the basin; showering, where the return water is routed through the tower's nozzles but the fans are inactive; and ventilation, in which the fans are run at a speed determined by the output of a PID controller based on the measured temperature of the water in the basin. A schematic of the simulation model is shown in Fig. 4.

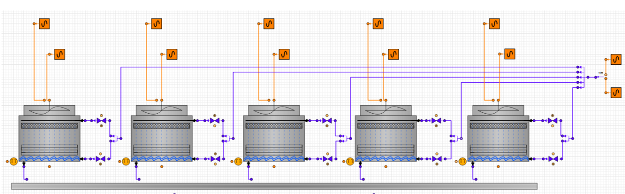

Figure 4: Implementation of the SF8 plant created from individual tower components in EcosimPro.

VIRTUAL COMMISSIONING SETUP

Upon completion of the cooling plant model implementation in EcosimPro, the final step required to create a virtual commissioning setup was to connect the simulation to a copy of the production control system running on a PLC. To accomplish this, OPC-UA was chosen as the communication protocol. The EcosimPro model can be compiled into an executable program which includes an OPC-UA server. The server exposes methods which allow an OPC-UA client to run the simulation for a given period of time. The server can also be configured to expose simulation variables which may be read from and written to. For the purposes of virtual commissioning, it is desired to write control signals to the simulation model, and read back the process variables which are used as inputs to the controller. For the cooling towers, the control signals are the valve commands which control the bypass and showering modes of operation, as well as the fan activation signals and speed setpoints, which are unique to each tower. The measured value is the water temperature in the basin.

The control system for the SF8 cooling plant is implemented in a Schneider Premium PLC. A copy of the control system was loaded into a laboratory PLC, and the Schneider OPC Factory Server application was used to expose PLC variables via an OPC-UA server. In order to connect the OPC-UA servers of the simulation and the PLC, an OPC-UA client application was created using an open source Python OPC-UA package[11]. This Python client performed the data exchange between the EcosimPro model and the PLC, including the necessary scalings of the variables. The client was also responsible for running the EcosimPro model for fixed periods of time, and synchronizing this with real time. Simulations were performed for periods of five seconds, which was slightly slower than the sampling rates used in the production control system, but still much faster than the time constants of the process.

CLOSED LOOP SIMULATION RESULTS

A number of different scenarios for possible temperature transients caused by a sudden loss of heat recovery plant were proposed by the process experts, and tested using the virtual commissioning system described above. A full description of the obtained results can be found in Peljo [10]. These scenarios represented particularly critical combinations of operating modes and ambient conditions, which represented the greatest challenges to the cooling plant control system.

One such scenario is a condition in which the ambient wet bulb temperature T_{wb} is 12 °C, the client heat power to be dissipated is 20 MW, and the WHR is operating at 6.3 MW. This represents a spring or autumn condition in which the LHC is running. A sudden loss of the WHR plant would require that the 6.3 MW it had been capturing would have to be dissipated by the cooling plant. This transition would have to occur sufficiently quickly to prevent an excessive rise in the temperature of the primary cooling water supply.

The results of a closed loop simulation of this scenario are shown in Fig. 5. The sudden loss of the WHR plant occurs at approximately 40 minutes into the simulation, and manifests itself as a sharp rise in return water temperature T_1 in the lower plot. Following this, the supply water temperature T_2 begins to rise. The controller output rises, and at approximately 46 minutes is high enough to cause an additional tower to enter ventilation mode. It should be noted that the fan speed range of 0-100% in fact corresponds to approximately 30–50 rpm, meaning that there are some discontinuities in the controlled cooling power of the plant. This is also the reason that the system is not in steady state at the beginning of the simulation.

After the activation of the ventilation in the second tower, the basin temperature begins to drop, and returns to the setpoint of 22 °C after approximately 30 minutes. During the transient the basin temperature rose less than 1 °C, which was well within the requirements stipulated by the process experts.

It was found that the behaviour of the control system in the remaining scenarios was also acceptable (see [10] for

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA131

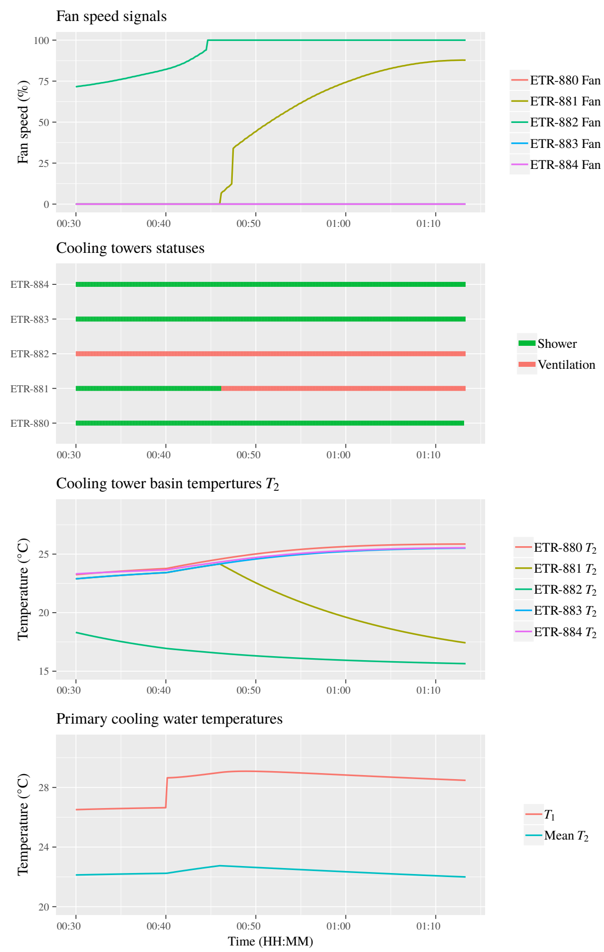

Figure 5: Simulation results for T_{wb} = 12 °C, client power 20 MW, and WHR power 6.3 MW, with WHR plant failure after approximately 40 minutes.

details). Based on these results it was concluded that the existing cooling plant and its control system would be able to cope with the worst case disturbance scenarios which may arise in conjunction with the introduction of the WHR plant.

CONCLUSION

In this paper the development of a dynamic simulation model for evaporative cooling towers has been presented. The purpose of the model was to create a virtual commissioning setup which could be used to analyze the behaviour of an existing control system, implemented in a PLC, to a proposed change in the cooling plant, namely the addition of a WHR plant. The open process control protocol OPC-UA was leveraged to create a generic interface between simulation model and PLC which allowed closed loop simulations to be made. A number of simulations were performed based on operational scenarios defined by the process experts. The simulation results indicated that the existing cooling plant and its controls were sufficient to deal with a possible fault in the WHR plant, and therefore that re-engineering of the control system in conjunction with installation of the WHR plant would not be required.

REFERENCES

[1] CERN, Ed. (2018). CERN and the Environment, `http://environmental-impact.web.cern.ch/environmental-impact/`

[2] S. Claudet, "CERN energy management, energy efficiency analysis and selected projects," in *4th Workshop Energy for Sustainable Science at Research Infrastructure*, 2017. `https://indico.eli-np.ro/event/1/contributions/7/attachments/69/105/5_CERN_Energy_Claudet.pdf`

[3] C. G. Lee and S. C. Park, "Survey on the virtual commissioning of manufacturing systems," *J. Comput. Des. Eng.*, vol. 1, no. 3, pp. 213–222, 2014. `doi:10.7315/JCDE.2014.021`

[4] B. Bradu, P. Gayet, and S.-I. Niculescu, "A process and control simulator for large scale cryogenic plants," *Control Eng. Pract.*, vol. 17, no. 12, pp. 1388–1397, 2009. `doi:10.1016/j.conengprac.2009.07.003`

[5] W. Booth, E. Blanco Viñuela, B. Bradu, and S. Sourisseau, "Virtual control commissioning for a large critical ventilation system: The CMS cavern use case," in *Proc. ICALEPCS'17*, Barcelona, Spain, 2018, pp. 92–98. `doi:10.18429/JACoW-ICALEPCS2017-MODPL02`

[6] V. Gesellschaft, *VDI Heat Atlas*, ser. VDI-Buch. Springer, Berlin, Heidelberg, 2010. `https://books.google.fi/books?id=0t-HrUf1aHEC`

[7] J. Kloppers and D. Kröger, "A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers," *International Journal of Heat and Mass Transfer*, vol. 48, no. 3, pp. 765–777, 2005. `doi:10.1016/j.ijheatmasstransfer.2004.09.004`

[8] G.-Y. Jin, "Modeling and optimization of building hvac systems.," PhD thesis, Nanyang Technological University, School of Electrical and Electronic Engineering, 2011. `https://dr.ntu.edu.sg/handle/10356/49960`

[9] G.-Y. Jin, W.-J. Cai, L. Lu, E. L. Lee, and A. Chiang, "A simplified modeling of mechanical cooling tower for control and optimization of hvac systems," *Energy Conversion and Management*, vol. 48, no. 2, pp. 355–365, 2007. `doi:10.1016/j.enconman.2006.07.010`

[10] M. Peljo, "Modeling of cooling towers under heat recovery," en, Master Thesis, 2018, pp. 82 + 8. `http://urn.fi/URN:NBN:fi:aalto-201812146556`

[11] *Github repository as of 27 September 2019*. `https://github.com/FreeOpcUa/python-opcua`