Technical Innovation Developed from Ten-year Research and Practice Collaboration of Private Sector and Academia on Building Energy Efficiency

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ABSTRACT

The paper presents fruitful results from ten-year collaborative research and practice carried out by Tsinghua University – Swire Properties Joint Research Centre on energy efficiency in HVAC systems in large-scaled commercial buildings. Substantial savings were obtained through retro-commissioning on HVAC systems with the assistance of control performance modelling during the building operation. The optimization was achieved not only by conventional system re-balancing/fine-tuning, but also through innovative technologies like data-driven modelling of chillers. Hand-in-hand joint efforts of the academia and the industry consolidated practical guidelines of testing and commissioning (T&C), and a series of case studies for building energy efficiency.

The knowledge accumulated from the existing building study was also transferred to the new building design and construction processes to improve the whole life-cycle building sustainability. T&C was stressed during the whole process from the design stage of T&C provision, the construction stage of T&C specifications to the operation stage of performance tests. This paper shares the experiences of the building energy consumption target setting and control during the whole process of design, construction and operation, through the joint efforts of a private sector and a university.

Keywords: *HVAC system, innovative technology, energy saving, existing building, new building*

1. INTRODUCTION

The buildings sector consumes about one-third of world energy and associates with almost one-third of global carbon dioxide (CO2) emissions. Energy efficiency in buildings was well recognized as an important approach to alleviate global warming and to achieve a sustainable future. However, a recent-published IEA report shows that building energy use has risen nearly 20% since 2000 although significant efforts on policy was adopted in recent years to improve building energy efficiency. Thus, the multiple-discipline joint-efforts may offer an alternative solution to industry and government on this crucial topic.

The collaboration of a private sector and the academia on building energy efficiency has been continued for ten years taking the real operating buildings as the living laboratories. The relationship started as the pilot study in 2007 and further developed to Tsinghua University – Swire Properties Joint Research Center for Building Energy Efficiency and Sustainability in 2011.

As the pioneer and leader in green building design and management with a long history on continuous improvement, the private sector is committed to incorporate environmental sustainability principles and practices throughout the business operations with long term goals and action plans.

The joint efforts not only fulfilled significant energy saving in the operating portfolio, but also demonstrated the increasing commitment on the real estate sustainable development and the influence to the industry by participated in the international research projects, i.e. IEA Annex 53, IEA Annex 66, and the US-China Clean Energy Research Center.

The field of this collaboration focuses on energy efficiency and sustainable built environment in commercial buildings, especially on Heating, Ventilation, and Air-Conditioning (HVAC) systems which dominate energy use in buildings. In this paper, the ten-year research and practice collaboration journey of the private sector and the academia is presented. The innovative technologies developed from the real applications as well as deployed into the reality are introduced.

2. FROM OPERATIONAL DATA TO EVALUATION METRICS

The collaborative works initiated from HVAC system and Indoor Environment Quality (IEQ) data gathering for saving potential analysis. The metrics to evaluate system performance, which were standardized and applicable for all HVAC systems, had been developed based on the collected data.

2.1 Operational data gathering and analysis in existing buildings

The operation of condensing water pumps and cooling towers not only affects electricity consumption in condensing side, but also influences energy performance of chillers. A case study below demonstrates the performance evaluation methodology.

Based on the annual hourly records of chiller saturated condensing temperature (SCT), chiller condensing water leaving temperature (CDWLT) and entering temperature (CDWET), and the outdoor wet bulb temperature (WBT), the performance of condensing side can be evaluated by three temperature differentials (dT) as shown in Figure 1a to 1c.

The first considered temperature difference, dT1, refers the differential between SCT and CDWLT which reflects heat transfer performance of the condenser. For common fresh water cooled chillers, dT1 should be maintained lower than 2K, otherwise the condensers should be cleaned for higher chiller efficiency, as shown in Figure 1a.

The second consideration, dT2, refers the differential between CDWLT and CDWET which is usually designed to around 5K. If the actual dT2 is obvious higher or lower than 5K, problems may be hidden in the operation of condensing pumps. Figure 1b shows annual hourly measured dT2 in the case. If dT2 during the year are significant higher than 5K, the insufficient condensing water flow rate could be identified, which deteriorated the performance of the efficiency.

The last considered, dT3, refers the differential between CDWRT and WBT which reflects the heat and mass transfer performance of cooling towers. In this case all-year round measured dT3 are shown in Figure 1c. It is obviously that dT3 in off-peak season are much larger than that in peak summer time. Based on the measured data analysis, a cooling tower operation scheme was suggested to achieve a smaller dT3 in the off-peak season, which resulted in higher chiller efficiency.

Figure 1a: dT1

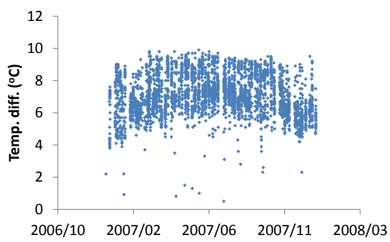

Figure 1b: dT2

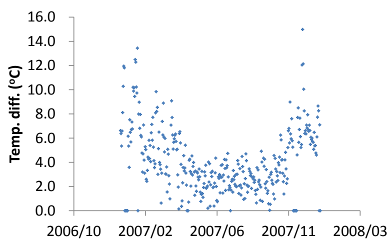

Figure 1c: dT3 annual hourly measured data

2.2 Metrics to evaluation system energy performance

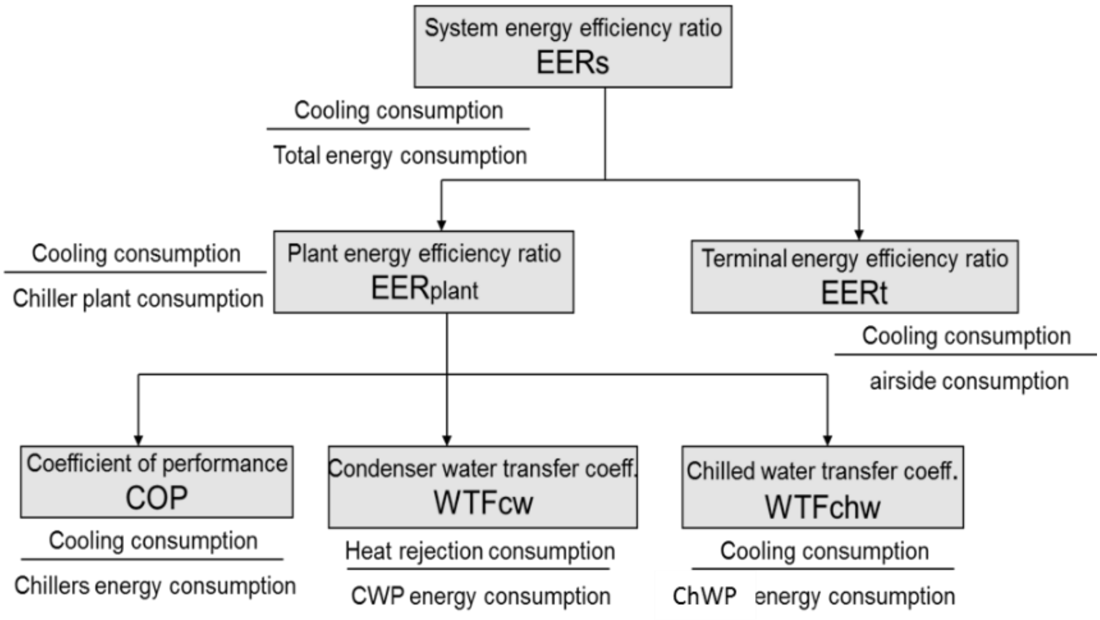

Figure 2: Key Performance Index (KPI) of HVAC system to evaluate energy performance of major systems / equipment based on measured operational data

The case studies of the existing buildings drew the conclusion that it is necessary to develop a systematic way to dig out energy saving potentials for built environment maintenance based on measured data. A standardized Key Performance Index (KPI) system was developed as the efficiencies of major systems / equipment in HVAC systems which can also be proposed for benchmarking, for target setting and control, as shown in Figure 2. Those metrics of efficiency can be compared with other similar systems on the apple-to-apple basis.

As shown in Figure 3, operational performance of 56 chiller plants were evaluated by the metrics and huge saving potentials in systems were figured out by the benchmarking.

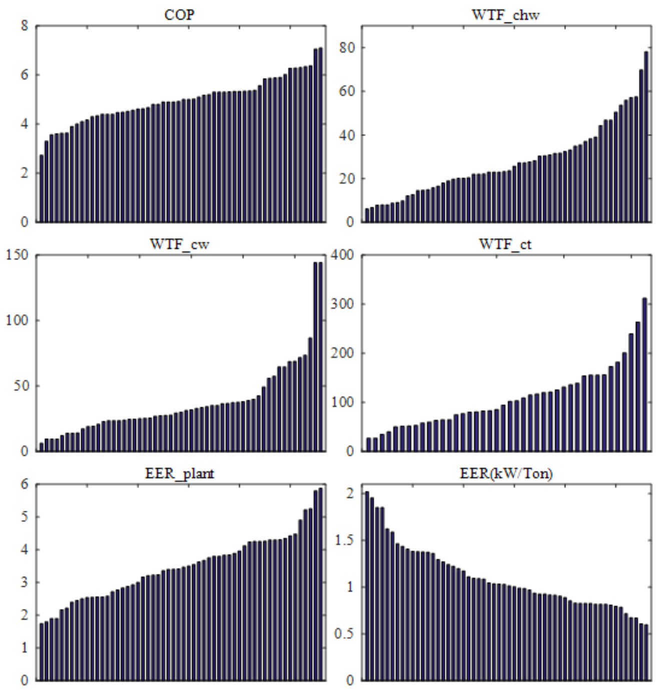

Figure 3: Benchmarking of 56 chiller plants through developed metrics on energy efficiency

3. FROM OPERATIONAL OBSERVATIONS TO MODELING AND ALGORITHM

The data-based evaluation on system performance disclosed significant saving potential on the operating systems in buildings. New methodology/technologies were also developed from the above exercises using the real buildings as the living laboratories for testing pilot initiatives on energy efficiency analysis and improvement. Fundamental studies were carried out including modelling and simulation and fine-tuned during the application of the algorithm for control to realize actual energy savings and efficiency improvement.

3.1 Concise graphic - Analytic method for chilled water system characteristics analysis

The phenomenon of “large flow – small ΔT” is always found in variable flow chilled water systems. A concise graphic-analytic method is introduced for the analysis on the overall performance characteristics of a group of cooling coils and identifying the probable problems.

The method uses the ideal curve of the relative cooling load vs. the relative flow rate as the baseline for the analysis. The cooling load imbalance and the hydraulic imbalance are analysed for their impacts on “large flow – small ΔT” phenomenon, which presents “collapse” in the performance curve.

Cooling load imbalance analysis

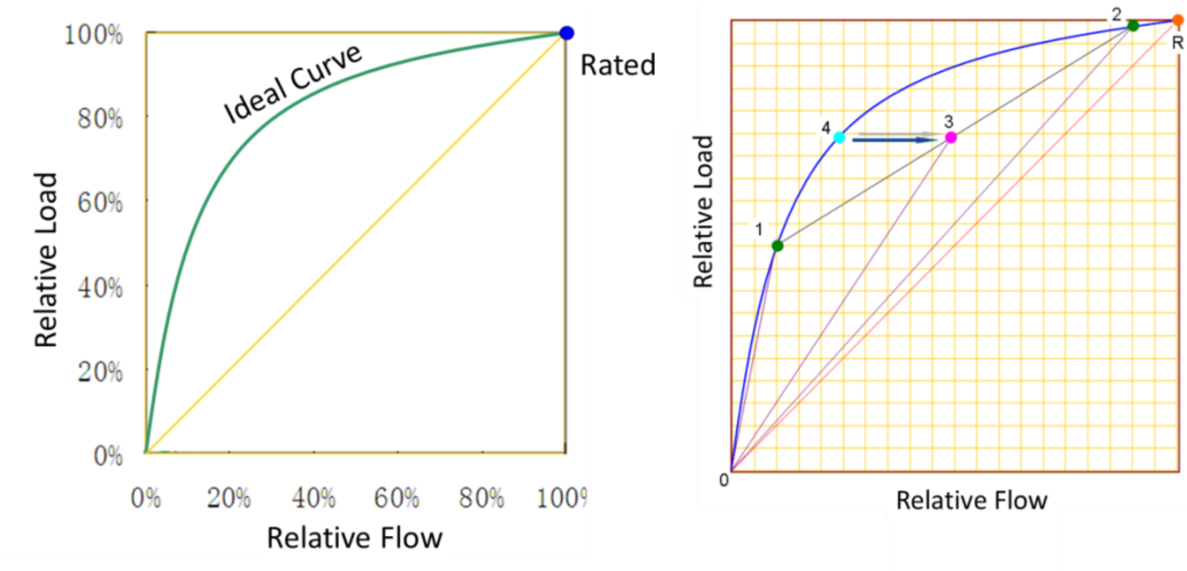

Figure 4: Cooling load imbalance analysis

If the two identical coils are working under different loads as “Point 1” and “Point 2” in Figure 4, the overall system operating condition is “Point 3”, which deviates from the ideal curve.

Hydraulic Imbalance Analysis

For the two identical coils, the control valve of one coil is faulty and fully open while the relevant air-side system is switched off. The other coil is under normal operation with the operating curve of “061R”. The overall system characteristic would be “543” (Figure 5a). If the malfunctioning valve is partially open, the system curve would be “5’4’3’”.

If the two identical coils are in operation, one is under normal control, the control valve of the other coil is faulty and fully open. The overall operating curve would be shifted to “53R” (Figure 5b).

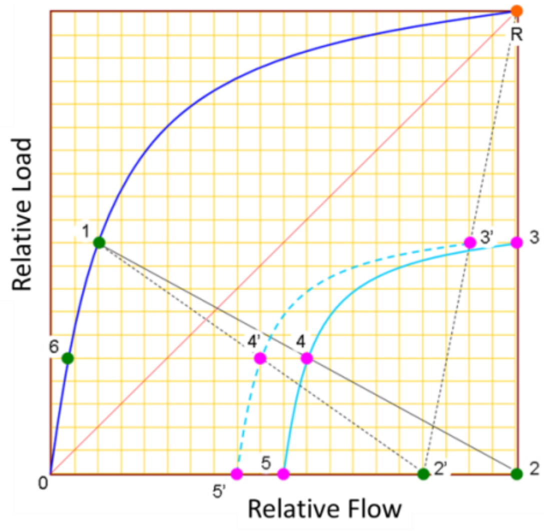

Figure 5a

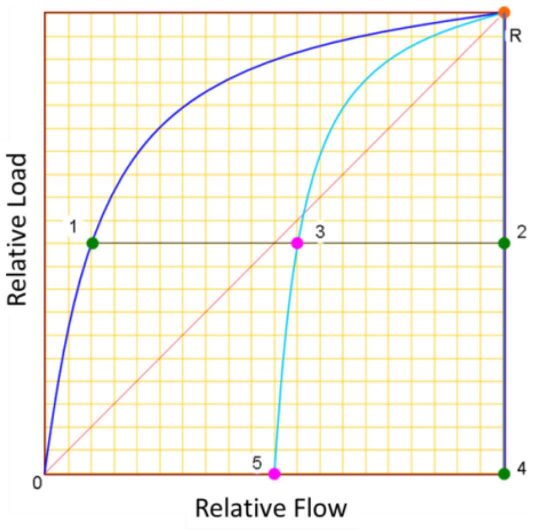

Figure 5b

Figure 5: Hydraulic imbalance analysis

3.2 Data-driven modelling of chiller

Chillers are the most energy consuming equipment in HVAC system. As the development of chiller technology, the rated efficiency of large scale centrifugal chillers or screw chillers is high. However, the chiller operating conditions always deviated from the rated point and lead to significant energy waste. Thus, it is important to continuously monitor the chiller operating points and make necessary optimization or retrofitting to improve the operating efficiency.

The chiller efficiency can be represented by the thermodynamic perfection of the cycle, which is defined in Equation 1. It illustrates deviation of operational COP, as defined in Equation 2, to the best condition which follows the reversed Carnot cycle as shown in Equation 3. The modeling is a typical data-driven type since all the parameters of the model can be measured directly from real operating system.

$$\gamma = COP \,/\, ICOP$$

Equation 1

$$COP = q \,/\, W$$

Equation 2

$$ICOP = T_{ev} \,/\, (T_{co} - T_{ev})$$

Equation 3

In above equations, is the thermodynamic perfectness, COP is the coefficient of performance, ICOP is the COP in the reversed Carnot cycle, q is the cooling energy produced (kW), W is compressor power (kW) and T is temperature in Kelvin. Subscripts ev and co represent evaporating and condensing respectively.

For constant speed chillers, the main influencing factors to the thermodynamic perfection are compressing pressure differential between evaporation and condensation, as well as the refrigerant mass flow rate. The former one can be represented by the differential between saturated evaporating temperature and saturated condensing temperature, expressed as dTev,co. The latter one can be approximately substituted by partial load ratio (PLR), which is the ratio of actual cooling output to rated cooling capacity.

The hourly operating data of chillers are shown in Figure 6. It was found that the running points of the chillers were far from the rated point, shown as the star in the Figure. It can be seen that the chiller thermodynamic perfection is quite low during most operation conditions. New chillers with relative smaller compression ratio were selected to replace the existing ones to make actual operation points closer to the rated point. Millions of kWh electricity savings were accomplished from this proper chiller replacement since the modeling and measured data played the important roles in this case.

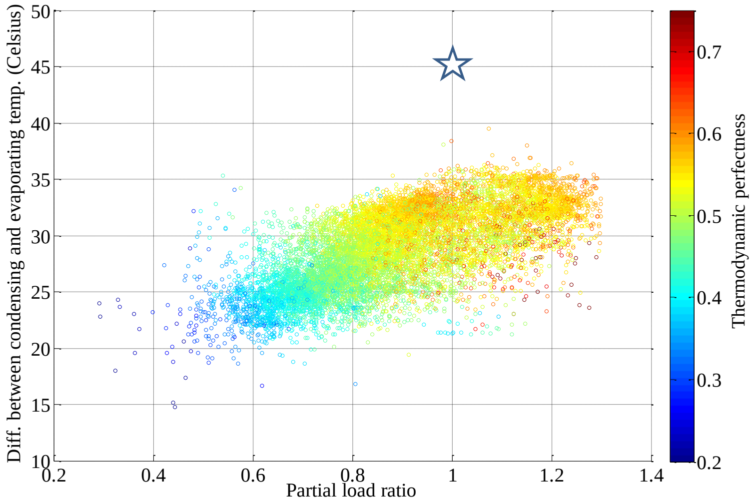

Figure 6: Chiller thermodynamic perfectness map with hourly measured data during a year

4. FROM OPERATIONAL EXPERIENCES TO DESIGN CRITERIA

Integrated Design Approach (IDA) is a concept where consideration of environmental performance of the development is placed at the start of a project and the objectives are to be met by the concerted effort of the development team. The knowledge accumulated from the existing building study was also transferred to the new building design and construction processes to improve the whole life-cycle building sustainability.

4.1 Solving oversizing capacity problems

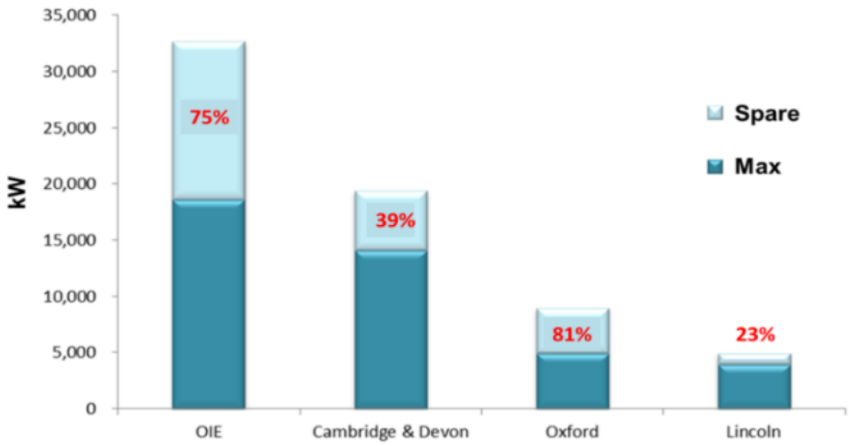

Figure 7: Oversized chiller plants

Oversizing of plant and equipment is a very common issue within the building industry. The result indicated the amount of oversizing ranges from 23% to 81% after a survey on several commercial buildings (Figure 7). The problem of oversizing increases the capital cost and sacrifices the system energy performance.

Variable speed drives can't solve the problem of oversizing. Although the variable speed drives can maintain a reasonably high efficiency during some part load conditions, the control range would be narrowed and the equipment would run at low efficiency if the loading is too low and has exceeded the turn down ratio limit.

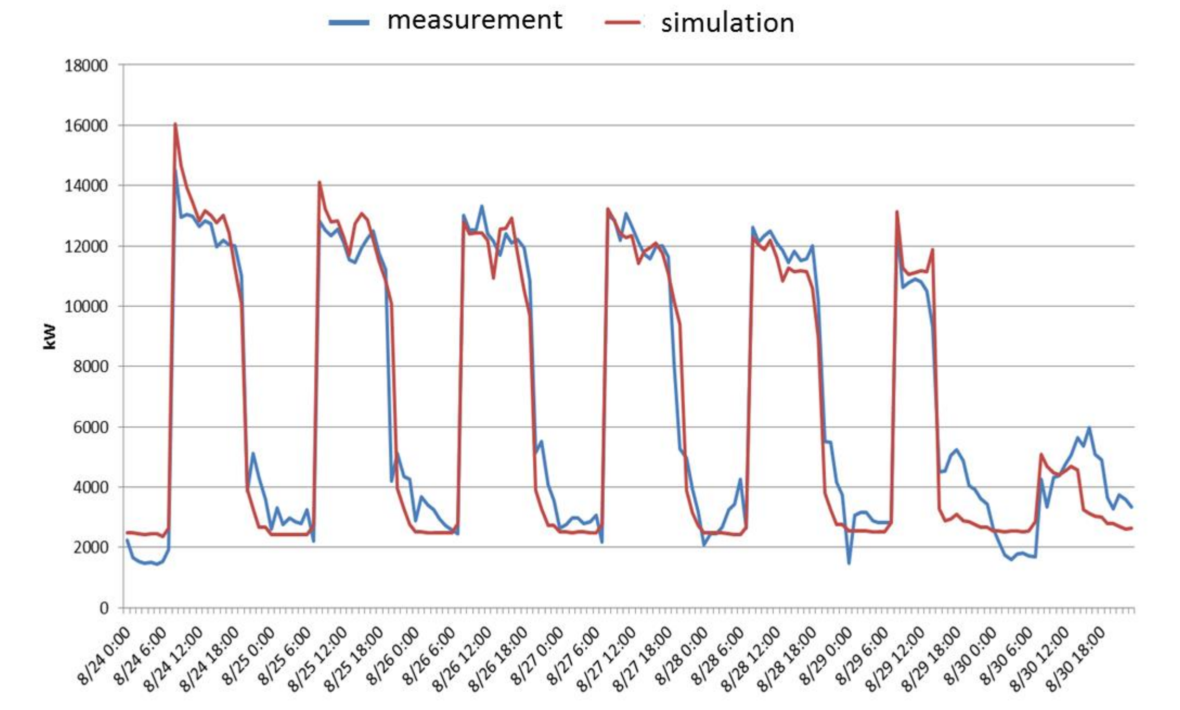

Figure 8: Calibrated simulation

Oversizing starts from load calculations which are done by computer simulation. The design input parameters are usually based on handbooks and local code of practices, which usually differ from the real situation. With the reference to the data collected as the input parameters, the simulation exercise showed that the estimated cooling load is much closer to the real demand (Figure 8). The database of the existing buildings would play the more active role for new building design. Further research works should be carried out on how to choose more realistic design parameters based on the operating data.

4.2 Detailed design for T&C and operation

In system design and equipment selection, part load efficiency should be addressed as the most important issue. The equipment should have the capacity to cater for a wide range of loading while maintaining the high efficiency. This can be achieved through the use of multiple units with different capacities and selecting of equipment with the right operating range and part load characteristics.

System efficiency should also be evaluated together with the current operating practices taking into account the control robustness. Too complicated control logics depending on multiple sensors would not be a good solution as multiple soft sensor errors are always difficult to be identified. To evaluate the system performance, sufficient provision of sensors/gauges/testing points is recommended. The guidelines of sensors/gauges/testing points provision need to be worked out with the detailed specifications.

Testing and commissioning (T&C) is the critical procedure to put the designed system to the real operation. Performance tests of major systems/equipment are standardized by the joint-efforts. The performance tests methodology and the relevant standard forms are developed for chillers, pumps, cooling towers, air handling units, primary air units, water balance, air balance, VAV systems and water-side system resistance analysis.

4.3 Publications and workshops

The Joint Research Center published a book entitled <The Analysis on Common Disputed Technical Topics for Building Energy Efficiency> (Figure 9) in August 2015. This co-publication, which is available in selected bookstores in Mainland China, presents six technical cases and explains the related concepts of integrated design and whole-process management, a system that enables commercial developers on energy efficiency throughout the building development process.

The six technical cases were summarized by the two parties together with their own opinions/methodology developed from accumulated practical experiences as well as the in-depth research works. In each case, the common misunderstanding areas were pointed out and clarified with detailed analysis.

Figure 9: Publications

The plant study case was also cited as a showcase in <2014 Annual Report on The Development of Building Energy Efficiency in China> (Figure 9), and it was the second time since 2010 (Figure 9) the joint-effort of energy performance and best practices adopted was recognised.

In past years, workshops sharing experiences from the Joint Research Center were hold every year in Beijing and/or Hong Kong. The research and practice collaboration pushed the boundaries of building energy research to the application and developed new benchmarks in building energy efficiency and sustainability. The platform also helps sharing with the industry peers and researchers about new building technologies and management processes related to achieving greater energy efficiency.

5. FURTHER COLLABORATION AND CHALLENGES

In the future phase of this collaboration project, one of the focuses is to build an Energy Management System (EMS) for the company's commercial buildings across Hong Kong and Mainland China. The EMS will allow real-time remote monitoring of the buildings' electricity consumption data. Both parties are expected to work hand-in-hand to optimize the structure of EMS and to investigate potential energy saving opportunities through the on-line system by built-in expert rules.

EMS had been developed by some developers with different features based on their particular needs. However, the data quality and data utilization are still facing big challenges.

The information management functions of BMS are also planned to be used for monitoring-based commissioning. The accumulated knowledge would be incorporated to develop the online fault detection and diagnosis (FDD) strategies as the existing BMS may not suit our demand. The joint-efforts are necessary to put this forward successfully.

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