Response Letter

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Manuscript Details
Title: A Two-phase PCBA Optimization with ILP Model and Heuristic for a Beam-head Placement
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General Response

Dear Editor-in-Chief, Associate Editor, and all Reviewers,

We sincerely appreciate the Editor-in-Chief, the Associate Editor, and all Reviewers for their thorough reading and insightful advice that helped us improve the manuscript's quality. Thanks to their recognition of the merits of the manuscript and their professional suggestions for revision. The major changes of this submission are listed as follows:

1) Mathematical model reformulation: We have revised the relevant formulation of the model in two ways. First, we elaborate on the model's improvements compared to previous research to highlight our advantages; second, we clarify the meaning of the constraints regarding the model's reduction. Furthermore, we've revised the statement of the meaning of constraints and variables in the model as per the reviewers' comments.
2) Experimental supplement: More than one reviewer commented on our experimental section, and all corresponding statement have been properly amended. We've re-organized the presentation of the experimental parameter set-up, and discussed the motivation, analyzed the results of the choice of Z-values for the objective function comparison.
3) Terminology and syntax check: We apologize for the syntax problems in the manuscript. All grammatical and syntactical errors raised by the reviewers have been fixed. We've reviewed the manuscript for the accuracy of relevant statements, professionalism of writing, and sentence flow. A professional grammar checker has reviewed every sentence before submitting this revised version.
4) Other modifications: Based on the reviewers' comments, we have revised the abstract and conclusion sections. In the abstract section, we have added relevant background knowledge and motivation for the research and refined the description of the proposed algorithm; we've reorganized the conclusion section to relate it more closely to the results of the experimental section while emphasizing the importance of the algorithmic core component. The two-phase framework design is also described in the introduction section.

In summary, we've 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've listed the reviewers' comments below in *italicized font* with red text and numbered the specific concerns. Our response is given in normal black font. The changes from the manuscript are given in blue. We sincerely hope this revised version is considered for publication in *IEEE Transactions on Industrial Informatics* and can be seen by more practitioners. Thanks for taking the valuable time to review our manuscript again.

Best wishes,
Authors of the manuscript.

Content

Response to the Reviewer #1

1. *In the modeling Section, it is unclear about the meaning of cycle groups, and some intermediate variables like γ, and λ.*

Response: Thanks for the comment. We're sorry for these unclear statements. As for the cycle group, it means the consecutive pick-and-place cycles with the same head task assignment.

Both the intermediate γ and λ are the product terms of the model, where γ represents whether the head h picks up component i from slot s in cycle group l and λ represents the number of pick-up operations corresponding to slot s in cycle group l. We give relevant explanations to the formulae where the variables are used and rechecked the meaning of the variables throughout the manuscript. It should be noted that some of the intermediate variables are used only for linearization operations and have no real meaning, so we have not added any description of these variables.

The manuscript is revised as

1) p. 2, col. 2, line 34: "The nozzle type, component type, and pick-up slot are the three basic compositions of the head task assignment. We call the consecutive pick-and-place cycles with the same head task assignment as the cycle group. "
2) p. 3, col. 1, line 9: "The nonlinear term $w_l \cdot p_{sl}$ in the objective can be replaced by an intermediate variable λ_{sl}, which represents the number of pick-ups from slot s in cycle group l and can be linearized with big-M method as…"
3) p. 3, col. 2, line 16: "with the nonlinear term $\gamma_{ishl} = u_{ihl} \cdot v_{shl}$, which represents whether the heads h picks up components i from slot s in cycle group l, is rewritten as …"

2. *The elimination of unsatisfactory results mentioned in Constraint (11) is confusing since it does not seem to be directly related to the optimization objective.*

Response: Thanks for the comment. We're sorry for these confusing statements. However, Constraint (11) is proposed to describe the relationship between the pick-up operation and component assignment, which is not related to elimination of unsatisfactory results.

Constraints (17)-(20) are proposed for the elimination of unsatisfactory results. These constraints are not the necessary condition for model solving but are utilized to reduce the domain of the solution. In fact, the constraints used to compress the solution domain only remove the duplicated solutions with the same objective value. The head will tend to prioritize more simultaneous pickups, as in Constraint (17). Constraint (18) limits the upper bound and lower bound of cycle group. In Constraint (19), a further consideration is that all heads are equipped with nozzles in each cycle, avoiding the redundant calculation of nozzle change brought by empty heads. Constraint (20) does not improve the model-solving capability, and we have removed it from the revised version.

We have revised the related statements in the manuscript as follows:

1) "~~Constraint (17) ensures the lower cycle group has no less workload than the higher cycle group.~~ Constraint (17) ensures that the lower cycle group has a higher priority in picking up components with more PAP cycles. "
2) "~~Constraint (18) gives the lower bound and upper bound of the number of PAP cycles, where~~

the upper one is given based on the heuristic initialize algorithm. The heuristic solution $\mathcal{W}_l$ gives the worst case for the number of total PAP cycles without nozzle change, and an optimal case is that all heads divide components equally; two of these cases give the upper bound and the lower bound of cycle groups in Constraint (19). "

3) "Constraint (20) presumes that all placement heads have nozzles, even if they do not pick up and position components, which helps to eliminate the unsatisfactory result. A general case is that all heads are not empty in Constraint (20), even if they do not pick up any components, which avoids the redundant calculation of nozzle change brought by empty heads. "

3. *In the experimental section, I suggest adding some statements to describe the parameter settings, e.g. the setting of "priority to n best" for "pool search mode".*

Response: Thanks for the advice. Following your professional suggestion, we have further improved the description of the parameter setting of the solver. As for the "priority to n best" searching (which is substituted by "Find multiple solutions"), the solver Gurobi provides parameters to select different modes for exploring the MIP search tree. The "priority to n best (find multiple solutions)" refers to the search process to find multiple n optimal solutions simultaneously. The research on this technique is well-established and has been integrated into the optimizer, so we have not discussed it in detail.

The relevant statements are added in the manuscript for a clearer description of parameter setting "In the first phase, we set the pool parameters and search mode, as well as the coefficients of the model based on the metrics' impact on assembly efficiency. We specify the following as the termination condition of the model-solving process because it takes a long time to solve the model completely: the currently optimal solution has not changed for more than 30 seconds. The big M value for linearization equals the number of placement points. The search mode is set to prioritize the 30 best solutions within the gap of 10^{-4}. In the second phase, the search step is dependent on the PCB layout, and the route roulette wheel is chosen for the random search of route relink with the upper 10 seconds."

4. *The value of "M" for big-M linearization should be given since too large or too small a value may affect the solving process.*

Response: Thanks for the advice. Since too large value may increase the search time and too small value may cause the model to be infeasible, the value of M being set to the number of placement points is appropriated. The relevant statement has been supplemented in Table III.

TABLE III

THE PARAMETER SETTING OF THE TWO-PHASE ALGGORITHM

Phase	Parameter	Setting
I	Coefficient T1 | T2 | T3	2 | 3 | 2
	Big-M value	$\|P\|$
	Pool search mode	Find multiple solution
	Pool solution	30
	Pool gap	10-4
	Terminated condition	Unchanged in 30 seconds

II	Search step	$\mathcal{R}\{x_p \mid p \in P\}/\lvert H \rvert$
	Selection method	Roulette wheel
	Terminated time (sec)	10

5. *Table V gives a comparison of the modeling-solving process with different test cases. However, the title of the table does not match the data presented well.*

Response: Thanks for the advice. We have revised the title to "COMPARISON OF THE MODEL-~~SOLVING PROCESS~~ OBJECTIVE VALUE FOR ~~WITH~~ DIFFERENT TEST CASES"

6. *Besides, we do not know why the authors chose to present the data in terms of the Z-value of the objective function, and an explanation is expected.*

Response: Thanks for the comment. In the modeling phase, we discussed the major factors affecting assembly efficiency. Different aspects are taken into account by different optimization methods, and there is a coupling between these factors. The results of our direct comparison by listing the major indicators are not intuitive and thus compared with the histogram in Fig. 3. The coefficients of the model in the manuscript are given based on the operation time of actual production actions. The Z-value is transformed from the standard deviation for the distance between the raw score and the mean score. Table IV shows the results of comparing the weighted objectives, using Z-values to enhance the comparability and generality of the data.

We have discussed the results of Table IV separately and revised the manuscript as follows "Table IV shows more general and comparable results of Z-values for weighted sub-objectives that are directly related to assembly efficiency. It can be seen that when dealing with a single type of component data (PCB1), TPPO, CPO, and AGM perform equally well. As the PCB becomes more complicated with more component types, the TPPO outperforms other mainstream algorithms, and there is also a tendency to increase gaps between the proposed algorithm and other research. " (p. 7, column. 2, line 5~13)

7. *There are some typos, like "focus" (p. 1, col. 2, line 9), "batch of component" (p. 2, col. 1, line 39), "blow" (p. 2, col. 2, line 44). I would suggest that the author do a more careful examination of the whole paper.*

Response: Thanks for the comment. We have checked the manuscript and revised the typos as follows:

- Early PCBA optimization research ~~focus~~ focuses on types … (p. 1, col. 2, line 9)
- The integrated model for PCBA optimization has ~~been~~ characteristics that combine ~~as a combination of~~ … (p. 1, col. 2, line 13)
- … an aggregated integer programming based on batches of components (p. 1, col. 2, line 39)
- ~~the ILP model covers the major metrics that affecting assembly efficiency~~ (p. 2, col.1, line 16)
- the slots corresponding to the pick-up operations directly affects the pick-up movements. (p. 2, col. 2, line 31)
- The assumptions for the PCBA process are listed ~~blow~~ below (p. 2, col. 2, line 44)

- including a component placer optimizer (CPO) employed in ~~an~~ industrial software … (p. 6, col. 2, line 23)
- The parameter settings of the proposed algorithm are listed in Table III. (p. 6, col. 2, line 36)
- the comparative histogram is ~~illustrated~~ shown in Fig. 3 (p. 7, col. 1, line 25)
- which are also the best ones found compared with ~~an~~other research (p. 7, col. 2, line 29)
- The test cases follow~~ing~~ the settings: TC-1 represents … (p. 7, col. 2, line 32)

8. The meaning of the notation used in the formula should be unique, and for example, "c" is the index of points, then it is not suitable as a corner marker for cycle coefficient "t_c".

Response: Thanks for your professional advice. To avoid confusion, the notation t_c, t_n, and t_p are replaced by T_1, T_2, and T_3, respectively.

9. Page 3, column 1, line 43, it's better to use "similar to" rather than "similar as".

Response: Thank you for your reminder. We are sorry for our careless mistakes and have corrected them.

10. Page 6, column 2, line 59, the phrases "illustrated" and "shown" seem to be duplicated.

Response: Thanks for the comment. We apologize for this one careless mistake and have corrected it.

11. Page 7, column 2, line 13, "following" should be "follow".

Response: Thanks for the advice. We have corrected it, and we also feel great thanks for pointing out this problem.

12. The formatting of references should be checked again.

Response: Thanks for the advice. We have rechecked the *IEEE Transaction on Industrial Informatics* reference format strictly line by line, and made changes like the journal abbreviations, etc.

Response to the Reviewer #2

1. *First, the authors should consider revising the abstract and conclusion sections. The abstract section should be supplemented with the purpose of the research. In the conclusion section, the author should summarize the results of the experiment, and a future research direction is expected.*

Response: Thanks for your professional advice. We have revised the abstract and conclusion sections after a detailed review of the relevant materials. In the abstract section, we briefly add the background and motivation of the research and refine the description of the methodology. In the conclusions section, we have appropriately cut out the repetition of the abstract and added the results obtained from the analyses in the experimental section.

1) The abstract section is revised as follows "The optimization of printed circuit board assembly (PCBA) for beam head placement machines is a multivariable and multiconstraint combinatorial problem. Current techniques falter in solving a variety of PCBA problems since heuristic algorithms lack theoretical guarantees of optimality, and mathematical modeling methods have high computational complexity for the whole problem. This article proposes a novel two-phase optimization for PCBA, integrating the advantages of mathematical modeling with heuristic algorithms. We divide the problem into head task assignment and placement route schedule. For the former, an effective integer linear programming (ILP) model with component partition is proposed, encompassing key efficiency-influencing factors. A recursive heuristic-based initial solution speeds up the solving convergence, while reduction and refinement strategies enhance model solvability. For the placement route schedule, a tailored greedy algorithm for the placement process yields high-quality solutions, leveraging the results of the model, and an aggregated route relink heuristic (ARRH) does further optimization. Additionally, we propose selection criteria for the solution pool of the model to pre-evaluate the placement movement, which builds the connection between the two phases. Finally, we validate the performance of the two-phase optimization, which provides an average efficiency improvement of 8.06%~24.32% compared to other mainstream research."
2) The conclusion section is revised as follows "This article presented a two-phase optimization approach for handling the head task assignment and placement route schedule after breaking the PCBA process down into two parts. By optimizing the primary subobjectives at the modeling phase and developing heuristic algorithms at the route schedule phase, the two-phase framework combined the advantages of both mathematical model and heuristic algorithms. We compared the weighted subobjective, which was related to the overall assembly efficiency, with both heuristic-based and model-based algorithms. The results showed that the proposed algorithms are more thorough than previous research. A series of specialized test cases validated the necessity of the pre-process technique, including the component partition approach, initial heuristic, and reduction strategies, to solve the model. Furthermore, we compared the moving distance and assembly time with other research. Although the placement path of our proposed algorithms was not the shortest for some PCB data, it improved the assembly efficiency because of the optimization in the first phase. The solving time of the two-phase algorithm was within

acceptable bounds, even though it was not faster than all the compared algorithms because we took more factors into account and searched a greater domain. Overall, the experimental results showed that the proposed two-phase optimization effectively solves PCBA problems, balancing the quality of the solution and computational cost. "

2. *Second, the model description should emphasize distinctions from previous studies, as the authors state, the model can be utilized to solve real-world problems (something that previous studies have not done).*

Response: Thanks for the advice. In terms of modeling, the major improvements we have made compared to previous work are as follows:

1) We introduce the concept of "cycle group" to reduce the complexity of the model, and at the same time, the linearization of the non-linear terms added to the model are discussed separately. From the experimental results, we can see that the model is able to achieve the optimal solution as well (compared to the model without grouping) for small-scale data. Moreover, the model is able to solve medium and larger-scale data, allowing it to be applied to real-world problems.
2) Our design of the constraints on the decision variables related to component pickup and feeder assignment is modified in the simplification of part of the summation process and enhances the model-solving speed.
3) We introduce redundant decision variables to simplify the constraint expression. The decision variables u and v can be replaced by the sum of γ, but it was not adopted due to model readability and solution efficiency considerations.

Besides the above-mentioned work in the modelling phase, we have also introduced methods such as initial solution production, model complexity reduction and solution pool selection criterion in other sections, which are used to further improve the efficiency of model solving.

3. *Third, in Section II-D, the authors add some constraints and claim to have reduced the range of the feasible domain; do these have an impact on the optimal solution of the model?*

Response: Thanks for the comment. We appropriately reduce the complexity of the model in accordance with the features of PCBA, which focus on two aspects: 1) limit the values of decision variables and 2) reduce the range of feasible domains. As for the latter, Constraints (17)-(19) are not the necessary condition for model-solving but are utilized to reduce the range of feasible domains further and round out inappropriate solutions ahead of time. The extra-constraints have no impact on the optimal solution of the model. We apologize for the confusion caused by the inappropriate wording, and the description of the relevant constraints has been revised as

1) "~~Constraint (17) ensures the lower cycle group has no less workload than the higher cycle group.~~ Constraint (17) ensures that the lower cycle group has a higher priority in picking up components with more PAP cycles. "
2) "~~Constraint (18) gives the lower bound and upper bound of the number of PAP cycles, where the upper one is given based on the heuristic initialize algorithm.~~ The heuristic solution $\mathcal{W}_l$ gives the worst case for the number of total PAP cycles without nozzle change, and an optimal

case is that all heads divide components equally; two of these cases give the upper bound and lower bound of cycle groups in Constraint (18). "

3) "~~Constraint (19) presumes that all placement heads have nozzles, even if they do not pick up and position components, which helps to eliminate the unsatisfactory result.~~ A general case is that all heads are not empty in Constraint (19), even if they do not pick up any components, which avoids the redundant calculation of nozzle change brought by empty heads. "

Constraint (20) does not improve the model solving capability, and we have removed it from the revised version.

4. Fourth, grammatical and typographical mistakes should be re-checked.

Response: Thanks for your valuable suggestions. We have checked the manuscript and fixed the grammatical and typographical errors found. We understand the importance of grammar and typography to the quality of a manuscript and have done our best to avoid similar errors.

5. Finally, I suggest that the authors add some references to the CVRP route schedule.

Response: Thanks for the comment. As mentioned in the manuscript "The PCBA process can be regarded as a capacitated vehicle route schedule problem [12], with restriction of a head-accessible point set, which proves it is nevertheless a NP hard problem, and the extra constraints rather increase the difficulty of solving the problem", we have cited some references that both related to PCBA optimization and CVRP route schedule as [5], [11], [12].

In [5], a two-stage mixed-integer linear programming (MILP) based on TSP (traveling salesman problem) and QAP (quadratic assignment problem) is proposed, which is a generalization of CVRP. The edge-based and route-based models have been developed in [11] for placement route schedules, and the branch-and-price method with effective branch rules solves the latter. In [12], the authors proposed that the pickup combination and sequencing problem is similar to the popular multi-compartment vehicle routing problem (MCVRP), and they proposed a mixed-integer programming model.

We have reviewed the recent literatures on CVRP published in IEEE and other mainstream journals, which unfortunately does not have much relevance to the topic of the manuscript. We believe that the cited references have provided an adequate discussion of CVRP and have modified the descriptions of the relevant citations. Thanks again for your suggestions!

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 the advice. In the solution framework of the integer programming model based on the branch-and-cut algorithm, starting the search with the initial solution helps find the optimal solution faster and provides guidance for the algorithm search direction, which in turn affects the whole search process. As shown in TABLE V, test case BASE and TC-2 represent the solution of the improved model without and with the initial solution, respectively. $\mathcal{O}_b$ and $\mathcal{O}_2$ are the objective values of the model, and $\mathcal{O}_2 = (\mathcal{O}_2 - \mathcal{O}_b)/\mathcal{O}_b$ is the gap between the base value and test case 2's value. The model-solving process can be quickly iterated with the aid of the initial solution, and under the terminated condition, the feasible solutions for PCB9 and PCB10 are not even attainable.

TABLE V

COMPARISON OF THE MODEL OBJECTIVE VALUE FOR DIFFERENT TEST CASES

	PCB	1	2	3	4	5	6	7	8	9	10
BASE	$\mathcal{O}_b$	934	312	336	396	432	390	288	158	164	196
TC-1	$\mathcal{O}_1$	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	$\mathcal{O}_2$	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	$\mathcal{O}_3$	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

2. *The authors combine a mathematical model and heuristics algorithms, and they call it a "two-phase". However, the motivation for the algorithm design should be given for each phase (in other words, whether it is feasible to choose a heuristic in the first phase).*

Response: Thanks for the advice. Both mathematical programming and heuristic algorithms have their own advantages for combinatorial optimization problems. Among them, the mathematical programming method can theoretically guarantee the optimality of the solution, while the heuristic algorithm has a strong global search capability and can be applied to large-scale combinatorial problem-solving. In the manuscript, we distill the key metrics that affect the efficiency of modeling in a way that can theoretically guarantee the optimality of the solution (or at least the gap with optimal solution). There are also some studies that have used heuristic algorithms for computation in the first phase, which we compare in the experimental section, and their assembly efficiency is not good. The direct search of the solution space for such a NP-hard problem is blind, and we use the solution of the first phase as a constraint for the second phase, which can branch out some of the worse solutions in advance.

To state the above point more clearly, we revise the introduction section as "In the second phase, we solve the placement route schedule problem of the assembly process using heuristic methods. The combination of mathematical modeling and heuristics ensures the optimality of the major subobjectives while taking into account the overall solving capability of the algorithms." (p. 2, col. 1, line 26~29)

3. *In the Abstract, the authors state too little about the research background (optimization for beam-head placement machine is not sufficient), which I think is not conducive to access by potential researchers in related fields.*

Response: Thanks for the advice. We apologize that the relevant statements on our abstracts are not satisfying. A brief description of the background and motivation of the research has been added in the abstract section.

The abstract has added the relevant statements: "The optimization of printed circuit board assembly (PCBA) for beam head placement machines is a multivariable and multiconstraint combinatorial problem. Current techniques falter in solving a variety of PCBA problems, since heuristic algorithms lack theoretical guarantees of optimality, and mathematical modeling methods have high computational complexity for the whole problem.". We hope that the revised abstract could appeal to a wider range of potential researchers.

4. *In terms of the structure of the paper, Sections II and III seem to correspond to the two phases of the proposed method, but I think that the titles are not appropriate.*

Response: Thanks for the advice. We have revised the title of Section II as "HEAD TASK MODEL FORMULATION". The title of Section III is revised as "ROUTE SCHEDULE HEURISTIC".

The description of the manuscript's organization is revised as follows "The rest of this article is organized as follows. In Sections II and III, respectively, each phase of the proposed two-phase optimization is discussed. An ILP model based on the analysis of factors influencing assembly efficiency and its corresponding solving techniques is proposed in Section II. ~~Section II discusses the assembly problem and presents an integer linear model with solving techniques.~~ The placement route schedule heuristic with determined greedy and random relink heuristic algorithms is present in Section III. In Section IV, we give the experimental results ~~of the proposed two-phase optimization~~ with a commercial optimizer Gurobi [21]. Section V concludes this article." (p. 2, col. 2, line 16~26).

5. *In the greedy-based route schedule heuristic, the meaning of the fancy script H is unclear (and contradicts the number of heads mentioned in the model).*

Response: Thanks for the comment. We are sorry for the unclear description of the greedy-based route schedule heuristic. The fancy script $\mathcal{H}$ represents the head list sequence of the searching process, which is different from the number of heads of the model. We have substituted it with $\widehat{\mathcal{H}}$, and the value of $\widehat{\mathcal{H}}$ is related to the search direction.

We have revised *Step II* in Section II-A and explained the value of head list $\widehat{\mathcal{H}}$ as "*Step II* generates the starting point list $\hat{\mathcal{S}}$, a linear sequence based on the search direction.

L→R: $\hat{\mathcal{S}} = \{\alpha + h \cdot \delta \mid h \in H\},\ \widehat{\mathcal{H}} = \mathcal{H}$

R→L: $\hat{\mathcal{S}} = \{\beta - h \cdot \delta \mid h \in H\},\ \widehat{\mathcal{H}} = \{|H|, |H-1|, \cdots, 1\}$

C→E: $\hat{S} = \{(3 \cdot \alpha + \beta) + (h-1) \cdot \delta / 2 \mid h \in H\}$,

$$\widehat{\mathcal{H}} = \{\lceil |H| + 1/2 \rceil - 1/2 - (-1)^h \cdot (\lceil |H|/2 \rceil - 1/2) \mid h \in H\}$$

The head list $\widehat{\mathcal{H}}$ represents the order in which the different heads are assigned corresponding to the search direction."

6. *The necessity of the solution pool should be given as all the solutions may be optimal.*

Response: Thanks for the advice. In the first phase, the proposed model includes the head and the feeder assignment, which together determine the movement path of the pickup process. However, we do not put the pickup process in the objective function in the modeling phase to solve effectively, resulting in distinct pickup paths for different optimal solutions. Furthermore, the model does not consider the layout of the placement points, but the model's solution restricts the set of points accessible to each head, and we build the relationship between the two phases to some extent by introducing two metrics, E_1, and E_2, to select the solution from the pool and pre-evaluated the quality of the final solution solved by using them as constraints.

The corresponding revision in the manuscript is: "In general, the solution of the model is not unique, and ~~different solutions indirectly affect the movements of the gantry.~~ standard solvers can systematically search for a solution pool- a collection of multiple optimal solutions. The model determines both the component assignment and feeder arrangement. However, the objective function does not incorporate the pickup process, which leads to different pickup paths that have the same objective values. The model also does not take into account the layout of the placement points, but its solution limits the set of points that each head can access.

As there is insufficient information regarding the points and sequence of heads place, we propose a fast pre-evaluation heuristic algorithm for selecting one result from the solution pool. " (p. 5, col. 1, line 16~29)

7. *To illustrate the role of the core components in the model-solving process, the authors compare the different test cases in Table V. However, the reason for the different calculation methods for PCB1~PCB10 in the selection of the benchmark values should be given.*

Response: Thanks for the advice. In Table V, all benchmark values for comparison are known optimal one. The different comparison values selected in the experiment are attributable to data size and model design. The origin model, without any pre-processing and solving techniques, is definitely the optimal condition; however, it can only be applied to small-scale data (PCB1~PCB3). Our study has further improved the model and proposed new solving techniques, which makes it possible to apply in larger scale data (PCB4~PCB7). PCB9 and PCB10 are the relatively complex data we selected, which have a long time to obtain the optimal solution, and for this reason, we define the search termination conditions. Although we cannot be in a position to guarantee its optimality, the solution obtained by the proposed model is the best among all methods.

We have revised the relevant discussion to avoid the confusion caused by the different choices of the benchmark: "We utilize the ~~near~~ known-optimal solution as a benchmark since it is hard to find the optimal one to a NP-hard problem for all PCBs. The benchmark value O_b of PCB~PCB3 are the optimal result for solving the original model. As the size of the data increases, the original model cannot find an optimal solution in an acceptable time. The solutions of PCB4~PCB10 are obtained after solving the proposed model for a sufficient amount of time (at least 6 hours) without the terminated conditions, which are also the optimal results from the proposed and comparative methods. ~~The improved model's solutions, which are also the best ones found compared with another research, are selected as the benchmark for PCB4~PCB7. The solutions of PCB8~PCB10 are obtained by solving the improved model with sufficient search time (at least 6 hours).~~ " (p. 7, col. 2, line22~32)

8. Minor English improvement is advised.

Response: Thanks for your reminder to improve the expression. All details of the manuscript and supplementary materials have been carefully checked. We cautiously believe that the expressions in the manuscript are already improved significantly to avoid grammar errors or inappropriate expressions.