EXPERIENCE SHARING OF ADOPTING ARTIFICAL INTELLIGENCE (AI) CHILLER PLANT OPTIMIZATION SOLUTION

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Abstract

How can AI assist to achieve carbon neutrality by 2050? To answer, we share our story regarding one of the corporate strategies of the Electrical and Mechanical Services Department (EMSD) – Smart E&M Systems with Artificial Intelligence (AI). It is a proactive approach by deploying chiller plant optimization control in in-service government buildings as one of the indispensable tools in making them smarter and greener. With the collaboration with the trade and stakeholders, as well as the digitalization technology application, EMSD targets to set an example for the industry to achieve better building energy efficiency using AI in the forthcoming timeline towards carbon neutrality.

This paper aims to present the challenges and hurdles faced, and the experience gained during the implementation of AI chiller plant optimization solution, which utilized the artificial neural network (ANN) technique and particle swarm optimization (PSO) algorithm for analysis of the variance in environmental conditions, building cooling load demands and system operations to optimize the overall system efficiency of air-cooled chiller plants in aged in-service buildings. The outcome elaborates an encouraging achievement of 5-10% energy saving for the revitalized chiller plants with intelligence and vibrancy.

Keywords

Artificial intelligence, chiller plant optimization, common hurdle, system requirement, implementation strategy

1. INTRODUCTION

Referring to the Chief Executive's 2020 Policy Address, it was announced that the Hong Kong Special Administrative Region (HKSAR) would strive to achieve carbon neutrality before 2050. Hong Kong's climate action plan was updated in October 2021 setting out a roadmap to carbon neutrality for electricity consumption (compared with 2015) in commercial buildings reduced by 15-20% by 2035 and 30-40% subsequently. [1]

Pursuant to the Hong Kong Energy End-use Data 2022 by EMSD, the electricity consumption of air-conditioning as End-use is 31% of the total electricity consumption by End-use in 2020. Reducing the electricity consumption of air-conditioning would definitely help to achieve the targets set out in timeline of the climate action plan. [2]

EMSD operates and maintains thousands of chiller plants in government and public buildings, with around three quarters are air-cooled chillers. Following the launch of another strategic plan related to the digitalization of electrical and mechanical (E&M) assets since April 2018, relevant installations including air conditioning plants in around 400 major government buildings of annual electricity consumption exceeding 500,000 kWh were digitized. To provide round-the-clock monitoring and prompt response to emergency events whenever necessary, Regional Digital Control Centres (RDCCs) at various districts were also set up for connections. With operating parameters collected, a data lake has been formed to facilitate the application of AI tools using big data technologies and deep learning algorithms in deriving specific real-time, continuous and automatic optimization control strategies for the digitized facilities, in particular air-cooled chiller plants.

2. CHILLER PLANT OPTIMIZATION USING AI

To start with, it is important to learn that a dominant factor for optimizing the energy performance of air-cooled chiller plant is to take advantage of high part-load efficiencies of variable speed drive (VSD) components which work at the most energy saving combination for meeting the building cooling load demand. In this study, a specific hybrid predictive operational chiller plant control strategy was developed employing AI as the data mining algorithm, with big data analysis based on voluminous actual acquired performance parameters by fully considering the characteristics of chiller plants without additional installation of large-sized and high-priced equipment. The future outdoor temperature, building cooling load demand and the corresponding power consumption of the chiller plant were then predicted using artificial neural network (ANN) model, while the optimized setpoints including chiller sequence, number of chillers in operation, chilled water supply temperature and chilled water pump running speed will be searched through particle swarm optimization (PSO) algorism. Fig. 1 illustrates a typical workflow of AI chiller plant optimization control from data collection, data processing (optimization) to data output. [3]

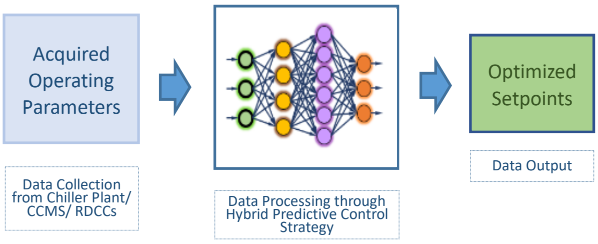


Fig. 1 Typical AI Chiller Plant Optimization Control Workflow

3. HURDLES ENCOUNTERED

There are quite a number of hurdles encountered in the process of transforming traditional air-cooled chiller plants to retrofitted ones with AI control in in-service buildings as shown in Fig.2.

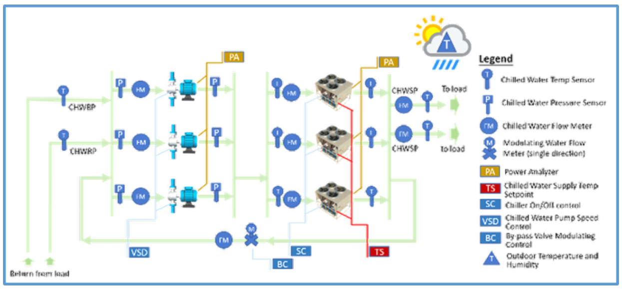


Fig. 2 Typical Air-cooled Chiller Plant Retrofitted with AI Control

Among thousands of them, the users may wish to consider setting priorities to those classified as "AI-ready" which mean that the set-up have been equipped with favorable conditions to work well with the AI, the readiness in terms of hardware, software and data quality.

3.1 Hardware Limitation

(a) As the energy saving of chillers and pumps at part-load condition is attributed to the benefit of varying the speed of compressors and motors, which is governed by the Affinity Law as listed in Equation 1.

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

Power is proportional to the cube of shaft speed

- *N is the shaft rotational speed (e.g. rpm)*
- *P is the shaft power (e.g. Watt)*

Equation 1: Affinity Law

To benefit, the existing chiller plant with constant speed drive gears which is normally adopted in aged in-service building is required to be upgraded or replaced to variable speed type. Likewise, variable primary flow chilled water system was not common in the past due to its necessity for more vigorous control, longer commissioning time, and better coordination among chillers, pumps and bypass valve. Following the advancement of technology, its application is most favorable to the chiller plant imposed with optimization control. Should the existing chilled water system not be variable primary flow type, adequate modification and improvement are required. Considering the possible service interruption and cost effectiveness, the user may wish to put forward the transformation task in line with the replacement schedule of aged or failure chiller. In particular, the impact of prolonged suspension on individual chiller plant without proper resilience or normal isolating valves should be attended cautiously.

(b) To facilitate the revitalization, a lot of measuring devices, sensors, wiring and control elements at the chilled water circuit of existing air-cooled chiller plant, which are deployed to transmit real-time operating parameters to a new mini-computer next to the CCMS on site or EMSD RDCC via a VPN tunnel secured by fire walls for onward data processing and output of optimized setpoints, are required to be recalibrated, repaired, modified, replaced and/or added. Again, the user may wish to arrange the said task in line with the retro-commissioning of chiller plant, especially the plant having been operated for certain period of time or its served building having been undertaken with major addition, alternation and/or improvement works. One should take note that the AI programme trained by the readings from uncalibrated, defective or inaccurate apparatus such as temperature sensors, flow meters, flow switches, etc. may lead to in-correct data analysis as well as improper setpoints prediction, and subsequent in-appropriate optimization control.

(c) In traditional air-conditioning system, a simple chiller sequence control strategy which aims to meet the building cooling load demand according to a delayed feedback of indoor climate conditions, and chilled water supply temperature setpoint by turning on and off of individual chiller through either manual or automatic operation in the CCMS. Fig. 3 shows a traditional sequence control for a typical chiller plant with 3 chillers in operation.

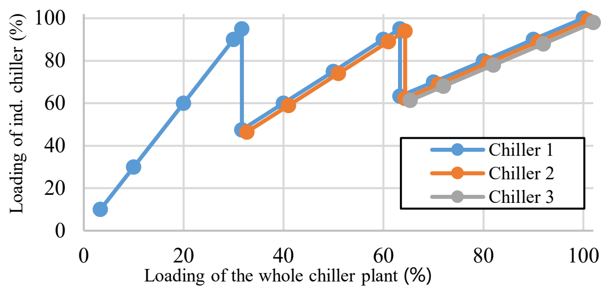


Fig. 3 Typical Traditional Chiller Plant Sequence Control

With the AI control, the equipment would be operated according to the predicted chiller sequence, number of chillers in operation, chilled water supply temperature and chilled water pump running speed such that the plant would run in the most efficient mode and hence its energy consumption would stay at the minimal as shown in Fig. 4.

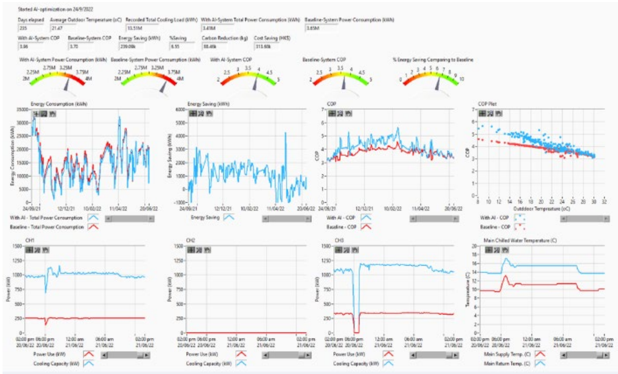


Fig. 4 Typical AI Chiller Plant Optimization Control

As some of the aged plants use timers, relays, switches and wiring to build their chiller sequence control circuits without connections reserved for high level interface with and remote control by other applications, the user may need arduous effort to digitize the circuits or upgrade the entire system to enable the AI control.

(d) Similarly, the setpoint of chilled water supply temperature is normally adjusted at the local control panel of aged chiller plant. This setting should be retrofitted to allow high level communication with and remote control by the AI system.

(e) At most of the existing chiller plants, there was no digitized temperature sensor for measuring real time outdoor temperature. To collect the information, dedicated outdoor temperature station at each venue would be required for the hybrid performance prediction model to carry out big data analysis and forecast of outdoor temperature as well as building cooling load demand in last and forthcoming moments which will then be used for the compilation of optimized setpoints. Fig. 5 illustrates a typical chart of outdoor temperature against building cooling load demand.

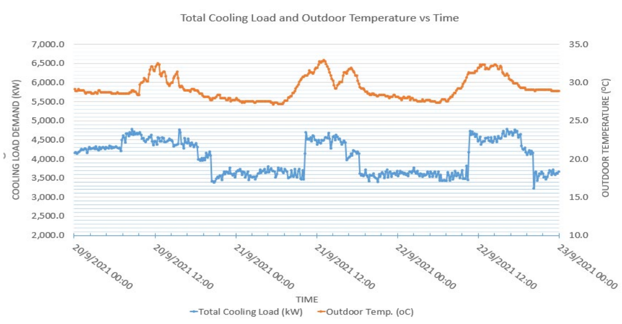


Fig. 5 Typical Outdoor Temp. vs Building Cooling Demand Chart

2.2 Software Limitation

(a) Usually, the service providers of CCMS adopt their own proprietary communication protocols and equipment tag-name hierarchies to develop the control system of existing air-conditioning plants in aged in-service buildings. To build a coherent platform with same communication property for big data analysis and predictive operational control by the AI, these apparatuses would be necessary to be modified, upgraded or replaced to a type with standardized communication protocol and unified naming convention for the interoperability among cooperating building automation devices in the plants.

(b) Should there be change of maintenance agents or migration of maintenance offices in previous years, part of the document related to the existing chiller plant, such as measurement and verification records, commissioning reports, design information, system operating particulars, manufacturer's performance results, etc. may be lost. This unavoidably hinders the AI service provider to get familiar with the configuration and operating efficiency of existing chiller plant.

(c) In early developed CCMS, the operating parameters of aged chiller plant were normally monitored and recorded without trend-log details due to the limitation of processing power and storage capacity at that moment. Relevant information to facilitate subsequent AI control would only be available upon the completion of modification, upgrading or replacement of CCMS with addition of trend-log mechanism.

(d) Some of the monitoring and control points in existing CCMS of aged chiller plant, which were not available for the AI control such as outdoor temperature and chilled water pump speed, would need to be retrofitted.

4. SYSTEM REQUIREMENTS FOR AI CONTROL

Before bringing the AI control for existing chiller plant in aged in-service building, fulfillment with the following chiller plant system requirements are the pre-requisite of successful chiller AI optimization programme: -

- chillers are incorporated with variable speed drive compressors;
- chilled water pumps to be variable speed controlled;
- chiller plant to be configured with variable primary flow chilled water system incorporating bypass control valve;
- chillers, pumps and associated accessories to work in normal conditions without any component failure;
- measuring meters, sensors and control devices to be operated properly;
- retro-commissioning for chilled water circuit to be completed;
- chiller sequence control circuit and chilled water supply temperature setpoints to be ready for high

level interface with and remote control by AI system;

- digitized outdoor temperature sensor to be equipped;
- remote chilled water supply temperature setpoint adjustment to be enabled in each chiller;
- data communication protocol and naming convention of equipment to be standardized and unified;
- trend-log mechanism in the CCMS to be enabled; and
- chiller plant fault protection logic developed and embedded in the original CCMS

Chiller plants adopted with most of the system requirements are considered as “AI-ready”.

5. IMPLEMENTATION STRATEGY

5.1 Hardware Installation

To retrofit with the AI control, the existing air-cooled chiller plant in aged in-service building would need proper installation of VSD gears, variable primary flow chilled water configuration, measuring devices, sensors, wiring, control elements and all associated accessories, including data connection to a new mini-computer next to the CCMS on site or to EMSD RDCC via an VPN tunnel secured by fire walls.

5.2 Software Installation

A specific AI chiller plant optimization programme using proprietary multi-paradigm programming language i.e. MatLab would be required. As an alternative, an open-source, high-level, general-purpose programming language such as python might be deployed. Enabling the system communication between the CCMS and AI programme, a common protocol such as Building Automation Control Network (BACnet) would be adopted. To ensure same device to be referred and worked on, a unified equipment naming convention would also be deployed like the one formulated in the EMSD BIM-AM standards and guideline as detailed in Fig 6.

Naming Convention Requirements

1	2	3	4	5	
Building & Block Code	Floor Code	Equipment Code / System Code / Room Code	Equipment ID / System ID / Room ID	Function or Status Code	Function or Status ID (OPTIONAL)
<=7	<=4	<=6	2 to 4	<=8	<=2
Remark (1)	Remark (2)	Remark (3)	Remark (4)		Remark (5)

Remarks:
(1) A Building & Block Code shall make reference to EMSD BIM-AM Standards and Guidelines 2.0. For a CCMS system with maximum character limit for a point name, this field can be simplified subject to approval and it shall then be used for all points in the CCMS system.
(2) A Floor Code can be omitted for points without physical locations e.g. Systems.
(3) Only one type of code should be used in this field.
(4) A minimum of 2 characters should be assigned as an ID unless it is not applicable.
(5) Normally this ID is not necessary and should be used only if required.

Fig. 6 Naming Convention of Equipment

Through the ethernet and network switches, relevant data would be refreshed with an interval, say, every 10 minutes or shorter from the CCMS for reading of measuring devices, sensors as well as control elements, and directly accessible by the AI programme for real time analysis, processing as well as derivation of the best operational setpoints for optimization control of air-cooled chiller plant at pre-determined duration such as every hour. Fig. 7 indicates a typical network connection of AI controlled chiller plant.

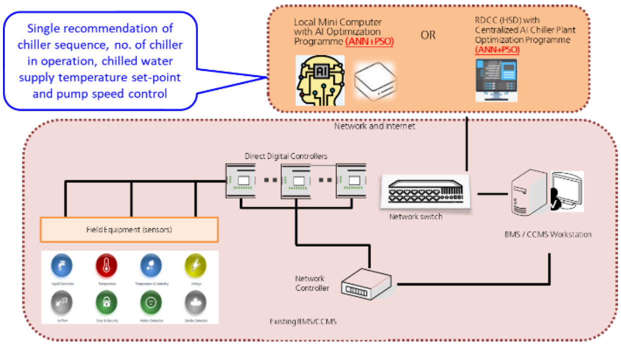


Fig. 7 Typical Network Connection of AI Controlled Chiller Plant

With the standardized and unified naming conventions for all digitized equipment and associated facilities, information become manageable among database of individual building or across cluster of buildings. A common Data Lake with a separate AI server could be set up to facilitate the application of AI tools using big data technologies and deep learning algorithms in a holistic and dynamic approach for the derivation of specific real-time, continuous and automatic optimization control strategies as shown in Fig. 8.

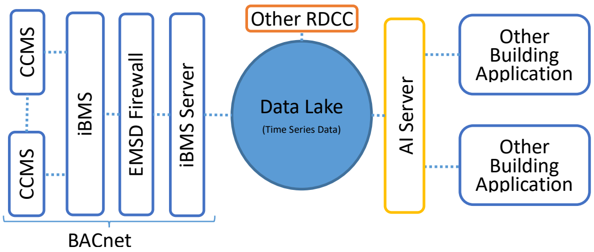


Fig.8 Typical configuration of Data Lake connected to RDCCs

Notwithstanding that the AI programme would send instruction to the CCMS recommending the optimized setpoints for the chillers and pumps, it should not override the chiller plant fault protection logic embedded in the CCMS e.g. pump fault changeover, chiller failure changeover, motorized valve interlocking with timer, etc.. Necessary modification on the control logic of CCMS by respective services provider, who is familiar with relevant control logic and programme structure of existing chiller plant, might be required to ensure the interfacing between the CCMS and AI system in right order.

To safeguard proper operation of air-cooled chiller plant, the AI programme would put a time stamp on each of its instructions for the user to recognize whether the plant running according to the optimized setpoints. Should there be irregularity of AI system or other considerations such as ad-hoc events, failure or scheduled maintenance of chiller plant equipment, the user may override the AI control by de-activating relevant button in the AI user interface created in the existing CCMS and manually switch ON/OFF any chiller or pump whenever necessary.

6. CASE STUDY

6.1 Implementation of AI in Local Medical Facilities

The EMSD has launched the AI chiller plant optimization programmes sequentially in 3 local medical facilities since January 2022. To illustrate, the chiller plant in one of the facilities, which is comprised of 6 air-cooled VSD chillers with each about 1,200 kW cooling capacity and 7 VSD chilled water pumps, is highlighted in Fig. 9 for discussion.

The plant is constructed with variable primary flow chilled water system. A chilled water by-pass modulating control valve allows the excessive chilled water flow through the by- pass pipe when the chilled water flow demand less than the minimum chilled water flow delivered by the pump at the lowest speed in the condition that only one chiller and one chilled water pump in operation.

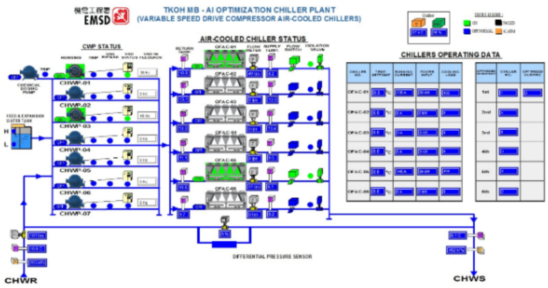
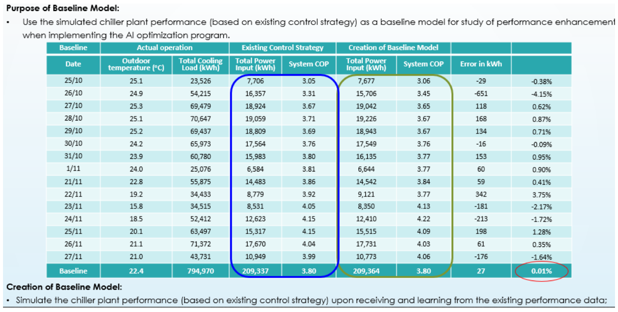


Fig. 9 Configuration of Chiller Plant in a Local Medical Facility

During the course of retrofitting, the existing configuration was checked against the system requirements in Paragraph 4 with a lot of measuring devices, sensors, wiring and control elements modified, replaced, re-commissioned and/or added. For example, the water commissioning valve at each chiller was re-calibrated and re-adjusted to the required water flowrate, which was further verified against the pump speed on site to ensure the pump running in line with the manufacturers' characteristic curve. To protect the pipework and equipment of air-conditioning system, the operating pressure of chilled water system was limited to that performed at the maximum and minimum speed of chilled water pumps. Similarly, the power analyzers of chillers and pumps were re-tuned to ensure the readings were valid and accurate.

6.2 Benchmark Model of Existing Chiller Plant under Conventional Control

It was difficult to evaluate the energy saving contributed by the AI optimization control during the implementation period as the system could not run under both AI mode and conventional mode simultaneously for direct comparison. To mitigate, a specific mathematical model was built as a benchmark to reckon the operating performance of existing chiller plant under conventional control by making reference to a full year historical data including outdoor temperature, total building cooling load demand, total power input and system coefficient of performance. Its error was found to be 0.01% in average as shown in Fig. 10 and considered acceptable.



Purpose of Baseline Model:

- Use the simulated chiller plant performance (based on existing control strategy) as a baseline model for study of performance enhancement when implementing the AI optimization program.

Baseline	Actual operation		Existing Control Strategy		Creation of Baseline Model			
Date	Outdoor temperature (°C)	Total Cooling Load (kWh)	Total Power Input (kWh)	System COP	Total Power Input (kWh)	System COP	Error in kWh	
25/10	25.1	23,526	7,706	3.05	7,677	3.06	-29	-0.38%
26/10	24.9	54,215	16,357	3.31	15,706	3.45	-651	-4.15%
27/10	25.3	69,479	18,924	3.67	19,042	3.65	118	0.62%
28/10	25.1	70,647	19,059	3.71	19,226	3.67	168	0.87%
29/10	25.2	69,437	18,809	3.69	18,943	3.67	134	0.71%
30/10	24.2	65,973	17,564	3.76	17,549	3.76	-16	-0.09%
31/10	23.9	60,780	15,983	3.80	16,135	3.77	153	0.95%
1/11	24.0	25,076	6,584	3.81	6,644	3.77	60	0.90%
21/11	22.8	55,875	14,483	3.86	14,542	3.84	59	0.41%
22/11	19.2	34,433	8,779	3.92	9,121	3.77	342	3.75%
23/11	15.8	34,515	8,531	4.05	8,350	4.13	-181	-2.17%
24/11	18.5	52,412	12,623	4.15	12,410	4.22	-213	-1.72%
25/11	20.1	63,497	15,317	4.15	15,515	4.09	198	1.28%
26/11	21.1	71,372	17,670	4.04	17,731	4.03	61	0.35%
27/11	21.0	43,731	10,949	3.99	10,773	4.06	-176	-1.64%
Baseline	22.4	794,970	209,337	3.80	209,364	3.80	27	0.01%

Creation of Baseline Model:

- Simulate the chiller plant performance (based on existing control strategy) upon receiving and learning from the existing performance data;

Fig. 10 Benchmark Model with Error of 0.01%

6.3 Creation of AI User Interface in Existing CCMS

The role of AI is to send instructions to the existing CCMS of aged chiller plant in in-service building such that its equipment work at the most energy saving combination for meeting the building cooling load demand. Should there be other considerations such as ad-hoc events, failure or scheduled maintenance of chiller plant equipment, irregularities of AI system, etc., the user could override the AI control by de-activating relevant button in the AI user interface created in existing CCMS and manually switch ON/OFF any chiller or pump whenever necessary as per Fig. 11.

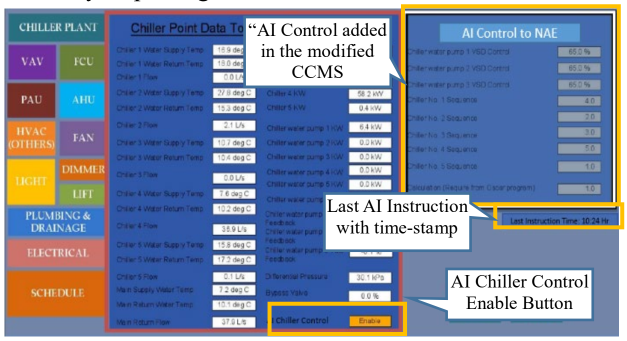


Fig. 11 AI User Interface Created in Existing CCMS

6.4 Result of AI Chiller Plant Optimization Solution

Having launched the AI chiller plant optimization programme over 1 year since January 2022, the system run stably with enhancement of both Coefficient of Performance (COP) and energy saving as shown in Fig. 12 & 13.

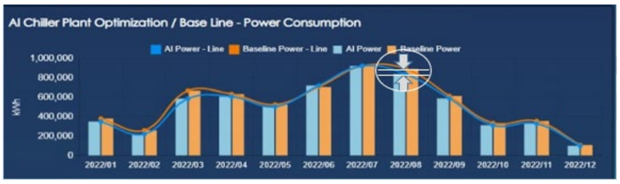


Fig. 12 Improvement of COP Using AI

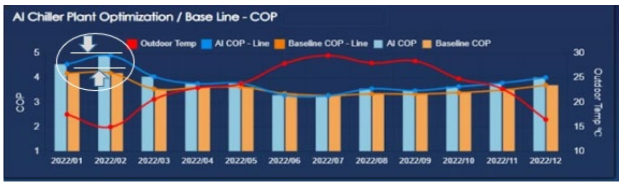


Fig. 13 Reduction of Energy Consumption Using AI

The blue bar shows the performance under the AI optimized scenario, whilst the orange bar shows that under the conventional control. On average, the COP and energy saving of the chiller plant were enhanced by about 6% in the period.

6.4 Mechanism to Optimize Energy Efficiency of the Retrofitted Chiller Plant

During the entire AI implementation period, the chiller operating patterns under the AI and conventional control are plotted below for analysis. (Fig. 14 & 15).

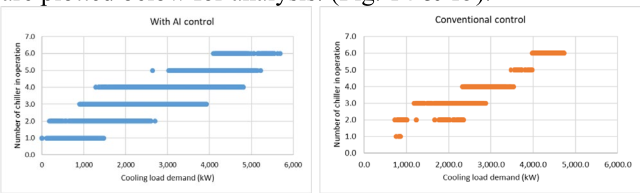
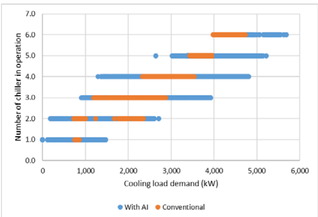


Fig. 14 Chillers Switched ON under AI and Conventional Modes



The blue line shows the number of chillers in operation to cater the building cooling load demand under the AI control, while the orange line shows that under the conventional control.

Fig. 15 Overlaying of Chillers under AI and Conventional Modes

It is interesting to observe that the AI decision is quite different from the traditional mindset of human being. For example, it is generally opined for an effective chiller plant optimization control involving lesser chiller units to be switched ON with each operated at full load as far as practicable. However, the AI did not follow this rule. It created another operating mode by switching on more chillers while each chiller running at partial load condition of about 45% of full capacity such that the COP and energy saving of chiller plant were the highest as indicated in Fig. 16, 17 & 18. Similar phenomenon of operating patterns in other 2 venues launched with AI optimization control was also noted.

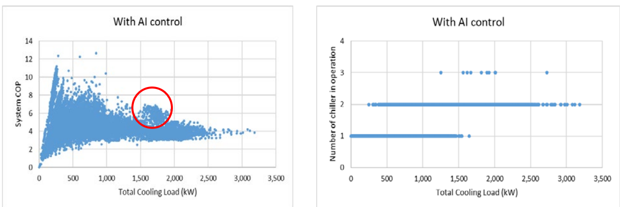


Fig. 16 COP of Chiller Plant and Number of Chillers Switched ON under AI Mode

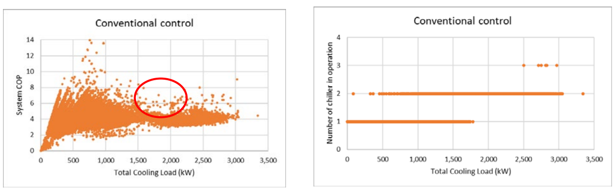


Fig. 17 COP of Chiller Plant and Number of Chillers Switched ON under Conventional Mode

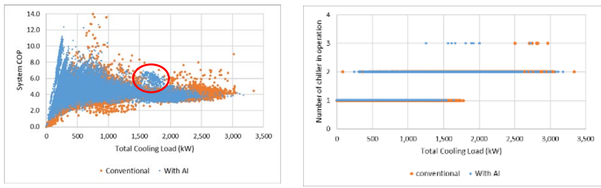


Fig. 18 Overlaid COP of Chiller Plant and Number of Chillers Switched ON under AI and Conventional Modes

The outcome for the chiller plant optimization using AI control in 3 aged in-service buildings elaborates an encouraging achievement of 5-10% energy saving, which certainly sets a good example for the industry to follow or explore other innovative measures for achieving the target of net-zero carbon emission in 2050.

7. WAY FORWARD

The EMSD together with experts from international institution and academic has developed a semantic data platform which consists of a graphical database for storing the semantic model and a time-series database for building data as shown in Fig. 19.

Fig.19 RDCC incorporated with semantic data platform at EMSD

Having digitally connected around 400 key government buildings to EMSD RDCCs, a common Data Lake has been established. A separate AI server would be set up for connection to the Data Lake to facilitate the application of AI tools using big data technologies and deep learning algorithms in a holistic and dynamic approach for the derivation of specific real-time, continuous and automatic optimization control strategies.

The common operating platform would allow the portability of data across not only various AI applications but also different chiller plants, leading to the development of more advanced energy optimization measures. Ultimately, it is expected a comprehensive predictive maintenance strategy would be developed such that the AI could forecast and alert the user should the operating conditions of an individual device required attention.

A number of enhancements below are in the pipeline for wider adoption of AI Chiller Plant Optimization :-

i.) Develop better chiller plant modelling algorithm with AI deep learning for air-cooled /water-cooled chiller plants;

ii.) Speed learning to shorten the AI learning process from 12 months to 1 month to expedite the benefit; and
iii.) Rapid cloning of AI models among chiller plants inside buildings using Semantic AI and simple single coding language.

The ultimate goal would be to delegate the routine plant operation and daily checking duty to the AI. With its accurate predictive power, the problematic components and equipment of air-conditioning system would be alerted, rectified and/or replaced by the user before any fault occurred, reducing the system down time and in turn enhancing the system reliability and availability. The manpower of plant operation would then be released for handling on-site scheduled maintenance, emergency repair and abnormal operation, as well as administering the overall plant performance and efficiency.

The AI is powerful for making decisions, but still need people's creativity and ingenuity. United with the IoT devices, the AI would create more energy saving measures, greener operations and smarter applications, which might be beyond the imagination of human being. In parallel, cybersecurity and ethical issues in the journey of adopting AI should be properly addressed with appropriate guidelines, standards and regulations in future.

To further extend the adoption of AI applications in the chiller plants, a practice note should be prepared and shared with the trade and stakeholders. EMSD looks forward with wider collaboration with the academia and greater bay area (GBA) partners in recognizing more successful stories of AI applications, in particular that serving for the achievement of carbon neutrality in 2050.

8. ACKNOWLEDGEMENT

The authors would like to thank The University of Hong Kong for their support in the programme coding works and Hospital Authority for sharing the operation data of the venue.

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