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The Printed-Circuit-Board Electroplating Parallel-Tank Scheduling With Hoist and Group Constraints Using a Hybrid Guided Tabu Search Algorithm

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ABSTRACT Current research investigates a parallel-tank scheduling problem with hoist and group constraints in printed-circuit-board (PCB) electroplating environment, where the hoist is used as a material handling device and PCBs need to be grouped for further processing. The purpose of the current research is to minimize the makespan and total weighted tardiness of PCB products. The weighted ideal point method is used to combine these two objectives into a single optimization objective. Moreover, a mixed integer programming model is developed to formulate the problem. Since the problem is proved to be NP-hard, a hybrid guided tabu search (HGTS) algorithm is proposed to optimize the objectives. A heuristic method based on small combination sequences called SCS is applied to search the better initial solution. Moreover, a problem-oriented guided neighborhood move strategy is adopted to improve the search efficiency in the proposed HGTS algorithm. The experiments are conducted on different size of problem instances. The performance of the proposed HGTS algorithm is investigated and compared with other existing algorithms. The detailed results indicate that the proposed HGTS algorithm performs better both in objective value and convergence speed. Finally, a real-world case is solved by the proposed HGTS, which validates that the proposed algorithm is effective and useful in solving the practical electroplating scheduling problem.

INDEX TERMS Hoist and group constraints, hybrid guided tabu search, parallel-tank scheduling, small combination sequences, weighted ideal point method.

I. INTRODUCTION

In recent years, research on scheduling problems integrated with material handling devices from modern production environment is gaining more attention both in industry and academia [1]–[3]. One type of the automated manufacturing systems is represented by production lines and they contain autonomous computer-controlled devices denoted by hoists. In these systems, the degree of automation is relatively high and the simultaneous production order scheduling and hoists scheduling can directly influence the completion time of the production plan. Therefore, efficient scheduling in such manufacturing systems plays a significant role to ensure efficiency of these production systems.

Current research investigates the scheduling problem in a mixed model electroplating line from a reputed PCB manufacturer in Guangzhou, China. During the whole production of PCB, the electroplating is one of the most critical processes which involves a series of chemical treatment processes on the PCBs and a hoist which plays the role of material handling device. Most literature on scheduling problems of the PCB electroplating line mainly focused on determining the hoist

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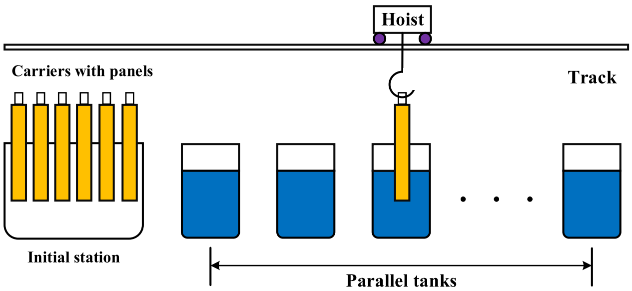

FIGURE 1. Configuration of the simplified electroplating system.

cyclic schedule [4]–[6], and only one type of product is considered in their research. However, in the current electroplating system, there are several identical parallel tanks which are used to perform the same procedure called copper plating (the main procedure in electroplating process), and each type of products has its fixed processing time in these parallel tanks. The copper plating takes much more time than other procedures (like degreasing, acid dip, rinsing, etc.) in the non-parallel tanks where different products have the same processing time. In the case company, the hoist schedule among non-parallel tanks has already been planned and fixed. Therefore the electroplating system is simplified here containing a single hoist and several identical parallel tanks as shown in Fig. 1. When the hoist is occupied by other tasks related to the non-parallel tanks, batches (i.e., carriers containing multiple panels) cannot enter or leave the corresponding tank. Moreover, some of the parallel tanks will be idle for a long time if the production sequence of jobs is not optimal. Therefore, the core conflict which exists here is between different processing time of batches in parallel tanks and the constrained hoist movement. Moreover, due to the fixed length of the carrier, panels are expected to be grouped into batches in order to improve the utilization of carriers before delivery to the electroplating line. The grouping of different panels depends on some common characteristics such as the size, shape, and processing time.

The current electroplating system scheduling problem comes from a real PCB company project which makes it different from the existing models in literature. It has a different complexity due to the existence of grouping of mixed PCB products and parallel-tank scheduling problem with a constrained hoist. The considered problem is aimed to minimize the makespan and total weighted tardiness of the PCB products in the electroplating system of the case company. A mixed integer programming model is formulated to describe the characteristics of the problem. The identical parallel-machine scheduling problem has been proved to be NP-hard problem [7]. However, the current problem is more critical and contains additional constraints which show the current problem is also NP-hard and it is hard to obtain an optimal solution in reasonable computational time. Therefore, a hybrid guided tabu search algorithm is developed to address the current problem. The proposed method introduces different scheduling rules and constraints which are based on the real scenario of the case company. The proposed problem and corresponding method in the current research are novel in the following aspects.

- Current research investigates a parallel-tank scheduling problem with a constrained hoist.
- Multiple types of PCB products are considered to be processed in the electroplating system for the current study.
- Grouping of different type of PCB products improves the utilization of carriers, which increases the complexity of the problem model.
- A hybrid guided tabu search algorithm is developed in the current study which involves small combination sequences and neighborhood guidance mechanism as its novel aspects.

The rest of this paper is organized as follows. Section 2 presents the literature on scheduling problem considering material handling devices and group constraint. Section 3 contains the problem description and mathematical model for the considered case company electroplating system. Section 4 comprehensively describes the proposed hybrid guided tabu search algorithm. Section 5 and 6 present the experimental results and a case study. Finally, the conclusions and future direction of the research are explained in Section 7.

II. RELATED LITERATURE

The literature research work related to the scheduling problem with material handling devices and group constraints is explained in this section. In most manufacturing systems, the material handling devices are computer controlled and these systems have constrained resources including the machines and material handling devices [8]. The movement of jobs depends on the material handling devices. In some studies, the transfer time is comparable with the processing time of jobs, which cannot be neglected [9].

Hoist scheduling problem (HSP) which considers the transfer of material using hoist has been paid lot of attention in literature. Phillips and Unger [10] proposed the first mathematical model for cyclic scheduling on a single-hoist. Since then, different researchers studied this problem. For example, Zhou and Li [11] developed a mixed integer linear programming model for the single hoist cyclic scheduling problem considering multiple number of identical parallel tanks. Zhou and Liu [12] proposed a heuristic algorithm to solve their considered two-hoist cyclic scheduling problem with hoist overlapping. Nait-Sidi-Moh and El-Amraoui [13] developed P-Temporal Petri Net models to describe hoist activities for different configurations of the electroplating line. Hindi *et al.* [14] proposed a heuristic algorithm using a non-standard constraint satisfaction problem model for single-hoist schedule with multiple products. The more recent works on HSP in different manufacturing environment have also been presented in literature [15]–[17].

However, most of the literature studies on HSP focused on obtaining an optimal cyclic schedule of hoists. In these research, only one type of product is considered, which may limit their practical applicability in real-world production environment of PCB manufacturing companies. The particular case of the considered electroplating system is essentially different from their models in literature. The considered scheduling problem contains multiple identical parallel tanks, which is similar to the parallel-machine schedule with material handling devices. Lin *et al.* [18] and Jeng *et al.* [19] considered a sequencing problem in a parallel-machine work cell with a robot for loading and unloading of multiple independent jobs of different processing times. They proposed heuristic algorithms and presented a branch and bound algorithm to find an optimal sequence of jobs and robot activities. Geismar *et al.* [20] provided a structural analysis of constant travel-time robotic cells. Moreover, Gultekin *et al.* [21] studied the scheduling problem of a 2-machine robotic cell. Fathian *et al.* [22] formulated a Petri Net model to get an optimal schedule of part sequencing and robot moves in a 2-machine robotic cell.

Nevertheless, the scheduling problems investigated in literature containing the movement of material handling devices in scheduling is relevant to some extent to the problem considered in the current research. Besides the scheduling problem of the material handling devices, current research also involves the parallel-machine scheduling problem with group constraints. A few research work has been found in literature considering group constraints in scheduling problem. Li *et al.* [23]–[25] studied the flexible flow shop problem with group constraints which are considered in three different stages, i.e., head, mid and tail group constraints respectively. Each stage of processing consists of several parallel machines and jobs in one group need to be assigned to the same machine. In addition, Kawamura *et al.* [26] considered a job shop problem where jobs dealing with the same process need to be grouped due to equipment constraints and it requires time to change groups on the line. They proposed a parallel tabu search method to solve the problem. Similarly, metaheuristic algorithms have also been developed in literature to find the optimal solution for sequence-dependent group scheduling problem [27], [28]. Furthermore, Lin *et al.* [29], Brucker *et al.* [30] and Sáenz-Alanis *et al.* [31] investigated batching problem on parallel machines. In these studies, similar jobs are grouped first, and later these groups are divided into batches according to the capacity of containers. Moreover, setup time is considered before a batch of a group is processed. The objective used to optimize in most of these studies is to find a schedule which minimizes the completion time and reduces tardy jobs. The grouping of jobs studied in literature in different manufacturing environments is similar to the grouping of PCBs on the carrier with the length limit. Moreover, the scheduling of PCBs is also significant for the efficient production in the electroplating system. Therefore, the current research considered the group constraint for parallel-tank scheduling problem.

In literature scheduling problem with material handling devices and group constraint, most of them considered to optimize single objective [23]–[25], [30], [32]. However, in most of the real-world production environment, more conflicting objectives are desired to optimize simultaneously. Some of them optimized linear combination of two or more objectives [27], [29] and some of them adopt Pareto concept to obtain Pareto solution [33], [34]. In consideration of practicability, current research considered to simultaneously optimize both makespan and total weighted tardiness by using the weighted ideal point method [35], which can convert a multi-objective problem into a single objective problem.

In literature different methods have been developed to obtain an optimal or near optimal schedule for the problems which have some similarities with the current research problem. For example, branch and bound algorithm [19], [36], linear programming [37], [38], heuristics [23]–[25], [29], some other metaheuristics [27], [39]–[43], and other methods specialized for related problems [22], [31], have been used and presented for scheduling of jobs with material handling devices in different manufacturing environment. Tabu search [44] is a metaheuristic method which can guide a local search solution to explore the solution space within the constraint of tabu list. It has been widely applied in different optimization problems [26], [45], [46]. Therefore, it is adopted to solve the current problem. Current research problem is novel to propose a mathematical model for the parallel-tank scheduling problem in electroplating line with mixed products considering hoist and group constraints. Furthermore, a hybrid guided tabu search algorithm involving a heuristic for better initial solution and an improved neighborhood structure for the current real-world problem is developed.

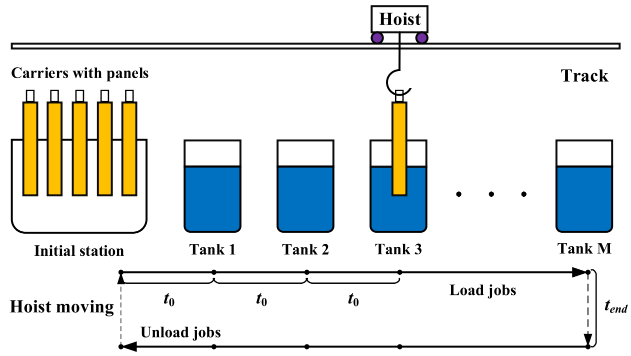

FIGURE 2. The hoist movement rule in the current simplified electroplating system.

III. PROBLEM DESCRIPTION

The description of the PCB electroplating system is presented in this section. The hoist movement rule is illustrated in Fig. 2.

The hoist carries batches and moves circularly. It raises one batch from the initial station and loads it into one of the idle tanks. Suppose the hoist moving time between two adjacent tanks is t_0. Then, the hoist moves to the tank M and stays for a fixed time t_{end}. In the real electroplating system, the hoist is occupied by other tasks in the non-parallel tanks during this time. Later, the hoist can make different choices according to the following three different conditions:

- If there are finished batches, the hoist should move towards the corresponding tank to unload the batch and return to initial station to start its next cycle.
- If there are idle tanks and no batch is finished, the hoist will move to the initial station for the next cycle directly.
- If no idle tank exists and no batch is finished, the hoist will move only when any batch in the tank is finished.

Consider the scheduling problem of N different orders of PCB panels on M identical parallel tanks to process in the electroplating system. All panels are grouped into N_b batches, and each batch contains Q_i $(i = 1, 2, \ldots, N_b)$ panels. Each order contains q_n $(n = 1, 2, \ldots, N)$ panels and $\sum_{i=1}^{N_b} Q_i = \sum_{n=1}^{N} q_n$. The panels will be grouped into batches for processing and the total width of panels in one batch cannot exceed the carrier length.

Some constraints and assumptions of the current problem are taken into consideration.

- The raising and lowering time of batches at any tank is zero.
- When the hoist returns to initial station, it starts a new cycle immediately.
- All the batches, tanks are available simultaneously at time zero.
- The hoist can operate only one batch at a time.
- A tank can only hold one batch at a time.
- No breakdowns of the hoist or tanks occur.

The problem is developed using the following notations and abbreviations. Some notations have been shown above and additional notations will be introduced when needed throughout the paper. The model is described below these notations.

A. NOTATIONS AND ABBREVIATIONS

Indices

n, n'	index to represent an order, $n, n' \in \{1, 2, \ldots, N\}$
i, i'	index to represent a batch, $i, i' \in \{1, 2, \ldots, N_b\}$
j, j'	index to represent a panel, $j, j' \in \{1, 2, \ldots, Q_i\}$
m, m'	index to represent a tank, $m, m' \in \{1, 2, \ldots, M\}$
k, k'	index to represent a hoist activity, $k, k' \in \{1, 2, \ldots, 2N_b\}$

Parameters

N	the number of orders
S	the set of orders, $S = \{1, 2, \ldots, N\}$
M	the number of parallel tanks
L	the carrier length
q_n	the number of panels in order n
l_{ij}	the length of panel j in batch i
d_{ij}	the width of panel j in batch i
t_0	the move time of hoist between two adjacent tanks
t_{end}	the fixed time for hoist to stay at tank M
LT_i	the time required for hoist to load batch i from the initial station to the corresponding tank
PB_i	the processing time of batch i
PO_n	the processing time of order n
SUM_i	the summation of LT_i, PB_i and Mt_0
w_n	the weight of order n regarding the objective function
D_n	the due time of order n
CB_i	the completion time of batch i
CO_n	the completion time of order n
MS	makespan
T_n	the tardiness of order n
TWT	the total weighted tardiness of all orders
Ω	a big number

Decision variables

N_b	the number of batches
Q_i	the number of panels in batch i
s_k	the start time of the kth hoist activity
t_{ij}	the order which panel j in batch i belongs to, $t_{ij} \in S$

$$x_{imk} \begin{cases} 1 & \text{the } k\text{th hoist activity is to load batch } i \text{ into tank } m \\ 0 & \text{otherwise} \end{cases}$$

$$y_{imk} \begin{cases} 1 & \text{the } k\text{th hoist activity is to unload batch } i \text{ from tank } m \\ 0 & \text{otherwise} \end{cases}$$

B. MATHEMATICAL MODEL

The considered problem model based on the considered assumptions is presented in this section. In Equations (1) and (2), two objectives are considered to minimize the makespan and the total weighted tardiness respectively.

$$\text{Min}Z_1 = MS \tag{1}$$

$$\text{Min}Z_2 = TWT \tag{2}$$

where $TWT = \sum_{n=1}^{N} (w_n T_n)$.

In the current research, the two objectives are combined into a single optimization objective by using the weighted ideal point method [35], as shown in Equation (3).

$$\text{Min}Z = \sqrt{\alpha(\frac{MS - Z_1^*}{Z_1^*})^2 + \beta(\frac{TWT - Z_2^*}{Z_2^*})^2} \tag{3}$$

where, Z_1^* and Z_2^* are the optimal values of each objective in current problem respectively, α represents the weight of orders regarding the producer and β represents the weight of orders regarding the customers.

The constraints of the model are described as follows.

1) CONSTRAINTS OF GROUPING

Constraints (4), (5), and (6) mean that different panels in one batch have the same length and the same processing time. Constraint (7) ensures that the total width of panels in each batch cannot exceed the carrier length.

$$l_{ij} = l_{ij'}; \quad \forall i \in \{1, 2, \ldots, N_b\}, \ \forall j, j' \in \{1, 2, \ldots, Q_i\} \tag{4}$$

$$PO_{t_{ij}} = PO_{t_{ij'}}; \quad \forall i \in \{1, 2, \ldots, N_b\}, \ \forall j, j' \in \{1, 2, \ldots, Q_i\} \tag{5}$$

$$PB_i = PO_{t_{ij}}; \quad \forall i \in \{1, 2, \ldots, N_b\}, \ \forall j, j' \in \{1, 2, \ldots, Q_i\} \tag{6}$$

$$\sum_{j=1}^{Q_i} d_{ij} \leq L; \quad \forall i \in \{1, 2, \ldots, N_b\} \tag{7}$$

2) CONSTRAINTS OF PANEL NUMBER

Constraint (8) means that the total number of panels is constant. The sum of panel quantities of each batch is equal to that of each order.

$$\sum_{i=1}^{N_b} Q_i = \sum_{n=1}^{N} q_n \tag{8}$$

$$\sum_{i=1}^{N_b} \sum_{j=1}^{Q_i} I(t_{ij} = n) = q_n; \quad \forall n \in S \tag{9}$$

In Constraint (9), $I(\cdot)$ is an indicator function with a value range of {0,1}, i.e., $I\,(\text{expression is ture}) = 1$, $I\,(\text{expression is false}) = 0$. This constraint means panels of different orders are distributed in various batches.

3) CONSTRAINTS OF HOIST ACTIVITIES, BATCHES AND TANKS

The hoist activities are divided into loading and unloading. Constraint (10) assures that only one batch can be assigned to each activity of the hoist.

$$\sum_{m=1}^{M} \sum_{i=1}^{N_b} (x_{imk} + y_{imk}) = 1; \quad \forall k \in \{1, 2, \ldots, 2N_b\} \tag{10}$$

Constraints (11) and (12) assure that each batch can only be assigned to one tank and will be loaded or unloaded once.

$$\sum_{m=1}^{M} \sum_{k=1}^{2N_b} x_{imk} = 1; \quad \forall i \in \{1, 2, \ldots, N_b\} \tag{11}$$

$$\sum_{m=1}^{M} \sum_{k=1}^{2N_b} y_{imk} = 1; \quad \forall i \in \{1, 2, \ldots, N_b\} \tag{12}$$

Constraint (13) requires the loading activity of each batch is performed before its unloading activity.

$$\sum_{k=1}^{k'} \sum_{m=1}^{M} x_{imk} \geq \sum_{k=1}^{k'} \sum_{m=1}^{M} y_{imk}; \quad \forall i \in \{1, 2, \ldots, N_b\}, \ k' \in \{1, 2, \ldots, 2N_b\} \tag{13}$$

Constraint (14) indicates that the loading and unloading activities of one batch take place in the same tank.

$$\sum_{k=1}^{2N_b} x_{imk} = \sum_{k=1}^{2N_b} y_{imk}; \quad \forall i \in \{1, 2, \ldots, N_b\}, \ m \in \{1, 2, \ldots, M\} \tag{14}$$

4) CONSTRAINTS OF VARIOUS CRITICAL TIME POINTS

Equation (15) gives the expression to calculate the moving time of the hoist while carrying a batch from the initial station to the corresponding tank.

$$LT_i = \sum_{m=1}^{M} \sum_{k=1}^{2N_b} (mt_0 x_{imk}); \quad \forall i \in \{1, 2, \ldots, N_b\} \tag{15}$$

Equations (16) and (17) give expressions to calculate the completion time of each batch and each order.

$$CB_i = \sum_{m=1}^{M} \sum_{k=1}^{2N_b} y_{imk}(s_k + Mt_0); \quad \forall i \in \{1, 2, \ldots, N_b\} \tag{16}$$

$$CO_n = \max_{1 \leq i \leq N_b} \{I(\sum_{j=1}^{Q_i} I(t_{ij} = n) > 0) \cdot CB_i\}; \quad \forall n \in S \tag{17}$$

The makespan is illustrated by the Equation (18), and Equation (19) gives the tardiness of each order.

$$MS = s_{2N_b} + Mt_0 \tag{18}$$

$$T_n = \max\{0, CO_n - D_n\}; \quad \forall n \in S \tag{19}$$

5) TIME CONSTRAINTS OF HOIST ACTIVITIES

The hoist activities include loading and unloading. Therefore, there are four different possibilities when the hoist is ready to start the next activity in a sequence position $(k+1)$, as shown in Constraint (20).

$$\begin{aligned} s_{k+1} \geq s_k + \sum_{m=1}^{M} \sum_{i=1}^{N_b} \sum_{m'=1}^{M} \sum_{i'=1}^{N_b} [(x_{imk} x_{i'm',k+1} + y_{imk} y_{i'm',k+1}) \\ \times (2Mt_0 + t_{end}) + x_{imk} y_{i'm',k+1} (Mt_0 + t_{end}) \\ + y_{imk} x_{i'm',k+1} Mt_0]; \quad \forall k \in \{1, 2, \ldots, 2N_b - 1\} \end{aligned} \tag{20}$$

In Constraints (21) and (22), suppose the lth $(l < k+1)$ hoist activity and the $(k+1)$th hoist activity are assigned to the same tank m.

Constraint (21) presents the ready time of the tank m for processing a new batch if the $(k+1)$th hoist activity is loading.

$$s_{k+1} \geq s_l + \sum_{i=1}^{N_b} (x_{iml} SUM_i + y_{iml} Mt_0) \quad \forall k \in \{1, 2, \ldots, 2N_b - 1\}, \forall m \in \{1, 2, \ldots, M\} \tag{21}$$

Constraint (22) ensures the batch to be finished in the tank m before it can be unloaded if the $(k+1)$th hoist activity is unloading.

$$s_{k+1} \geq s_l + x_{iml}(LT_i + PB_i) \quad \forall k \in \{1, 2 \ldots, 2N_b - 1\}, \quad \forall m \in \{1, 2 \ldots, M\},\ \forall i \in \{1, 2 \ldots, N_b\} \tag{22}$$

6) CONSTRAINTS OF DECISION VARIABLES

Constraints (23) and (24) show the possible values of all decision variables.

$$s_1 = 0, s_k \geq 0; \forall k \in \{2, 3, \ldots, 2N_b\} \tag{23}$$

$$x_{imk} = \{0, 1\}, y_{imk} = \{0, 1\}, t_{ij} \in S, N_b \in N^*, Q_i \in N^* \tag{24}$$

$$\forall k \in \{1, 2, \ldots, 2N_b\}, \quad \forall m \in \{1, 2, \ldots, M\}, \quad \forall i \in \{1, 2, \ldots, N_b\}, \quad \forall j \in \{1, 2, \ldots, Q_i\}$$

IV. THE HYBRID GUIDED TABU SEARCH ALGORITHM

Tabu search (TS) is a metaheuristic approach designed to obtain a near optimal solution of the combinatorial optimization problem [47]. It simulates human memory, introducing a flexible storage structure and a corresponding tabu criteria to avoid trapping the solution in local optima. Moreover, tabu search forgives some of the good solutions in tabu list to achieve the global optima. However, the defect of TS algorithm is that it has strong dependence on initial solution. A better initial solution can search better solutions in solution space, but a poor initial solution can reduce the convergence speed of TS. In addition, TS operates only one solution at a time in the search process, resulting in poor search solution.

For this current special problem, a hybrid guided tabu search (HGTS) algorithm based on small combination sequences is developed to find an optimal schedule of the research problem. The small combination sequence consists of several certain batches, which is used to generate a better initial solution and is also taken as a guide to generate neighborhood solutions to find the optimal solution quickly. The main procedure of the proposed HGTS algorithm is illustrated in detail in this section.

A. ORDER SPLITTING AND TANK SELECTION RULES

In general, the manufacturing enterprises take the production order as the smallest unit for tracking and transfer. If different panels from an order are distributed in multiple dispersed batches, the first finished batch will wait a long time before the last batch finishes processing, which will affect the subsequent processes. Therefore, the order splitting rule (R1) is proposed as follows: For order n, panels are hung on the carriers one by one. Order n is divided into F_n full batches (if the total width of panels of order n is less than the carrier length, $F_n = 0$) and at most one non-full batch. These non-full batches can be grouped if satisfying group constraint.

When the hoist is ready to load or unload a batch, tank selection rule (R2) is considered:

- When loading a batch, select the nearest available tank to the initial station.
- When several batches are ready to be unloaded, the hoist is required to select the earliest finished batch.

1	3	5	1	2	6	3	2	2	8	7

FIGURE 3. The encoding scheme.

B. ENCODING AND DECODING

The encoding method used for the current problem is based on integer encoding method. Positive integers $1 \sim N$ represent the full batches, while $(N+1) \sim 2N$ represent the non-full batches. For order n, the corresponding non-full batch is denoted as $(n+N)$. Fig. 3 shows an encoding sample when $N = 4, F_1 = 2, F_2 = 3, F_3 = 2, F_4 = 0$.

In the proposed encoding method, the non-full batches $(N+1) \sim 2N$ can be grouped if the adjacent batches satisfy the group constraint. For example, in Fig. 3, suppose batches 8 and 7 can be grouped, the two non-full batches will be combined into one batch.

The decoding operation

Step 1: Perform the grouping operation for the current solution, and the actual processing sequence PS of batches is obtained.

Step 2: Let $k = 0$ and $ES_m = 0$ for all tanks. (ES_m is the earliest start time for loading a new batch in tank m).

Step 3: Increase k by 1. Select the tank m with the least ES_m (break tie according to the rule R2), and assign the kth hoist activity on tank m. If hoist activity is loading, the first batch i in PS is selected and loaded into tank m, then delete this batch from PS. The end time of the kth hoist activity $ET_k = ES_m + mt_0$. If hoist activity is unloading batch i', $ET_k = ES_m, CB_{i'} = ET_k$.

Step 4: Update the ES_m of each tank:

- For the tank m, if the kth hoist activity is loading, $ES_m = ET_k + PB_i + Mt_0$; otherwise, $ES_m = ET_k$;
- For any other tank g (g≠m) which is occupied by any batch, if the kth hoist activity is loading, $ES_g = \max\{ET_k + (2M - m)\, t_0 + t_{end}, ES_g\}$; otherwise, $ES_g = \max\{ET_k + 2Mt_0 + t_{end}, ES_g\}$;
- For any other idle tank h (h≠m, g≠m), if the kth hoist activity is loading, $ES_h = ET_k + (2M - m)\, t_0 + t_{end}$; otherwise, $ES_h = ET_k$.

Step 5: Repeat Step 3 and Step 4 until all batches are completed ($k = 2N_b$). $MS = ET_{2N_b}$. The value of CB_i is obtained in Step 3, therefore TWT can be calculated according to Equations (17) and (19).

C. INITIAL SOLUTION

In the case company, PCB products are divided into two categories A and B. Category A has a less and constant processing time, while category B needs much more processing time which varies according to different process requirements. However, the hoist has its frequency of movement. Batches with different processing times will disrupt the original takt time. Therefore, it is necessary to make combinations of the batches with different processing times to be loaded in the different positioned tanks to cater to the movement frequency of the hoist.

According to the movement rule of the hoist in Fig 2, the hoist moving time of one cycle is at least $(2Mt_0+t_{end})$. The production will be smooth and rhythmic when the processing time of all batches is $SV = (2Mt_0 + t_{end})M$. Generally, in the case company, the processing time of category A is a constant value P_0 which is much less than SV. However, the processing time of category B is $P_f (f = 1, 2, \ldots, D)$ (D is the number of the processing time values of category B) which is higher than SV. Therefore, it is required to choose the two categories of PCB products to make combinations to let the average processing time near to SV with a proper ratio. For example, $SV = 90$, the batches in category A have processing time of 40 while the batches in category B have processing time of 120. Then the batches will be loaded by the hoist involving the following combination, i.e., B-B-A sequence. The average processing time of this small combination sequence is $93.33 = (120 + 120 + 40)/3$ which is near to 90. Moreover, when making the combination sequences, the following two conditions are taken into consideration.

Condition 1: In any small combination sequence, the number of batches with the processing time P_0 or batches with the processing time P_f cannot exceed 3, and one of these two numbers is 1. For example, if the number of batches with processing time P_0 is 2 or 3, then the number of batches with processing time P_f can only be 1. (The scale of the combination is small so that it will be more flexible in sequencing.)

Condition 2: For any combination sequence, the deviation between the average processing time and SV is required to be within a percentage range λ. If several ratios of P_0 and P_f are feasible, then the combination sequence with the closest average processing time to SV is chosen. If no ratio of P_0 and P_f is feasible, the combination is not allowed. For example, if $\lambda = 20\%$, $SV = 90$, $P_0 = 40$, and $P_1 = 120$, suppose the ratios of P_0 and P_1 are 1:1, 1:2, 2:1, 1:3, and 3:1, while the average processing time are 80, 93.3, 66.7, 100, and 60 respectively. The time 66.7 and 60 are out of bounds while 93.3 is the closest average processing time to SV. Therefore, the corresponding ratio related to the average processing time 93.3 is selected, i.e., 1:2 is selected as the ratio of P_0 and P_1.

Based on the considered conditions of combination sequences and the earliest due date (EDD) strategy, a heuristic algorithm called SCS is developed to generate a feasible initial solution. The flow chart of the proposed SCS heuristic algorithm is presented in Fig. 4, while the step by step procedure is explained as follows.

Grouping operation

Step 1: Splitting operation is performed for the current orders using the rule R1. The set NF is used to store the non-full batches.

Step 2: Sort the non-full batches in the order of their due times from small to large.

*Step 3:*Select the first batch in NF and find out the batches which can be grouped with the first one. Select the one with

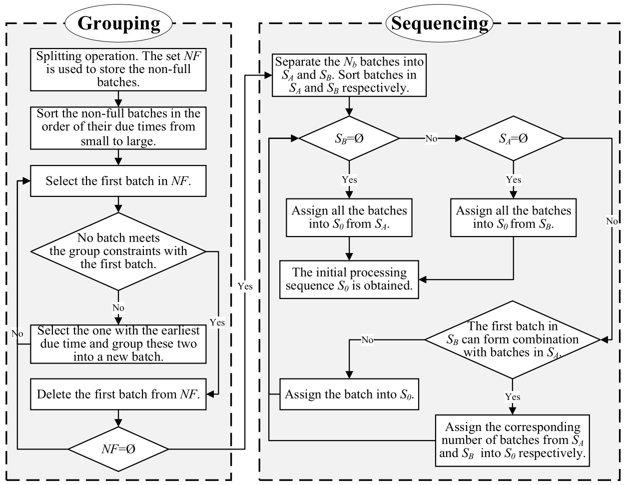

FIGURE 4. The flow chart of the SCS heuristic algorithm.

the earliest due time and group these two into a new batch, repeat Step 3. If no batches can be found, delete the current first batch from NF and repeat Step 3 until $NF = \emptyset$.

Sequencing operation

Step 1: The grouping operation generates N_b batches. Separate the N_b batches into two sets S_A (category A) and S_B (category B). Sort the batches in S_A and S_B respectively in the order of their due times from small to large.

Step 2: If $S_B = \emptyset$, assign all the batches in S_A into S_0 (the initial sequence), and go to Step 5; otherwise, go to Step 3.

Step 3: If $S_A = \emptyset$, assign all the batches in S_B into S_0, and go to Step 5; otherwise, go to Step 4.

Step 4: If the first batch in S_B can form a feasible combination sequence with batches in S_A, assign the corresponding number of batches from S_A and S_B respectively in the order of their due times from small to large into S_0; otherwise, assign the batch into S_0. Return to Step 2.

Step 5: The initial processing sequence S_0 is obtained.

D. MOVES AND NEIGHBORHOOD

One of the important steps of TS algorithm is the definition of the move set that can create a neighborhood. Among many types of moves considered for permutation problems, insert moves (I-move) and pairwise exchange moves (E-move) are the two move types which have been used in many studies [45], [48]. In the proposed HGTS algorithm, only I-move is considered because it is related to the batch combination. The procedure of the considered move is explained here.

Suppose $v = (a, b)$ represents a pair of positions $a, b \in \{1, 2, \ldots, N_c\}$ (N_c is the number of batches before grouping) in the solution π. The pair $v = (a, b)$ defines a move in solution π, and the move v generates a new solution π_v by moving the batch $\pi(a)$ from position a to position b in the following way: $\pi_v = (\pi(1), \ldots, \pi(a-1), \pi(a+1), \ldots, \pi(b), \pi(a), \pi(b+1), \ldots, \pi(N_c))$ if $a < b$ and $\pi_v = (\pi(1), \ldots, \pi(b-1), \pi(a), \pi(b), \ldots, \pi(a-1), \pi(a+1), \ldots, \pi(N_c))$ if $a > b$.

TABLE 1. The move probabilities.

Probability	θ_1	θ_2	θ_3	θ_0
Processing time of $\pi(a)$	Processing time of $(\pi(b)\ \pi(b+1))$ or $(\pi(b-1)\ \pi(b))$			
P_0	$(P_0\ P_4)$,$(P_0\ P_5)$, $(P_1\ P_3)$,$(P_2\ P_2)$,$(P_2\ P_3)$, $(P_3\ P_3)$,$(P_3\ P_4)$, $(P_3\ P_5)$,$(P_3\ P_6)$	$(P_1\ P_1)$,$(P_1\ P_2)$, $(P_1\ P_4)$,$(P_1\ P_5)$, $(P_1\ P_6)$,$(P_2\ P_4)$, $(P_2\ P_5)$,$(P_2\ P_6)$, $(P_4\ P_4)$,$(P_4\ P_5)$, $(P_4\ P_6)$,$(P_5\ P_5)$, $(P_5\ P_6)$	Others	If $\pi(a)$ is non-full and $\pi(b+1)$ or $\pi(b)$ can be grouped with $\pi(a)$. $(a < b)$
P_1	$(P_0\ P_1)$	$(P_0\ P_0)$,$(P_0\ P_2)$, $(P_0\ P_3)$,$(P_0\ P_6)$, $(P_1\ P_1)$	Others	If $\pi(a)$ is non-full and $\pi(b-1)$ or $\pi(b)$ can be grouped with $\pi(a)$. $(a > b)$
P_2	$(P_0\ P_2)$	$(P_0\ P_0)$,$(P_0\ P_1)$, $(P_0\ P_3)$,$(P_0\ P_6)$,	Others	
P_3	$(P_0\ P_0)$,$(P_0\ P_6)$	$(P_0\ P_1)$,$(P_0\ P_1)$, $(P_0\ P_3)$	Others	
P_4	$(P_0\ P_0)$,$(P_0\ P_6)$	$(P_0\ P_1)$,$(P_0\ P_1)$, $(P_0\ P_3)$	Others	
P_5	$(P_0\ P_0)$,$(P_0\ P_6)$	$(P_0\ P_1)$,$(P_0\ P_1)$, $(P_0\ P_3)$	Others	
P_6	$(P_3\ P_3)$,$(P_3\ P_4)$, $(P_3\ P_5)$,$(P_4\ P_4)$, $(P_4\ P_5)$,$(P_5\ P_5)$	$(P_1\ P_2)$,$(P_1\ P_3)$, $(P_2\ P_3)$	Others	

$N(\pi)$, the neighborhood of π, consists of solution π_v generated by moves from a given set $\boldsymbol{V} = \{v = (a, b) | a \notin \{b, b+1\},\ a, b \in \{1, 2, \ldots, N_c\}\}$. Note that if $|a-b| = 1$, move $v = (a, b)$ and move $v' = (b, a)$ are equivalent. Therefore, the set $\boldsymbol{V}$ contains only one effective move.

In the proposed move strategy, a guided neighborhood move method is used during the move to avoid premature convergence and local optima. When moving a full batch, it is considered to satisfy the required ratios of combination sequences, and different move probabilities are set to obtain different target positions. If this move is closer to the required ratios of combination, the move probability value will be greater. Similarly, when moving a non-full batch, first it is considered to satisfy the grouping operation and then to satisfy the required ratios of combination sequences. The move probabilities are shown in Table 1.

In Table. 1, suppose that the ratios of P_0 and P_1, P_0 and P_2, P_0 and P_3, P_0 and P_4, P_0 and P_5 are 1:3, 1:2, 1:1, 2:1, 3:1 respectively. Suppose P_6 and P_0 cannot perform a combination sequence. The probabilities of $\pi(a)$ moving to any position are $\theta_0, \theta_1, \theta_2, \theta_3$ respectively. If $\pi(a)$ is a non-full batch, the probability of moving to the batches that can be grouped with $\pi(a)$ is θ_0 $(\theta_0 > \theta_1 > \theta_2 > \theta_3)$. In addition, the move probability is sequence independent. For example, the move probability of (P_0P_4) is equal to that of (P_4P_0).

The probability denotes the possibility of the move $v = (a, b)$. When performing the move operation, a pair of positions (a, b) is generated randomly to obtain the probability of move $v = (a, b)$. If this move happens, a neighborhood solution is obtained; otherwise, this move is given up, and another move is searched. The procedure continues until the number of neighborhood solutions is up to the specified threshold $Nei/2$. After the move operation, the new generated neighborhood solutions are allowed to crossover using precedence preservative crossover (PPX) operator [49] to produce $Nei/2$ offspring. The PPX operation is shown in Fig 5 as follows. Generate a vector which is randomly filled with elements of the set $\{1, 2\}$. The vector represents the order in which the elements are taken out from Parent1 and Parent2. The offspring inherits its leftmost element from one of the two parents in accordance with the order given in this vector. After an element is selected, it is deleted from both parents. The step is repeated until both parents are empty. After the PPX operation, Nei neighbourhood solutions have been generated.

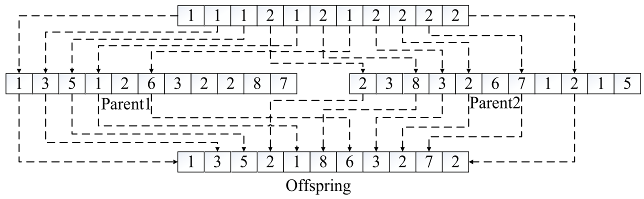

FIGURE 5. The PPX operator example.

E. TABU LIST

In the proposed HGTS algorithm, a short term memory of the search history is represented by a cyclic list $TL = (TL_1, TL_2, \ldots, TL_{leth})$ of a fixed length $leth$ called tabu list, where TL_t is the current selected neighborhood solution. The tabu list is initiated by zero number of elements in it. Once a neighborhood solution π_v is selected, the corresponding TL_t is added to TL in the following way: set $TL_t = TL_{t-1}$, $t = (leth, leth{-}1, \ldots, 2)$ and set $TL_1 = \pi_v$.

F. THE PROPOSED HGTS ALGORITHM

In this section, the HGTS algorithm based on combination sequences is proposed for the considered objective "$\text{Min}Z = \sqrt{\alpha(\frac{MS-Z_1^*}{Z_1^*})^2 + \beta(\frac{TWT-Z_2^*}{Z_2^*})^2}$" for the parallel-tank scheduling problem. The step by step procedure of the proposed HGTS algorithm is presented below:

Step 1: Construct an initial solution π_0 using the SCS heuristic algorithm. Set $TL = \emptyset$ and $iter = 0$. $Z(\pi_0)$ is the corresponding objective value. Set $\pi^* = \pi_0$, and π^* is the current best solution and $Z^* = Z(\pi_0)$ is the current best objective value. Aspiration function $A(v, \pi) = Z(\pi^*)$.

Step 2: Let $iter = iter + 1$. If $Z(\pi_{v_l}) = Opt\ \{Z(\pi_v), \pi_v \in N(\pi)\}$ and $Z(\pi_{v_l}) < A(v, \pi)$, let $\pi = \pi_{v_l}$, and go to Step 4.

Step 3: If $Z(\pi_{v_k}) = Opt\,\{Z(\pi_v), \pi_v \in N(\pi) \backslash TL\}$, let $\pi = \pi_{v_k}$.

Step 4: If $Z(\pi) < Z(\pi^*)$, let $\pi^* = \pi$, $Z(\pi^*) = Z(\pi)$, and $A(v, \pi) = Z(\pi^*)$.

TABLE 2. Processing time values related to different number of tanks.

M	Processing time of category A (min)	Processing time of category B (min)	Ratio of combination
10	25	70	1:2
		80	1:1
		90	1:1
		100	2:1
		110	2:1
		120	2:1
15	40	100	1:3
		120	1:2
		140	1:1
		150	1:1
		180	2:1
		200	2:1

Step 5: Update the tabu list *TL* and Check the stopping criterion. If the stopping criterion is reached, stop; otherwise go to Step 2.

V. EXPERIMENTAL RESULTS

The performance of the proposed HGTS algorithm is measured and presented in this section. The effectiveness and performance of the proposed HGTS algorithm is compared with the HGTS/GM algorithm where the guided neighborhood move is removed from HGTS in order to demonstrate the effectiveness of the neighborhood move strategy. Furthermore, the standard tabu search (TS), particle swarm optimization (PSO) [50] and genetic algorithm (GA) [51] where SCS heuristic is not considered to generate initial solutions are also compared with the proposed HGTS algorithm. The SCS heuristic algorithm can be evaluated by comparing the HGTS/GM to the standard TS. For GA, PPX is selected as the crossover operator and 2-exchange is selected as the mutation operator. For PSO, the crossover and mutation operations are used to replace the update operations of particle velocity and position [50]. In this section, a series of test experiments are conducted with the stopping criterion set as the corresponding maximum CPU elapsed time. All algorithms are coded in Python and run on a PC with Intel Core i7 3.1 GHz CPU, 16GB RAM computer.

A. EXPERIMENTAL DATA SPECIFICATIONS

The specifications of required data for these experiments are listed below:

- Processing times of batches which have several constant values related to the number of tanks are given in Table. 2.
- The due times (the unit of due time is hour) are generated from discrete uniform (DU) distribution, which is related to the number of tanks and orders, as given in Table. 3.
- The numbers of different processing time values of category B (denoted by R) are 2, 4 and 6 respectively. Each instance can be labelled in the form of "N_M_R". For example, "20_15_2" represents that the instance contains 20 orders and 15 tanks with 2 processing time values of category B.
- The other experimental parameters are listed in Table. 4.

TABLE 3. Due time values related to different number of tanks and orders.

M	N	Due time (hrs)
10	20	DU[1, 3]
	50	DU[4, 7]
	80	DU[6, 12]
15	20	DU[2, 4]
	50	DU[5, 9]
	80	DU[7, 13]

TABLE 4. Experimental parameters.

Parameters	Notation	Value
The number of panels in order n	q_n	DIU[10, 60]
The length of panels in order n	l_n(inch)	DIU[18, 24]
The width of panels in order n	d_n(inch)	DIU[12, 18]
The length of the carrier	L(inch)	360
The move time of hoist between two adjacent tanks	t_0(s)	3
The fixed time hoist has to wait at tank M	t_{end}(s)	270
The weight of type n	w_n	DU[0.1, 0.5]
The weight of products regarding the producer	α	0.7
The weight of products regarding the customers	β	0.3
The ratio of category A in each instance		0.4

TABLE 5. Parameter settings of HGTS, PSO and GA.

HGTS	PSO	GA
Neighbor size: 40 Tabu list size:8 Stopping time: 8s (N = 20)	Population size: 40 Stopping time: 8s (N = 20)	Population size: 40 Stopping time: 8s (N = 20)
Neighbor size: 80 Tabu list size: 11 Stopping time: 40s (N = 50)	Population size: 80 Stopping time: 40s (N = 50)	Population size: 80 Stopping time: 40s (N = 50)
Neighbor size: 120 Tabu list size: 14 Stopping time: 120s (N = 80)	Population size: 80 Stopping time: 120s (N = 80)	Population size: 120 Stopping time: 120s (N = 80)
θ_0: 0.95 θ_1: 0.8 θ_2: 0.6 θ_0: 0.3	Inertial coefficient (w): 0.9 Learning coefficient (c): 0.5	Crossover rate: 0.95 Mutation rate: 0.05

B. PARAMETER SETTINGS

To ensure a fair comparison, the parameter settings for the proposed HGTS algorithm and other compared algorithms are optimized. Pilot experiments are conducted for HGTS, PSO and GA with different parameter configurations in advance. The parameters are presented in Table. 5.

C. COMPARISON AMONG ALGORITHMS

The performance of the proposed HGTS algorithm is compared against the algorithm HGTS/GM, the standard TS, PSO and GA. Eighteen instances are constructed based on the corresponding relative data. First, each instance is run 25 times for each algorithm independently aimed to obtain the ideal point, i.e., minimizing the makespan and *TWT* respectively, obtaining the value of Z_1 and Z_2 of each instance. Then, each instance is run 25 times for each algorithm aimed at minimizing the objective value Z. To further evaluate the performance of the proposed HGTS algorithm, the results

TABLE 6. Optimization results of the proposed HGTS, HGTS/GM, TS, PSO and GA.

Problem sets	*Best*	Gap (%)	HGTS			HGTS/GM			TS			PSO			GA		
			Opt	Mean	ARPD	Opt	Mean	ARPD	Opt	Mean	ARPD	Opt	Mean	ARPD	Opt	Mean	ARPD
20_10_2	0.031	3.6	**0.032**	**0.038**	**0.233**	0.036	0.041	0.309	0.041	0.050	0.624	0.047	0.053	0.716	0.057	0.063	1.039
20_10_4	0.049	2.0	**0.050**	**0.066**	**0.341**	0.066	0.068	0.382	0.070	0.080	0.627	0.073	0.083	0.674	0.083	0.108	1.189
20_10_6	0.060	1.7	**0.061**	**0.073**	**0.221**	0.069	0.080	0.329	0.081	0.089	0.487	0.084	0.094	0.560	0.109	0.120	0.993
20_15_2	0.035	0.0	**0.035**	**0.044**	**0.256**	0.046	0.051	0.439	0.053	0.060	0.712	0.057	0.065	0.847	0.067	0.080	1.282
20_15_4	0.036	0.0	**0.036**	**0.045**	**0.260**	0.044	0.052	0.434	0.052	0.057	0.579	0.059	0.070	0.941	0.071	0.082	1.260
20_15_6	0.045	0.7	**0.046**	**0.056**	**0.227**	0.054	0.062	0.361	0.057	0.070	0.536	0.062	0.080	0.757	0.080	0.095	1.101
50_10_2	0.061	3.5	**0.063**	**0.077**	**0.257**	0.068	0.088	0.436	0.081	0.091	0.487	0.088	0.107	0.750	0.093	0.117	0.914
50_10_4	0.055	3.1	**0.057**	**0.064**	**0.162**	0.061	0.070	0.283	0.075	0.082	0.500	0.076	0.092	0.682	0.092	0.107	0.951
50_10_6	0.030	0.7	**0.030**	**0.038**	**0.251**	0.039	0.045	0.478	0.042	0.052	0.730	0.047	0.059	0.962	0.051	0.061	1.030
50_15_2	0.041	2.5	**0.042**	**0.052**	**0.280**	0.054	0.061	0.487	0.062	0.071	0.738	0.067	0.079	0.947	0.079	0.089	1.192
50_15_4	0.037	2.0	**0.038**	**0.052**	**0.384**	0.049	0.058	0.560	0.059	0.066	0.763	0.058	0.069	0.846	0.068	0.079	1.113
50_15_6	0.048	1.2	**0.049**	**0.060**	**0.246**	0.056	0.068	0.396	0.063	0.070	0.454	0.068	0.075	0.544	0.083	0.095	0.956
80_10_2	0.071	2.2	**0.073**	**0.085**	**0.195**	0.085	0.097	0.370	0.102	0.112	0.579	0.099	0.120	0.693	0.119	0.130	0.834
80_10_4	0.053	1.9	**0.054**	**0.066**	**0.240**	0.061	0.074	0.391	0.074	0.084	0.568	0.076	0.088	0.651	0.085	0.107	0.999
80_10_6	0.040	4.5	**0.042**	**0.052**	**0.276**	0.048	0.060	0.490	0.064	0.074	0.837	0.069	0.078	0.941	0.079	0.092	1.274
80_15_2	0.041	2.3	**0.042**	**0.055**	**0.328**	0.047	0.059	0.440	0.059	0.069	0.681	0.065	0.077	0.867	0.069	0.082	0.999
80_15_4	0.037	3.8	**0.038**	**0.047**	**0.277**	0.046	0.051	0.397	0.055	0.070	0.927	0.059	0.075	1.046	0.067	0.077	1.106
80_15_6	0.040	3.9	**0.041**	**0.052**	**0.315**	0.049	0.057	0.434	0.062	0.070	0.754	0.065	0.073	0.822	0.079	0.083	1.073
Hit rate			18/18	18/18	18/18	0/18	0/18	0/18	0/18	0/18	0/18	0/18	0/18	0/18	0/18	0/18	0/18

obtained by HGTS are compared with the best solutions for each instance. Regarding the nonlinearity of the proposed model, the approximate optimal solutions can be obtained by all the compared algorithms running for large number of cycles [52], [53]. The performance of all algorithms is evaluated based on different indicators including quality of solutions and convergence. The performance measure Relative Percentage Deviation (RPD) [54] is calculated for each algorithm as follows:

$$RPD = \frac{Sme_{sol} - Best}{Best} \times 100\% \tag{25}$$

where $Some_{sol}$ is the solution obtained by one algorithm for one instance and *Best* is the obtained best solution among all the algorithms for the same instance. Table. 6 shows the results of mean value, optimum value and the average RPD (ARPD) for each instance. Hit rate indicates that the ratio of the corresponding algorithm outperforming others. The optimal results are highlighted in **bold** font. Gap represents the percentage of deviation of the optimal result from *Best*. Table. 7 represents the results obtained from T-tests. The confidence level for all tests is set to 95% (corresponding to $\alpha = 0.05$). The h value of 1 or -1 indicates that the proposed HGTS performs significantly better or worse than the compared algorithm, while the h value of 0 indicates that there is no significantly difference between HGTS and the compared algorithm.

As indicated in Table. 6, the performance of the proposed HGTS algorithm is significantly superior to other compared algorithms for all the tested instances. Moreover, the maximum gap is only 4.5%. The second best algorithm is the HGTS/GM. Compared with the standard TS, PSO and GA, HGTS and HGTS/GM can obtain the lowest values in terms of the mean value, optimum value and the ARPD for all the instances. Moreover, according to the T-tests results in Table. 7, the HGTS outperforms TS, PSO and GA for all the instances. Compared with the HGTS/GM, the HGTS obtains significantly better results for 16 out of 18 instances, which also indicates that the HGTS shows the statistically better performance than HGTS/GM.

In addition, to verify the statistical validity of the ARPD results, obtained by different algorithms, a one-factor analysis of variance (ANOVA) technique where the algorithm type is the single factor is applied after checking the normality, homoscedasticity and independence. Fig. 6 illustrates the mean plot with Tukey's HSD (honestly significant difference) intervals considering 95% confidence level for the five compared algorithms. Note that the overlapping of any two algorithms shows that there is no statistical difference between them. It can be seen that the proposed HGTS algorithm obtains the best values of ARPD for all the instances, then the HGTS/GM algorithm, and finally the TS, PSO and GA, which also shows that the HGTS performs statistically better than the other four algorithms.

TABLE 7. The T-tests results for the proposed HGTS algorithm with Compared Algorithms.

Problem sets	(HGTS, HGTS/GM)		(HGTS, TS)		(HGTS, PSO)		(HGTS, GA)	
	p	*h*	*P*	*h*	*p*	*h*	*p*	*h*
20_10_2	1.150e-02	1	3.635e-10	1	2.243e-12	1	6.936e-19	1
20_10_4	8.460e-02	0	1.787e-06	1	2.317e-08	1	4.524e-12	1
20_10_6	3.810e-02	1	9.158e-10	1	2.574e-11	1	2.703e-19	1
20_15_2	3.541e-05	1	3.487e-13	1	9.830e-15	1	7.491e-15	1
20_15_4	3.892e-06	1	4.887e-08	1	3.680e-14	1	9.999e-17	1
20_15_6	2.200e-03	1	5.879e-09	1	2.798e-09	1	9.503e-17	1
50_10_2	9.699e-06	1	1.960e-06	1	2.081e-10	1	2.311e-12	1
50_10_4	1.400e-03	1	1.260e-07	1	2.327e-14	1	8.950e-15	1
50_10_6	2.256e-06	1	1.270e-08	1	6.608e-15	1	7.977e-14	1
50_15_2	2.100e-03	1	2.490e-10	1	1.113e-11	1	1.336e-15	1
50_15_4	2.029e-04	1	2.920e-09	1	4.833e-09	1	6.414e-13	1
50_15_6	7.796e-06	1	3.483e-07	1	3.058e-11	1	7.439e-15	1
80_10_2	8.116e-08	1	2.687e-11	1	2.612e-15	1	1.302e-15	1
80_10_4	2.440e-02	1	3.122e-11	1	1.774e-10	1	1.357e-13	1
80_10_6	4.435e-05	1	3.943e-12	1	1.379e-14	1	4.213e-16	1
80_15_2	6.780e-02	0	1.574e-06	1	3.745e-12	1	2.024e-13	1
80_15_4	1.805e-04	1	4.944e-12	1	3.335e-13	1	3.809e-18	1
80_15_6	1.680e-02	1	1.717e-07	1	1.068e-09	1	2.238e-10	1

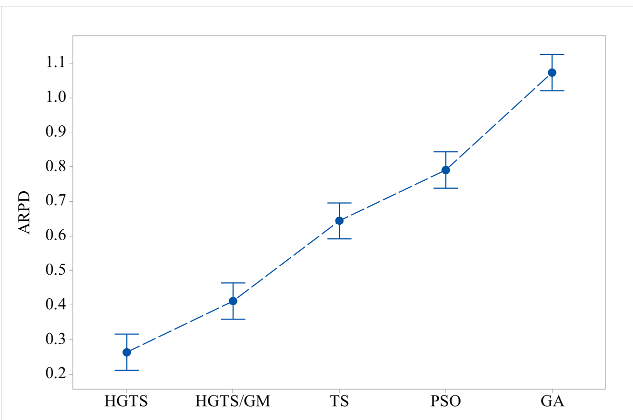

FIGURE 6. The mean plot of the ARPD among different algorithms with Tukey's HSD intervals considering 95% confidence level.

Furthermore, the evaluation of the objective value of different algorithms is investigated by convergence curves, which are used to illustrate the process of one algorithm approaching the optimal solution. The best solutions obtained by each algorithm for the four instances "20_10_6", "20_15_4", "50_15_2", and "80_15_6" are selected to illustrate the convergence curves of the proposed HGTS, HGTS/GM, TS, PSO and GA, which are presented in Fig. 7. It can be seen that, for the same computational time, the values of the objective function of the proposed HGTS algorithm are minimum among all the compared algorithms, which shows the proposed HGTS algorithm has a better convergence performance of converging to better optimal results against its competitors. Moreover, in each plot from Fig. 7, the convergence curves of the proposed HGTS and HGTS/GM start from the same point (solution) which is better than the initial solutions generated randomly of TS, PSO and GA. It indicates that the SCS heuristic algorithm can get a better initial sequence.

Compared with the HGTS/GM, TS, PSO and GA, the main reasons for the superior performance of the proposed HGTS algorithm can be explained as follows: First, the SCS heuristic algorithm based on small combination sequences can obtain a better initial solution, which can greatly improve the search efficiency. The statistical results between the algorithms HGTS/GM, TS, PSO and GA can support this viewpoint. Second, the guided neighborhood move strategy can increase the ability of local exploitation, which makes HGTS quickly converge to optimal solutions. Finally, the crossover operator improves the exploration ability of HGTS.

In summary, the above experimental results indicate that the proposed HGTS algorithm significantly outperforms other competitors. Therefore, the proposed HGTS is effective in solving the current electroplating parallel-tank scheduling problem.

VI. CASE STUDY

The electroplating parallel-tank scheduling problem comes from a real-world electroplating workshop of a PCB manufacturer in China, which is investigated to test the performance of the proposed HGTS algorithm to optimize both makespan and *TWT*. The following case is taken as an exam-

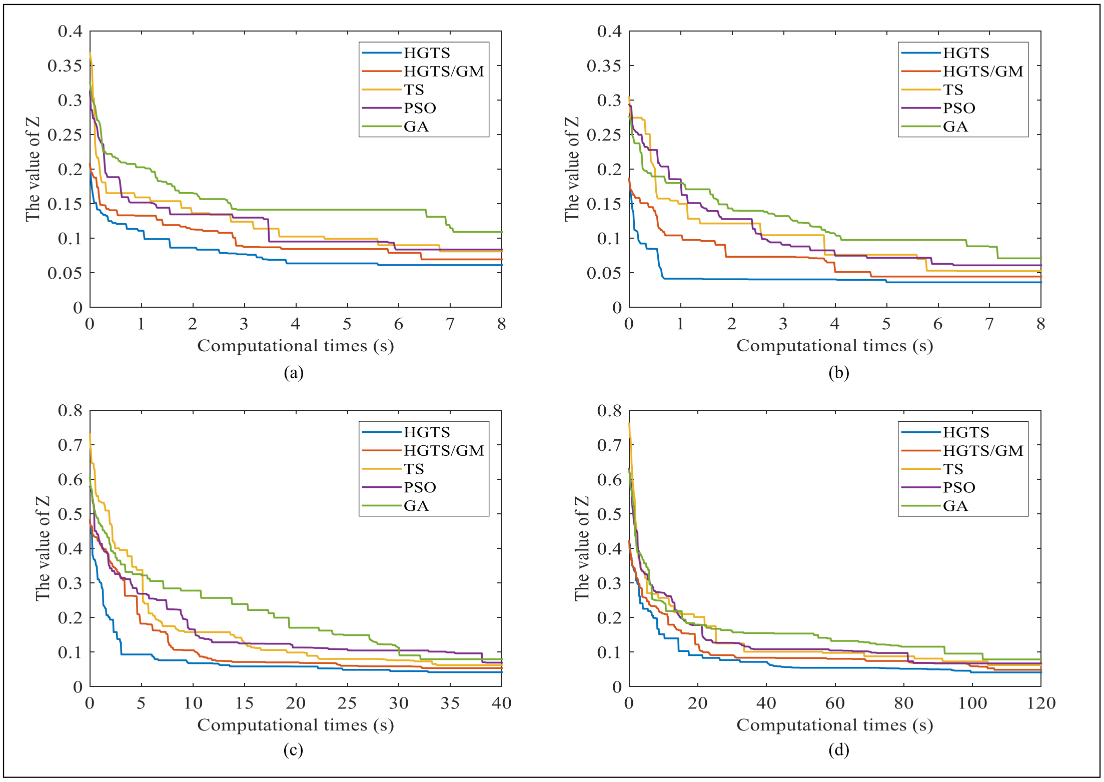

FIGURE 7. Convergence curves of the proposed HGTS, HGTS/GM, TS, PSO and GA. (a) Convergence curves of different algorithms for instance 20_10_6. (b) Convergence curves of different algorithms for instance 20_15_4. (c) Convergence curves of different algorithms for instance 50_15_2. (d) Convergence curves of different algorithms for instance 80_15_6.

ple where there are 20 orders of panels required to be processed in the electroplating system with 15 parallel tanks. The related data including panel number, panel size, order due time, order weight and processing time are provided in Table. 8. Other data including carrier length and hoist moving time have been listed in Table. 4.

The optimized batch sequence obtained by the proposed HGTS algorithm after performing 400 iterations is [10, 12, 32, 29, 30, 11, 10, 9, 11, 27, 3, 34, 33, 38, 36, 17, 17, 20, 39, 28, 26, 6, 1, 5, 5, 35, 15, 4, 3, 1, 2, 2], and the corresponding value of makespan and *TWT* is (259.5min, 99.9min). And the empirical batch sequence from the real-world workshop obtained by the grouping precedence strategy and the earliest due date (EDD) strategy is [12, 32, 11, 11, 10, 10, 30, 29, 9, 28, 26, 27, 34, 33, 6, 5, 5, 38, 17, 17, 36, 15, 35, 4, 3, 3, 20, 39, 2, 2, 1, 1], and the makespan and *TWT* is (295.45min, 247.75min). It can be observed that the solution obtained by HGTS is obviously superior to the empirical solution. The Gantt charts of these two solutions are illustrated in Fig. 8. Note that the color box denotes the actual processing time, while the black box represents the retention time of each batch in the electroplating system. Each color represents one order and the numbers 21 to 40 represent the non-full batch. Some boxes contain two colors meaning that the two orders are grouped into one batch. Moreover, the dashed line denotes the corresponding order is delayed. As shown in Fig. 8, the makespan and the delayed time in Fig. 8(a) is much smaller than those in Fig. 8(b).

TABLE 8. The related data of orders.

Order No.	Panel number	Panel size (inch)		Due time (hrs)	Weight	Processing time (min)
		Width	Length			
1	60	12	18	4	1	40
2	60	12	18	4	1	40
3	54	13	20	3.5	1	40
4	24	15	20	3.5	1	40
5	48	15	20	3	1	40
6	30	16	21	3	1	40
7	18	16	21	2.5	1	40
8	12	14	21	2.5	1	40
9	24	16	22	2.5	1	100
10	48	17	22	2.5	1	100
11	42	17	22	2.5	1	100
12	30	18	24	2.5	1	100
13	12	12	18	3	1	120
14	12	12	18	3	1	120
15	30	14	21	3.5	1	120
16	18	18	24	3.5	1	120
17	54	13	20	3.5	1	150
18	18	15	21	3.5	1	150
19	18	18	24	4	1	150
20	24	15	21	4	1	150

It indicates that the case result obtained from the proposed HGTS algorithm is significantly superior to the empirical result of the real-world factory planners. Therefore, the

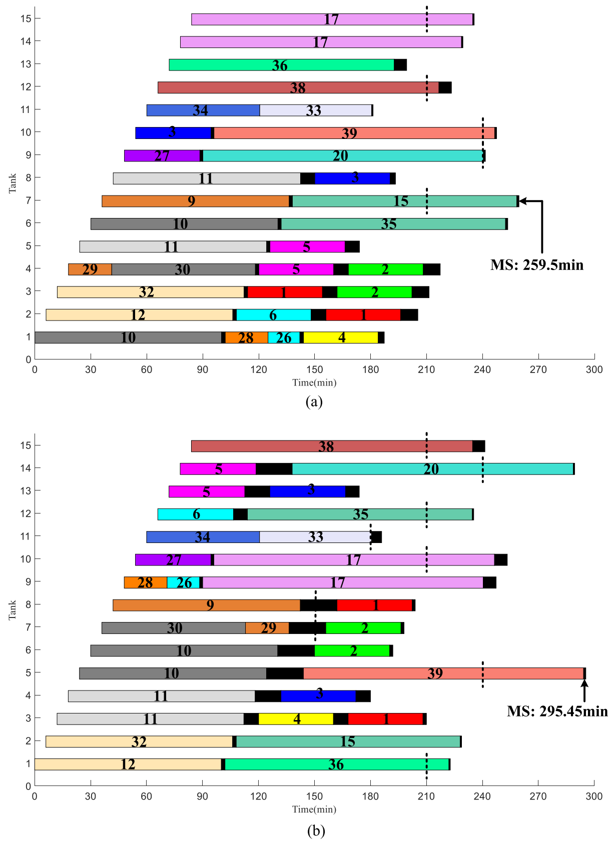

FIGURE 8. **The Gantt charts of solutions obtained by the proposed HGTS and the original sequence. (a) Gantt chart of the solution obtained by HGTS. (b) Gantt chart of the empirical sequence.**

proposed HGTS algorithm can solve the electroplating parallel-tank scheduling problem with hoist and group constraints effectively and efficiently.

VII. CONCLUSIONS AND FUTURE RESEARCH

In the current research, a parallel-tank scheduling problem with hoist and group constraints in PCB electroplating environment is presented. A bi-criteria objective function is considered to minimize the makespan and total weighted tardiness, and the weighted ideal point method is used to combine these two objectives into a single optimization objective. For the case company, the hoist movement rule is analysed and a mixed integer programming model is developed to describe the current problem. Since this is an NP-hard problem, a novel hybrid guided tabu search algorithm, together with small combination sequences to generate a better initial solution and a guidance mechanism to generate neighborhood solutions, is proposed to obtain the near optimal solution. Experiments are performed on different size of problems to demonstrate the effectiveness of the proposed HGTS. Results indicate that the proposed HGTS outperforms its competitors. Finally, the proposed HGTS algorithm is applied in a real-world case and the result indicates that HGTS can solve the current problem effectively.

However, in current research, only parallel-tank area with one hoist is considered while most real PCB production lines contain non-parallel tank area and more than one hoist. In future study, two or more hoists and non-parallel tank area will be considered to find the optimal schedule of PCB input sequence and hoist move sequence.

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