Response Letter

Dec 19, 2023

Manuscript Details
Title: A Two-phase PCBA Optimization with ILP Model and Heuristic for a Beam-head Placement
ID: T-ASE-2023-1583

Authors' Response

Dear Reviewing Editor, Associate Editor, and all Reviewers,

We sincerely appreciate the Reviewing Editor, the Associated Editor and all Reviewers for their thorough reading and insightful advice that helped us improve the manuscript's quality. Thanks to their recognition to the merits in the manuscript and their professional suggestions for revision. The major change of this submission is the mathematical model reformulation, terminology check, experimental supplementation etc., which are listed as follows:

1) Mathematical model reformulation: We have reformulated the mathematical model in section IV. All the nonlinear terms have been discussed and a separated linear integer model is presented. We have revised the objective function for efficiency and further strengthen the constraints between component assignment and feeder assignment. A specific example of the solution for the model is given for more intuitive understanding of decision variables.
2) Terminology check: We apologize for the inaccurate statements and have revised the phases of "optimality" and "efficient" throughout the manuscript. The "optimality" is replaced by "high-quality", and "efficient" is replaced by "effective". These modifications are supported by relevant experiments.
3) Experimental supplementation: The section of experiments has been divided into experimental setup and comparative experiments. In the first subsection, we provide a detailed description of the platform, data, and algorithm parameters used for the experiments. The second subsection gives the experimental result. We have compared the solution quality between the proposed algorithms and mainstream research. The effectiveness of the core components of the two-phase optimization have been verified, including the effectiveness of the initial solution, reduction and refinement strategies, and terminated condition etc. Additionally, the solving efficiency has been compared in the experiment.

We have also tweaked the presentation, examples and figures of the manuscript, and made detailed revisions based on the Associated Editor and Reviewers' comments. Point-by-point responses to these comments can be found on the following pages. We have listed the reviewers' comments below in *italicized font* with blue text and numbered the specific concerns. Our response is given in normal font, and the changes to the manuscript are given in the red text and additions are given in underlined red text. We sincerely hope this revised version is considered for publication in *IEEE Transactions on*

Automation Science and Engineering and can be seen by more practitioners, throw a brick to catch the development of the electronic manufacturing industry.

Best wishes,

Authors of the manuscript.

Content

Response to the Associate Editor

1. *The terms "optimal" and "optimality" should be used only to denote the exact (best possible) solution of the problem, while "high-quality" or "good" should be backed by quantitative experimental comparisons.*

Response: Thanks for your advice. We apologize for the inaccurate representation of "optimality" in several places in the manuscript. It is not appropriate to refer to the solution of the model as optimal (esp. for the model is only part of the two-phase framework). Specially, we have double checked the relevant statements in the manuscript, and made the following revision:

- Page 1, second column, first paragraph, revise as "including visual recognition and positioning, advanced motion control, ~~optimal~~ scheduling techniques, etc. In this article, we study the ~~optimal~~ scheduling optimization techniques …".
- Page 2, first column, second paragraph, revise as "To improve the overall solution quality, we further select the ~~optimal~~ result the solutions of the model from the pool of the first phase".
- Page 3, second column, second paragraph, revise as "we employ a component partition strategy for ~~an approximation model that ensures that the key objectives influencing assembly efficiency are optimum~~ the ILP model. "
- Page 6, second column, last paragraph of Section IV, revise as "In general, the ~~optimal~~ solution of the model is not unique… ".
- Page 8, second column, second paragraph, revise as "The proposed method can find the ~~optimal~~ solution rapidly when…"
- Page 9, first column, first paragraph, revise as "…the ILP model-based technique ensures that the solution ~~is optimum and~~ outperforms the industrial solvers. "
- Page 9, first column, first paragraph of Section VII, revise as "the model-based solution method ensures that the result is deterministic and ~~the optimum of~~ optimizes the major performance indicators."

Although the optimality of the solution cannot be guaranteed, the formulation of "high quality" solution in the revised manuscript is supported by subsequent experimental results. The "high quality" is reflected in two aspects, the model's objective and the actual assembly time, which are listed in Table V and Table VII, respectively.

2. *Second, the term "efficient" should be used to denote a polynomial (at most, pseudopolynomial) time algorithm. So, most claims of optimality and efficiency in the paper should probably be reformulated to match the actual situation.*

Response: Thanks for your advice. The advantage of the proposed model lies in its availability to deal with the problem of optimizing PCB assembly data for industrial production (which is consistent with the data for the experiments). In industrial applications, where the number of component types and nozzle types is finite, the component partition strategy reduces the dependence of model complexity on the number of placement points. We apologize for wrongly summarizing this property as efficient (which does not satisfy the polynomial complexity). In fact, a more accurate term would be effective or tractable. Similarly, we have double checked the relevant statement and made the following revision:

- Page 1, first Column, first paragraph, revise as "An ~~efficient~~ effective integer linear programming (ILP) model with component partition is proposed…".
- Page 2, Column 1, first paragraph, revise as " An ~~efficient~~ effective integer linear programming (ILP) model with … ".

To illustrate the "effective", we added a comparison experiment to the experimental section to illustrate the time taken to solve the model. Three mainstream research is selected for comparison. A general conclusion is that since the manuscript considers more factors, the solving time is still acceptable, even though it does not have a quicker solving time. The relevant statement for solving efficiency has been added in the manuscript as "Lastly, we make a comparison of the model's solving time ... As modeling methods, TPPO (the proposed method) is solved longer because of the inclusion of pickup constraints compared to AGM but is significantly faster than HGA. Except for single component type, the solving times of another evolutionary-based technique, CDGA and TPPO are relatively near to one another. Even though the PCB10 requires more time for TPPO, its assembly efficiency is higher, and the time is within an acceptable amount."

TABLE VIII

COMPARISON OF THE SOLVING TIME OF THE PROPOSED MODEL WITH MAINSTREAM ALGORITHMS

PCB	TPPO	CPO	AGM	HGA	PCB	TPPO	CDGA	AGM	HGA
1	0.4	-	0.3	138.2	6	34.7	30.1	0.5	264.2
2	4.2	41.0	0.2	218.2	7	32.0	30.1	1.1	94.2
3	15.9	35.7	0.2	373.0	8	67.6	20.1	0.9	88.0
4	31.5	36.8	0.3	134.6	9	46.4	23.0	0.4	158.9
5	31.5	33.5	0.4	172.8	10	95.3	27.0	1.2	153.9

3. *The mathematical formulation is not linear but is solved with a mixed integer linear solver. The linearization, that has probably been adopted, should be discussed, in particular stating whether it is exact, relaxed (that is, possibly allowing unfeasible solutions) or restricted (that is, possibly removing feasible solutions).*

Response: Thanks for your comment. All the linearization has been adopted is exact, and linearization methods adopted in the manuscript include big-M method, variable substitution, and equivalence transformations. The decision variables in the model are all integers and the linearization methods do not change the feasible domain. We have reformulated the mathematical model, which has three nonlinear terms in Section IV, and have linearized them. The nonlinear term $w_l \cdot p_{sl}$ in the objective can be replaced by an intermediate variable λ_{sl}, which can be linearized with big-M method as

$$\begin{cases} \lambda_{sl} \leq M \cdot p_{sl} \\ \lambda_{sl} \leq M \cdot w_l \\ \lambda_{sl} \geq w_l - M \cdot (1 - p_{sl}) \end{cases} \quad \forall s \in S_e, l \in L$$

Constraint (3) with nonlinear term $w_l \cdot p_{sl}$ can be linearized as

$$\begin{cases} c_{ihl} \leq M \cdot u_{ihl} \\ c_{ihl} \leq M \cdot w_l \\ c_{ihl} \geq w_l - M \cdot (1 - u_{ihl}) \end{cases} \quad \forall i \in I, h \in H, l \in L$$

Constraint (8) determines the number of nozzle change

$$d_{lh} = \frac{1}{2} \sum_{j \in J} \left| z_{jhl} - z_{jh(l+1)} \right|$$

which can be linearized as

$$\begin{cases} d_{lh} = \frac{1}{2} \sum_{j \in J} \left(d_{jhl}^{+} + d_{jhl}^{-} \right) \\ z_{jhl} - z_{jh(l+1)} = d_{jhl}^{+} - d_{jhl}^{-} \quad \forall j \in J, h \in H, l \in L \\ d_{jhl}^{+} \geq 0, d_{jhl}^{-} \geq 0 \end{cases}$$

The term $\gamma_{ishl} = u_{ihl} \cdot v_{shl}$ can be linearized as

$$\begin{cases} \gamma_{ishl} \leq u_{ihl} \\ \gamma_{ishl} \leq v_{shl} \\ \gamma_{ishl} \geq u_{ihl} + v_{shl} - 1 \end{cases} \quad \forall i \in I, s \in S, h \in H, l \in L$$

It can be seen that the linearization of the manuscript is exact, and the objective (1) with replacement $w_l \cdot p_{sl}$ by λ_{sl}, and constraints (2), (4)~(7), (9)~(17) consist an integer linear model.

4. *The authors seem to denote as "meta-heuristics" the local search heuristics that end up in a locally optimal solution. By definition, a meta-heuristic goes beyond ("meta") local optima. They also attribute "little comprehension of the underlying mechanism" of the problem to meta-heuristics, that on the contrary are based on a deep analysis of the properties of the problem (except for few very bad implementations of genetic algorithms). The statement that "constructive heuristics ... improve the quality of the solution by guiding the search direction" seems to have little relation constructive algorithms (may be they refer to local search heuristics?).*

Response: Thanks for your comment. We apologize for the misrepresentation. The statement has been revised as "~~Meta-heuristic is tackled at the price of efficiency, with little comprehension of the underlying mechanism of the optimization problem.~~ Meta-heuristics are stochastic search methods with relatively low convergence rate, and it is a great challenge when dealing with complex combinatorial optimization problems. … Constructive heuristics ~~design search rules based on the structure of the problem~~ are intuitive or empirically designed algorithms that give feasible solutions …". In practice, construction heuristics tend to be more advantageous (at a smaller cost) in dealing with large-scale combinatorial optimization problems, with the disadvantage that the quality of the solution cannot be guaranteed. In the manuscript, we use the model's solution as the constraint of the constructive heuristic search, which can improve the lower bound of the solution, reduce the search space, and thus obtain high-quality solutions.

5. *The "prejudge" means to get a premature opinion based on insufficient information, which is probably not what the proposed algorithm is meant to do.*

Response: Thanks for your comment. We apologize for that there may be a lack of clarity in the presentation. The "prejudge" mentioned in the manuscript refers to an estimated moving distance of the assembly path. For PCBA problem, we have decomposed it into head task assignment and placement route schedule problem. The optimal solution of the model is not unique, and solving the placement route schedule problem with all head task assignment solutions as constraints is time consuming and intractable. Therefore, after completing the first phase, we must select one of the many solutions of the ILP model to enter the next phase for route schedule.

As your comment, prejudgment is based on insufficient information. The insufficiency of information is mainly reflected in the fact that, relying only on the solution of the head task model, we can only know the set of points accessible by each head, and are not sure about the specific points and order in which each head is placed. The "prejudge" refers to replacing the computed value of the actual moving distance with an estimated one based on the layout of the different types of placement points on the board.

Based on the above discussion, we have adjusted the content of the manuscript to avoid ambiguity for readers as: "…we further select ~~the optimal result~~ the solutions of the model from the pool of the first phase. ~~based on the placement route prejudgment.~~ When there is insufficient information regarding the points and sequence of heads place, the prejudgment heuristic provides a fast selection criterion based on the estimated assembly path of the pool of solutions."

Response to the Reviewer #1

1. *The problem(s) to be solved for the PCBA are not specified in the title of this paper. I think this is not helpful for readers to catch the problems to be solved in this paper.*

Response: Thanks for your advice. We have revised the title of the manuscript as "A Two-phase PCBA Optimization with ILP Model and Heuristic for a Beam-head Placement Machine. " We hope such modifications will help relevant practitioners to catch the manuscript which may contribute to their research.

2. *The comparative results are shown in Table III. However, it is found that the results are very rough. It needs to show the Z value of your objective function so as to identify the best one.*

Response: Thanks for your advice. We have revised Table V (Table III for previous version) with Z value of the objective function as shown below. The analysis of Table V and corresponding sub-objectives value has been discussed in the experimental section as "When comparing the Z-values of weighted sub-objectives in Table V, it becomes evident that AGM is not as effective as the methods that consider pick-up efficiency, such as TPPO, CPO, HGM and HGA. In the majority of PCBs, the cycle counts of TPPO and CPO are comparable. However, TPPO performs better in terms of nozzle changes and pick-up. In summary, TPPO outperforms the other four mainstream research studies in terms of weighted objectives. ".

TABLE V
COMPARISON OF THE OBJECTIVES OF THE PROPOSED MODEL WITH MAINSTREAM ALGORITHMS

PCB Case	Proposed ILP Model	Industrial Optimizer	Cell Division GA	Aggregated Model	Hybrid GA
1	**-0.448**	**-0.448**	-0.446	**-0.448**	1.789
2	**-0.846**	-0.679	-0.279	-0.153	1.650
3	**-1.089**	**-1.809**	0.898	0.603	0.677
4	**-0.864**	-0.318	0.625	1.420	**-0.864**
5	**-0.942**	0.211	0.211	1.461	**-0.942**
6	**-0.996**	1.208	-0.254	0.883	-0.840
7	**-0.527**	-0.370	-0.360	1.783	**-0.527**
8	**-1.470**	-0.104	0.005	1.331	0.238
9	**-1.100**	-0.936	0.127	1.147	0.763
10	**-0.715**	-0.431	-0.325	1.764	-0.293
AVG	**-0.900**	-0.295	0.020	1.010	0.165

3. *It needs to give more explorations on the results. For example, in case 2 why the pick-up numbers are different in different approaches (120 in the proposed ILP model, 124 in the Cell Division GA)? Given the fixed number of 120 for the component type C1 and the fixed number of 96 for the component type C2, then should not the total number of pick-ups be fixed 120+96?*

Response: Thanks for your comment. Since multiple heads can pick up multiple components at once, we refer to these simultaneous operations as a pickup, which explains why the 216 points in case 2 only need to be picked up 120 times. We apologize for not explaining this in detail, which could confuse the readers, and a clearer example has been added to the manuscript in Section III as "The beam-heads are mechanically designed for simultaneous pick-up operations to improve efficiency. Simultaneous operations for pick-up by multi-heads are counted as single pick-up. ⋯ An example is shown in Fig. 2, where heads 3, 4, and 5 pick-up components from slots F9, F11, and F13, respectively, which is counted as one pickup. Subsequently, head 1 is moved to slot F22 to pick up the component; the gantry is then moved again to align heads 2 and 6 onto slots F30 and F38 for one pickup, for a total of 3 pickups. Taking the head 1 aligned slot for pickup as the equivalent slot, the gantry moves through a total of 23 slots on the feederbase. ".

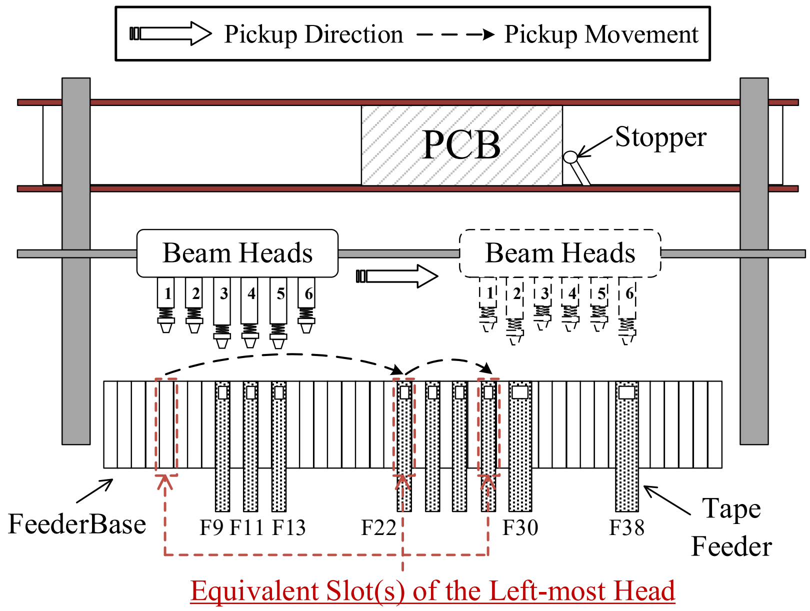

Fig. 2. Schematic diagram of the pick-up process for beam-head placement machine.

4. *The Table III is still not a good presentation of the results. It only displays the results of three decision variables (d_{lh}, w_l, u_l), but we cannot see the results of the other decision variables. It is suggested to show a higher resolution to a solution obtained by, at least, your proposed method based on a small-scale example. I think a better presentation that you can use is representing the solutions corresponding to the decision variables defined in your ILP model through the use of a small-scale instance. This gives a consistent presentation in terms of the ILP you develop.*

TABLE II

A SPECIFIC EXAMPLE FOR THE SOLUTION OF THE ILP MODEL

Cycle	H1	H2	H3	H4	H5	H6
#1 w_1=44		$u_{1,2,1}$=1 $v_{1,2,1}$=1 $z_{1,2,1}$=1	$u_{1,3,1}$=1 $v_{1,3,1}$=1 $z_{1,3,1}$=1	$u_{4,5,1}$=1 $v_{2,4,1}$=1 $z_{2,4,1}$=1	$u_{2,5,1}$=1 $v_{3,5,1}$=1 $z_{1,5,1}$=1	$u_{3,6,1}$=1 $v_{4,6,1}$=1 $z_{1,6,1}$=1
#1 w_2=22	$u_{4,1,2}$=1 $v_{2,1,2}$=1	$u_{2,2,2}$=1 $v_{3,2,2}$=1	$u_{1,3,2}$=1 $v_{1,3,2}$=1	$u_{4,4,2}$=1 $v_{2,4,2}$=1	$u_{2,5,2}$=1 $v_{3,5,2}$=1	$u_{3,6,2}$=1 $v_{4,6,2}$=1

	$z_{2,1,2}$=1	$z_{1,2,2}$=1	$z_{1,3,2}$=1	$z_{2,4,2}$=1	$z_{1,5,2}$=1	$z_{1,6,2}$=1

Response: Thanks for comment, A small-scale instance has been given in the manuscript, which is described as "Additionally, we present the solution for a small instance consisting of four component types, each with 110, 88, 66, and 88 points. Table II lists the non-zero values of the decision variables u_{ihl}, v_{shl}, z_{jhl} and w_l along with the feeder allocations, which are $f_{1,1} = 1$, $f_{4,2} = 1$, $f_{2,3} = 1$, $f_{3,4} = 1$ and others are zero. There are 44 cycles in the first cycle group and 22 cycles in the second. Component type 2, for instance, is allocated to slot 3 and is picked up with nozzle type 1 by head 5 in the first cycle group and by head 2 and head 5 in the second cycle group. "

5. *In the experiment result (section VI), it is better for you to give a parameter setting subsection and the experimental result subsection, which helps improve the structure of this paper.*

Response: Thanks for your advice. We have reorganized the experiment (section VI) into two subsections: parameter setting and comparative experiments. In the first subsection, we present the parameter settings of the two-phase algorithm, including model coefficients, terminated condition, and solution pool parameters, as well as the PCB data for the experiments. In the second subsection, we conduct comparison experiments between the proposed algorithm and four mainstream methods, which mainly include sub-objective comparison, running time, assembly movement and assembly time, and we add experiments to illustrate the effectiveness of the core components on the algorithm's effectiveness.

6. *How about the feeder assignment, the assignment of components (types) to the feeders appears to impact the performance of the machine.*

Response: Thanks for your comment. The feeder assignment problem can be viewed as a location problem. In the manuscript, the feeder assignment is a part of head task assignment, which is a key factor in pickup efficiency. The feeder assignment has a great impact on assembly efficiency in two aspects: pick-up operations and movement process. For the former, several beam-heads oriented to different slots can pick up components simultaneously. The latter affects the movement of the pickup procedure according to the location position. Furthermore, depending on the component type, the heads must decide whether to move to the ANC to change the nozzle for simultaneous pickup.

We have added these to the manuscript in Section III: "The feeder assignment determines the travel path of the heads' pickup process, and for multi-heads to pick up components simultaneously, the heads need to change the nozzles according to the component type in the feeder, all of which can affect pickup efficiency. "

7. *What is the function of the parameter ε you define in the Table I?*

Response: Thanks for your comment. The parameter ε can be regarded as a weighting coefficient. In the PCB assembly, the feeder is usually assigned centrally in a range of several consecutive slots, and the time spent on its moving accounts for a small proportion of the overall assembly time. We observe in the following example that for two different solutions, whose main performance metrics (except for the pickup travel distance) are identical. We number the heads distributed side by side from left to right (H1 is short for head 1).

The index in the table below indicates the cycle group index, and the feeder slot is indicated by the number in the column where the heads are located. We assume that the distance between the heads is equal to the distance between the slots, therefore in the first cycle group of Case A, the first four heads can perform one simultaneous pickup, and the last two heads can perform another simultaneous pickup, for a total of two pickups each cycle.

Case A:

Index	H1	H2	H3	H4	H5	H6	PAP cycles
1	1	2	3	4	2	3	44
2	1	2					22

Case B:

Index	H1	H2	H3	H4	H5	H6	PAP cycles
1	1	2	3	4		3	44
2	1	2	3	4			22

Both case A and B have the same number of pickups (the heads pickups twice per cycle for the first 44 cycles and pickups once per cycle for the last 22 cycles, for a total of 110 pickups). However, for case A, the H1 first moves to slot 1 (the first four pick up simultaneously), then H5 moves to slot 2 (the last two pick up simultaneously), and we can see that the heads move a total of 3 slots per cycle. Similarly, for case B, the heads move 4 slots per cycle for the first cycle group. Therefore, the assembly efficiency of case A is better than case B. A small pickup travel distance can also have a large impact on the overall efficiency after many repetitive cycles of pickup. Therefore, we use a small weighting parameter to select the better one from them.

In the revised manuscript, since the small value of the coefficient may affect the solving efficiency of model, we combine the pickup moving distance and the placement moving distance as a criterion for selecting a solution from the solution pool. The related content has been added in the subsection IV-D as " In general, the optimal solution of the model is not unique, and different solutions indirectly affect the movement of the gantry. We propose a fast heuristic algorithm for selecting one result from the solution pool. First, the assignment of head task determines the traveling path of the pickup process as

$$E_1 = \frac{\tau}{r}\sum_{l \in L} w_l \cdot \mathcal{R}\{v_{shl} \cdot (s - h \cdot r + r) | v_{shl} \neq 0, s \in S, h \in H\}$$

where $\mathcal{R}$ denotes the range of the set. " The pick-up and placement process prejudgment together complete the selection of the solution pool.

8. In Tables II and III, change "Case" to "PCB Case" will be better for understanding.

Response: Thanks for your advice. We have changed "Case" to "PCB" for all tables, since "Case" is used for the test case in Table VI.

9. In page 4, the assumption of ignoring the movement of the beam-head to ANC is justified?

Response: Thanks for your comment. We are sorry for our insufficient explanation. In fact, for the proposed model, the coefficient for nozzle change incorporates the process of moving to the ANC and the time taken for the change operation, therefore we say that it is reasonable to ignore this factor. In the Section III of the manuscript, we have modified this assumption as " ~~The beam-heads movement to ANC for nozzle change is Ignored,~~ The time spent moving to the ANC for nozzle change is included in the nozzle change time, …"

10. The "Step X" in Section III is buried in the text. The use of a boded style format is suggested for improving readability.

Response: Thanks for your advice. It's very presumptuous of us to guess that you're referring to the use of a bolded (rather than boded) style format of "Step X" in Section IV and V (rather than Section III). We have revised the relevant style format.

11. The notations (D, T, ΔD, ΔT) in Table IV have not been specified.

Response: Thanks for your comment. We have added this statement to the experimental section as: "The notation D (replaced by $\mathcal{D}$) and T (replaced by $\mathcal{T}$) represent the moving distance and assembly time, while the superscripts T, P, C, A and H represent the proposed method, industrial component placer optimizer, cell division GA [14], aggregated model [11] and hybrid GA [3], respectively. ΔD (replaced by $\Delta\mathcal{D}$) and ΔT (replaced by $\Delta\mathcal{T}$) correspond to the improvement rates of D (replaced by $\mathcal{D}$) and T (replaced by $\mathcal{T}$), respectively, relative to our proposed method comparing with different methods. "

12. A future research direction is expected.

Response: Thanks for your advice. We have added an outlook for future research direction in the conclusion section, as "Future research can focus on the mathematical model; while the model has been enhanced in terms of completeness, there is still opportunity for improvement in terms of solving efficiency. How to generate the initial solutions by utilizing the structural characteristics of the route schedule problem and designing a better local search strategy can be further developed by other practitioners. Finally, different problem decoupling methodologies are expected to be thoroughly researched. "

Response to the Reviewer #2

1. *From the introduction throughout the paper, the authors refer to efficient and optimal solutions. These problems are NP-hard or worse in most cases and it is not clear how the claim of efficiency and optimally is met. Please revise and reformulate these claims of optimality and / or efficiency as they cannot both hold.*

Response: Thanks for your advice. We apologize for this wrong statement. Regrettably, our proposed method is neither efficient nor is the solution optimal. However, the proposed model still has value for application.

The optimality we propose is conditional optimality, specifically the assembly efficiency is evaluated in terms of the ILP model objective function, and the solution of the model is optimal (meaning optimal in terms of the objective function). We evaluate the assembly efficiency in terms of an objective function with an estimated property, which from the experimental results leads to at least a high-quality solution (compared to other methods). For algorithmic complexity, it is more accurate to say that the model is effective and can be applied to real-world problems.

We have revised all the phrases about optimality (replaced by "high quality") and efficiency (replaced by "effective") in the manuscript, and we have also added statements to the experimental section to support the rationale for such a modification.

2. *The abstract claims that an "efficient integer linear programming (ILP)" model is presented. ILP is also NP-hard in general. Please show how and why is the ILP model efficient in general, or at least for the practical cases evaluated.*

Response: Thanks for your advice. We are sorry for not guaranteeing that the model is efficient (which does not have polynomial complexity). However, this does not affect its application to real-world problems, and we add the results of the computation time in the experimental section, which would at least suggest that the algorithm is effective in the practical cases evaluated.

3. *The mathematical program presented in the paper is not linear in its current form, see equation 11 on page 4 containing the product of two decision variables.*

Response: Thanks for your comment. The decision variables in the manuscript are all integer variables. In equation 11 on page 4, two multiplying variables are both binary variables, and their product is also a binary variable. A general way to deal with the binary product term is equivalence transformations. As for binary variables x, y, z, and $z = x \cdot y$, we have the equation that

$$\begin{cases} z \le x \\ z \le y \\ z \ge x + y = 1 \end{cases}$$

which is a linear equation. Linearization methods adopted in the manuscript include big-M method, variable substitution, and equivalence transformations. All the non-linear terms have been linearized and a separate integer linear model has been given in the manuscript.

4. *A relaxation of these constraints is made by the paper, but it is recommended that the relaxed version (if it is an ILP) is presented separately and the issue pointed out above in (2) is discussed.*

Response: Thanks for your comment. The model presented in the manuscript is an integer linear model without a relaxation version. We note that there are some statements that may give rise to ambiguities, such as the discussion in Section IV-B. The content exposition has been revised: " ~~The first step in adopting the standard method to solve the model is typically to find a feasible solution to the relaxation form of the model.~~ In the solution framework of the integer programming model based on the branch-and-cut algorithm, starting the search with the initial solution help find the optimal solution faster and provide guidance for the algorithm search direction, which in turn affects the whole search process.".

5. *The abstract and results also claim that "high-quality solutions" are obtained. This can be the case even for NP-hard problems, but it requires a comparison to existing method or a proof of approximation ration in order to better understand the "high-quality" qualification.*

Response: Thanks for your comment. To illustrate the "high-quality" of the solution obtained by the proposed method, several sets of experiments with different characteristics (referring to component and nozzle types) have been selected for comparison and validated on a physical platform. The comparison method contains multiple mainstream methods including mathematical modeling and meta-heuristics. The comparison dimensions include two parts: assembly distance and movement path. The experimental results show that for assembly time our proposed method improves 8.06% with respect to industrial optimizer, 13.06% with respect to cell division GA, 24.32% with respect to aggregated model, and 24.31% with respect to hybrid GA.

6. *In the result, the authors present an evaluation of the method on practical PCB instances. It is not clear how many of these instances are generated and how many are actual cases from production (like IPC9850). A suggestion here is to either add more actual industrial cases, or to generate PCB instances using similar probability distribution of the different nozzle types as in the industrial cases.*

Response: Thanks for your comment. In the experimental section, we have added a description of the experimental data as "In Table III, which lists the basic parameters of the model and the characteristic of the PCB data, we select 10 different PCB data; among them, the first one is an international standard speed-test data IPC9850; the second to the fifth data with relatively less component types and randomly generated placement points are applied to test the generalizability of the algorithm; the last five are selected from the actual industrial sites, to validate the application of the algorithm in practice. "

7. *Also: on page 8 it is correctly observed that the PCB8 case was not fully solvable, invalidating the earlier claims of optimality and efficiency.*

Response: Thanks for your comment. We apologize that the term "optimality" is not accurate. A more accurate term, "high-quality", replaces the term "optimality". The claim of "high-quality" is supported by experimental data in Table V and Table VII. For PCB8~PCB10, even though it is not fully solvable (under the predetermined terminated condition), we compare the solution with the benchmark (the currently known optimal solution), which has a gap between them less than 11.22%, which we consider it is acceptable (which is a compromise between solution quality and efficiency). This solution of proposed two-phase algorithm also shows its advantage in assembly efficiency in comparison with other mainstream methods.

As for the solution efficiency, we also compare it with other mainstream studies in Table VIII. The search time is acceptable in solving different problems, and the relevant statement in the manuscript is added as "Lastly, we make a comparison of the model's solving time, CPO is not included in the comparison since the specific algorithm is not disclosed. … As modeling methods, TPPO is solved longer because of the inclusion of pickup constraints compared to AGM but is significantly faster than HGA. Except for single component type, the solving times of another evolutionary-based technique, CDGA and TPPO are relatively near to one another. Even though the PCB10 requires more time for TPPO, its assembly efficiency is higher, and the time is within an acceptable amount of time."

TABLE VIII

COMPARISON OF THE SOLVING TIME OF THE PROPOSED MODEL WITH MAINSTREAM ALGORITHMS

PCB	TPPO	CPO	AGM	HGA	PCB	TPPO	CDGA	AGM	HGA
1	0.4	-	0.3	138.2	6	34.7	30.1	0.5	264.2
2	4.2	41.0	0.2	218.2	7	32.0	30.1	1.1	94.2
3	15.9	35.7	0.2	373.0	8	67.6	20.1	0.9	88.0
4	31.5	36.8	0.3	134.6	9	46.4	23.0	0.4	158.9
5	31.5	33.5	0.4	172.8	10	95.3	27.0	1.2	153.9

As mentioned earlier, the term "efficient" has been replaced by "effective", and the term "optimal" has been replaced by "high-quality" in the manuscript.

8. *page 1, first paragraph introduction states: "we study the optimal scheduling techniques of the surface assembly...". I would recommend to change this to "scheduling optimization techniques" as optimal scheduling probably cannot be attained in these cases efficiently.*

Response: Thanks for your advice. We very much recognize your comment and have revised the content in the abstract.

9. *page 2: please reformulate the phrase starting as "Meta-heuristic is tackled at the price", its meaning is not clear in its current form.*

Response: Thanks for your advice. We have reformulated the phrase starting as "~~Meta-heuristic is tackled at the price~~" with statement "Meta-heuristics are stochastic search methods with relatively low convergence rate and it is a great challenge to deal with constraints for complex optimization problems."

10. *page 2: phrase "the proposed model is more comprehensive than conventional modeling approach", I think more explanation of this is required in the results section, why it is more*

comprehensive?

Response: Thanks for your advice. We think that the proposed model (Two-Phase PCBA Optimization, TPPO) is more comprehensive based on the model's application and experimental results in two ways: first, its objective function includes the key factor of pickup efficiency and thus has a higher assembly efficiency (as shown in Fig.4) compared with an aggregation-based model (AGM), and second, it has decision variables of feeder allocation which has not mentioned in the previous research.

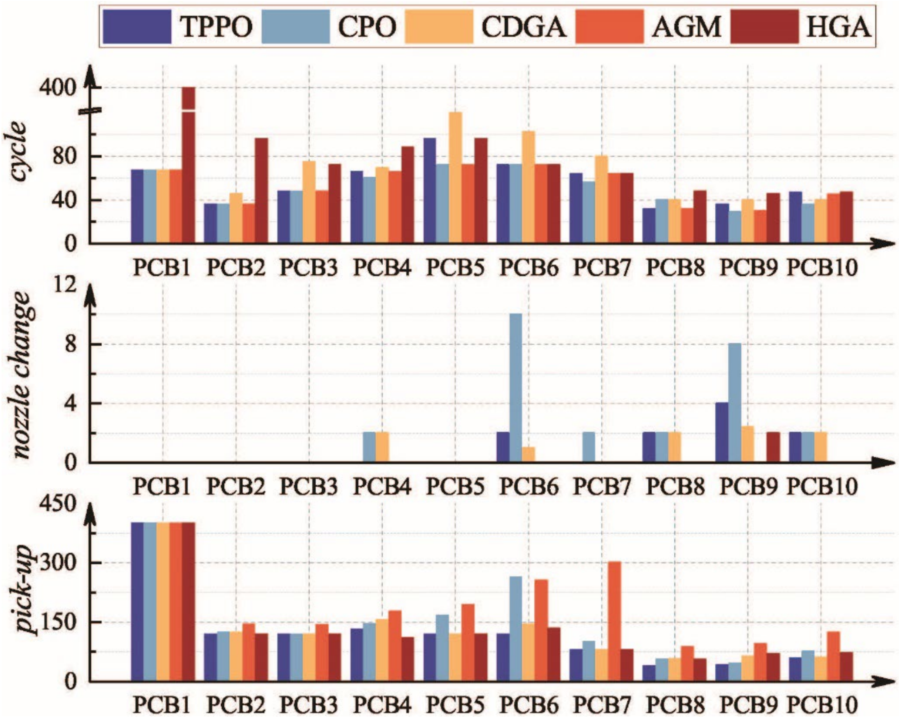

Fig. 4. The histogram of the sub-objectives' comparison between proposed model and mainstream algorithms.

A more accurate statement would be "the proposed model is more comprehensive than the conventional approach, rather than only for modeling approach." We have added statement to the experimental section to illustrate the comprehensiveness of the proposed modeling approach, as "<u>The cycle scheduling difficulties are better handled by model-based TPPO, AGG and industrial solver CPO, whereas evolutionary-based CDGA and HGA typically have more PAP cycles because of the stochastic search. AGM and HGA forbid changing the nozzle, which prevents some of the simultaneous pick-up operations from being carried out and lowers the overall efficiency. Both TPPO and AGM are model-based algorithms; however, the former takes into account the mechanical characteristics, and has a greater pick-up efficiency. When comparing the Z-values in Table V, it becomes evident that AGM is not as effective as the methods that consider pickup efficiency, such as TPPO, CPO, HGM and HGA. In the majority of PCBs, the cycle counts of TPPO and CPO are comparable. However, TPPO performs better in terms of nozzle changes and pick-up. In summary, TPPO outperforms the other four mainstream research studies in terms of weighted objectives.</u> "

11. *page 2: phrase "the two-phase method ensures the optimality", I suggest reformulating this as there is no optimality reached in the results, (remember, these problems are NP-hard)*

Response: Thanks for your advice. We apologize for this hasty statement. What we would like to present is that the proposed model guarantees to obtain high quality solutions, which mainly reflected in that the objective function of the model contains the major factors affecting the assembly efficiency. We have revised the phrase as "the first phase guarantee high-quality solution because of the objective of the ILP model covering the major factors that affecting the assembly efficiency." This statement has been verified in subsequent experiments.

12. page 2: phrase "we further select optimal results" how do we know these are "optimal".

Response: Thanks for your comment. We apologize for referring to the solution of the model as the optimal results, which is not appropriate, and have modified the statement as "we further select the ~~optimal~~ solutions of the model from the pool …"

13. page 2: towards the bottom, phrase "An efficient integer linear model", please separately present the ILP and indicate why is efficient. ILP in general is NP-hard (and NP-complete to decide) and there are no known efficient methods to solve it (in general).

Response: Thanks for your comment. In the 4th response, we have given a separate model. In fact, the problem solved is also a NP-hard problem, and the proposed method does not have polynomial complexity. We apologize for the inaccuracy of the statement "efficient", and a more accurate term would be "effective". That is, the proposed methodology can be used in solving practical problems (as present in the experiment section). All the term "efficient" has been revised as "effective".

14. page 2: second column, point 3 "high-quality solution guarantee" needs to be reformulated in light of the earlier observations.

Response: Thanks for your comment. We have provided additional clarification in our 5th response.

15. page 3: first column, towards the bottom, phrase "restricted capacity vehicle routing". Capacitated vehicle routing is also NP-hard in general, it would be good to know what restrictions are employed.

Response: Thanks for advice. As described in the manuscript, we regard the placement route scheduling problem as a restricted capacity vehicle routing problem. They are similar in that the number of points that can be visited during a tour (which we call a cycle for the assembly process) is limited (depending on the number of heads). The difference is that the set of points that may be accessed for each tour (limited by the component type allocated to each head) is different for each tour, and the expected moving position of the head is different even though the same point is placed by various heads in a tour.

We have rewritten the description of the assembly process in Section III and included a description of what restrictions are employed as "The placement route schedule problem can be regarded as capacity vehicle route schedule problem, with restriction of head-accessible point set. In addition, even for the same point, the gantry moves to different position when different heads are placed. It is shown that the placement route schedule problem is nevertheless an NP-hard problem, and the added constraints rather increase the difficulty of solving the problem.".

16. page 3: second column, phrase "To reduce complexity of the model..." please clarify how and why optimality can be reached through partitioning.

Response: Thanks for your comment. We apologize for that the optimality cannot be reached through partitioning. The implication described in the manuscript is that the proposed models that employ the component partitioning strategy can guarantee the optimum of the key metrics. We have noticed that this statement is open to ambiguity and revised as "The first phase method guarantees high-quality solution because of the objective of the ILP model covering the major metrics that affecting the assembly efficiency. "

The experiments and statements about component partition have also been added to the manuscript as "As shown in Table VIII, comparing with the TPPO, we can conclude that the component partition is an effective way to improve the search efficiency. The model without component partition can only be applied in solving small scale data, for PCB1~PCB3, the solving time is 21.41, 70.18 and 193.23 seconds respectively, which is much larger than the proposed model."

17. page 3 and 4: the mathematical program is not linear, there are several cases of decision variables being multiplied. Please clarify if there are relaxations to this model that make it linear, and if so, present a separate ILP.

Response: Thanks for your comment. All the non-linear terms have been discussed and linearized. A separate ILP has been given in the manuscript.

18. page 5: second column, last paragraph: some relaxation to the problem are made here, please clarify how does this relate to actual practical cases (can we make these relaxations in practice).

Response: Thanks for your comment. We think what you are referring to should be the reduction and refinement of the model, which contains two aspects. First, the adjacent from two feeders is ignored since the mechanical structure of the heads determines that there is a certain spacing between the feeders that are picked up simultaneously. Spaced assignment is a common strategy, especially for small to medium sized data with a limited variety of components. To prove this statement, we added the relevant experiments in Section IV. Second, the relative slots of the feeder assignments determine the pickup operations. As stated in the manuscript, "the feeders are usually densely arranged in a limited range of the feederbase and slots farther away from the PCB are always ignored", we use a reference slot to qualify the starting slot of the leftmost feeder of the assignment, which in turn determines the assignment of all feeders.

The statement of the former is revised as "First, the large number of available feeder slots increases the difficulty of solving the model. The number of interval slots between adjacent feeders is ~~usually r-1~~fixed for small and medium-scale data. ~~Thus, setting r=1 does not affect the optimality of the solution but~~ Ignoring the spacing between adjacent feeder is a common strategy which can substantially reduce the complexity of the model."

Related experiments are supplemented in the experiment section. As shown in Table VI, TC-1 and TC-3 represent the solution of the model with and without reduction and refinement strategy. $\mathcal{F}_b$ refers the currently known optimal solution (regardless of the time cost). The experimental results conclude that "Regarding the reduction and refinement technique, despite the fact that theoretically it helps achieve better solutions, the model iterates more slowly in practice and has a larger gap than the improved model under the terminated condition." The feasibility of these strategies is further verified by our physical validation on a self-developed placement machine.

TABLE VI
COMPARISON OF MODEL SOLVING PROCESS WITH DIFFERENT TEST CASE

	PCB	1	2	3	4	5	6	7	8	9	10
BASE	$\mathcal{F}_b$	934	312	336	396	432	390	288	158	164	196
TC-1	$\mathcal{F}_1$	934	312	336	396	432	390	288	158	168	218
	$\mathcal{G}_1$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.44	11.22
TC-2	$\mathcal{F}_2$	934	312	336	396	432	390	288	162	-	-
	$\mathcal{G}_2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.53	-	-
TC-3	$\mathcal{F}_3$	934	312	336	396	432	390	288	172	192	220
	$\mathcal{G}_3$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.86	17.07	12.24

19. page 6: start if paragraph V. "large solution space" (not broad)

Response: Thanks for advice. We have reformulated the phrase "~~The solution space for the placement route schedule is broad~~" as "The placement route schedule problem has a large solution space".

20. References: I suggest more references to literature on SMT assembly robotic head route planning, and maybe one or two articles on "capacitated vehicle routing" as it was used in the problem solution.

Response: Thanks for your advice. We have added more references to literature on related head route planning and capacitated vehicle routing in Section II as "Placement route schedule is one of the significant subproblems that has been extensively researched. The edge-based and route-based models have been developed in [22], and the latter is solved by branch-and-price methods with effective branch rules. Research has been done on greedy constructive heuristics in [3], [8], [11]. The challenges have also been solved using multi-objective evolutionary algorithms [23] and bilevel ant colony methods [24]. In [25], a two-phase method for small instances is proposed that combines an integer model with a travel salesman problem solver. Other studies have also focused on learnt methods. A heuristic sequencing method based on Hopfield networks is proposed in [26], and constructive heuristics are the emphasis of [27], with deep reinforcement learning techniques employed to learn improvement heuristics. "

Response to the Reviewer #3

1. *An initial solution is generated to the relaxation. The reviewer thinks the solution quality should be evaluated to demonstrate the effectiveness of the heuristic.*

Response: Thanks for your advice. We have added relevant experiment in Table VI to illustrate the role of the initial solution in improving the efficiency of the solving process. In the manuscript, we call the model that used the component partition, reduction and refinement techniques as the improved model, and the model without the proposed techniques as the original model. The benchmark value $\mathcal{F}_b$ is the currently optimal solution. (For small scale PCB, it is obtained by solving the original model; for medium scale PCB, it is obtained by comparing the better one of the mainstream studies and solution of the improved model with sufficient searching time.)

The formula for the test case t's gap is $\mathcal{G}_t = \left(\frac{\mathcal{F}_t}{\mathcal{F}_b} - 1\right) \cdot 100\%, t = 1,2,3$. As can be shown in Table VI for TC-2, the improved model's highest gap from the benchmark is 11.22%. The effectiveness of the initial solution has been stated in the manuscript as "The model solution can be quickly iterated with the aid of the initial solution, and in the terminated situation, the feasible solutions for PCB9 and PCB10 are not even attainable."

TABLE VI

COMPARISON OF MODEL SOLVING PROCESS WITH DIFFERENT TEST CASE

	PCB	1	2	3	4	5	6	7	8	9	10
BASE	$\mathcal{F}_b$	934	312	336	396	432	390	288	158	164	196
TC-1	$\mathcal{F}_1$	934	312	336	396	432	390	288	158	168	218
	$\mathcal{G}_1$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.44	11.22
TC-2	$\mathcal{F}_2$	934	312	336	396	432	390	288	162	-	-
	$\mathcal{G}_2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.53	-	-
TC-3	$\mathcal{F}_3$	934	312	336	396	432	390	288	172	192	220
	$\mathcal{G}_3$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.86	17.07	12.24

* Excerpts from the manuscript: "TC-1 represents the solution of improved model; TC-2 represents the solution of the improved model without the initial solution; and TC-3 represents the solution of improved model without the reduction and refinement technique."

2. *Similarly, the core components of the two-phase approach are required to be evaluated to verify the necessity of their existence.*

Response: Thanks for your advice. The core components of the two-phase approach are discussed from several perspectives as blow.

1) Mathematical Model

An integer linear model is proposed in the manuscript to optimize the head task assignment of the PCB. In terms of optimization objectives and constraints, the proposed model is more comprehensive than previous research. The necessity of the model is it effectively optimizes key sub-objectives that affect assembly efficiency. We have discussed the advantages of the proposed method when dealing with the sub-objectives in the experimental section. Based on the results in

Table V and Table VII, a preliminary conclusion is that methods that handle weighted sub-objectives better tend to have higher assembly efficiency.

2) Component Partition Strategy

As shown in Table VII, compared with the TPPO (proposed algorithm), we can conclude that the component partition is an effective way to improve the search efficiency. The model without component partition can only be applied in solving small scale data, for PCB1~PCB3, the solving time is 21.41, 70.18 and 193.23 seconds respectively, which is much larger than the proposed model of 0.4, 4.2 and 15.9 seconds. The model without component partition cannot be solved for other experimental data under terminated condition.

3) Initial Solution for the Model

The initial solution helps improve the efficiency of the solving process, which has been discussed in the 1st response.

4) Model Refinement and Reduction

We have made a comparison about with and without the reduction and refinement technique in the experiment section. Even though theoretically it helps achieve better solutions, the model iterates more slowly in practice and has a larger gap than the improved model under the terminated condition. Spaced assignment is a common strategy, especially for small to medium sized data with a limited variety of components. To prove this statement, we added the relevant experiments in Section IV. Second, the relative slots of the feeder assignments determine the pickup operations. As stated in the manuscript, "the feeders are usually densely arranged in a limited range of the feederbase and slots farther away from the PCB are always ignored.".

Related experiments are supplemented in the experiment section. As shown in Table VI, TC-1 and TC-3 represent the solution of the model with and without reduction and refinement strategy. $\mathcal{F}_b$ refers to the currently known optimal solution (regardless of the time cost). The experimental results conclude that "Regarding the reduction and refinement technique, despite the fact that theoretically it helps achieve better solutions, the model iterates more slowly in practice and has a larger gap than the improved model under the terminated condition." The feasibility of these strategies is further verified by our physical validation on a self-developed placement machine.

TABLE VI

COMPARISON OF MODEL SOLVING PROCESS WITH DIFFERENT TEST CASE

	PCB	1	2	3	4	5	6	7	8	9	10
BASE	$\mathcal{F}_b$	934	312	336	396	432	390	288	158	164	196
TC-1	$\mathcal{F}_1$	934	312	336	396	432	390	288	158	168	218
	$\mathcal{G}_1$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.44	11.22
TC-2	$\mathcal{F}_2$	934	312	336	396	432	390	288	162	-	-
	$\mathcal{G}_2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.53	-	-
TC-3	$\mathcal{F}_3$	934	312	336	396	432	390	288	172	192	220
	$\mathcal{G}_3$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.86	17.07	12.24

5) Selection Criteria for Solution Pool

The selection criteria are applied to select a solution from the solution pool of the model as a constraint for the next phase optimization. In general, the optimal solution of the model is not unique, and different solutions indirectly affect the movement of the gantry. The selection criteria for solution pool follow from two aspects. On the one head, we check the pick-up movement process, since for the same number of pick-ups, the heads could choose different slots, and it may lead longer movement. The small distances can also increase time consumption due to frequent starts and stops, especially for multiple repetitive cycles. On the other hand, we propose a fast prejudgment heuristic to evaluate the lengths of placement process.

The related statements have been modified as "In general, the optimal solution of the model is not unique, and different solutions indirectly affect the movement of the gantry the quality of the placement route schedule result. We propose a fast heuristic algorithm for selecting one result from the solution pool. First, the assignment of head task determines the traveling path of the pickup process as

$$E_1 = \frac{\tau}{r}\sum_{l\in L} w_l \cdot \mathcal{R}\{v_{shl} \cdot (s - h \cdot r + r) | v_{shl} \neq 0, s \in S, h \in H\}$$

where $\mathcal{R}$ denotes the range of the set.

Regarding the placement movement, the fundamental idea is to sort the placement points in a non-decreasing manner with regard to the x-coordinate by grouping them according to the type of component. The placement points set for each head is constrained by the component type of the head task assignment. The first w_l points of the corresponding component type $\sum_{i\in I} i \cdot u_{ihl}$ are assigned to the head h, followed by the subsequent w_l points, and so forth. For each head in the cycle group, we implement a route schedule for the centroids of the assigned points; the length of placement route movement is denoted by E_2. Out of all the solutions, the one with the minimal $E_1 + E_2$ is selected for the next phase optimization."

6) Route schedule heuristic

As the second phase, route schedule heuristic is a tailored algorithm for beam-head structure movement. The algorithm is designed based on the mechanical structure of the beam-head placement machine. We have compared the movements of different algorithms, and the moving length is close to that of industrial CPO and better than other mainstream research, under the premise of guaranteeing the "high-quality" of the solution.

7) Route Re-link Heuristic

Re-link heuristic is a strategy to further improve the route schedule result. We have explained the necessity for this approach in the manuscript: "A relink heuristic is required for the placement route improvement technique, which overcomes the shortcoming of the greedy method of excessively lengthy moving distance in the last few cycles. " Since the route re-link heuristic mainly adjusts the placement movement that makes up a small portion of the whole, it does not result in a high improvement in the overall movement as shown in Table VIII.

The related statements about the core components discussed above have been supplemented in the manuscript.

3. The motivations of setting the predefined termination times should be given.

Response: Thanks for your advice. It is difficult to solve the model completely for all PCBs due to its complexity. In practice, one is usually reluctant to consume a lot of time for the optimal solution; in other words, "high quality" solution is enough. Considering the different processing capabilities of the model for PCBs with different scales, we change the condition for the termination of the search process from a hard constraint on time to a soft constraint, i.e., it terminates when the currently optimal solution does not change for more than 30 seconds.

The motivations of setting terminated condition follow two aspects. On the one head, the results in Table VI show that the gap between the obtained solution and the benchmark can be limited to less than 11.22%, and the overall performance is significantly better than other mainstream methods.

On the other hand, in Table VIII, we compared the solving time of proposed algorithm and mainstream research. A general conclusion is that since the manuscript considers more factors, the solving time is still acceptable, even though it does not have a quicker solving time. The relevant statement has been added in the manuscript as "Lastly, we make a comparison of the model's solving time, CPO is not included in the comparison since the specific algorithm is not disclosed. As modeling methods, TPPO is solved longer because of the inclusion of pickup constraints compared to AGM but is significantly faster than HGA. Except for single component type, the solving times of another evolutionary-based technique, CDGA and TPPO are relatively near to one another. Even though the PCB10 requires more time for TPPO, its assembly efficiency is higher, and the time is within an acceptable amount."

TABLE VIII
COMPARISON OF THE SOLVING TIME OF THE PROPOSED MODEL WITH MAINSTREAM ALGORITHMS

PCB	TPPO	CPO	AGM	HGA	PCB	TPPO	CDGA	AGM	HGA
1	0.4	-	0.3	138.2	6	34.7	30.1	0.5	264.2
2	4.2	41.0	0.2	218.2	7	32.0	30.1	1.1	94.2
3	15.9	35.7	0.2	373.0	8	67.6	20.1	0.9	88.0
4	31.5	36.8	0.3	134.6	9	46.4	23.0	0.4	158.9
5	31.5	33.5	0.4	172.8	10	95.3	27.0	1.2	153.9

4. *The statistical analysis should be given.*

Response: Thanks for your advice. The supplementary statistical analysis has been given as following aspects.

1) Model evaluation: The model evaluation follows with comparison as two aspects: the Z-value of weighted sub-objectives and single sub-objectives. The proposed model clearly outperforms the mainstream methods in terms of weighted objective values. In addition, we discuss the results of different methods' sub-objectives to further elaborate the superiority of the proposed model.
2) Strategies analysis: To validate the effectiveness of the model improvement strategy, we analyze the gap between the solution under different test cases and the currently known optimal solution. From the experimental results, the proposed strategies have advantages in obtaining an initial feasible solution, speeding up the search etc., which further help obtain better solutions.
3) Solution quality: We first compared the length of the movement paths of the different algorithms.

Assembly efficiency is the ultimate indicator of the quality of the solution, we selected 10 PCBs to be validated on the experimental platform. The results demonstrate the high quality of solution compared with others.

4) Solving efficiency: The experimental results show that in terms of solving time, the algorithm is not the fastest due to its more considerations, but it is still acceptable. The proposed algorithm is faster than hybrid genetic algorithm, and it has a similar solving time compared with cell-division genetic algorithm.

Around the above aspects, the discussion of statistical analysis has been added to the experimental section.