INHERENT ERRORS IN CUC-BASED MODELS: EXAMPLES

This section aims to elucidate the error types 2 to 4 discussed in the main manuscript by providing a simple example for each. While the cluster used in these examples consists of relatively inflexible units and experiences large step changes in load, it's important to note that these conditions do not fully represent a real-world, large-scale power system.

A. *Type 2*

To illustrate the first type of overestimation of the ramp-down rate in the CUC and TSCUC models, let's consider a 4-hour demand profile shown in Table I. Assume two units have been online for at least 4 hours.

Table I
DEMAND PROFILE FOR ILLUSTRATING ERROR TYPE 2

Time (h)	1	2	3	4
Demand (MW)	340	340	300	200

In the UC model, if no additional units are started, it implies that in hour 4, one unit must be at its maximum capacity while the other is shut down. In hour 3, this necessitates one unit generating 200 MW and the other 100 MW. To meet the 340 MW demand in hour 2, the unit scheduled for shutdown in hour 4 must generate a maximum of 120 MW. Simultaneously, the unit generating at its maximum in hour 3 (according to equations 6-7) must have produced 220 MW in hour 2 to allow for the decrease in output from hour 2 to 3. However, since the maximum output is 200 MW, this UC solution is infeasible and would result in load shedding and high costs. Therefore, a unit must be started in hour 1 to avoid load shedding. Consequently, the three units can manage the demand reduction from hours 2 to 3 together. The UC model results are shown in Fig.1(a). As observed in the UC model, a third unit was started due to the maximum capacity constraints of individual units. However, in the CUC model, the maximum cluster capacity in hour 2, according to equation (22), is 400 MW, and there is no need to start a new unit. The cost of the CUC model is 14370 $, while the UC model's cost is 15290 $. The cost obtained for the CUC model is lower than the UC model's cost due to this error. The CUC model results are shown in Fig.1(b).

Fig.2(c) shows the TSCUC model results. Executing the UC model in the second stage results in 20 MW of load shedding in hour two. The associated cost is $214130. Due to this error, the cost obtained for the TSCUC model is higher than the UC model's cost.

B. *Type 3*

To illustrate the second type of overestimation of the ramp-down rate in the models, let's consider a 6-hour demand profile shown in Table II.

The UC results are depicted in Fig.2(a). The UC model initially schedules one unit online for the first hour. Four units must be started in the second hour to accommodate the load increase from hour one to hour two. In the best-case scenario, the output of the first unit decreases by 20 MW for the second hour, and the other four units generate 380 MW combined. If the first unit's generation decreases by 20 MW each hour, we

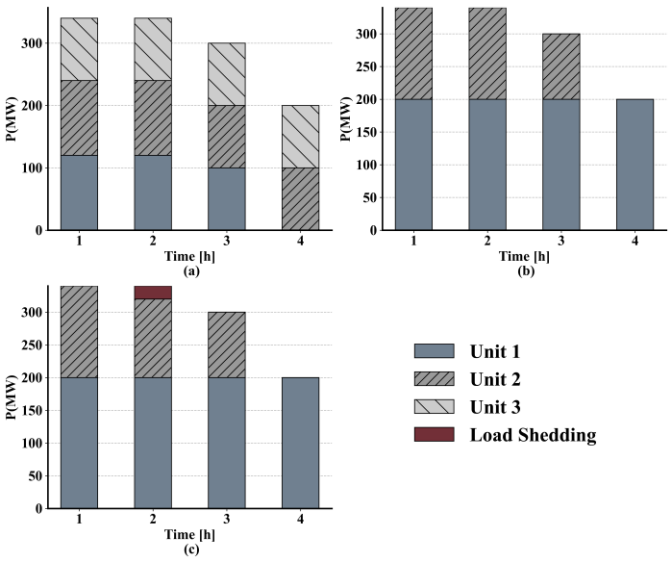

Fig. 1. Comparative results: (a) UC, (b) CUC, and (c) TSCUC.

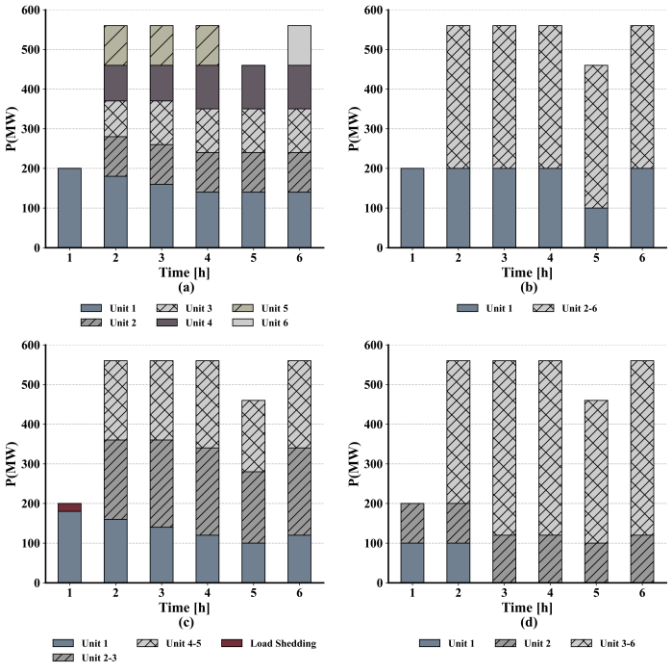

Fig. 2. Comparative results: (a) UC, (b) CUC and ICUC, (c) TSCUC, and (d) BCUC.

Table II
DEMAND PROFILE FOR ILLUSTRATING ERROR TYPE 3

Time (h)	1	2	3	4	5	6
Demand (MW)	200	560	560	560	460	560

will have a total ramp-down capacity of 80 MW available in hour 4. Therefore, it is necessary to shut down one unit and start the sixth unit in hour 6 to compensate for the 100 MW load increase. However, according to Fig.2(b), in the CUC and ICUC models, the ramp-down capacity from hour 4 to 5, based on equation (26), equals 20 × 5, and the fifth unit is not shut

down in hour 5. In the TSCUC model, 20 MW of load shedding occurs in the first hour to ensure that the units started in the second hour each generate 100 MW so that the cluster output in hour 5 can decrease by an additional 20 MW. The results of the TSCUC model are shown in Fig.2(c). In the BCUC model, according to equation (32), one unit is started in hour one, and the first unit, assuming it has been online for more than 3 hours, is shut down in hour 3. As a result, five units have ramp-up capacity available in hour 3, so these five units can be used in hour 5 to meet the 100 MW decrease. The results of the BCUC model are shown in Fig.2(d).

Additionally, the number of start-ups and shutdowns in the UC and BCUC models is the same, and the cost difference is only in the fixed operating cost. In the BCUC model, one more unit was online in hours 1, 2, and 5. Consequently, the BCUC model, despite the scheduling error, meets the flexibility requirements with a low-cost error. Table III provides a cost comparison of all models. The objective function value of the ICUC method is the same as that of the CUC method.

Table III
COMPARATIVE COST OF MODELS FOR ERROR TYPE 3

Model	UC	CUC	ICUC	TSCUC	BCUC	PCUC
Cost ($)	39550	38780	38780	238540	39639	39550

C. Type 4

To illustrate the third type of overestimation of the ramp-down rate in the models, let's consider a 4-hour demand profile shown in Table IV.

Table IV
DEMAND PROFILE FOR ILLUSTRATING ERROR TYPE 4

Time (h)	1	2	3	4
Demand (MW)	140	230	230	140

The UC model results are shown in Fig.3(a), and as can be seen, load shedding occurs in hours two and three. In hour two, a unit needs to be started, and in hour 4, a unit needs to be shut down. Therefore, in the UC model, the first unit must reduce its output to 120 MW in hour two to reach an output of 100 MW (the shutdown ramp capacity) in hour three and then shut down in hour four. To meet the load in hour two, the second unit is started with an output of 100 MW.

However, the first and second units combined generate 220 MW, resulting in 10 MW of load shedding. In hour three, the first unit will generate a maximum of 100 MW, and the second unit will generate a maximum of 120 MW (due to ramp-up capacity), resulting in 10 MW load shedding.

The CUC model results are shown in Fig.3 (b). In the CUC model, no load shedding occurs, and according to the minimum up/down time constraint (equations 19-20), a unit is started in hour 2. In hour 4, according to equation (19), a unit must be online. Consequently, the newly started unit is indistinguishable, and the CUC model shuts down the same unit that was started in hour 2. As mentioned above, this error also occurs in the ICUC and PCUC models, and the results are identical to the CUC model. The cost comparison of all models is provided in Table V.

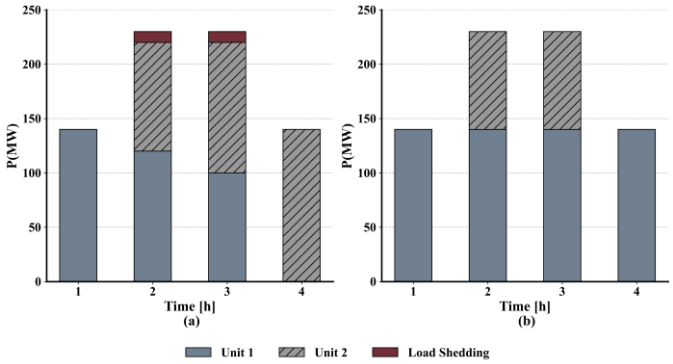

Fig. 3. Comparative results: (a) UC, and (b) CUC.

Table V
COMPARATIVE COST OF MODELS FOR ERROR TYPE 4

Model	UC	CUC	ICUC	TSCUC	BCUC	PCUC
Cost ($)	209620	9860	9860	209620	209620	9860