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Q_Dispatched[d_6]. d_6's next idle signal time is 7.5h.

d_4 is idle and Q_Idle[d_4]->first = v_{10} is a regular operation, directly set v_{10} with start time 0h and finish time 9h. d_4's next idle signal time is 9h.

At this moment all machines at t_0 are processed, as shown in Fig. 3a. Calculate the next earliest idle signal time, obviously t_1 = 7.5h.

At the moment t_1 = 7.5h. Due to v_9 having been finished, operation v_6 becomes schedulable. Similarly, the scheduling result at moment t_1 can be seen in Fig 3b. Fig. 3c shows the scheduling result when t_2 =9h. Fig. 3d shows the final solution.

IV. SIMULATION EXPERIMENT

In order to verify the effectiveness of the proposed differential evolution algorithm based on DUO and MIS in this work, an instance X1 was collated from a real workshop. Where X1 contains 5 products, as the DOT format data are shown in Appendix. In the instance X1, shown in Appendix, product P_1 is v_1 to v_{11} with a due time of 60h; product P_2 is v_{12} to v_{27} with a due time of 70h; product P_3 is v_{28} to v_{49} with a due time of 85h; product P_4 is v_{50} to v_{55} with a due time of 30h and product P_5 is v_{56} to v_{75} with a due time of 80h. The operations {v_1, v_2, v_4, v_6, v_{14}, v_{15}, v_{17}, v_{18}, v_{29}, v_{30}, v_{44}, v_{47}, v_{49}, v_{50}, v_{61}, v_{64}, v_{68}, v_{70}} have high precision demands.

The following method was used as a control method for the experiment: the objective functions and constraints shown in equations (1) to (6) were transformed into a mathematical model that could be processed by the operations research optimizer OR-Tools. And after obtaining a mathematical model that OR-Tools can handle, the instance X1 is solved using OR-Tools for 12h and then the result is output and recorded as OR-12. The OR-12 result is then compared with the proposed method. The population size of the proposed differential evolution is 100, max generation is 150.

Fig. 4 is the Gantt chart of instance X1 according to the proposed method in this paper, where the total tardiness is 31.25h and the total setup time is 0.75h. The virtual setup operation is s_{76} and s_{77}, where the tardiness of P_1 is 2h, 11h for product P2, 5h for product P_3, 12h for product P_4, and 1.25h for product P_5.

Fig. 5 shows the Gantt chart obtained by the OR-12 method, where the total tardiness is 26h and the total setup time is 0h. The tardiness of product P_1 is 1h, P_2 is 9h, P_3 is 6h, P_4 is 4h and P5 is 6h.

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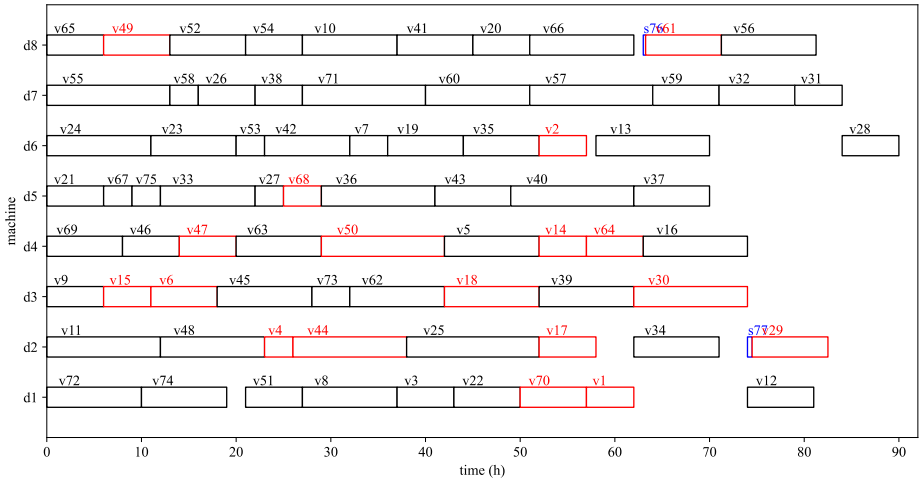

Fig 4: Gantt chart of the instance X1 by proposed method

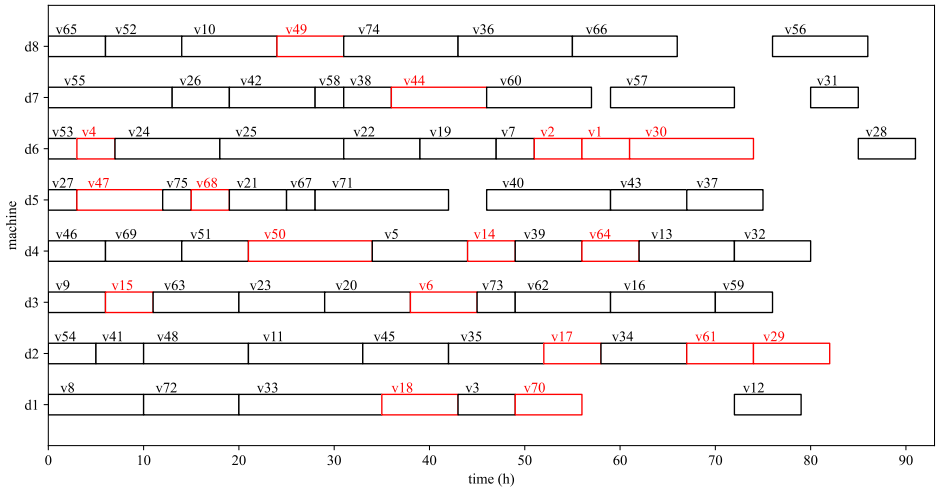

Fig 5: Gantt chart of the instance X1 by OR-12 method

In the result of the algorithm proposed in this work, the tardiness for P_3 and P_5 are shorter than OR-12. However, for the most influential product P_4, the proposed algorithm achieves tardiness of 12 h, which is higher than the 4 h obtained by the OR-12 method. Because of its very high accuracy as an operational optimizer, it is appropriate to use OR-12 as a reference for comparison. X1 was run independently 10 times by the proposed method and the results shown in Fig. 4 were obtained 8 times, indicating that the algorithm proposed in this paper is highly stable and can achieve similar scheduling quality to the OR-12 method in only a few tens of seconds.

V. CONCLUSION

In this work, we investigate the integrated scheduling problem considering both precedence constraint and machine-state-related setup time and proposed a mathematical model for the problem. This work takes into account integrated scheduling problem while other scheduling studies focused on Job shop or Flow

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shop in which there is no precedence constraint and machine-state-related setup time. The proposed DUO provides a population updating strategy without parameters. The proposed MIS can decode the operation string to a solution that satisfies precedence constraint and machine-state-related setup time. Compared with the OR-12 method, the proposed differential evolution algorithm based on DUO and MIS in this paper can give similar results to it in a very short time.

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