Development of A Multiple Index Assessment Model of Domestic Hot Water System with A Case Study of Star Hotels in Shanghai

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SUMMARY
With full-time assurance of hot water supply and highly-demand comfort of hotel guests, domestic hot water (DHW) system becomes one of the most critical equipment systems to ensure the outstanding performance in high-standard hotels. This paper presents the development of a multiple index assessment model with three-layer hierarchy for DHW system in public building. Two star hotels in Shanghai were selected for case study and detailed field test to demonstrate the effectiveness of applying the model. Result shows that DHW system in Hotel B is overall better than Hotel A, with 58.7% of system efficiency in Hotel B in summer condition and 108.2% in winter condition, much higher than 32.4% in Hotel A in summer condition. Heat loss and user comfort are also proposed to be considered in the operation of DHW system.

INTRODUCTION
China's building energy consumption in 2012 (excluding biomass) is about 690 million tce (tons of standard coal), accounting for about 19.1% of total energy consumption. Moreover, the energy consumption from public buildings, such as malls, hotels and office buildings, occupies 26.3% of the above 690 million tce. (BERC 2014) In high-standard hotels, domestic hot water (DHW) system becomes one of the most critical equipment systems to ensure the outstanding performance, with full-time assurance of hot water supply and high-demand comfort from guests. In China, the supply of DHW has become one of the most important factors influencing the growth of the public building energy consumption. A field test shows that the DHW can take up 38.9% of the total gas consumption in a Shanghai star hotel (BERC 2014), which is worthy of attention in the energy saving potential assessments.

Various researches have addressed the importance of consumption prediction in DHW system, including the time use pattern, the seasonal variance and individual difference. For instance, the result of daily basis DHW in 182 Finnish apartments (Ahmed, K. et al. 2015) finds significant DHW consumption difference in different months, averagely with 38 L/person/day in July and 42 L/person/day in November, respectively. Also, numerous researches aim to improve the accuracy of the DHW prediction through detailed modelling. Some specific models are widely applied in this field such as stochastic bottom-up model (Fischer, D. et al. 2016; Aki, H. et al. 2016), linear time-series model (Bacher, P. et al. 2013) and neural networks (Aydinalp, M. et al. 2004).

Field test is an important method to evaluating and deep analyzing the operation of DHW system. Heat loss is a widespread problem in DHW supply process, resulting in much lower efficiency than the design condition. For instance, a survey of 7 centralized DHW supply systems in Beijing shows that system efficiencies are within 29 to 56%, much lower than the test gas boilers (approximately 78-80%). (Jingqi An et al. 2016) Other researches shows similar results, which indicate various heat loss rates in DHW systems, such as 10-90% in US (ASHRAE 2011) and 23-89% in Denmark (B Hm, B. 2013).

However, there are still few researches concerning about the assessment model of DHW system. A survey of various DHW systems types in UK (P-J. Boait et al. 2012) proposes a method to standardizing the comparison process, including the normalization of supply temperature, energy input and consumption volume. A European reference standard EN 15326 (CEN, 2008) is available to evaluate heating systems in building, especially various types of DHW systems. This standard mainly focuses on the efficiency of heat source and energy loss in distribution process.

Considering most studies above directly related to residential buildings rather than public buildings, an effective method to assess DHW system is essential to the energy conservation in hotels. This paper presents the development of a multiple index assessment model based on the investigation of DHW systems located in two star hotels in Shanghai. The investigation conducted detailed surveys and field tests in summer and winter in both hotels, called Hotel A and Hotel B. A three-layer hierarchy model is proposed to assess the DHW system, which represents total energy level evaluation, load and system efficiency evaluation and operation strategies evaluation. Several practical recommendations are also proposed in discussion to enhance the energy-saving potentials in the two hotels.

METHODS
Buildings and systems description
The investigation in this study is accomplished based on the actual consumption data and operation parameters in two star hotels in Shanghai, China. Essential information about the hotels and DHW systems is shown in Table 1. Hotel A is a 5-star hotel opened in 2010, located in Putuo District, Shanghai. Hotel A applies the conventional DHW system, which use gas boilers as heat source. Hotel B is a 4-star hotel opened in 1997, located in Xuhui District, Shanghai. Hotel B was retrofitted in 2014 to meet the cost management and energy conservation requirements, replacing the old equipment with some green energy techniques, such as steam exhaust heat recovery and carbon dioxide heat pumps.

More detailed DHW system descriptions of Hotel A and B are shown in Figure 1 and Figure 2, respectively. In hotel A, the heat demand from the whole building is provided from 3 gas boilers with the nominal heat capacity of 2.1MW. The heat demand includes space heating, ground heating, DHW, swimming pool and SPA. Therefore, 5 different pipes in the primary loop are design to draw out from the water segregator, to meet various heat functions. Specifically, the DHW system is divided into 6 regions in the secondary loop, in which High I
region (28F-32F), High II region (21F-27F), High III region (15F-20F) and High IV region (7F-12F) represents the demand from guest room, Low region and laundry room represents the demand from other places. In the field test, High II region (21F-27F) was chosen to conduct detailed measurement and data collection.

In Hotel B, the heat source of DHW is steam before the retrofitting. The new system differs from the old system mainly in two aspects. First, the system applies the heat recovery technique in the steam exhausts from laundry room, rather than directly using the energy from the steam. Second, 6 carbon dioxide heat pumps replace the steam to be the main heat source for the DHW in guestroom, 2 for High region, 2 for Low region and 2 for Staff Region with identical system design, respectively. Figure 2 shows the system description of Low region, in which detailed field test is conducted. This system includes a pair of heat pumps, one heat exchange tank and one heat storage tank. When the DHW produced by the carbon dioxide heat pumps is more than the end use, the hot water is preferentially stored in the heat storage tank, and the water stored therein is pressed to reheat in the heat pumps. If the end use of hot waters is larger than the capacity of the heat pumps, the system would take hot water directly into the heat exchange tank, while the heat storage tank to add more.

Figure 1. Heating primary water system description in Hotel A

![Figure 1. Heating primary water system description in Hotel A](image1.png)

Figure 2. Low region DHW system description in Hotel B

![Figure 2. Low region DHW system description in Hotel B](image2.png)

Table 1. Essential information of the building and system description in Hotel A and B

<table>
<thead>
<tr>
<th>Categories</th>
<th>Items</th>
<th>Hotel A</th>
<th>Hotel B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Place</td>
<td>Putuo District</td>
<td>Xuhui District</td>
<td></td>
</tr>
<tr>
<td>Star</td>
<td>5-star</td>
<td>4-star</td>
<td></td>
</tr>
<tr>
<td>Opening Year</td>
<td>2010</td>
<td>1997</td>
<td></td>
</tr>
<tr>
<td>Building Area/m²</td>
<td>68900 (Parking Lots: 8700)</td>
<td>31840</td>
<td></td>
</tr>
<tr>
<td>Guest Room Area/m²</td>
<td>34000</td>
<td>14139</td>
<td></td>
</tr>
<tr>
<td>Guest Room Num/m²</td>
<td>501</td>
<td>349</td>
<td></td>
</tr>
<tr>
<td>Heating source</td>
<td>Gas Boiler</td>
<td>Steam exhausts and heat pumps</td>
<td></td>
</tr>
<tr>
<td>Heat Storage Tank</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>DHW supply time</td>
<td>24h/day</td>
<td>24h/day</td>
<td></td>
</tr>
<tr>
<td>Control Strategy</td>
<td>Base on the temperature in the primary and secondary side</td>
<td>Base on the temperature in the heat storage tank and return water</td>
<td></td>
</tr>
</tbody>
</table>

Multiple index assessment model of domestic hot water system

The assessment model of DHW system proposed in this study is a three-layer hierarchy model with multiple indexes that can describe the operation characteristics and energy consumption level of the whole system. The first layer represents the total energy level, which can indicate the energy saving potential through benchmarking. The second layer represent the load and system efficiency, which reveals the actual need from the end users and evaluate the operation performance of the whole system. The third layer represents the operation strategies, which describe the system in several aspects including distribution, heat loss, heat source equipment efficiency and user comfort. All the energy in the model is normalized to unit GJ by the coal equivalent calculation method, in which the conversion factor is set at 2.61 from electricity to heat.

The energy level layer includes only one index, $Q_{TR}$, which represents the total energy consumption per guestroom. Reasonable energy consumption level per guestroom is an effective indicator of good the energy management, by benchmarking with other similar star rate hotels or similar brands in the same hotel group. This index can be obtained by direct splitting from the energy audit, or from the estimation of Equation (1).

$$Q_{TR} = \int_0^T Wdt$$  (1)
The heat source group includes one index, the heating equipment efficiency, which can be defined as Equation (6).

\[
\mu_{HH} = \frac{Q_{AR}}{Q_{TR}} \tag{6}
\]

Where \( Q_{AR} \) represents the actual energy consumption per guestroom, \( Q_{TR} \) represents the total energy consumption per guestroom.

The heat loss group includes two indexes. The first index, the heat loss percentage, is defined as Equation (7).

\[
\theta_{HL} = \frac{Q_S - Q_{AR}}{Q_{TR}} \tag{7}
\]

Where \( Q_S \) represents energy consumption of pumps, \( Q_{AR} \) represents the actual energy consumption of pumps, and \( Q_{TR} \) represents the total energy consumption of pumps.

Figure 3. A three-layer hierarchy multiple index assessment model of DHW system

In some cases, \( \theta_{HL} \) is rather difficult to accurately calculate due to the lack of DHW water flow measurement. So in practice, the average daily difference of supply and return temperature \( \Delta T_{s} \) is an effective index to show the extent of heat loss during the distribution process in pipes.

The comfort group includes one index \( \Delta T_{s} \), the average difference of peak-time supply temperature, which can be expressed as Equation (8).

\[
\Delta T_s = \max\{t_{s,peak}\} - \min\{t_{s,peak}\} \tag{8}
\]

The peak-time can be determined from the actual DHW use pattern from the field test, which is typically set at 8:00-10:00 and 19:00-23:00.

RESULTS

DHW assessment indexes comparison

The indexes value that can be calculated from the field test in Hotel A and B. The results are separated into summer and winter condition, which are shown in Table 2 and Table 3, respectively. Some index values of hotel A in winter condition is left blank due to the lack of continuous water flow measurement.

From the comparison, DHW system in Hotel B is overall better than Hotel A, especially in the aspect of energy consumption level and system efficiency. From the view of system design, DHW system in Hotel B is more decentralized, and applies more renewable energy techniques. However, the complexity of the control in two tanks leads to less user comfort in Hotel B, that \( \Delta T_s \) is larger than Hotel A in the peak demand period. Detail comparison and analysis on the system operation would be discussed in the following parts.

Table 2. DHW assessment index values in Hotel A and B (Summer Condition, 2015)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Index</th>
<th>Unit</th>
<th>Hotel A</th>
<th>Hotel B</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( Q_{TR} )</td>
<td>MJ/(room d)</td>
<td>35.5</td>
<td>14.7</td>
</tr>
<tr>
<td>II</td>
<td>( G_{R} )</td>
<td>L/(room d)</td>
<td>109.3</td>
<td>85.7</td>
</tr>
<tr>
<td>II</td>
<td>( Q_{AR} )</td>
<td>MJ/(room d)</td>
<td>11.5</td>
<td>8.6</td>
</tr>
<tr>
<td>II</td>
<td>( \mu_{SYS} )</td>
<td>/</td>
<td>32.4%</td>
<td>58.7%</td>
</tr>
<tr>
<td>III</td>
<td>( WTF_{T} )</td>
<td>/</td>
<td>10.0</td>
<td>193.7</td>
</tr>
<tr>
<td>III</td>
<td>( WTF_{A} )</td>
<td>/</td>
<td>3.2</td>
<td>85.6</td>
</tr>
<tr>
<td>III</td>
<td>( \mu_{HH} )</td>
<td>/</td>
<td>0.82</td>
<td>1.36</td>
</tr>
</tbody>
</table>
### Table 3. DHW assessment index values in Hotel A and B (Winter Condition, 2016)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Index</th>
<th>Index Unit</th>
<th>Hotel A</th>
<th>Hotel B</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$Q_{TR}$</td>
<td>MJ/(room·d)</td>
<td>42.2</td>
<td>/</td>
</tr>
<tr>
<td>II</td>
<td>$G_{AR}$</td>
<td>L/(room·d)</td>
<td>/</td>
<td>142.7</td>
</tr>
<tr>
<td></td>
<td>$Q_{AR}$</td>
<td>MJ/(room·d)</td>
<td>/</td>
<td>45.7</td>
</tr>
<tr>
<td></td>
<td>$\mu_{SYS}$</td>
<td>/</td>
<td>/</td>
<td>108.2%</td>
</tr>
<tr>
<td>III</td>
<td>$\Delta W_{T}$</td>
<td>/</td>
<td>/</td>
<td>72.1</td>
</tr>
<tr>
<td></td>
<td>$WT_{fa}$</td>
<td>/</td>
<td>/</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>$\theta_{NL}$</td>
<td>/</td>
<td>/</td>
<td>22.4%</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{AV}$</td>
<td>K</td>
<td>13.2</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{S}$</td>
<td>K</td>
<td>3.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>

#### Heat flows breakdown

The heat flows breakdown provides a visual summary of the heat demand in buildings, which could moreover clearly reflect the conversion process and heat loss in the distribution process. In the field test, the heat flow data from a typical day are applied for further analysis both in Hotel A and Hotel B.

As shown in Figure 4, the heating system in Hotel A can be divided into four conversion process: energy input (gas), heat equipment (boiler), primary water loop and secondary water loop. Specifically, DHW secondary loop is further calculated to identify the level of real energy consumption in DHW end use. In summer condition, DHW takes up most of the heat demand in Hotel A, around 70.7% of the total gas energy. Heat source and distribution prove to be the most significant two factors to affect the heat loss, which account to 58.7% of the energy input and 93.8% of the total energy loss.

![Figure 4. The heat flow breakdown of a typical day in Hotel A (Summer condition, 2015)](image)

DHW system in Hotel B is tested in detail with the comparison of Low region and High region, summer and winter condition. After retrofitting, heat pumps provide most of the energy demand for DHW use, both in summer and winter. In a summer typical day, the heat from laundry steam exhaust only accounts for 2.3% of the total supply heat. The heat loss rate in Hotel A differs between Low and High region, summer and winter condition, within the scale between 21.8% and 57%, which requires fine control considering the system design and demand pattern change in different sub-systems.

#### Heat source operation

Two types of heat source are compared in this case study, the hot water boilers in Hotel A and CO$_2$ heat pumps in Hotel B. The $\mu_{HQ}$ in Hotel A in summer condition is only 0.82, much lower than 1.32 in Hotel B. To make it clear, the $\mu_{HQ}$ in Hotel B is normalized by divided the conversion factor 2.61, and added up the influence of the steam heat. In practical tests, the efficiency of heat pumps is evaluated by COP, which can be derived from the ratio of the generating heat and input electricity.

The $\mu_{HQ}$ in Hotel A is much lower than the nominal efficiency 92%~95%, which results from the oversize selection of equipment capacity and frequent on-off cycle during the operation process. Take the summer condition for example, in which only one boiler is enough for the total heat demand, the period of the on-off cycle is about 60 min in the peak time and 90 min in the valley time, as shown in Figure 8. The daily average duty ratio of the boiler is only 0.23, lead to significant amount of heat loss during the off time. The daily average heat power of boiler is only 233 kW, much lower than 2100 kW, the nominal heat capacity. Huge gap between the actual heat demand and capacity selection and constant low load rate are the two crucial reasons for the low performance of boiler. In winter condition, the period of on-off cycle is about 16 min in peak time, with the shift of the opening of one boiler and two boilers.

![Figure 6. The heat flow breakdown of a typical day in Low region, Hotel B (Winter condition, 2016)](image)

![Figure 7. The heat flow breakdown of a typical day in High region, Hotel B (Winter condition, 2016)](image)
The $\mu_{\text{HP}}$ in Hotel B is higher than 1 for the actual COP of heat pumps can exceed the conversion factor 2.61. The field test result for single heat pump in 3 different regions in summer condition is shown in Figure 9. Repeated tests were applied to one heat pump to diminish the result error. Test shows that only one heat pump in summer condition can exceed the level of nominal COP 4.45. The average COP of heat pumps in Hotel B is 3.59 in summer and 4.11 in winter, still lower than the nominal COP.

Figure 8. The on-off cycle of boiler operation of a typical day in Hotel A (Summer condition, 2015)

**Distribution and heat loss**

Compare to space heating and cooling, the energy consumption level of pumps in DHW systems is often neglected, due to its small proportion to the total energy input. Especially for less centralized systems like Hotel B, the $W_{\text{TF}}$ can achieve 193.7, indicating the high efficiency of the distribution process. So in the heating systems, the distribution energy inefficiency usually results from the lack of control in primary water loops. In Hotel A, the $W_{\text{TF}}$ in winter condition is 72.1, much higher than 10.0 in the summer condition. The operation strategy of pumps in primary loop is identical in summer and winter, which is set opening of 2 pumps in 24 hours without frequency conversion. In the view of actual end use level, the $W_{\text{TF}}$ of Hotel A is only 3.2, even lower than the COP of heat pumps.

Heat loss problem is widespread in DHW systems, especially for centralized systems in public buildings. The $\theta_{\text{HL}}$ in summer condition is 60.5% in Hotel A and 57.0% in Hotel B, indicating great amount of energy loss during the pipe distribution. Comparison from Figure 5 and Figure 6 shows that the heat loss amount in Low region in summer and winter is nearly equal, but the $\theta_{\text{HL}}$ can vary due to DHW demand change from different season and occupancy rate.

Moreover, the DHW heat consumption in summer condition in Hotel B can be divided into two periods, daytime (9:00-19:00) and nighttime (19:00-next day 9:00). Result from Figure 10 and Figure 11 shows that $\theta_{\text{HL}}$ is 79% in daytime and 48% in nighttime, with relative low DHW demand and high demand respectively.

**User comfort**

User comfort is hardly discussed in the researches of DHW systems, but from field test and investigation, the comfort problem is worth concerning due to the potential influence of the guest satisfaction. One aspect that can describe the user comfort is the time and temperature assurance of the DHW supply. The time assurance requires the hot water from any tap in guestroom should achieve the end use temperature (like 40 °C) within a few seconds, but practically it is hard to obtain this data in a building level. Instead, the temperature assurance can be indicated by $\Delta T$, the average difference of peak-time supply temperature. It is fairly easy and precise to calculate during the field test.

From Table 2 and Table 3, the user comfort of Hotel A is quite good in summer condition with less than 1K of $\Delta T$. In winter condition, $\Delta T$ became larger due to lower cold water and increasing DHW demands. However, $\Delta T$ in Hotel B is significant higher than Hotel A. As shown in Figure 12, the DHW supply and return temperature fluctuates much during the peak time, mainly resulting from the ineffective control from its complex strategies, especially the shift between two heat water tanks.

Figure 9. The daytime DHW energy consumption of a typical day in Hotel A (Summer condition, 2015)

Figure 10. The nighttime DHW energy consumption of a typical day in Hotel B (Summer condition, 2015)

Figure 11. The change of DHW supply and return temperature of a typical day in Hotel B (Summer condition, 2015)
DISCUSSION
The primary objective of this research is to develop a model based on indexes to assess the operation of DHW systems in public buildings, especially in hotels. More concretely, the emphasis was placed on the description of energy consumption level and different aspect influencing the operation of DHW systems. The indexes from the assessment model can be used as effective indicators to help the energy audit engineers and the operation managers grasp the overall operation level of certain DHW system, also discover potential problems in system design and control strategies.

The research also proposes some typical problems in DHW system through case study and field tests. Conventional heat source such as boiler tends to loss in efficiency compared to renewable heat equipment such as heat pump. However, the control of the supply temperature is easier and more stable in conventional ones, which can be concluded from the comparison in Hotel A and B. Distribution process should also be concerned during the operation, and can be improved in two aspects. The first is to optimize the control strategies with appropriated methods, such as adding frequency converters for pumps, lowing the DHW temperature in valley time. The second is to avoid overcentralized system in the design process, especially one central heating plant that can provide all types of heat demands in a public building. More attention should also be paid to the user comfort in the DHW system. Related control strategies should both consider the energy conservation and temperature stability.

Limited buildings studied in this research, means that the assessment model still need more cases to demonstrate its effectiveness and universality. More work should be done in the future to standardize the field test procedure, and propose reasonable index constraint values that can regulate the energy efficiency an DHW system in public building should achieved.

CONCLUSIONS
A three-layer hierarchy model is proposed in this study to assess the operation of DHW system in public buildings. Two star hotels in Shanghai were selected for case study and detailed field test to demonstrate the effectiveness of applying the model. Result shows that DHW system in Hotel B is overall better than Hotel A. The system efficiency in Hotel B is 58.7% in summer condition and 108.2% in winter condition, much higher than 32.4% in Hotel A in summer condition. This difference mainly results from the gap between the heat equipment efficiency in two hotels, which is 1.36 in summer and 1.51 in winter for Hotel B, only 0.82 in summer for Hotel A. Both systems show significant proportion of heat loss in operation, with 50.7% in summer and 22.4% in winter for Hotel B, 60.5% in summer for Hotel A. However, the DHW user comfort in Hotel A is better than Hotel B. The average difference of peak-time supply temperature in Hotel B is 3.8K in summer and 5.0K in winter respectively, which may cause dissatisfaction from the guests.

REFERENCES