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ABSTRACT

This study starts with a survey on the end-user's behaviour on operating a multi-split VRF air-conditioning system and progresses with reasonable assumptions and finally, mathematical models are used to generate the calculation equations. Taking a one-to-four multi-split system as an example, step by step, a new performance rating approach for a multi-split air-conditioning system is developed.

Keywords: multi-split system, VRF, air-conditioning, performance rating, dummy unitary system, SPLV, IPLV

1. INTRODUCTION

A multi-split air-conditioner is a refrigeration system that consists of one outdoor unit and multiple indoor units and the indoor units can be controlled independently. The capability to turn on and off the multiple indoor units independently distinguishes a multi-split air-conditioner from a typical unitary system. This characteristic makes it possible to practice energy-saving through modulating the load request via turning on or turning off indoor units. Today, multi-split systems have been widely used for centralized air-conditioning applications, including domestic, commercial and offices as well (Wu *et al*., 2012).

This study starts with a survey on the operation of typical centralized air-conditioning systems to understand the end user's operating behaviour and a series of modelling follows to build up a new performance rating approach. In the process, a one-to-four system (i.e. one outdoor unit connected to four indoor units) is used as an example. The study can serve as a new direction for future discussion and practice in the discipline of multi-split system performance rating.

2. BUILDING TYPE & END-USER OPERATION BEHAVIOUR SURVEY

A typical residential house/apartment includes 2 to 4 bed rooms and one living room. For most of the time, different indoor units are put into service. For example, the living room indoor unit is called into service during the dinner time around 18:00pm through 20:00pm while the bed room units are turned off. Later on, more bed room units are turned on and the living room unit is turned off. It is normal for a residential application multi-split system to operate under partial load for most of its service life.

For a multi-split air-conditioner installed at shops and restaurants, we often see full load operations during the peak business time, while part load operations are expected for the rest of day. Take a restaurant as an example, all indoor units are turned on around lunch and dinner time while in the middle of the afternoon (say from 14:00p to17:00pm), some of the indoor units are turned off due to reduced customer presence and load.

A typical office building sees normal office hours and after hours. During the after hours, most of the indoor units are turned off and the system operates under very light load. During the normal office hours, it is believed most of the indoor units are put into service and the system almost operates 100%. Interestingly, our survey reveals that this is not the case.

Let us examine the third floor of a typical office building with a size of 2300 square meters (shown in Figure 1). The vast space left in the middle is the cubicle areas occupied by the general staff while the partitioned spaces at the top, bottom and right sides are used as the individual offices for managers, small meeting rooms, training rooms and the canteen. A few small laboratories occupy the space at the left side. Ten multi-split air-conditioning systems are installed to cover the 2300 square meters, with 10 outdoor units and 41 indoor units in total. On average, one 10HP outdoor unit powers 4.1 indoor units in this case. The small boxes in Figure 1 represent the locations of the indoor unit installations.

Areas with no more than two indoor units installed are called separated space and larger areas with three or more indoor units installed are called open space. Thus the cubicle area in the middle is classified as an open space while the rest is classified as separated spaces. Table 1 shows the statistics of the different spaces and the number of corresponding indoor unit installations. It is clear, 70% of the space we surveyed here is used as separate spaces and only 30% is used as the open space. It is worth to point out that even during the normal office hour the indoor units in the separated spaces can be turned on or off frequently, depending on the occupancy of the spaces by the individuals.

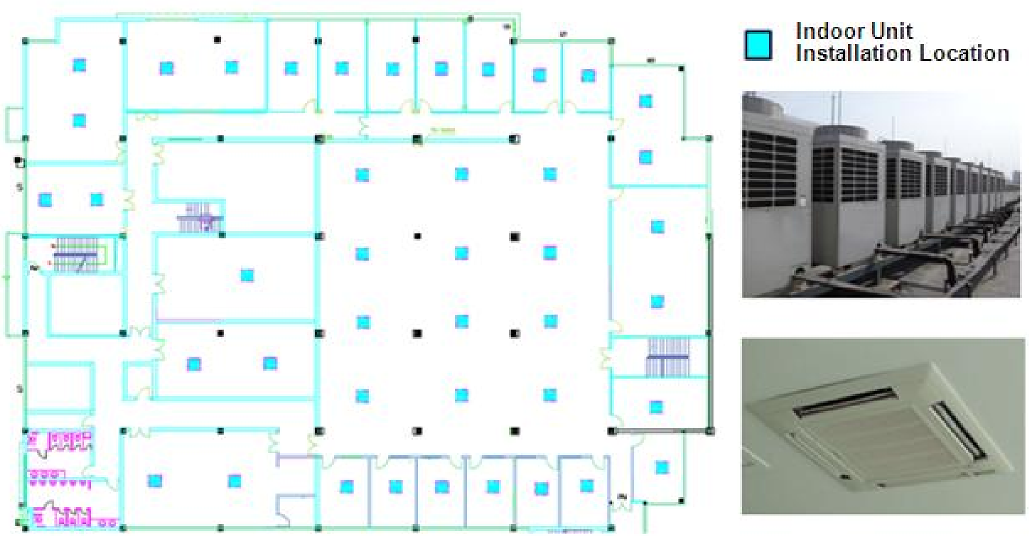


Figure 1: A Typical office floor layout

Table 1: Indoor unit installation quantity in different spaces

Room Statistics	Number of Rooms	Number of Indoor Units	Percentage
Room with Single Indoor Unit	15	15	37%
Room with Two Indoor Unit	7	14	34%
Open Space (Cubicle Area)	4 Row by 3 Colum	12	29%
Total		41	100%
Note: 10 indoor units, each powering 4.1 indoor units on average			

Figure 2 shows the 24-hour air-conditioning power consumption rate for the office floor described above. It shows about 60% of the total energy is consumed during the office hours from 9:00am to 18:00pm. A local dip between noon and 15:00pm could be due to the lunch break, when some of the terminals are turned off when people leave office for lunch out. The rest 40% of the energy consumption is out of the normal office hours and it tells some of the indoor units are kept on before and after office hours.

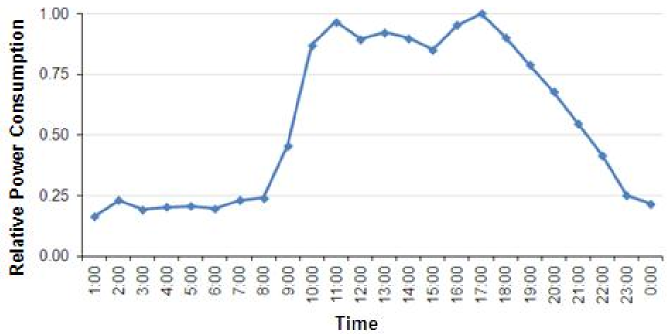


Figure 2: 24-hour air conditioning power consumption rate (100% used at peak time)

Let us have a closer look at one 10 HP system that serves 3 separate offices, including 2 small ones and 1 large one. Table 2 shows the real time power consumption of the system that demonstrates strong correlation (0.997) with the total horse power of the indoor units turned on. When the total horse power of the turn-on indoor units decreases, the total power consumption drops accordingly though the power consumption per unit space increases to some extent. This characterizes the energy conservation possibility and potential through mindful operating behaviour that all VRF system OEM's are promoting and the practice should be encouraged.

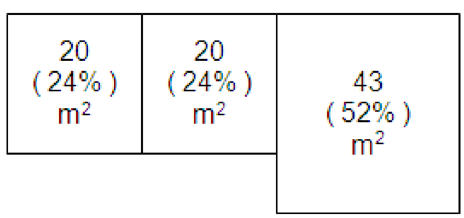


Figure 3: Three separate offices served by one 10HP VRF system

Table 2: Real time power consumption of the10HP VRF system

Number Of Indoor Units Turned On	Space Covered, m^2	Percentage Of Space Covered	Percentage Of Power Consumption	Ratio Of Power Consumed To Space Covered
1	20	24%	36%	1.49
2	43	52%	61%	1.18
3	63	76%	82%	1.08
4	83	100%	100%	1.00

A two week long survey followed on the actual usage of these 10 multi-split systems, dated from August 9th to 23rd during the hottest days of 2012 cooling season. The on/off status of all 41 indoor units was recorded three times a day at 10:15am, 15:15pm and 19:15pm, respectively. The timing selection was intended for a better representation of all day usage. The collected data show (in Figure 4), in this peak cooling season of middle August, 92% of the indoor units in the open area were kept on and only 58% of the indoor units in the separated areas were kept on during the office hours (the statistics at 19:15pm was not included). On average, 68% of the total indoor units were kept on during normal office hours.

The use of the air-conditioning in a separated space heavily depends on the actual demand, i.e. when the space is occupied, the corresponding indoor unit(s) is turned on; otherwise, it is likely to be kept off. This applies to not only the cooling season, but the heating season as well, and is independent of the ambient temperature to a large extent during the cooling and heating seasons. Therefore, a survey conducted over a certain period is representative of the on/off status of the whole cooling (and heating) season.

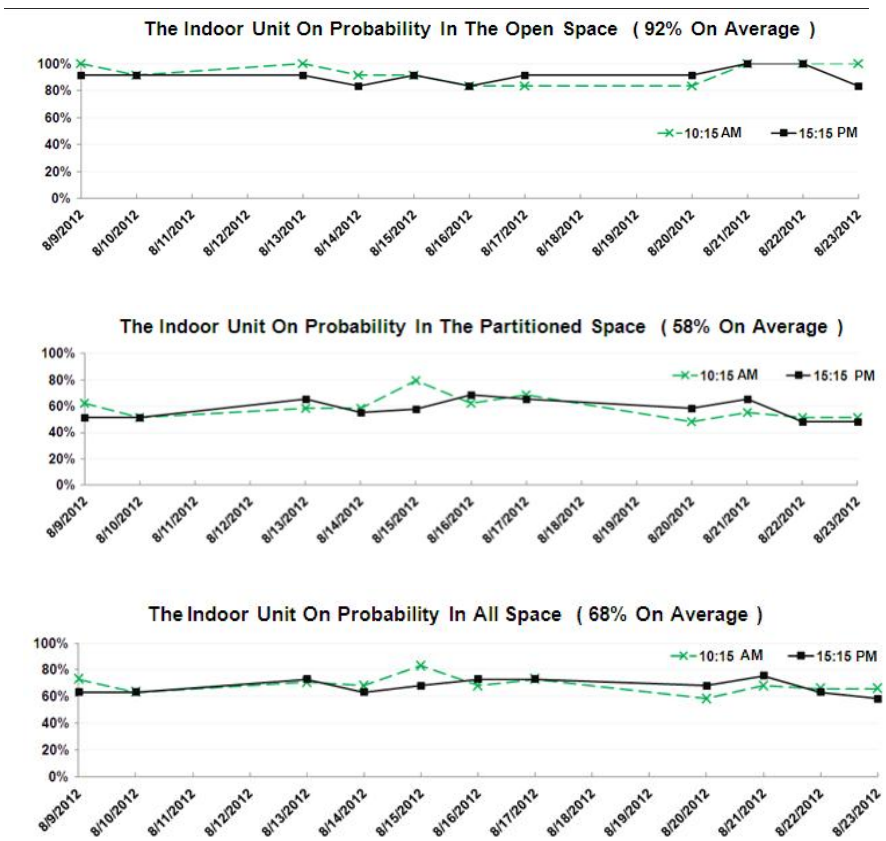


Figure 4: Survey results of indoor unit On/Off status (actual usage of 10 multi-split systems)

3. A NEW APPROACH ON RATING A MULTI-SPLIT VRF SYSTEM

With some assumptions outlined below and based on the ON probability for a general indoor unit, the probabilities for one multi-split system to operate only one indoor unit, or 2 indoor units, …, and all indoor units can be modelled.

Take a system with one indoor unit and 4 outdoor units as an example (termed as a one-to-four system below), if the ON probability of a general indoor unit is x%, the probabilities for such a system to operate zero (0) indoor unit (system is off completely),or only one indoor unit, or only two indoor units, or only three indoor units, or all four indoor units are calculated as (note, the multiplier in front of the below calculation is the combination of possible different scenarios. For example, there are 6 different combinations to operate 2 units out of 4 in total)

- Probability to operate only one indoor unit, and 3 turned off (1 out of 4 combination is 4): 4 * x% * (1 - x%) ^{3}
- Probability to operate 2 indoor units, and 2 turned off (2 out of 4 combination is 6): 6 * x% ^{2} * (1 - x%) ^{2}
- Probability to operate 3 indoor units, and 1 turned off (3 out of 4 combination is 4): 4 * x% ^{3} * (1 - x%)
- Probability to operate all 4 indoor units (4 out of 4 combination is 1): 1 * x% ^{4}
- Probability to operate 0 indoor unit (0 out of 4 combination is 1): 1 * (1 - x%) ^{4}

In order to allow us better understand the operation of such a one-to-four multi-split system, four dummy unitary systems are introduced here to equivalently replace the four different operation conditions of this one-to-four system, with each representing each of these four operating conditions:

1) Dummy unitary air-conditioner ONE: consisting of the same outdoor unit and one indoor unit. The capacity of the indoor unit is 25% of the total, thus the cooling capacity is reduced to 25% of the original multi-split system
2) Dummy unitary air-conditioner TWO: consisting of the same outdoor unit and two indoor units. The combined capacity of these two indoor units is 50% of the total, thus the cooling capacity is reduced to 50% of the original multi-split system
3) Dummy unitary air-conditioner THREE: consisting of the same outdoor unit and three indoor units. The combined capacity of these 3 indoor units are 75% of the total, thus the cooling capacity is reduced to 75% of the original multi-split system
4) Dummy unitary air-conditioner FOUR: consisting of the same outdoor unit and all four indoor units. The combined capacity of the four indoor units maintains and the cooling capacity equals to the original multi-split system

During the whole cooling season, the dummy systems ONE, TWO, THREE and FOUR are used to replace the original multi-split system when it operates with only one, or only two, or only three and all four indoor units, respectively. Obviously, the total delivered cooling capacity of these four dummy unitary systems equals to the total cooling capacity from the original multi-split system and the total power consumption by these four dummy systems equals to the total power consumption by the original multi-split system, therefore, the seasonal cooling efficiency SPLV of the original multi-split system, defined by the total cooling capacity divided by the total power consumption of the multi-split system, equals to the sum of the delivered cooling capacity delivered by the four dummy unitary systems divided by the total power consumption by all of these four dummy systems.

$$
\begin{aligned}
SPLV &= \frac{\sum C_{All}}{\sum P_{All}} = \frac{C_1 + C_2 + C_3 + C_4}{P_1 + P_2 + P_3 + P_4} \\
&= \frac{1}{\frac{C_1}{\sum C_{All}} \cdot \frac{1}{SEER_1} + \frac{C_2}{\sum C_{All}} \cdot \frac{1}{SEER_2} + \frac{C_3}{\sum C_{All}} \cdot \frac{1}{SEER_3} + \frac{C_4}{\sum C_{All}} \cdot \frac{1}{SEER_4}} \\
&= \frac{1}{A \cdot \frac{1}{SEER_1} + B \cdot \frac{1}{SEER_2} + C \cdot \frac{1}{SEER_3} + D \cdot \frac{1}{SEER_4}}
\end{aligned}
$$

C_1, C_2, C_3, C_4 represent the delivered cooling outputs from the dummy system ONE, TWO, THREE and FOUR, respectively, during the whole cooling season and the sum equals to the total cooling capacity of the original multi-split system.

P_1, P_2, P_3, P_4 represent the power consumptions by the dummy systems ONE, TWO, THREE and FOUR, respectively, during the same cooling season.

$SEER_1,\ SEER_2,\ SEER_3,\ SEER_4$ represent the seasonal efficiencies of the four dummy systems, respectively.

A, B, C and D represent the ratios of the delivered cooling capacity outputs to the total cooling capacity of the multi-split system, from the dummy systems ONE, TWO, THREE and Four， respectively, i.e. $\frac{C_1}{\sum C_{All}}$ $\frac{C_2}{\sum C_{All}}$, $\frac{C_3}{\sum C_{All}}$, $\frac{C4}{\sum C_{All}}$. A, B, C and D can be viewed as the weightings for the seasonal efficiencies $SEER_1$, $SEER_2$, $SEER_3$, $SEER_4$ of the 4 dummy systems ONE, TWO, THREE and FOUR used for the SPLV calculation.

As an example here, Nanjing (capital city of Jiangsu Province, China)'s climate is used for the office building heat load calculation, 21°C is set as the balance point (zero heat load point), 35°C as the full cooling load point, with 947 total cooling operation hours.

The operating hours for the dummy unitary systems ONE, TWO, THREE and FOUR can be calculated by multiplying the total cooling hours by the percentages of the operating probabilities of the dummy systems, respectively. The percentages can be calculated as follows. For example, if the general ON probability is 68%, the calculated running probabilities of the 4 dummy systems are

- Probability to operate dummy system ONE: $4*\ 68\%*(1-68\%)^3 = 8.9\%$
- Probability to operatedummy system TWO : $6*\ 68\%^2\ (1-68\%)^2 = 28.4\%$
- Probability to operate dummy system THREE: $4*\ 68\%^3\ (1-68\%)^1 = 40.3\%$
- Probability to operatedummy system FOUR: $1*\ 68\%^4 = 21.4\%$
- Probability to turn the system completely off, $1*(1-68\%)^4 = 1\%$

With these ratios, the running hours of these four dummy unitary systems under different ambient temperatures can be proportionally calculated and are tabulated in Table 3 and shown in Figure 5.

Table 3: The operating hours of the four dummy unitary systems under different ambient temperatures

Ambient Temperature ℃	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	Total
Building Cooling Hours	81	65	73	81	79	81	81	82	68	70	59	54	48	18	6	1	0	947
All Indoor Off	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.7	0.7	0.6	0.6	0.5	0.2	0.1	0.0	0.0	10
Dummy Unitary One	7.2	5.8	6.5	7.2	7.0	7.2	7.2	7.3	6.1	6.2	5.3	4.8	4.3	1.6	0.5	0.1	0.0	84
Dummy Unitary Two	23.0	18.5	20.7	23.0	22.4	23.0	23.0	23.3	19.3	19.9	16.8	15.3	13.6	5.1	1.7	0.3	0.0	269
Dummy Unitary Three	32.6	26.2	29.4	32.6	31.8	32.6	32.6	33.0	27.4	28.2	23.7	21.7	19.3	7.2	2.4	0.4	0.0	381
Dummy Unitary Four	17.3	13.9	15.6	17.3	16.9	17.3	17.3	17.5	14.5	15.0	12.6	11.5	10.3	3.8	1.3	0.2	0.0	202
One-to-four Multi-split System	80	64	72	80	78	80	80	81	67	69	58	53	47	18	6	1	-	937

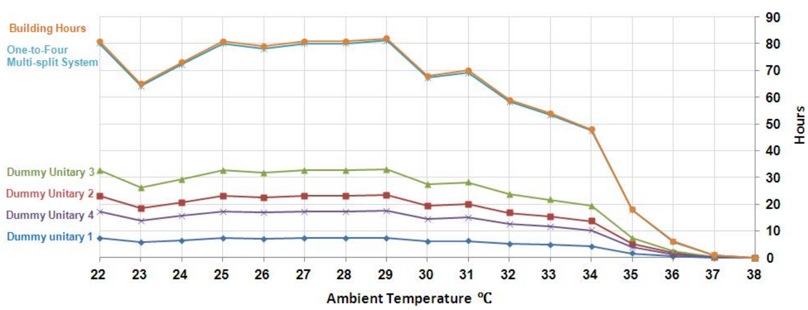


Figure 5: The running hours of four dummy unitary systems under different ambient temperatures

Multiplying the operating hours under different ambient temperatures by the relative load (# of turned on indoor units multiplied by delta temperature) brings about the total cooling season capacity C_1 for the dummy unitary system ONE, C_2 for the dummy unitary system TWO, C_3 for the dummy unitary system THREE and C_4 for the dummy unitary system FOUR. Summarizing the cooling season capacity C_1, C_2, C_3, C_4 generates the total cooling capacity $\sum C_{All}$ of the original multi-split system. The 4 weighting factors A, B, C and D are calculated as $\frac{C_1}{\sum C_{All}}$, $\frac{C_2}{\sum C_{All}}$, $\frac{C_3}{\sum C_{All}}$ and $\frac{C4}{\sum C_{All}}$. Table 4 tabulates a case for a general turn-on probability of 68%.

1) The ratio of the delivered cooling season capacity of dummy unitary ONE to the total cooling season capacity of the original multi-split system is 3.3%
2) The ratio of the delivered cooling season capacity of dummy unitary TWO to the total cooling season capacity of the original multi-split system is 20.9%
3) The ratio of the delivered cooling season capacity of dummy unitary THREE to the total cooling season capacity of the original multi-split system is 44.4%
4) The ratio of the delivered cooling season capacity of dummy unitary FOUR to the total cooling season capacity of the original multi-split system is 31.4%

Table 4: The relative loads for the 4 dummy systems & the summation under different ambient temperatures in a cooling season & the corresponding weights (Temperature delta X probability X # of turned-on indoor units)

Ambient Temperature ℃	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	Total	Weight
Dummy Unitary One	0.1	0.2	0.3	0.5	0.6	0.8	0.9	1.0	1.0	1.1	1.0	1.0	1.0	0.4	0.1	0.0	0.0	10.3	3.3%
Dummy Unitary Two	0.8	1.3	2.2	3.3	4.0	4.9	5.8	6.7	6.2	7.1	6.6	6.6	6.3	2.6	0.9	0.2	0.0	65.4	20.9%
Dummy Unitary Three	1.7	2.8	4.7	7.0	8.5	10.5	12.2	14.1	13.2	15.1	14.0	14.0	13.5	5.4	1.9	0.3	0.0	139.0	44.4%
Dummy Unitary Four	1.2	2.0	3.3	4.9	6.0	7.4	8.7	10.0	9.3	10.7	9.9	9.9	9.5	3.8	1.4	0.2	0.0	98.5	31.4%
One-to-four Multi-split System	3.9	6.3	10.6	15.7	19.2	23.6	27.5	31.9	29.7	34.0	31.5	31.5	30.3	12.2	4.4	0.8	0.0	313.2	100%

The weighting factors A, B, C and D (3.3%, 20.9%, 44.4% and 31.4%, respectively in Table 4) should vary with different general ON probability of the indoor units. Tables 5, 6 and 7 present three cases for a probability of 50%, 68% and 80%, respectively.

Table 5: A, B, C and D weight calculation based on general turn-on probability of 50%

Case 1, The General On Probability					50%
Quantity Of Operating Indoor Units	Nominal Load Rate %	Dummy Unitary ON Probability	Equivalent Dummy Unitary	Relative Load = Dummy Unitary ON Probability X Quantity Of Operating Indoor Units	Cooling Capacity Percentage Delivered By the Dummy Unitary Systems (In Replace of the Multi-split System), i.e. theWeights A,B, C & D
0	0%	6.0%			
1	25%	25.0%	Dummy ONE	0.250	12.5%
2	50%	37.5%	Dummy TWO	0.750	37.5%
3	75%	25.0%	Dummy THREE	0.750	37.5%
4	100%	6.3%	Dummy FOUR	0.250	12.5%

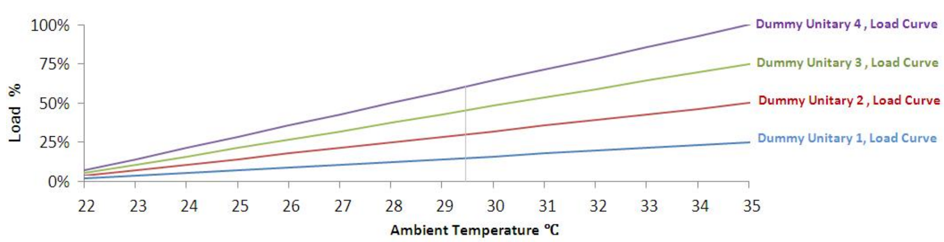
Table 6:A, B, C and D weight calculation based on general turn-on probability of 68%

Case 2 , The General On Probability					68%
Quantity Of Operating Indoor Units	Nominal Load Rate %	Dummy Unitary ON Probability	Equivalent Dummy Unitary	Relative Load = Dummy Unitary ON Probability X Quantity Of Operating Indoor Units	Cooling Capacity Percentage Delivered By the Dummy Unitary Systems (In Replace of the Multi-split System), i.e. the Weights A,B, C & D
0	0%	1.0%			
1	25%	8.9%	Dummy ONE	0.089	3.3%
2	50%	28.4%	Dummy TWO	0.568	20.9%
3	75%	40.2%	Dummy THREE	1.207	44.4%
4	100%	21.4%	Dummy FOUR	0.855	31.4%

Table 7:A, B, C and D weight calculation based on general turn-on probability of 80%

Case 3 , The General On Probability					80%
Quantity Of Operating Indoor Units	Nominal Load Rate %	Dummy Unitary ON Probability	Equivalent Dummy Unitary	Relative Load = Dummy Unitary ON Probability X Quantity Of Operating Indoor Units	Cooling Capacity Percentage Delivered By the Dummy Unitary Systems (In Replace of the Multi-split System), i.e. the Weights A,B, C & D
0	0%	0%			
1	25%	2.6%	Dummy ONE	0.026	0.8%
2	50%	15.4%	Dummy TWO	0.307	9.6%
3	75%	41.0%	Dummy THREE	1.229	38.4%
4	100%	41.0%	Dummy FOUR	1.638	51.2%

Ideally, the seasonal efficiencies of the four dummy unitary systems $SEER_1$, $SEER_2$, $SEER_3$, $SEER_4$ are calculated (integrated) thru the cooling capacity and the corresponding power consumption under different ambient temperatures, but this approach could be very cost-prohibitive due to the huge amount of laboratory testing. A more practical approach is to use the efficiency of these dummy unitary systems under a specified ambient temperature to approximate their seasonal efficiency. Theoretically, the efficiency (EER) of a unitary system under one ambient temperature will match the seasonal efficiency SEER (illustrated in Figure 6) and this simplification could reduce the testing requirement significantly without compromising the key philosophy of this new VRF system's rating approach. The rating of a unitary system is not a focus of this study and a simplified approach will be used below.



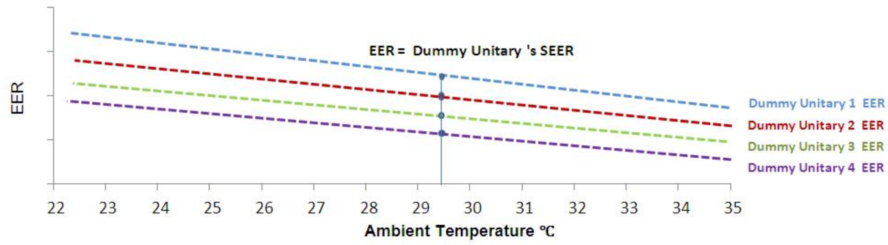


Figure 6: Load curves and EER curves for the four dummy units under different ambient temperatures

The ambient temperature is chosen where 50% of the delivered cooling capacity by the unitary system happens below this ambient temperature while the rest 50% happens above this ambient temperature. This specific temperature could be different for different dummy unitary system and the same ambient temperature is assumed here and further work is needed for improvement. The Nanjing climate generates an ambient temperature of 29.6C (Table 8 and Figure7).

Table 8: Ambient temperatures at 50% load are the same for all dummy units

Ambient Temperature ℃	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Dummy Unitary One	0.1	0.3	0.7	1.2	1.8	2.6	3.5	4.5	5.5	6.6	7.7	8.7	9.7	10.3
Dummy Unitary Two	0.8	2.1	4.4	7.7	11.7	16.6	22.3	29.0	35.2	42.3	48.9	55.5	61.8	65.4
Dummy Unitary Three	1.7	4.5	9.3	16.3	24.8	35.3	47.5	61.6	74.8	89.9	103.9	117.9	131.3	139.0
Dummy Unitary Four	1.2	3.2	6.6	11.5	17.5	25.0	33.6	43.6	53.0	63.7	73.6	83.5	93.0	98.5
One-to-four Multi-split AC Unit	3.9	10.2	20.9	36.6	55.8	79.4	107.0	138.8	168.5	202.5	234.1	265.5	295.8	313.2

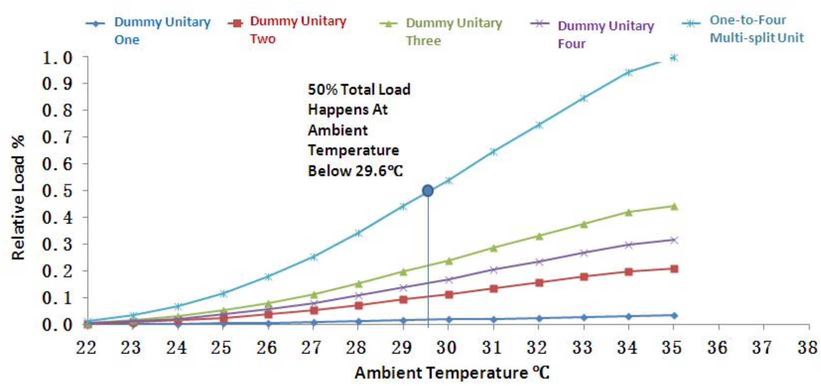


Figure 7: The integrated seasonal load for 4 dummy unitary systems (relative)

Up to this point, we have all of the building blocks to complete the modeling for a multi-split air-conditioner system's performance rating (Figure 8). It starts with an end-user operation behavior survey and progresses with reasonable assumptions and finally, mathematical models are used to finish the process.

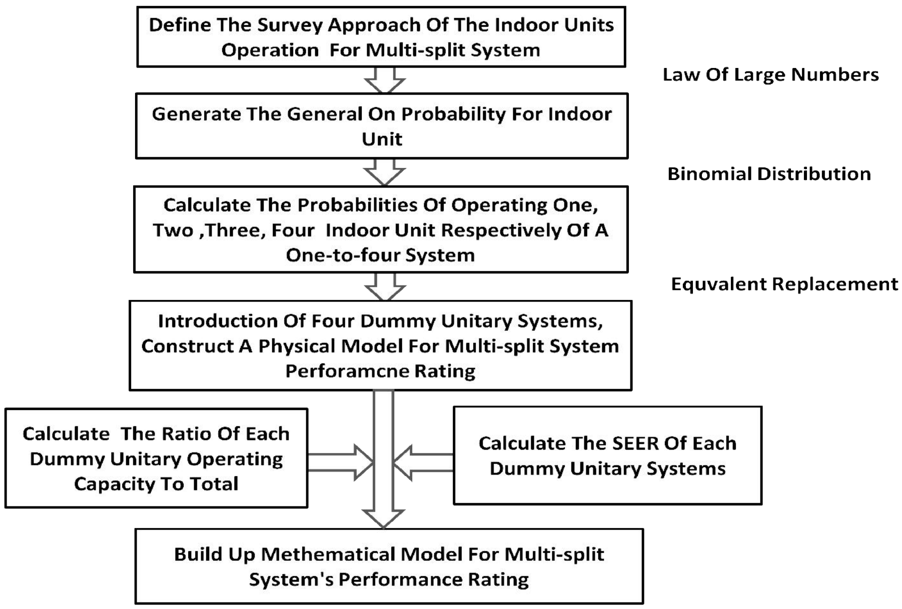


Figure 8: Road map for the new multi-split (VRF) system performance rating approach development

4. SUMMARY

This study starts with a survey on the end-user's behavior on operating a multi-split VRF air-conditioning system. The ON/OFF statistics of the indoor units is used to generate the general ON probability. Taking a one-to-four multi-split system as an example, a new performance rating approach is proposed.

Out of the fear with the complexity of a multi-split air-conditioning system, there is a trend in the regulation 'community' to treat such a VRF system as a derivative of a unitary system and keep all of the indoor units on in the modeling of the performance rating. The next upgrade for China's national standard GB/T 18837(GB, 2002) 'Multi-connected air-condition (heat pump) unit' is moving in this direction (with one deviation to have only one indoor unit shut-off when the 25% partial load performance is tested). This simplification ignores the fundamental difference between a multi-split system and a unitary system, thus presents a high risk of over-rating the multi-split system. It is our hope that the study presented here can serve as a solid step forward for the future discussion and practice in the multi-split system performance rating discipline.

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