DYNAMIC MODELLING OF A DISTRICT COOLING NETWORK WITH MODELICA

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ABSTRACT

This research aims to define a modelling approach to simulate District Cooling Systems (DCS). A model of the network has been developed using the equation-based object-oriented language Modelica. This model includes a cooling production plant, a distribution network of pipes and 6 substations. This integrated modelling approach allows us to study interactions between substations cooling demand and cooling production plant efficiency. Hourly measurements from Eastern Paris DCS are used as inputs for cooling demand. A simplified model of substations with ideal control has been developed. A performance-based model of electric chiller taking into account variable evaporator entering conditions has also been developed. System simulation results are presented and discussed. Chiller electricity consumption accounts for 61% of total electricity consumption. CPU time is of 30 s for a simulation period of 1 week. As an application, an alternative control strategy at substations level is evaluated. Impacts on electricity consumption of chiller, chilled-water pump and distribution pump are analyzed and discussed. In our case study, total electricity consumption reduction is not significant.

INTRODUCTION

Climate change and fossil fuels depletion are two major issues to tackle and are directly related to energy consumption. Energy consumption for space cooling increased by 60% globally from 2000 to 2010 (IEA 2014). Cooling can be either supplied by an individual installation or by a DCS. DCS supply cold water through pipes in combination with cold storage (UNEP 2014). In Paris, the reductions of primary energy use CO_2 and refrigerant emissions by using DCS have been assessed respectively to 50%, 50% and 90% (CLIMESPACE 2013). DCS offer economical (electricity and water costs) and environmental benefits (CLIMESPACE and ADEME 2011) and are expected to supply an increasing share of the cooling demand.

Since 1991, CLIMESPACE, the industrial partner of this research, has operated and developed the DCS of Paris. 10 compressor-driven production plants and 3 cold storage sites supply cooling water to 550 substations for a global cooling capacity of 310 MW. Renewable energy (river free-cooling, geothermal) and waste cold recovery (heat-pump evaporator) energy sources have been implemented to improve continuously the energy efficiency of DCS. DCS is connected to the global electricity market, with variable electricity prices and demand response incentives. As a consequence, DCS operators need advanced decision-support tool to cope with both increased operational complexity and multiple high performance targets.

Today, several models have been developed for District Heating Systems (DHS), including heat production, distribution and consumption. Existing modeling tools are either integrated in a single simulation environment or coupling several simulation environments (Huber and Nytsch-Geusen 2011). Component models (e.g the production plant) are either physical (Soons et al. 2014) or statistical (Elci et al. 2013). Most of the physical models takes into account temperature dynamics and consider hydraulics to be in steady-state (Benonysson 1991). To our knowledge, dynamic, integrated and physical DCS models have not been extensively developed. This research aims, as a first step, to define a modelling approach to simulate efficiently large-scale DCS with physical models, taking into account temperature dynamics, pressure losses and chillers part-load performances. The model presented in this paper is developed with the aim to be linked to an optimization algorithm in order to provide DHS operators with a control strategy which minimizes electricity consumption.

SIMULATION

Modelling and simulation approach

The model includes a chilled-water production plant, a district cooling network and 6 substations. Cooling load at substation level is considered as an input. The approach for production and district cooling modelling is defined as integrated (Huber and Nytsch-Geusen 2011), contrary to (Elci et al. 2013).

An integrated approach requires multi-domain modelling, i.e. enabling modelling of combined disciplines such as electrical, thermodynamics, fluid dynamics and control systems.

The modelling and simulation environment Dymola (Dassault Systèmes AB 2014) with the Modelica language (Modelica Association 2014) is chosen while offering multi-domain modelling, modularity, realistic control behaviour and flexibility according to (Soons et al. 2014) and (Wetter and Haugstetter 2006). Modelica is a freely-available, equation-based object-oriented language. Advantages of equation-based object-oriented modelling are extensively explained in (Wetter 2010). A simulation environment (e.g. Dymola) translates a Modelica model into executable code. In Modelica models, equations are acausal, in opposition to causal (procedural) code where equation order matters for numerical solving.

(Basciotti and Pol 2011) pointed out advantages in using Modelica and Dymola in simulation of complex DHS. This modelling approach is particularly adapted to our study since it allows to observe the dynamic response of the system during transient periods and to study interactions between network cooling demand and cooling plant efficiency.

Case study

In this paper, a simple DCS is considered as a first case study. This case study is inspired from a sub-network of Eastern Paris DCS operated by CLIMESPACE (Figure 1). Modelling and simulation of full-scale Eastern Paris DCS is computationally intensive and lead to initialization barriers. Indeed, an initial guess of flow rates in substations close to the solution is necessary due to non-linearity. Solutions to handle a larger number of substations are under development.

The production plant is composed of 1 centrifugal compressor-driven chiller. Global cooling capacity is sized to satisfy peak cooling demand in the proposed application study (see Figure 9). Chiller condenser is water-cooled by the Seine River. Cooling capacity and COP are shown in Figure 5. Chilled water (2°C/10°C) is supplied through a Distribution Cooling Network (DCN). The distribution network is composed of 1.8 km of insulated steel pipes either buried in the ground or passing through technical sewage galleries. 6 substations are connected to the DCN (approx. 100 000 m² of total floor area).

Model

Model libraries *Modelica Standard Library* 3.2.1 and *Buildings* 1.6 (Wetter 2010) have been used and original models have been developed on purpose.

Models references can be found in Table 1.

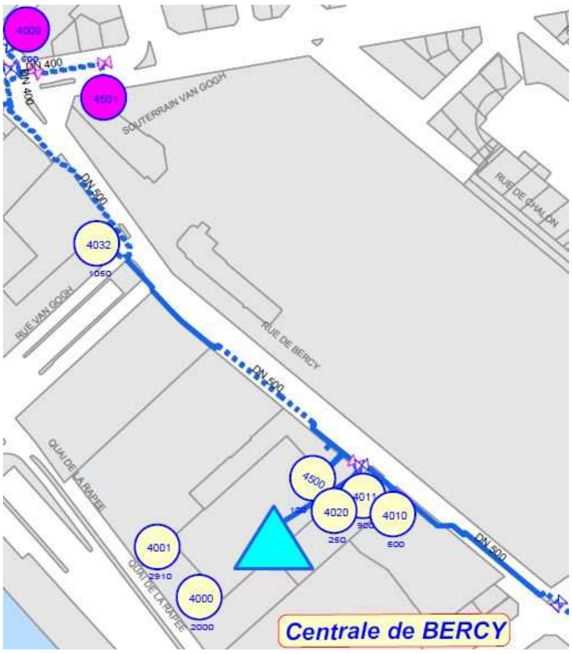

Figure 1: Map of the modelled sub-network from CLIMESPACE GIS. The cyan triangle stands for the CWPP. White and pink circles stand for substations. Substations 4500, 4020, 4011 and 4010 are aggregated in the model. Supply and return line are represented with a single blue line.

Table 1 : Models and partial models references

MODEL	MODELICA PATH
Water	Modelica.Media.Water.ConstantPropertyLiquidWater
Fluid interface	Buildings.Fluid.Interfaces.PartialTwoPortInterface
Flow resistance	Buildings.Fluid.BaseClasses.PartialResistance
Static energy conservation	Buildings.Fluid.Interfaces.StaticTwoPortConservationEquation
Pipe	Buildings.Fluid.FixedResistances.Pipe Modelica.Fluid.Pipes.StaticPipe Buildings.Fluid.FixedResistances.FixedResistanceDpM
Chiller	Buildings.Fluid.Chillers.BaseClasses.PartialElectric
Water volume	Buildings.Fluid.MixingVolumes.MixingVolume
Pump	Buildings.Fluid.Movers.FlowMachine_m_flow Buildings.Fluid.Movers.FlowMachine_dp
Valves	Modelica.Fluid.Valves.ValveIncompressible
Heat exchanger	Buildings.Fluid.HeatExchangers.ConstantEffectiveness

Figure 2 shows inputs, sub-models used in the global model and connections through fluid and heat ports. Fluid ports contain variables for pressure, mass flow and enthalpy. Heat ports contain variables for temperature and heat flow. At nodes, a model translator imposes conservation equations for *flow* variables (Wetter 2010). The model used for water properties is simplified medium model for liquid water with linear dependency of internal energy and enthalpy with temperature and with constant density.

Inputs to the DCS model are listed and classified into sub-models in Table 2. Hourly real values are interpolated such that first derivative is continuous, in order to ensure smoothness of the input signal. A second order filter is applied to pumps and valves input signals to model component dynamics.

1. Substations

6 substations are connected to the DCN (see Figure 2). Figure 3 defines terminology for the substation model. Building cooling load is prescribed on the secondary side with cooling demand, secondary return temperature set-point and secondary supply temperature set-point. A control valve on the primary return pipe set primary mass flow rate according to cooling demand and available differential pressure. The substation model calculates valve flow coefficient k, primary return temperature T_{p2}, primary mass flow rate $\dot{m}_p$ and secondary mass flow rate $\dot{m}_s$. Inputs are summarized in Table 2. Parameters are heat exchanger effectiveness ε, heat exchanger flow coefficient k_e, control valve minimum flow coefficient k_{min} (fully-open conditions), rated heat flow rate $\dot{Q}_n$ and secondary supply temperature set-point.

Table 2: Inputs to the DCS model

SUB-MODEL	**INPUT**	**UNIT**	**DATA TIME STEP**
Substations	Cooling demand $\dot{Q}$	kW	1 hour
	Secondary return temperature set-point T_{s2}	°C	Constant input
DCN	Undisturbed ground temperature T_g	°C	
CWPP	Distribution pump differential pressure set-point Δp	Pa	
	Evaporator leaving temperature set-point $T_{e,l}$	°C	
	Condenser pump mass flow rate set-point $\dot{m}_c$	kg/s	
	Cooling water heat exchanger valves opening	Boolean	1 hour
	Cooling water pumps mass flow rate $\dot{m}_{cw}$	kg/s	1 hour
	Seine river temperature T_{cw}	°C	1 hour

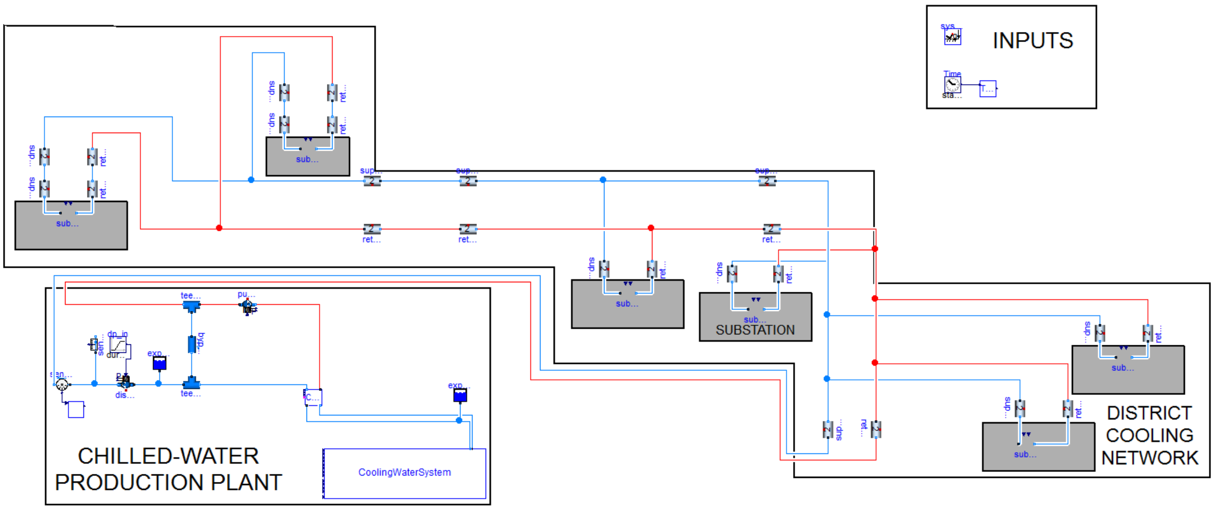

Figure 2 : DCS model in the Dymola environment. Inputs, substations, district cooling network and chilled-water production plant sub-models are emphasized into black rectangles. Blue lines represent connections through fluid ports on the supply line. Red lines represent connections trough fluid ports on the return line.

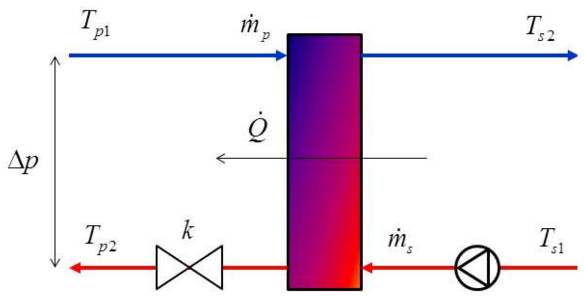

Figure 3: Substation model terminology. On the left-hand side, primary loop connected to the DCN (blue: supply line; red: return line), with control valve. On the right-hand side, secondary loop connected to the building cooling system, with secondary pump. On the middle, plate heat exchanger connected to primary and secondary loops.

The substation model calculates the heat flow rate $\dot{Q}$ from secondary to primary loops, primary return temperature T_{p2}, primary mass flow rate $\dot{m}_p$ and secondary mass flow rate $\dot{m}_s$. Inputs are recalled in Table 2. Parameters are heat exchanger effectiveness ε, heat exchanger flow coefficient k_e, control valve minimum flow coefficient k_{min} (fully-open conditions), rated heat flow rate $\dot{Q}_n$ and secondary supply temperature set-point. Buildings and Modelica.Fluid libraries contains hydraulic, heat transfer and control sub-models to build a detailed substation model (Soons et al. 2014). However, continuous controllers (e.g. PID) for control valve and secondary pump are computationally intensive and, to our experience, lead to initialization failure for large DCS. It is not suitable with the aim of simulating large DCS within an acceptable time for operational optimization. A simplified approach is hence proposed and is inspired from (Adelior France and SAFEGE Ingénieurs-Conseils 2011). Ideal control of both secondary pump and control valve is assumed. Secondary supply and return temperatures are assumed to be equal to set-point values at any time. Heat exchanger effectiveness is assumed to be constant. Mass flows assumption in (3) was checked *a posteriori* : in the simulated operating conditions, temperature difference at primary side is greater than temperature difference at secondary side. Physical governing equations are:

$$\dot{Q} = \dot{m}_p c_p \left(T_{p2} - T_{p1}\right) \tag{1}$$

$$\dot{Q} = \dot{m}_s c_p (T_{s1} - T_{s2}) \tag{2}$$

$$\varepsilon = \frac{(T_{p2} - T_{p1})}{(T_{s1} - T_{p1})} \quad as\ \dot{m}_p < \dot{m}_s \tag{3}$$

$$\Delta p = (k + k_e)\dot{m}_p{}^2 \qquad if\ k < k_{min}\ then\ k = k_{min} \tag{4}$$

$\{(1), (2), (3), (4)\}$ is a system of 4 non-linear equations with 4 unknown $\{T_{p2}, \dot{m}_p, \dot{m}_s, k\}$. Please note that the first branch of the *if* clause in (4) corresponds to conditions where cooling demand cannot be met.

Model implementation in Modelica has been carried out according to guidelines addressed to thermo-fluid model developers (Wetter 2010). It is built from base classes of the Buildings library and implements {(1), (2), (3), (4)} at top-level. It extends a fluid interfaces to connect $\dot{m}_p, T_{p1}, T_{p2}$ and Δp with the DCN model. It extends a flow resistance model to compute $\dot{m}_p$. A first order response is added to improve convergence when k is near k_{min}. It takes into account heat flow rate $\dot{Q}$ to the primary side through a static heat conservation equation.

2. District cooling network (DCN)

The DCN model is composed of a supply line and of a return line. The structure is simple, with no branches and no loops. Pipes are buried and insulated. Inner diameter ranges from 100 mm to 600 mm. Total length is 1.8 km. Conservation equations for energy, mass and momentum are solved in order to obtain temperature, pressure and mass flow in the DCN. In DHS modelling literature (Palsson 2000) and commercial software (Schneider Electric 2012) (Bentley 2013), so-called pseudo-dynamics models are used. Temperature transport delay, heat distribution losses and friction losses are taken into account. Mass flow rates are assumed to be in steady-state because pressure waves is 1000 times faster than temperature wave dynamics (Benonysson 1991). Temperature governing equation is recalled in (Gabrielaitiene 2011). It is a partial derivative equation with a convection term along one direction (enthalpy), a transient term (inertia) and a source term (heat distribution gains). (Benonysson 1991) developed a numerical method called the node method to solve it. It was shown to be more accurate and more computationally efficient than the element method. However, its use is restricted to networks with no loops and with 1 CWPP only. Hence, it does not fit with our long-term modelling requirements. Used pipe model is with finite volume discretization along flow path, flow resistance and heat exchange with the environment. Physical parameters are pipe geometry, roughness and insulation. Conservation equations are assumed to be pseudo-dynamic. Number of discretized volumes is restricted to 2 per pipe in order to reduce simulation time. Ground temperature T_g at heat port is assumed to be constant.

3. Chilled-water production plant (CWPP)

The CWPP model is composed of the chilled-water closed loop, the condenser closed loop and the Seine river cooling water open loop (Figure 4). Its physical interfaces are the DCN and the Seine river water.

Its sub-models are: an electric compressor-driven chiller, 7 pumps (distribution, chilled-water, condenser, cooling water), an hydraulic by-pass, pipes, 6 valves and 3 heat exchangers.

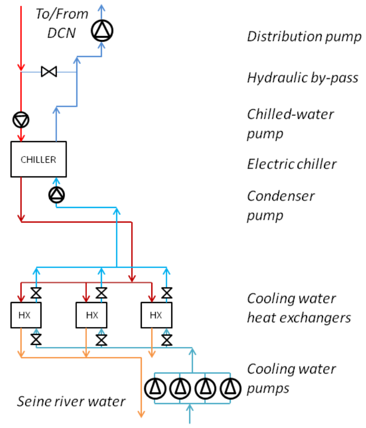

Figure 4 : Flow chart of CWPP

The real CWPP is composed of 7 chillers, which can be by-passed if Seine river water temperature is lower than return temperature (*free-cooling* mode).

a. Chiller

The centrifugal chiller model is based on performance curves. It calculates thermal performances and electrical power depending on temperature conditions on evaporator and condenser sides and on part-load ratio. It is a reformulation based on the DOE-2.1 chiller model and the *EnergyPlus* Chiller:Electric:EIR (University of Illinois and Ernest Orlando Lawrence Berkeley National Laboratory 2014). In order to estimate impacts on power input P of the chiller from variable conditions at evaporator inlet performances curve and governing equations read as:

- $PF_{RATIO}(T_{e,e}, T_{c,e})$: Ratio of cooling capacity C to rated cooling capacity C_{NOM} as a bi-quadratic function of entering evaporator temperature and entering condenser temperature (see Figure 5)
- $EIR_{TEMP}\left(T_{e,e}, T_{c,e}\right)$: Ratio of EIR at full-load to rated EIR as a bi-quadratic function of entering evaporator and condenser temperatures (see Figure 5)
- $EIR_{PLR}\,(PLR)$: Ratio of EIR at part-load to EIR at full load as a quadratic function of part-load ratio (Figure 6)

$$PLR = \frac{c_p \dot{m}_e (T_{e,e} - T_{e,l})}{C_{NOM} \times PF_{RATIO}} \tag{5}$$

$$P = \frac{C_{NOM}}{COP_{NOM}} \times PF_{RATIO} \times EIR_{TEMP} \times EIR_{PLR} \tag{6}$$

$$PLF = \frac{COP}{COP_{100\%}} = \frac{PLR}{\frac{P}{P_{100\%}}} = \frac{PLR}{EIR_{PLR}} \tag{7}$$

Models parameters are 15 performance curves coefficients, rated values (capacity, COP, flow-rates) and design ranges. Performances curves coefficients have been calibrated against real measurements from CLIMESPACE CTM with a least-square error method. High entering evaporator temperature and low part-load conditions are not among the calibration data set. Model is not accurate in this domain. COP decreases with entering condenser temperature, increases with entering evaporator temperature (see Figure 5) and reaches its maximum value at a part-load ratio of 0.75 (see Figure 6). In the chiller Modelica partial model, thermal mass is added at the condenser and at the evaporator with water mixing volumes. PF_{RATIO} and EIR_{TEMP} have been reformulated at the model top-level.

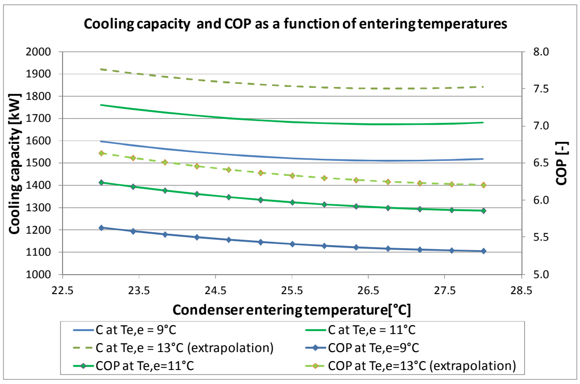

Figure 5: Chiller model - Cooling capacity (left axis) and COP (right axis) as a function of entering temperatures. Curves are calibrated against measurements. Dotted line represents operating points outside of calibration range.

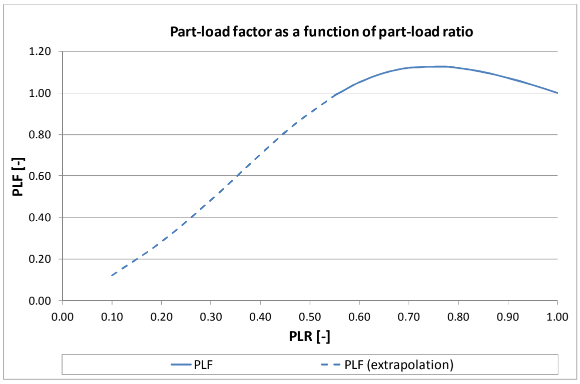

Figure 6 : Chiller model - PLF as a function of PLR. Curve is calibrated against measurements. Dotted line represents operating points outside of calibration range.

b. Pumps

Electrical power of pumps (Figure 4) is calculated as:

$$P_p = \frac{\dot{V}_p \Delta p_p}{\eta} \tag{8}$$

Prescribed value is either flow rate or pressure raise.

Mass flows in the DCN are set by substations control valves (see Substations). Chilled-water pump mass flow rate is set to be 10% greater than distribution pump mass-flow rates to avoid heating of controlled evaporator leaving temperature with return temperature. Global efficiency (variable speed drive, motor, pump) is assumed to be constant.

c. Pipes

The flow model that accounts for pressure losses in the chiller evaporator and in the chiller condenser interpolates from a nominal point given as a parameter. The hydraulic by-pass (see Figure 2 and Figure 4) model is a simple pipe model without storage of energy. Pressure calculation accounts for the height difference between inlet and outlet fluid ports, as absolute pressure value is of interest at each node of the DCN. As mass flow rate in this component is low, flow model is assumed to be laminar and calculated from nominal values.

d. Valves

Valves are connected at cooling water heat exchanger inlet fluid ports (Figure 4). Flow model is calculated from an operating point (fully-open) given as parameters. Valve opening/pressure losses characteristics is assumed to be linear. Control signals are read from measurements.

e. Heat exchangers

3 heat exchangers are connected between cooling water and condenser loops (Figure 4). The model used assumes constant effectiveness as in (3). Fouling caused by Seine river cooling water is accounted for with an effectiveness of 0.5. Heat dissipation is neglected.

DISCUSSION AND RESULT ANALYSIS

Simulation setup and performances

A simulation period of 1 week during summer has been selected. Under these conditions, 1 compressor chiller is committed to chilled-water production without *free-cooling*. Inputs are CLIMESPACE CTM data from 08/2013 (see Figure 7). Cooling demand ranges from 325 kW to 1370 kW (aggregated value). It shows a daily variation and a significant reduction during weekend. Seine river temperature ranges from 21.6°C to 22.7°C. Its daily variations exhibit a delay with respect to cooling demand profile. DASSL solver is used. Simulation time step is variable and set by the numerical solver. Translated model is composed of 41 linear equations (3 systems) and of 39 non-linear equations (4 systems). Computational time is 30s with this simulation setup with a Intel Core i5 at 2.60GHz processor.

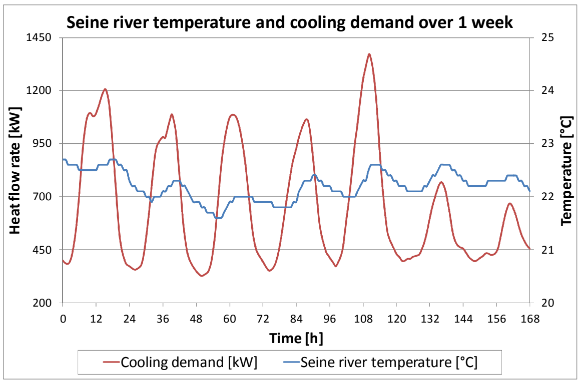

Figure 7: Inputs - Seine river temperature and cooling demand over 1 week

Global DCS model

Chiller electricity consumption is the largest share of global electricity consumption (61.2%, see Figure 8).

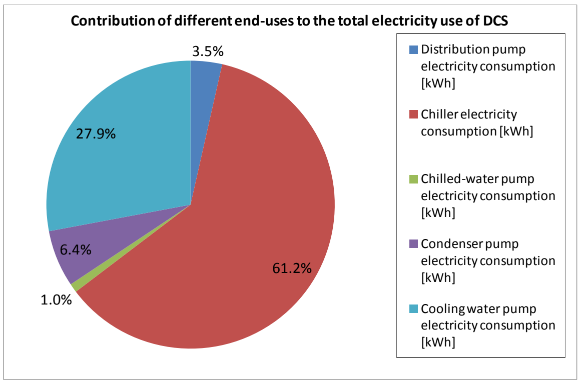

Figure 8: Contribution of different end-uses to the total electricity use of DCS. NB: condenser and cooling water pump mass flows are not controlled but set to nominal values. Heat exchanger pressure losses and the former approximation explain why chilled-water pump electricity consumption is lower.

Chiller entering temperatures, PLR and COP are plotted in Figure 9. Entering condenser temperature follows variations of Seine river temperature (see Figure 7). Entering evaporator temperature depends, in the first order, on return temperature, with a delay due to evaporator water loop thermal mass. PLR reaches maximum at t=109h as cooling demand reached maximum (see Figure 7), condenser entering temperature is increasing and evaporator entering temperature is decreasing. One can focus on the period from t=72h to t=96h corresponding to a work-day. From t=78h to t=84h, as PLR increases, COP increases until it reaches a maximum value. From t=84h to t=90h, it steadily decreases as entering condenser temperature is increasing and entering evaporator temperature is decreasing. From t=90h to t=93h, COP drops as PLR rapidly decreases.

Scenario evaluation

As an application, a sensitivity analysis on substation secondary return temperature is studied. In order to reduce flow rates in the distribution network and in the evaporator water loop, required secondary return temperature is increased.

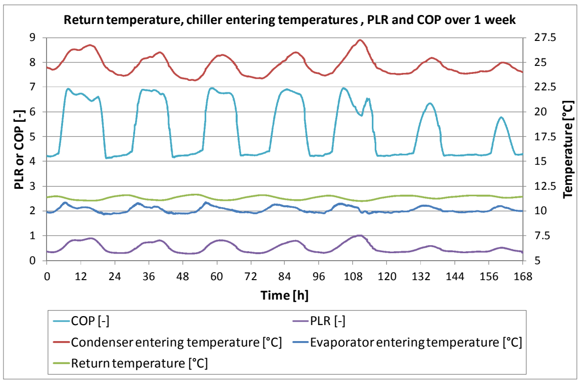

Figure 9: Chiller model – Entering temperatures PLR and COP

Impacts on electricity consumption (chiller, chilled-water and distribution pumps) and distribution thermal losses are evaluated against a reference scenario ("Case 1") described here before. Secondary return temperature increase of 1.5 K ("Case 2") and of 3 K ("Case 3") are investigated. It is assumed that substations secondary design and control allow a temperature increase while meeting the building cooling demand. Figure 10 shows power input under "Case 3" compared to "Case 1", with a focus on chiller and distribution pump power inputs. "Case 2" and "Case 3" describe a similar behaviour. Power input is lower at low load and at peak load. Electricity consumption is however higher (+1.6% in "Case 3") due to a lower PLR (see Table 3). Distribution and chilled–water pump electricity consumption is decreased (23.2% and 45.8% respectively in "Case 3") due to lower mass flow rates. Distribution thermal losses are lower (-20.2% in "Case 3") due to lower temperature difference with ground temperature. Impact on total electricity consumption is not significant (-0.2% in "Case 2" and +0.3% in "Case 3"). An annual simulation will evaluate impact on *free-cooling* mode. A variable differential pressure set point would further decreases distribution pump electricity consumption.

A chilled-water pump control taking into account chiller PLR/PLF characteristics through entering evaporator temperature would yield in decreased total electricity consumption. Share of pumps electricity consumption and subsequently global electricity consumption reduction are expected to be higher.

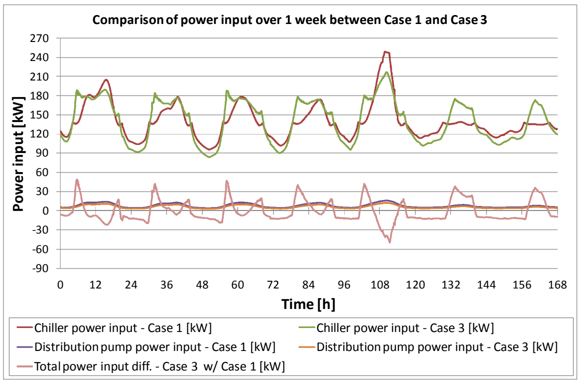

Figure 10: Global model - Comparison of power input over 1 week between "Case 1" and "Case 3"

CONCLUSION

A physical, dynamic and integrated model of DCS has been developed in the equation-based object-oriented language Modelica. A simplified model of substation has been implemented in order to reduce simulation time of large DCS. At this current phase of development, CPU time for is 30 s for a simulation period of 1 week. A chiller model from the literature has been reformulated in function of evaporator entering temperature instead of evaporator leaving temperature. Impacts on electricity consumption caused by variations at the secondary side of substations can be analyzed through a system simulation on a summer period. *Free-cooling* mode will be introduce to account for winter and mid-season operation. Further works will focus on modelling at full-scale the CLIMESPACE Eastern Paris DCS in order to carry out a calibration and validation process. Differential pressure and chiller loading are two optimization variables on which our research and development effort will be carried out, in order to build a decision-support tool for DCS operation.

Table 3: Impact evaluation of "Case 2" and "Case 3" with respect to "Case 1" (reference case)

SUB-SYSTEM	RESULT	CASE 1	CASE 2	CASE 3	Variation Case 2 w/ Case 1	Variation Case 3 w/ Case 1
CONSUMPTION	Secondary return temperature (mean value) [°C]	11.6	13.1	14.6	1.5 K	3.0 K
	Cooling demand [kWh]	110618	110618	110618	0.0%	0.0%
	Water volume [m^3]	11791	10220	9040	-13.3%	-23.3%
DISTRIBUTION	Distribution pump electricity consumption [kWh]	1341	1164	1029	-13.2%	-23.2%
	Distribution thermal losses [kWh]	16198	14445	12928	-10.8%	-20.2%
PRODUCTION	Return temperature (mean value) [°C]	11.5	12.8	13.8	1.3 K	2.3 K
	PLR (average) [%]	51.3%	40.6%	40.6%		
	Cooling production [kWh]	126816	125063	123547	-1.4%	-2.6%
	Chiller electricity consumption [kWh]	23351	23702	23721	1.5%	1.6%
	Chilled-water pump electricity consumption [kWh]	375	267	203	-29.0%	-45.8%
	Condenser pump electricity consumption [kWh]	2442	2442	2442	0.0%	0.0%
	Cooling water pump electricity consumption [kWh]	10663	10663	10663	0.0%	0.0%
GLOBAL	Total electricity consumption [kWh]	38173	38237	38059	0.2%	-0.3%
	COP production [-]	3.44	3.37	3.34		
	COP consumption [-]	2.90	2.89	2.91		

NOMENCLATURE

C = chiller maximum cooling capacity
C_{NOM} = chiller maximum cooling capacity at rated conditions
COP = ratio of chiller cooling heat flow rate at the evaporator to power input
COP consumption = ratio of cooling demand to total power input
COP production = ratio of CWPP cooling heat flow rate to total power input
$COP_{100\%}$ = COP at full-load
COP_{NOM} = COP at full-load and rated conditions
c_p = specific heat for liquid water
CTM = Centralized Technical Management
CWPP = Chilled-water production plant
DCN = District Cooling Network
DCS = District Cooling System
DHN = District Heating Network
DHS = District Heating System
EIR (chiller) = ratio of power input to chiller cooling heat flow rate at the evaporator
GIS = Geographic Information System
k_e = substation heat exchanger flow coefficient
k = substation control valve flow coefficient
k_{min} = substation minimum control valve flow coefficient
P = power input to chiller compressor
$P_{100\%}$ = power input to chiller compressor at full-load
P_p = power input to a pump
PLR = chiller part-load ratio
PLF = chiller part-load factor
$\dot{m}_c$ = condenser mass flow rate
$\dot{m}_{cw}$ = cooling-water mass flow rate
$\dot{m}_p$ = substation primary mass flow rate
$\dot{m}_s$ = substation secondary mass flow rate
$\dot{Q}$ = substation heat flow rate
$\dot{Q}_n$= substation rated heat flow rate
$\dot{Q}_{sp}$ = substation heat flow rate set-point (cooling demand)
T_g = undisturbed ground temperature
T_{cw} = cooling water temperature
T_{p1} = substation primary supply temperature
T_{p2} = substation primary return temperature
T_{s1} = substation secondary return temperature
T_{s2} = substation secondary supply temperature
$T_{e,e}$ = chiller evaporator entering temperature
$T_{e,l}$ = chiller evaporator leaving temperature
$T_{c,e}$ = chiller condenser entering temperature
$T_{c,l}$ = chiller condenser leaving temperature
$\dot{V}_p$ = pump volume flow rate
Δp = substation differential pressure
Δp_p = pump pressure raise
ε = substation heat exchanger effectiveness
η = pump global efficiency

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