A Study on a New Performance Rating Approach for a Multi-Split (VRF) Air-Conditioning System

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Outlines

- Applications & Energy Saving Practice Of A VRF System
- A Small Scale End-User Operation Behavior Survey
- A New Performance Rating Approach For A VRF System
A Multi Split (VRF) Air Conditioning System

- A Multi Split Air-conditioning (VRF) System Consists Of One Outdoor Unit And Multiple Indoor Units. The Indoor Units Can Be Controlled Independently.
- A VRF System Distinguishes Itself From A Unitary System Thru
  » Capability To Turn On And Off The Multiple Indoor Units Independently
  » Energy-saving Practice Through Modulating The Load Request Via Turning On/Off Indoor Units.
- A Good VRF Performance Rating Approach Must Consider The Aspects Of Indoor Unit Turn On/Off
Different Applications & Energy Saving Practice Of A Multi Split (VRF) System

- **Residential House/Apartment Application**
  - Different Indoor Units Put Into Service At Different Timing To Save Energy
  - Living Room Indoor Unit Is Called Into Service During The Dinner Time While The Bed Room Units Are Off.
  - Later, More Bed Room Units Are Turned On And Living Room Unit Is Turned Off

- **Shops And Restaurants Application**
  - Full Load Operations During The Peak Business Time, While Part Load Operations Are Expected For The Rest Of Day

- **Office Building Application**
  - During The Normal Office Hours, It Is Believed Most Of The Indoor Units Are Put Into Service And The System Almost Operates 100%.
  - During The After Hours, Most Of The Indoor Units Are Turned Off And The System Operates Under Very Light Load.
## Operation Behaviour Of A Multi Split System

### (A 1-To-4 System As An Example)

<table>
<thead>
<tr>
<th>Cooling Season</th>
<th>Moment 1</th>
<th>Moment 2</th>
<th>Moment 3</th>
<th>Moment 4</th>
<th>Moment 5</th>
<th>Moment 6</th>
<th>Moment 7</th>
<th>Moment 8</th>
<th>Moment 9</th>
<th>Moment 10</th>
<th>Moment 11</th>
<th>Moment 12</th>
<th>Avg. SUI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID 1</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>ID 2</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>ID 3</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>ID 4</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
</tbody>
</table>

### Case 0: All ID OFF

### Case 1: Only One ID ON

- Only 1 ID ON

### Case 2: Two ID ON

- 2 ID ON
- 2 ID ON
- 2 ID ON
- 2 ID ON
- 2 ID ON
- 2 ID ON
- 2 ID ON
- 2 ID ON

### Case 3: Three ID ON

- 3 IE ON
- 3 IE ON
- 3 IE ON
- 3 IE ON
- 3 IE ON
- 3 IE ON
- 3 IE ON
- 3 IE ON

### Case 4: All 4 ID ON

- All 4 ID On
- All 4 ID On
- All 4 ID On
- All 4 ID On
- All 4 ID On
- All 4 ID On
- All 4 ID On
- All 4 ID On
A Mini-Survey On End-user Operation Behavior In A Typical Office Building

- A Typical Office Building (2300 M²), With 10 Outdoor 10HP Units And 41 Indoor Units
  - Open Space In The Middle Occupied By The General Staff
  - Separated Spaces Around The Wall For Individual Offices, Meeting Rooms, Training Rooms

<table>
<thead>
<tr>
<th>Room Statistics</th>
<th>Number Rooms</th>
<th>Number Indoor Unit</th>
<th>ID Unit Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room with Single Indoor</td>
<td>15</td>
<td>15</td>
<td>37%</td>
</tr>
<tr>
<td>Room with Two Indoors</td>
<td>7</td>
<td>14</td>
<td>34%</td>
</tr>
<tr>
<td>Open Space (Cubicle Area)</td>
<td>4 Row 3 Colum</td>
<td>12</td>
<td>29%</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

Note: 10 outdoor units, each powering 4.1 indoor units on average
Survey Results Of Indoor Unit ON/OFF Operation Behavior In A Typical Office Building

- In Separated Spaces, Unit ON/Off Heavily Relates To Whether The Space Is Occupied Or Not. The On-Probability Is Significantly Lower Than Expected.
We Can Introduce 4 Dummy Unitary Systems To Equivalently Replace The 4 Different Operation Conditions Of A 1-To-4 VRF System

<table>
<thead>
<tr>
<th>Dummy UAC</th>
<th>Indoor Unit On ‘Quantity’</th>
<th>Outdoor Unit</th>
<th>All On Indoor Unit Capacity % Of Total Indoor Units</th>
<th>Capacity Rate Of The Original Multi-Split System</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAC 1</td>
<td>1</td>
<td>Same</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>UAC 2</td>
<td>2</td>
<td>Same</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>UAC 3</td>
<td>3</td>
<td>Same</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>UAC 4</td>
<td>4</td>
<td>Same</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

One

Two

Three

Four

Indoor Unit On ‘Quantity’

Outdoor Unit

Outdoor Unit

Outdoor Unit

Outdoor Unit

Dummy UAC 1

Dummy UAC 2

Dummy UAC 3

Dummy UAC 4

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HVAC Systems
Seasonal Efficiency SPLV Of A Multi Split (VRF) Air Conditioner

- The Seasonal Cooling Efficiency SPLV of the original multi-split system defined as the total cooling capacity divided by the total power consumption of the multi-split system
  - The total cooling capacity of these four dummy unitary systems equal to the total cooling capacity from the original multi-split system
  - The total power consumption by these four dummy systems equals to the total power consumption by the original multi-split system

- SPLV of the original multi-split system equals to the sum of the cooling capacity delivered by the four dummy unitary systems divided by the total power consumption by all of these four dummy systems
SPLV Calculation (1)

\[ SPLV = \frac{\sum C_{All}}{\sum P_{All}} = \frac{C_1 + C_2 + C_3 + C_4}{P_1 + P_2 + P_3 + P_4} \]

- \( \sum C_{All} \) Total Cooling Capacity Of The Original Multi-split System During The Whole Cooling Season
- \( \sum P_{All} \) Total Power Consumption Of The Original Multi-split System During The Whole Cooling Season
- \( C_1, C_2, C_3, C_4 \) The Respective Delivered Cooling Outputs From The Dummy System ONE, TWO, THREE And FOUR During The Whole Cooling Season
- \( P_1, P_2, P_3, P_4 \) The Respective Power Consumptions Of The Dummy System ONE, TWO, THREE And FOUR During The Whole Cooling Season
SPLV Calculation (2)

More,\n
$$SPLV = \frac{\sum C_{All}}{\sum P_{All}} = \frac{C_1 + C_2 + C_3 + C_4}{P_1 + P_2 + P_3 + P_4}$$

$$= \frac{1}{\sum C_{All} \cdot SEER_1 + \sum C_{All} \cdot SEER_2 + \sum C_{All} \cdot SEER_3 + \sum C_{All} \cdot SEER_4}$$

$$= \frac{1}{A \cdot \frac{1}{SEER_1} + B \cdot \frac{1}{SEER_2} + C \cdot \frac{1}{SEER_3} + D \cdot \frac{1}{SEER_4}}$$

$SEER_1$ $SEER_2$ $SEER_3$ $SEER_4$

Represent The Seasonal Efficiencies Of The Four Dummy Systems, Respectively

Represent The Ratios Of The Delivered Cooling Capacity Outputs From The Dummy Systems ONE, TWO, THREE And Four, Respectively, To The Total Cooling Capacity Of The Multi-split System, Denoted By A, B, C & D As The Weight Factors For Seasonal Efficiencies Of Dummy Systems ONE, TWO, THREE And FOUR Used For The SPLV Calculation

The Next Step Is How To Get The Weights?
Operation Probability of 4 Dummy UAC’S – A Equivalent Replacement Of The Multi Split System

- Take A System With 1 Outdoor Unit & 4 Indoor Units Multi Split System As An Example. If The ON Probability Of A General Indoor Unit Is X%,
  - Probability To Operate Only 1 Indoor Unit, And 3 Turned Off
    - 1 Out Of 4 Combination Is 4: \(4 \times X\% \times (1 - X\%)^3\)
  - Probability To Operate 2 Indoor Units, And 2 Turned Off
    - 2 Out Of 4 Combination Is 6: \(6 \times X\%^2 \times (1 - X\%)^2\)
  - Probability To Operate 3 Indoor Units, And 1 Turned Off
    - 3 Out Of 4 Combination Is 4: \(4 \times X\%^3 \times (1 - X\%)\)
  - Probability To Operate All 4 Indoor Units
    - 4 Out Of 4 Combination Is 1: \(1 \times X\%^4\)
  - Probability To Operate 0 Indoor Unit
    - 0 Out Of 4 Combination Is 1: \(1 \times (1 - X\%)^4\)
An Calculation Example

- For Example, If The General ON Probability Is 68%, The Calculated Running Probabilities Of The 4 Dummy UAC Systems Are

  - Probability To Operate Dummy ONE: \[4 \times 68\% \times (1 - 68\%)^3 = 8.9\%\]
  - Probability To Operate Dummy TWO: \[6 \times 68\%^2 \times (1 - 68\%)^2 = 28.4\%\]
  - Probability To Operate Dummy THREE: \[4 \times 68\%^3 \times (1 - 68\%)^1 = 40.3\%\]
  - Probability To Operate Dummy FOUR: \[1 \times 68\%^4 = 21.4\%\]
  - Probability To Turn The System Completely Off: \[1 \times (1 - 68\%)^4 = 1.0\%\]
Seasonal Operating Hours Of Four Dummy Unitary Systems

- Running Hours Of These Four Dummy Unitary Systems Under Different Ambient Temperatures Can Be Proportionally Calculated

Nanjing, Capital City Of Jiangsu, China’s Climate Is Used For Office Building Load Calculation Here
Weightings A, B, C, D Calculation

- Total Seasonal Capacity C1 Of The Dummy Unitary System ONE:
  » Multiplying The Operating Hours Of Dummy Unitary System ONE Under Different Ambient Temperatures By The Relative Load (Capacity Percentage X Temperature Delta)

- Similar Calculation To Bring About Total Seasonal Capacity C2, C3, C4 For Dummy UAC’s TWO, THREE, FOUR

- Summarizing The Cooling Season Capacity C1, C2, C3, C4 Generates The Total Cooling Capacity Of The Original Multi-split System $\sum C_{All}$

- The 4 Weighting Factors A, B, C, D Are Calculated As

  $$A = \frac{C_1}{\sum C_{All}}, \quad B = \frac{C_2}{\sum C_{All}}, \quad C = \frac{C_3}{\sum C_{All}}, \quad D = \frac{C_4}{\sum C_{All}}$$
Weightings A, B, C, D Calculation Example

- For Example, If The General ON Probability Is 68%
  - The Weighting A Of Dummy Unitary ONE Is 3.3%
  - The Weighting B Of Dummy Unitary TWO Is 20.9%
  - The Weighting C Of Dummy Unitary THREE Is 44.4%
  - The Weighting D Of Dummy Unitary FOUR Is 31.4%

<table>
<thead>
<tr>
<th>Ambient Temperature °C</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
<th>31</th>
<th>32</th>
<th>33</th>
<th>34</th>
<th>35</th>
<th>36</th>
<th>37</th>
<th>38</th>
<th>Total</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dummy Unitary One</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.4</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>10.3</td>
<td></td>
<td>3.3%</td>
</tr>
<tr>
<td>Dummy Unitary Two</td>
<td>0.8</td>
<td>1.3</td>
<td>2.2</td>
<td>3.3</td>
<td>4.0</td>
<td>4.9</td>
<td>5.8</td>
<td>6.7</td>
<td>6.2</td>
<td>7.1</td>
<td>6.6</td>
<td>6.6</td>
<td>6.3</td>
<td>2.6</td>
<td>0.9</td>
<td>0.2</td>
<td>0.0</td>
<td>65.4</td>
<td></td>
</tr>
<tr>
<td>Dummy Unitary Three</td>
<td>1.7</td>
<td>2.8</td>
<td>4.7</td>
<td>7.0</td>
<td>8.5</td>
<td>10.5</td>
<td>12.2</td>
<td>14.1</td>
<td>13.2</td>
<td>15.1</td>
<td>14.0</td>
<td>14.0</td>
<td>13.5</td>
<td>5.4</td>
<td>1.9</td>
<td>0.3</td>
<td>0.0</td>
<td>139.0</td>
<td></td>
</tr>
<tr>
<td>Dummy Unitary Four</td>
<td>1.2</td>
<td>2.0</td>
<td>3.3</td>
<td>4.9</td>
<td>6.0</td>
<td>7.4</td>
<td>8.7</td>
<td>10.0</td>
<td>9.3</td>
<td>10.7</td>
<td>9.9</td>
<td>9.9</td>
<td>9.5</td>
<td>3.8</td>
<td>1.4</td>
<td>0.2</td>
<td>0.0</td>
<td>98.5</td>
<td></td>
</tr>
<tr>
<td>One-to-four Multi-split</td>
<td>3.9</td>
<td>6.3</td>
<td>10.6</td>
<td>15.7</td>
<td>19.2</td>
<td>23.6</td>
<td>27.5</td>
<td>31.9</td>
<td>29.7</td>
<td>34.0</td>
<td>31.5</td>
<td>31.5</td>
<td>30.3</td>
<td>12.2</td>
<td>4.4</td>
<td>0.8</td>
<td>0.0</td>
<td>313.2</td>
<td></td>
</tr>
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</table>
### A, B, C And D Weightings

**Based On General Turn-on Probability Of 68%**

<table>
<thead>
<tr>
<th>Case 1, The General On Probability</th>
<th>68%</th>
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</thead>
<tbody>
<tr>
<td>Quantity Of Operating Indoor Units</td>
<td>Nominal Load Rate %</td>
</tr>
<tr>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>1</td>
<td>25%</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>75%</td>
</tr>
<tr>
<td>4</td>
<td>100%</td>
</tr>
</tbody>
</table>
SEER Of Four Dummy Unitary Systems

- Ideally, the seasonal efficiencies $SEER_1$, $SEER_2$, $SEER_3$, $SEER_4$ of the four dummy unitary systems are calculated (integrated) through actual efficiency testing under different ambient temperatures. This approach could be very time-consuming & cost-prohibitive due to the huge amount of laboratory testing.

- Theoretically, the efficiency (EER) of a unitary system under one ambient temperature will match the seasonal efficiency SEER.

- A more practical approach is to use the efficiency of these dummy unitary systems under a specified ambient temperature to approximate their seasonal efficiency, i.e. set $SEER = EER$ under a specified ambient temperature.

- This simplification could reduce the testing requirement significantly without compromising the key philosophy of this new VRF system’s rating approach.
In this study, the ambient temperature is chosen where the delivered cooling capacity by the unitary system splits 50-50 below & above this temperature.

Nanjing city climate generates an ambient temperature of 29.6°C for efficiency EER₁, EER₂, EER₃, EER₄ testing.
Generate The General On Probability For Indoor Unit

Calculate The Probabilities Of Operating One, Two, Three, Four Indoor Unit Respectively Of A One-to-four System

Introduction Of Four Dummy Unitary Systems, To Build-Up A Physical Model For Multi-split System Performance Rating

Calculate The Ratio Of Each Dummy Unitary Operating Capacity To The Total

Get The SEER Of Each Dummy Unitary Systems

Build Up Mathematical Model For A Multi-split System's Performance Rating

\[ SPLV = \frac{1}{A \cdot SEER_1} + \frac{1}{B \cdot SEER_2} + \frac{1}{C \cdot SEER_3} + \frac{1}{D \cdot SEER_4} \]
Thank You