APPLICATION OF THE AIR-CONDITIONING SYSTEM ENERGY SIMULATION FOR COMMISSIONING (ACSES/CX) TOOL TO HVAC SYSTEM COMMISSIONING

Part 1: Explanation of ACSES/Cx and Application to Design Stage Commissioning of a Large Heat Source Plant

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ABSTRACT

Commonly provided HVAC system simulation tools are not necessarily satisfactory for the investigation of operational improvement and renovation planning because the effectiveness of using a large amount of measurement data accumulated in a Building Energy Management System (BEMS) is limited. For example, although evaluation of refrigerator based on the actual thermal load would be useful for operational performance improvement and decision making of renovation design, this type of investigation is usually very difficult due to the limited features of simulation tools.

In the present study, we first explain the specific features of the Air-Conditioning System Energy Simulation for Commissioning (ACSES/Cx) tool for HVAC system simulation, which was specially developed for use in the commissioning process. The results of applying ACSES/Cx to design stage commissioning for the renovation of an existing large-scale heat source plant are then presented.

INTRODUCTION

To predict the performance of a building and its building systems using simulation is a common interest in every country. EnergyPlus, EPS-r and DEST are the well known examples of such sort of simulation tools and the importance of these tools is increasing due to the strong desire for energy conservation in the building sector in the whole world. In Japan also newly developed two simulation tools named Building Energy Simulation Tool, BEST and Life Cycle Energy Management, LSEM tool have been recently and separately released from the extra-governmental organizations for the same purpose.

Although in operational improvement and the renovation design of HVAC systems of an existing building, the effective use of a large amount of past operation data accumulated in a Building Energy Management System (BEMS) or Building Automation System (BAS) is very important in simulation, commonly provided HVAC system simulation tools such as the above mentioned Japanese tools are not necessarily satisfactory for this purpose because of the limited features of the tools.

The authors developed the Air-Conditioning System Energy Simulation for Commissioning (ACSES/Cx) tool, an HVAC system simulation tool, in order to overcome the limitations encountered upon introducing new features. In the present report, the specific features of the tool are first briefly explained focusing on the advantages for use in commissioning. The experience and results obtained through application to the operation of an existing large-scale heat source plant and the design stage commissioning for the renovation are then shown and the usefulness of the tool is discussed.

SIMULATION TOOL FOR COMMISSIONING

Although some new approaches for using HVAC system simulation tools to find rational operation strategies have been reported, most of such tools were basically developed for use in the design stage rather than in the analysis of existing building systems. The primary use of these tools is to determine the energy consumption under specific design conditions or input. On the other hand, in the operational improvement or renovation design of an existing HVAC system, the following functionalities are desired in simulation tools:

1) A function to introduce measurement data as simulation input. For example, calculating air-conditioning load using measured room temperature and/or humidity instead of the design room condition is very important in order to increase the accuracy of the simulated heat load.

2) A user interface to ease the above-described data selection. In other words, if a complicated handling process is required during the simulation, a mistake may occur due to the cumbersome process.

3) A user interface enabling arbitrary measured data to be used as auxiliary input for an objective sub-system. For example, the measured temperature of

the cooling water should be used in place of the simulated temperature in the performance test of a refrigerator in the commissioning process. In this case, a function such that the data set can be used as the input for the component is indispensable.

4) A function to compare measured data with the simulated data, hopefully using a graphical interface. Comparison of measured and simulated data would be an important goal of simulation during the commissioning process. A number of important findings can be extracted through such a comparison. For example, the difference between the two data sets may reveal the existence of faults, such as a malfunction or the degradation of sub-systems or components, an inadequate operational strategy, or the inappropriate use of a building. In addition, the degree of improvement that will be attained can be estimated by simulating a fixed system based on fault diagnosis.

5) A function to implement an actual control strategy together with control parameters and to simulate using actual control signal data. Discrepancies between real and simulated behaviors of an analyzed HVAC system are often caused by differences in automatic control. In particular, assigning proper parameters or a control threshold is very important in order to eliminate such discrepancies. In some cases, control faults can be found through comparison of simulated results using a given control algorithm and results obtained by a measured control signal.

6) A user interface by which to easily input the performance of components. Inputting precise component performance is very important in order to obtain satisfactory simulation accuracy. In addition, since the performance charts are provided from component suppliers in a variety of documents, associated sub-tools should be developed for the purpose of extracting the model parameters. Otherwise, simulation tools will not be effective.

ACSES/CX SIMULATION TOOL

The ACSES/Cx simulation tool was developed by combining several sub-tools that have been developed for specific purposes since the late 1990s. The Sub-tool examples are calculation of heating and cooling load using room temperatures and internal energy use measurement, natural ventilation with multiple rooms, performance of thermal storage systems, and total performance of multiple pump groups. This type of sub-tool development is continuing and such tools are still being added to ACSES/Cx.

Total structure of ACSES/Cx

ACSES/Cx is made by embedding all sub-systems in the MATLAB/Simulink environment to enhance the ease of data handling and the graphical user interface. The overall structure of ACSES/Cx is shown in Figure 1.

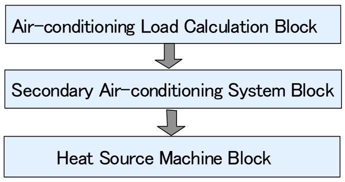


Figure-1 Overall structure of ACSES/Cx

Figure 2 shows a sub-system in the secondary air-conditioning system block as an example. The sub-system is an air-handling unit composed of separate components, such as an air-to-air heat exchanger, the control valve of a cooling coil, the PI control of the valve, a steam coil, and simulated data output. Any type of sub-system, such as the AHU system shown above, can be built by connecting basic components according to design drawings. Basic component, such as a refrigerator, an air-handling unit, a heat exchanger, a pump, and a fan, are provided as standardized models ready to use.

Figure 3 shows the structure of the heat source

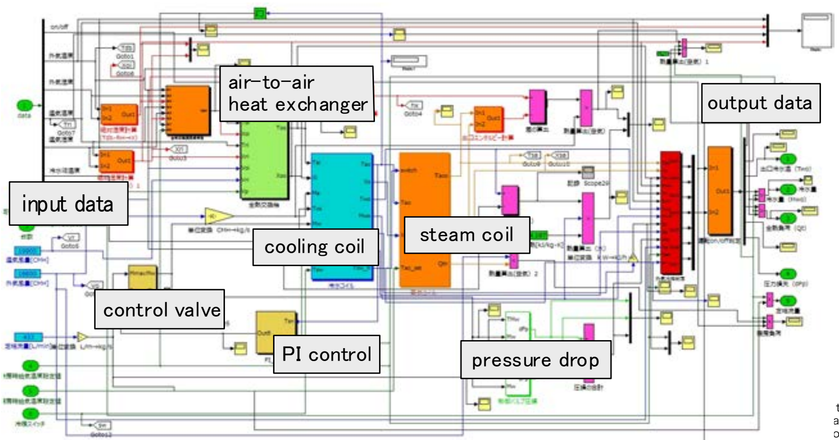


Figure-2 Example of an AHU sub-system

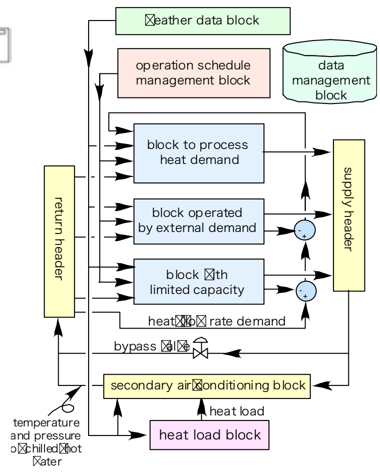


Figure-3 Structure of heat source machine block machine block. The block contains three main heat source (HS) blocks: an HS block processing heat demand, an HS block operated by external demand, and an HS block with limited capacity.

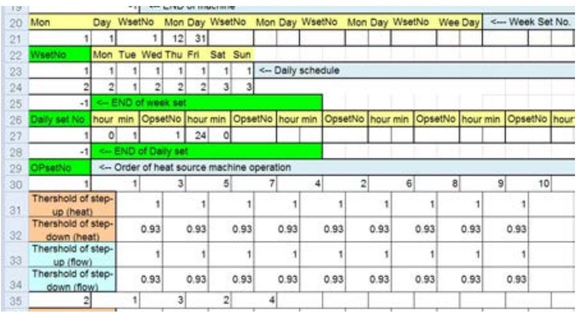
The HS block to process heat demand is a group of ordinary heat source machines, which process the heat demanded by the secondary air-conditioning system. Although this is ordinary operation, if the demand is less than the total capacity of the machines, the number of operated machines is determined according to the given threshold.

The HS block operated by external demand is a machine group that is operated by external demand rather than internal demand. The example is an absorption refrigerator, which is operated in accordance with a co-generation plant. In other words, the refrigerator is operated not by the demand of the secondary air-conditioning system, but rather by the external electricity demand. Therefore, the cooling capacity cannot be controlled based on air-conditioning demand.

The HS block with limited capacity is a machine group such as a thermal storage system, which behaves in a manner similar to the first block, except that the machine group is forced to stop if the stored heat is expended.

Description of operation schedule

In simulation, the operation of the system is controlled by the operation schedule management block. Figure 4 shows the Excel form with which the user can specify the desired schedule. The operational time schedule is planned on weekly and daily bases. Threshold values, performance parameters, and the order of machine operation can be described easily and systematically using the form.



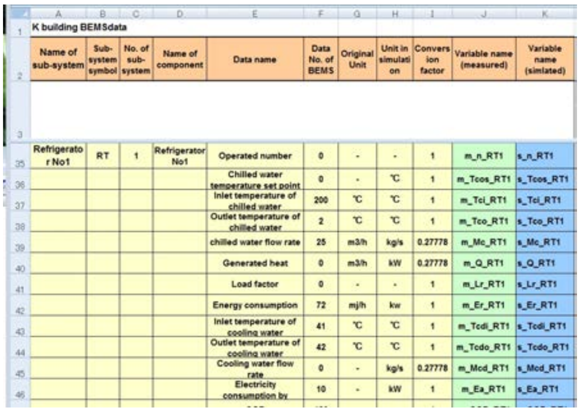
20	Mon	Day	WsetNo	Mon	Day	WsetNo	Mon	Day	WsetNo	Mon	Day	WsetNo	Wee	Day	<--- Week Set No.
21	1	1	1	12	31										
22	WsetNo	Mon	Tue	Wed	Thu	Fri	Sat	Sun							
23	1	1	1	1	1	1	1	1	<-- Daily schedule						
24	2	2	1	2	2	2	3	3							
25	-1	<-- END of week set													
26	Daily set No	hour	min	OpsetNo	hour	min	OpsetNo	hour	min	OpsetNo	hour	min	OpsetNo	hour	min	OpsetNo	hour
27	1	0	1	1	24	0									
28	-1	<-- END of Daily set													
29	OPsetNo	<-- Order of heat source machine operation													
30	1	1	3	5	7	4	2	6	8	9	10				
31	Thershold of step-up (heat)	1	1	1	1	1	1	1	1	1					
32	Thershold of step-down (heat)	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93					
33	Thershold of step-up (flow)	1	1	1	1	1	1	1	1	1					
34	Thershold of step-down (flow)	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93					
35	2	1	3	2	4										

Figure-4 Operation schedule input form

Measured data incorporation

ACSES/Cx can incorporate measured data for two purposes: 1) comparison of simulated and measurement resulted to determine faulty operations or malfunctions; and 2) for use as simulation input to test the performance of a component or sub-system and the operational condition. As an example of the first purpose, the schedule defined by the form can be compared with the actual operation data on a graph in order to test whether the system is operated according to the desired schedule.

Figure 5 shows an Excel form for incorporating measured data. In general, so many types of data are available from BEMS that a set of data together with their corresponding labels is fixed to a sub-system in order to facilitate input and reduce mistakes. Tool users need only enter the data number used in the BEMS in column F of the form. At present, BEMS data are entered in CSV format and are converted into a specific format, which is readable by MATLAB, by a separately developed tool. The labels of the simulated data are also standardized, as shown in Figure 5. As an optional function, unit conversion of each data set can be performed by specifying the conversion factor in column I.



K building BEMSdata

	Name of sub-system	Sub-system symbol	No. of sub-system	Name of component	Data name	Data No. of BEMS	Original Unit	Unit in simulation	Conversion factor	Variable name (measured)	Variable name (simlated)
35	Refrigerator No1	RT	1	Refrigerator No1	Operated number	0	-	-	1	m_n_RT1	s_n_RT1
36					Chilled water temperature set point	0	-	℃	1	m_Tcos_RT1	s_Tcos_RT1
37					Inlet temperature of chilled water	200	℃	℃	1	m_Tci_RT1	s_Tci_RT1
38					Outlet temperature of chilled water	2	℃	℃	1	m_Tco_RT1	s_Tco_RT1
39					chilled water flow rate	25	m3/h	kg/s	0.27778	m_Mc_RT1	s_Mc_RT1
40					Generated heat	0	m3/h	kW	0.27778	m_Q_RT1	s_Q_RT1
41					Load factor	0	-	-	1	m_Lr_RT1	s_Lr_RT1
42					Energy consumption	72	mj/h	kw	1	m_Er_RT1	s_Er_RT1
43					Inlet temperature of cooling water	41	℃	℃	1	m_Tcdi_RT1	s_Tcdi_RT1
44					Outlet temperature of cooling water	42	℃	℃	1	m_Tcdo_RT1	s_Tcdo_RT1
45					Cooling water flow rate	0	-	kg/s	0.27778	m_Mcd_RT1	s_Mcd_RT1
46					Electricity consumption by	10	-	kW	1	m_Ea_RT1	s_Ea_RT1

Figure-5 Data definition form

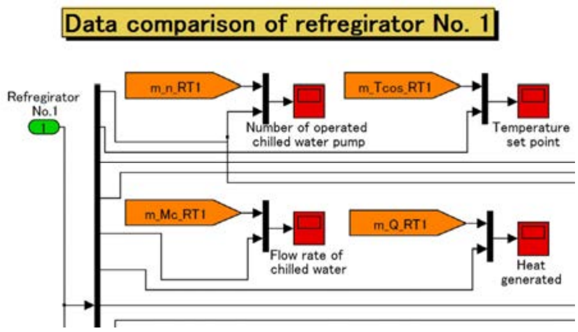


Figure- 6 Data comparison window

ACSES/Cx has a standardized window mechanism to compare measured and simulated data, as shown in Figure 6. Two data sets, namely, measurement and simulation data, can be graphically displayed by the Scope function of Simulink. Since data labels are standardized, a data set group for a specific component is fixed and provided as a standardized window component. Users can use this group as a ready-to-use group.

Summing the simulated results

ACSES/Cx has a function to sum arbitrary desired data by entering “1” in column L or M, as shown in the example of Figure 5, and the results are written to a file.

Component model

Each component of an HVAC system is modeled by mathematical formulas, which are based on models in handbooks and textbooks on HVAC systems. All of the models have been validated numerous times based on actual measurement data. Each model is embedded in a MATLAB function of MATLAB/Simulink and is provided as a ready-to-use component model. Therefore, with the exception of special components, which are not provided as ready-to-use components, users can make a system model by connecting the components based on a design diagram. Users need only input the performance parameters of the components. The parameter window of the pump model is shown in Figure 7 as an example. All parameter windows are built using a MATLAB/Simulink function.

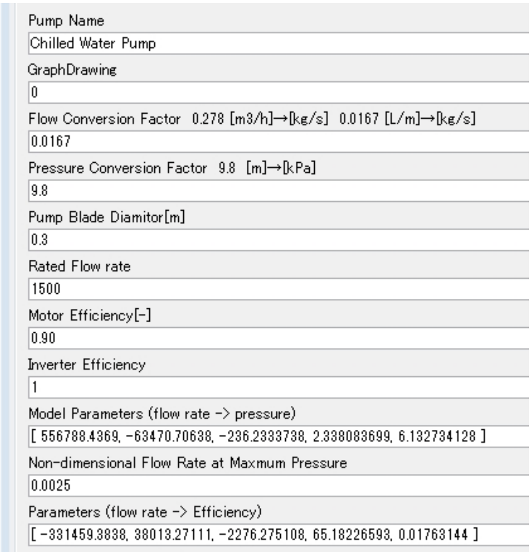


Figure-7 Model definition window

EXAMPLE APPLICATION

Testing simulation accuracy

The ACSES/Cx tool was applied to the large-scale heat source plant shown in Figure 8, which is situated in a complex building with a total floor area of approximately 236,000 m^2. The building owner requested that the plant be renovated, with the goal of reducing energy consumption by more than 30% and reducing CO_2 emissions. As the work of first stage of commissioning, we investigated the performance of the system and then analyzed the design plan submitted by the design team as the second stage of commissioning. The ACSES/Cx tool was used for both stages.

In the first stage, the simulation model of the present system was built, and the accuracy was tested. In this modeling, only the heat source machine block is used by feeding the measured flow rate and returning chilled water temperature from the secondary system. The first diagram of the model is shown in Figure 9 as an example. The simulation time step is one minute, which gives the pseudo-nonstationary behavior of the system and resolution so as to control the starting and stopping of components.

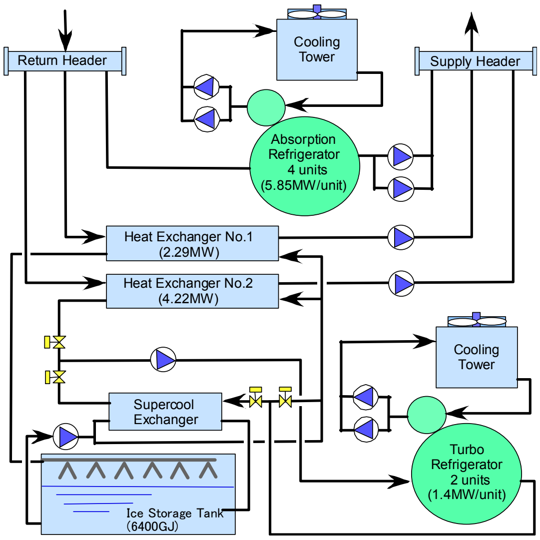


Figure-8 Configuration of the heat source plant

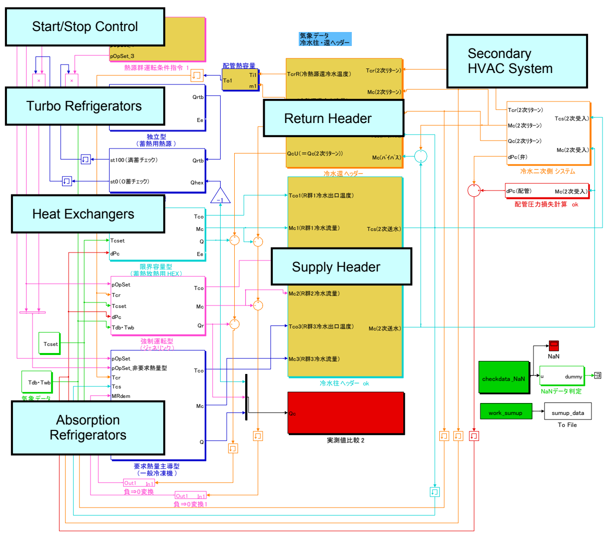


Figure-9 MATLAB/Simulink configuration of the plant

As an example, Figure 10 compares the measured and simulated heat supplied to the secondary system for three days. The significant oscillation in the simulation is due to frequent starting and stopping of refrigerators. However, such oscillation is not found in the measured data because the data sampling time is one hour, which does not provide sufficient resolution to illustrate such behavior. Figure 11 compares the measured and simulated variations of the number of operated refrigerators with time. Oscillation is also observed at night in the simulation data. These results indicate that the simulation results are sufficiently accurate to analyze the performance of the system.

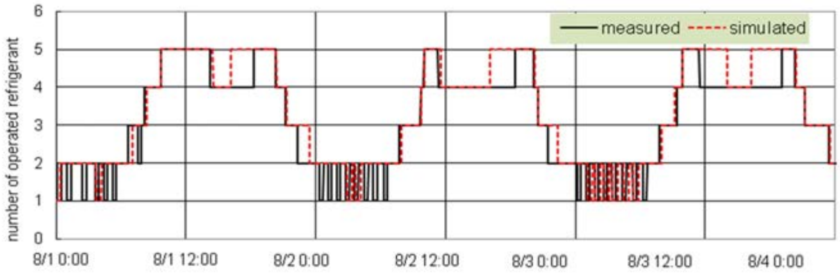


Figure-10 Comparison of total heat supplied (measured and simulated)

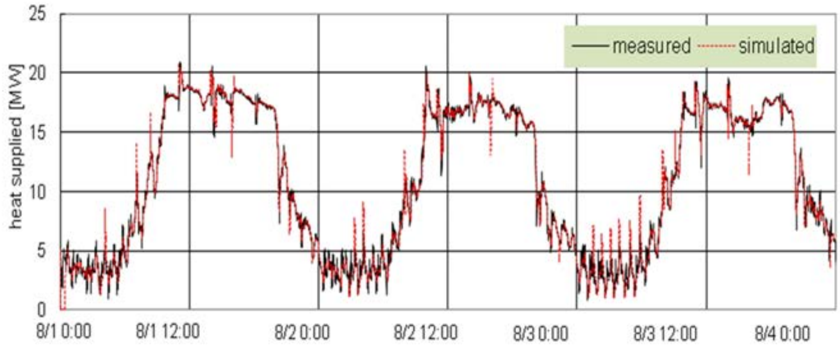


Figure-11 Comparison of number of operated refrigerators (measured and simulated)

Considerations for the operation of the present plant

Since the temperature difference between supply and return chilled water has a significant impact on the energy consumption of pumps, it is important to keep

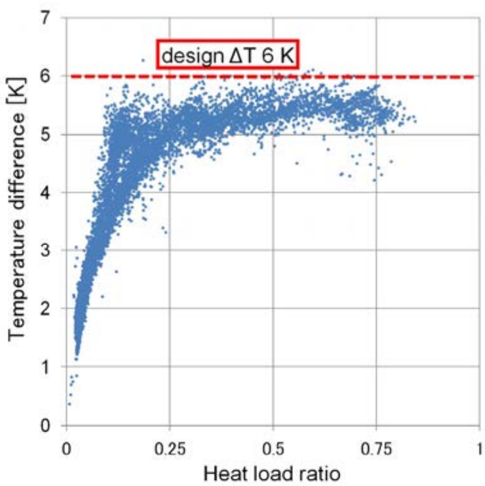


Figure-12 Relationship between chilled water temperature difference and heat load ratio

this temperature difference as close as possible to the design value. In this plant, the design value is 6 K. Figure 12 shows that the difference is maintained near 6 K if the heat load ratio, which is defined as the value of the load divided by the total refrigerator capacity, is high but becomes diverges significantly if the ratio is low. Since the rated capacity of one refrigerator has a heat load ratio of 0.25, a small difference occurs during the operation of one refrigerator. The frequency distribution of the difference shown in Figure 13 indicates that the plant is operated with a difference of less than 4 K for approximately 40% of the time.

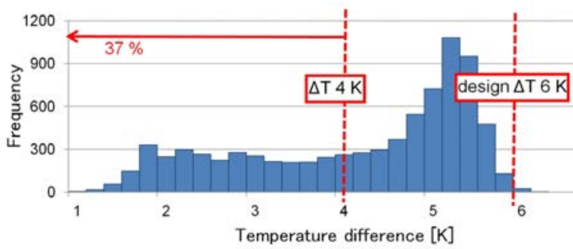


Figure-13 Frequency distribution of chilled water temperature difference

The occurrence of a small temperature difference depends on the characteristics of the secondary air-conditioning system. However, the difference is not so bad compared to general systems. One reason for this favorable condition is the existence of bleed-in control, the advantages and disadvantages of which are investigated in Part 2 of the present study.

Investigation of present operation by ACSES/Cx

Here, we describe the degree to which the temperature difference and the step-up and step-down threshold values for the number of operated refrigerators affect system performance.

We first investigated the degree to which energy consumption is reduced when the average temperature difference reaches the design value of 6 K, rather than 5.1 K. Table 1 shows the results. The chilled water flow rate, the electricity used by the pump, and the average number of refrigerators operated are decreased by 16%, 7%, and 10%, respectively, from the present operation. However, the reduction in the total energy consumption is only 2%.

We also investigated how performance is affected by the threshold value for step-up and step-down of the operated number of refrigerators. Step-up and step-down are activated based on the heat and flow rate requirements of the secondary system. If the temperature difference of chilled water is small, the step-up action activated by the required flow rate dominates the step-up action by the required heat. Therefore, in order to ensure safe operation, step-up is activated when one of the step-up conditions is satisfied, but step-down is activated only when both conditions are satisfied. This sophisticated activation mechanism makes deciding the threshold difficult.

Table-1 Impact of temperature difference and threshold

Date Aug. 4/2009		CASE 1 (dT = 6 K)		CASE 2 (dT = measured)		CASE 3 (Threshold = 132%)	
Temperature difference	[K]	6.0	(100%)	5.1	(85%)	5.2	(87%)
Chilled water flow rate	[m3/day]	39,849	(100%)	46,067	(116%)	44,912	(113%)
Number of refrigerators operated	[-]	2.32	(100%)	2.55	(110%)	2.00	(86%)
Pump electricity consumption	[kWh/day]	39,014	(100%)	41,620	(107%)	35,245	(90%)
Total primary energy consumption	[GJ/day]	1,568	(100%)	1,596	(102%)	1,505	(96%)

The refrigerator considered in the present study is a tandem type, which has two chilled and cooling water pumps. This makes deciding the threshold even more difficult. In the present study, only one case of threshold value of 66%, which is adapted to the present plant, is tested as an example. This means that the second pump is started when a required value exceeds the threshold value of 66%+2% and is stopped when the required value falls below 66%-2%. The electricity used by pumps and the total energy consumption are decreased by 10% and 4%, respectively, as shown in Table 1.

Although we presented only two examples, simulation using ACSES/Cx has been shown to be a useful tool for helping to improve the present operation by simulating possible strategies. In addition, problems and specific characteristics revealed by the simulation of the present operation are very valuable for use in renovation design.

Design commissioning of a proposed design by ACSES/Cx

The design plan for renovation was submitted by the design team according to the owner's project requirement of a more than 30% reduction in primary energy consumption. The commissioning team validated the submitted design using ACSES/Cx.

The following three types of heat source plant were proposed as potential systems having high performance, and, based on investigation by the design team, one of these plants was determined to be the best plan.

Case-A: Four turbo refrigerators, each with a capacity of 5.3 MW.

Case-B: Four turbo refrigerators, each with a capacity of 4.8 MW, and an ice-storage system using a 2.1-MW turbo refrigerator.

Case-C: Four turbo refrigerators, each with a capacity of 4.8 MW, and two absorption refrigerators, each with a capacity of 0.6 MW, operated by the discharged heat from a co-generation system.

Since the partial load efficiency was found to be poor in the present system, we investigated how much energy would be saved by installing an inverter turbo refrigerator (ITR) instead of a conventional refrigerator in Case-A. The simulation results revealed that the energy consumption of the refrigerators and the energy consumption of the entire system were reduced by 10% and 6%, respectively, due to the high COP (up to 14.1) under partial load operation of the ITR.

Since the capacity of the refrigerator is the same as in the submitted design, we investigated the impact of using a smaller-capacity 3.5-MW refrigerator with the goal of achieving the same partial load efficiency improvement in Case-A. The average number of operated refrigerators and the frequency of step-up and step-down operation were found to decrease by 15% and 20%, respectively. However, the total energy consumption increased by 4%. Although this increase is due to the increase in pump energy consumption of the larger refrigerator operation, the increase in total energy consumption depends on how the total capacity is allocated to each refrigerator, and a more precise investigation involving simulations for different capacity allocation cases is needed.

The building is long because it incorporates a train station. Installed chilled water supply pumps equipped with rotational control by inverter is also considered effective in Case-A. The simulation results revealed that the average rotational speed of the pumps was 66% of the rating, resulting in a 60% reduction in energy consumption in pumps and an 11% reduction in energy consumption for the entire system.

Case-B uses low-cost electricity available at night, and Case-C reduces peak demand of electricity in order to reduce costs. However, neither case provides the expected cost savings. Although the same conclusion was reported by the design team, the results provided important corroborating information considering the huge investment required in order to renovate the large heat source plant.

The cost increase in Case-B is due to the use of a very-low-COP turbo refrigerator for the ice-storage system. In Case-C, the cost of natural gas for the co-generation plant is the cause to surpass the cost in Case-A even though both the commodity and basic charge of electricity are minimized.

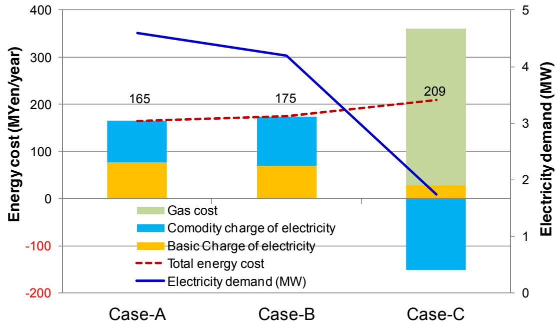


Figure-14 Case study results for renovation

CONCLUSIONS

The characteristics of the ACSES/Cx simulation tool, which was developed specifically for the commissioning of HVAC systems, were described, and the results of applying ACSES/Cx to a large-scale heat source plant were presented as an example to show the usefulness of the tool.

We first applied the tool to analyze the present operation. Two example results were shown; one is the degree of energy increase resulted by the deviation of the chilled water temperature difference from design value and another is the effect of on/off threshold values for the refrigerators on energy consumption. It was found that the former has only 2% degree of effect for total energy consumption but the latter has a large effect by 10%.

Second we applied it to the evaluation of the renovation design plans proposed by the design team. Investigation results showed that the quantitative difference in energy consumption between the plans and the causes of the difference.

The tool ACSES/Cx has been developed since 1997 under author's supervise and mainly applied to the commissioning projects of existing building systems. The tool has been developed by gathering individual sub-system models which were developed in each project so far. The tool will be open to the engineers, who are willing to use it for HVAC system commissioning, thorough the website of the Nonprofit Organization named Building Services Commissioning Association of Japan recently.

ACKNOWLEDGEMENTS

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