Response Letter CYB-E-2024-11-3326

Hyper-Heuristic Optimization Using Multi-Feature Fusion Estimator for PCB Assembly Lines with Linear-Aligned-Heads Surface Mounters

Foreword

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

We sincerely thank you for your thorough reading and insightful advice that helped us significantly improve the manuscript's quality. We have carefully considered all received comments for the preparation of the revised version. The major changes to the document are summarized as follows:

1) INTRODUCTION: We have revised the introduction to the assembly line equipment, especially the analysis about the surface mounter is the bottleneck equipment. The workflow of the linear-head type as well as its operation characteristics have also been further elaborated.
2) PROBLEM FORMULATION: We further analyze the relationship between the main constraints and the optimization task in the problem, adding to the complexity of the problem and giving a more intuitive schematic.
3) ALGORITHM: For the two important components of the proposed algorithmic framework: the estimator and the placement point allocation algorithm, we have elaborated on the composition of the former, while the latter has adapted the algorithmic flow, the design ideas, and the presentation of the key steps.
4) EXPERIMENT: As suggested by reviewer 2, we added a set of comparison experiments to compare the effect of a single underlying operator, compared the call share of different operators, and analyzed the role of different underlying heuristics in the search process.

The research content of the article is closely related to the actual industrial needs, which are completed on the PCB production line relying on the field. After the submission of the article, we have carried out a lot of research work simultaneously, in which some of the principle/experimental comments have been repeatedly verified. We believe that the revised content has advantages in terms of clarity of presentation, sophistication of algorithms, and the unobtrusiveness of applications.

In summary, we made detailed revisions based on all received comments. Point-by-point responses to these comments can be found below. Reviewers' comments are in *italicized red font*, whereas our responses are given in normal black font. Changes in the manuscript are given in blue underlined font, and excerpts from the original manuscript in black underlined font. We sincerely hope this revised version meets the requirements for publication in *IEEE Transactions on Cybernetics*. Thank you very much for taking your valuable time to review our manuscript again.

Sincerely,

The Authors

Content

Responses to Associate Editor

1. *The manuscript requires a clearer distinction of its novelty, as hyperheuristic optimisation has already been widely applied to similar problems.*

Response: Thanks for your comment. From a methodological point of view, we have incorporated a series of new techniques in the design of the hyper-heuristic framework to improve search efficiency and the quality of solutions. From the perspective of the research object, this manuscript focuses attention on the linear-head surface mounters with multi-type component assembly function.

Specifically, this research is the first systematic study of load balancing for linear-aligned-head surface mounters. The special feature of this type of machine assembly task is that its efficiency is not only related to the number of points assembled but also the points attributes. The number of points, component types, nozzle types and the specific optimization algorithm all have a significant impact on the final assembly efficiency. In the framework of the existing hyper-heuristic algorithms, we incorporate several new technologies and algorithms in the load balancing process and the evaluation of individual metrics to improve the quality of the solution. Experimental results also show further that our optimization results have outperformed mainstream research and industrial solvers under different production line configurations.

In summary, in addition to the existing presentation of the contribution in INTRODUCTION, we have added the following statements around the novelty of the proposed algorithm:

The algorithm design is tailored to the structural characteristics of the linear-aligned head surface mounters. The hyper-heuristic framework employs techniques with domain knowledge, which results in improved mechanisms for the search and evaluation process, achieving accuracy of solution evaluation, efficiency of the search process and balanced allocation of results. Compared to state-of-the-art algorithms and industrial solutions, the proposed HHO-MFFE enables higher assembly efficiency.

2. *The effectiveness of low-level heuristics should be evaluated with appropriate indicators supported by experimental results.*

Response: Thank you for your comment. As recommendation of reviewer #3, we have added two related experiments, the first one on the optimization effect of a single heuristic, and the second one on the percentage of each LLH invoked for the high-quality solution obtained during the hyper-heuristic search. The relevant experimental data and analytical conclusions are shown below:

First Experiment:

Ten PCBs are employed to compare the performances of various LLHs. Table VII shows the optimization results of load allocation, where A_p, A_c, A_n and A_r are target-driven LLHs, i.e., minimum points, component types, nozzle types and ratio, respectively; A_k, A_g and A_u is the target-driven LLHs; and *HH* is the result of the hyper-heuristic. Both minimum A_p and A_k achieve higher assembly efficiency by more balanced cycles and placement points. Results of LLHs that indirectly affect efficiency or single objective-related have low efficiency. All single-LLHs fail to achieve the hyper-heuristic effect.

TABLE VII ASSEMBLY LINE BALANCING SOLUTIONS OBTAINED BY VARIOUS LLHS

PCB	A_p	A_n	A_c	A_r	A_k	A_g	A_u	HH
2-1	10.06	10.26	9.52	9.88	9.72	9.79	10.70	**8.17**
2-2	15.38	18.28	16.12	19.97	14.75	17.66	16.01	**13.92**
2-3	20.46	20.48	20.00	23.06	20.10	22.81	19.18	**18.12**
2-4	18.98	25.97	19.87	26.24	21.17	27.06	22.84	**18.38**
2-5	22.36	28.25	26.14	29.64	21.13	32.34	22.94	**19.68**
2-6	28.81	35.23	28.79	38.40	28.78	33.84	27.69	**28.19**
2-7	46.21	45.29	40.47	51.13	42.57	45.42	43.27	**33.89**
2-8	52.07	59.06	50.44	59.39	51.73	63.46	49.05	**47.19**
2-9	66.93	67.80	65.82	84.64	65.98	68.50	65.42	**61.18**
2-10	135.68	143.67	143.01	168.83	139.76	146.01	149.82	**118.83**

Second Experiment:

Further, we compare the ratio of the number of each LLH using in the hyper-heuristic, as shown in Fig. 5. Balancing the number of placement points among surface mounters is the main task of optimization, and the ratio of target-driven operators is higher than data-driven ones in the remaining LLHs. Nozzle change-related A_g occurs relatively less frequently in the assembly process, thus for most of the data, the pickup-related A_u is more oriented in the search process.

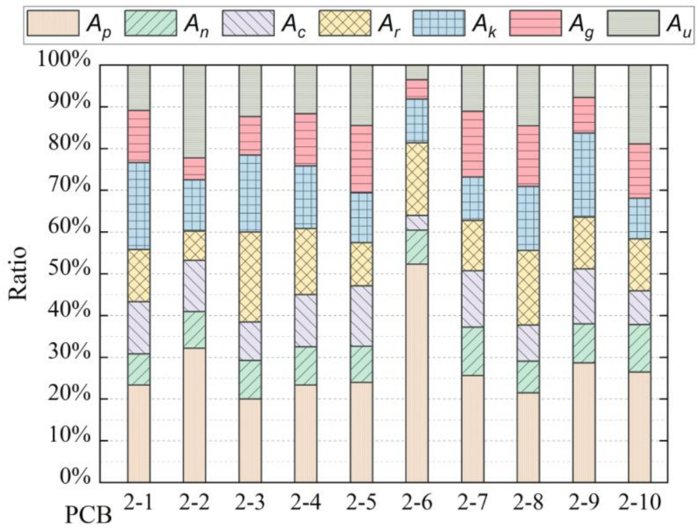

Fig. 5 Ratio of the number of each LLHs using in the hyper-heuristic.

3. *The computational complexity needs to be further analysed theoretically and comparatively.*

Response: Thank you for your comment. We agree that it is necessary to analyze the computational complexity of such optimization problems with large-scale solution spaces and give an explanation in terms of theoretical analysis and comparative experiments.

In Problem Formulation, we analyze the complexity theoretically as:

PCBALS can be regarded as a special type of assembly line optimization which is known to be NP-hard. It has a higher level of decision and higher complexity compared with a single-machine. The production optimization of surface mounters can be viewed as a combination of warehouse locating, task assignment and route schedule problems. There are various combinations of component allocation between different machines. Specifically, each assembly component may be assigned to multi-candidate machines with different processing times, resulting in an exponential growth of the number of feasible solutions.

In the EXPERIMENT, we compare the computational complexity of the proposed method, and the comparison experiments with the following analysis:

The genetic algorithm consists of relatively basic operators, which allow it to search quickly at the cost of solution quality. The hyper-heuristic and hybrid algorithms use a more complex time-fitting approach and account for component duplication, resulting in longer times than that of the genetic algorithm. The proposed hyper-heuristic is more efficient than the hybrid algorithm, and the quality of the solution it provides is higher. Evaluating the quality of the candidate solutions takes a large part of the solving time of the hyper-heuristic. PCB2-5 and PCB2-10 are more complex. Single-machine optimization takes longer for PCBs with larger number of components and nozzle types, resulting in relatively poor solving efficiency.

4. *The problem formulation would benefit from a figure illustrating the main constraints and relationships*

Response: Thank you for your comment. We fully agree that visual representation can enhance the clarity of the problem formulation. As recommended, a new Fig. 2 has been added to the revised manuscript (Section III - Problem Formulation).

To illustrate the relationship of the research more clearly, we have made the following additions to the manuscript, based on Fig. 2 as:

The relationship of the PCB assembly line balancing is illustrated in Fig. 2, which is mainly composed of inputs, outputs, constraints, estimators and two optimization tasks. Among them, the inputs are the PCB to be assembled, which also includes the component information of the placement point; the constraints can be divided into machine configuration, assembly priority and available tools. The optimization task consists of two parts: line balancing and assembly process optimization of surface mounter, which have a coupled relationship; the former is generally regarded as the input of the latter, and the latter is used to evaluate the quality of the former solution. In the specific task allocation, the allocation of assembly tools and components for lines determines the head and feeder assignment of each component for surface mounter, which further determines the key performance indicators affecting the assembly efficiency; the assignment of placement points in load balancing affects the quality of the assembly route schedule of the surface mounter, which also has an impact on the overall assembly efficiency. The complexity of the assembly tasks determines that it is difficult to directly get the productivity; an estimator evaluates the actual assembly time based on the surface mounter's operating process and guides the line balancing.

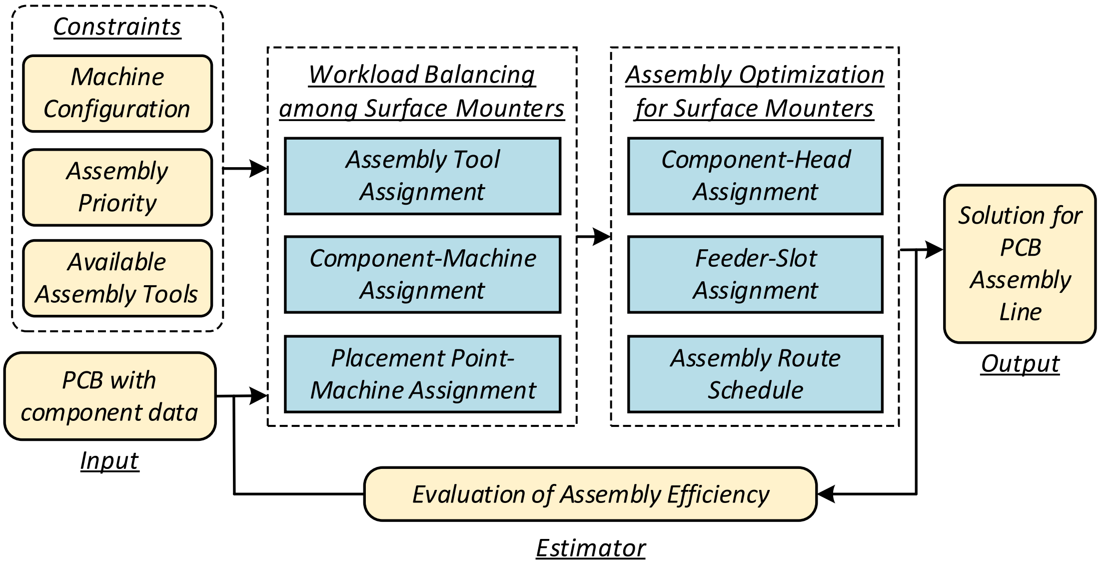

Fig. 2. Main optimization tasks and constraints in PCB assembly line optimization problems.

5. while the link between single machine and line optimisation should be explained more explicitly.

Response: Thanks for your advice. We appreciate your suggestion to further clarify their relationship.

Unlike traditional load balancing, where it is difficult to evaluate the productivity of the surface mounter directly based on the results of task (component) assignment, we need to fully optimize the surface mounter's production tasks to accurately obtain the assembly time. For optimization with a large number of feasible solutions, this is a rather time-consuming process. A hierarchical solution approach reduces the complexity of the problem and improves the efficiency of the search, and hence the quality of the solution, by employing approximation or estimation strategies in the single-machine optimization phase to eliminate poor solutions. Their relationship has been analyzed in the previous response in conjunction with Fig. 2, as

The optimization task consists of two parts: line balancing and assembly process optimization of surface mounter, which have a coupled relationship; the former is generally regarded as the input of the latter, and the latter is used to evaluate the quality of the former solution. In the specific task allocation, the allocation of assembly tools and components for lines determines the head and feeder assignment of each component for surface mounter, which further determines the key performance indicators affecting the assembly efficiency; the assignment of placement points in load balancing affects the quality of the assembly route schedule of the surface mounter, which also has an impact on the overall assembly efficiency.

The revised statements not only elaborate on the direct relationship between the two problems but also discuss the relevance of their sub-problems and their effect on assembly efficiency, further supporting the motivation for the hierarchical design of the proposed algorithm.

6. *Additional clarification is needed for certain details.*

Response： Thanks for your advice. We apologize that we have not been able to give sufficient clarification for certain details. In the revised version, we have added and improved statements in the following ways:

1) INTRODUCTION: We have revised the introduction to the assembly line equipment, especially the analysis about the surface mounter is the bottleneck equipment. The workflow of the linear-head type as well as its operation characteristics have also been further elaborated.
2) PROBLEM FORMULATION: We further analyze the relationship between the main constraints and the optimization task in the problem, adding to the complexity of the problem and giving a more intuitive schematic.
3) ALGORITHM: For the two important components of the proposed algorithmic framework: the estimator and the placement point allocation algorithm, we have elaborated on the composition of the former, while the latter has adapted the algorithmic flow, the design ideas, and the presentation of the key steps.

7. *Future research directions should be outlined in the conclusion.*

Response: Thank you for your comment. The vision of our research is to improve the efficiency of a production line consisting of linear-aligned-head surface mounters with multiple types of components to be assembled. In this manuscript, we study the optimization of production lines for a single type of PCB. However, with the rapid development of consumer electronics and other markets, manufacturers are faced with heavier tasks of high-mix, low-volume production, which require both higher production efficiency and stability. Based on this, we conclude with the future research as:

Future research can focus on load balancing optimization of flexible PCB assembly lines. For high-mix, low-volume PCB production tasks, its efficiency is affected by the configuration adjustments of surface mounters. This involves the optimization of the scheduling of dynamic production tasks, enhancing the efficiency of the feeder module changeover, etc., which is beneficial to shorten the productive cycle, reduce the storage cost, so that the small- and medium-batches can achieve profitability comparable to that of mass manufacturing, and improve the efficiency, robustness and stability of the assembly line.

8. *Careful proofreading is needed to improve language and clarity.*

Response: Thank you for your comment. We appreciate your suggestion regarding the need for enhanced language precision and clarity. In response to your comments, we have adjusted and revised the manuscript according to the following perspectives:

1) A fluent English-speaking co-author to refine grammar, syntax, and word choice.
2) Utilized Grammarly Editor for systematic language checks.
3) Standardized technical terminology throughout the manuscript.
4) Reformulated ambiguous statements in algorithms of estimator and aggregated cluster.
5) Draw several new schematic diagrams (Fig. 2 for problem relationship, Fig. 4 for framework of estimator and Fig. 5 for the role of low-level heuristics) to visually summarize the proposed framework

9. *Authors please check and compare your results with latest published works, such as from this transaction.*

Response: Thank you for your comment. We fully agree with your suggestion to compare with the latest published works. In recent years, the hybrid spider-monkey algorithm has a wide range of applications in complex optimization problems due to its powerful global search capability, and the following are excerpts from the relevant literature applied to PCB assembly line optimization:

[26] J. Mumtaz, Z. Guan, L. Yue, L. Zhang, and C. He, "Hybrid spider monkey optimisation algorithm for multi-level planning and scheduling problems of assembly lines, " *Int. J. Prod. Res.*, vol. 58, no. 20, pp. 6252 – 6267, Oct. 2020.

[27] Y. Chen, J. Zhong, J. Mumtaz, S. Zhou, and L. Zhu, "An improved spider monkey optimization algorithm for multi-objective planning and scheduling problems of PCB assembly line, " *Expert Syst. Appl.*, vol. 229, p. 120600, Nov. 2023.

[36] J. Zhong, Y. Chen, and J. Mumtaz, "A multi-objective scheduling optimization method for PCB assembly lines based on the improved spider monkey algorithm, " in *the 2nd ICAME*. MDPI, 2022, p. 15.

Unfortunately, none of the above literature can be directly applied to the comparison experiments. The study in [26] is a multi-level optimization problem, and the assembly line optimization is only one of the levels, and the optimization results are limited by the overall planning; the studies in [27] and [36] are multi-objective optimization problems, and the efficiency optimization is one of the objectives considered. For these reasons, we have integrated the coding and search approach in [27] and [36] as part of hybrid optimization. From the experimental results, it can be seen that the percentage of hybrid optimization relative to proposed hyper-heuristic after incorporating spider monkey algorithm is reduced from 12.18% to 8.67, indicating the effectiveness of the hybrid spider monkey algorithm.

In Section V-E, we have adapted the comparison experiments as:

The main task of the line optimizer is to allocate components to machines. In this section, the proposed algorithm is compared with an industrial solver from an advanced manufacturer released in 2022, the integrated algorithm [4], and the hybrid algorithm [9]. The industrial solver is an optimizer embedded in a production line management tool for surface mount assembly lines. The integrated algorithm is a genetic-based method that provides solutions for PCB assembly line by designing operators to search the feasible domain. The hybrid algorithm combines random search, local search, and evolutionary algorithms, etc. Since the spider monkey algorithm has been widely used in PCB assembly line optimization [26, 27, 36], this section further integrates it into it and improves it based on the coding and searching approaches proposed in [26, 36]. The industrial solver provides complete solutions from assembly line balancing to surface mounter optimization, and the rest of the single-machine optimizations are based on the methods proposed in [7].

In summary, among all the compared methods, we have both the latest optimizer (industrial solver) released by Hanwha, an advanced mounter manufacturer, as well as classical optimization method (integrated algorithm) and method that incorporates the latest research (hybrid algorithm). Thus, we believe that our comparison experiments are adequate.

10. There are limited analyses of the coupling between the single machine optimization and entire line optimization. The authors should give further explanation of the two problems, as they are also the motivation for the suggested framework.

Response: Thank you for your comment. We apologize that in the suggested framework, we did not provide a clear explanation of the coupling between the two problems. In the previous response, we have analyzed the relationship between the constraints of the single surface mounter and the production line, the optimization task (with the subproblems therein), and added the relevant diagrams.

In the following discussion, the correlation between the sub-problems is somewhat indicative of the coupling between the problems

In the specific task allocation, the allocation of assembly tools and components for lines determines the head and feeder assignment of each component for surface mounter, which further determines the key performance indicators affecting the assembly efficiency; the assignment of placement points in load balancing affects the quality of the assembly route schedule of the surface mounter, which also has an impact on the overall assembly efficiency.

In the previous response, we have analyzed the relationship between the single surface mounter and the production line constraints, the optimization task (with subproblems therein). There are not only constraints between the subproblems, but at the same time varying degrees of influence on the results of the group line optimization. Immediately after, we briefly analyze the coupling of production lines and machines:

Assembly process optimization focuses on the performance improvement of individual machines, through optimizing the feeder configuration, pickup operations, movement path, etc. Meanwhile, assembly line optimization focuses on improving the efficiency of the entire process. The performance of the surface mounter directly affects the efficiency of the line, while the assembly task assignment also affects the utilization rate of the machine. A large number of combinations for component allocation makes it difficult to get high-quality solutions, and computing effort increases rapidly as the problem scales up, needing massive resources even for small-scale data. For the unique mechanics of linear-aligned-heads, single-machine production simulations with long running time, as well as traditional time estimators with large errors are no longer applicable. In production line optimization, it is necessary to reasonably allocate the assembly tasks of each mounter to balance the load, which requires an accurate and fast estimator of the assembly process of the surface mounters.

Responses to Reviewer #1 Comments

No further revisions were requested for the manuscript.

Response： We sincerely appreciate the reviewer’s time and constructive suggestions throughout the review process.

Responses to Reviewer #2 Comments

1. *In Fig.1, is the last equipment of PCB Assembly Line unloader or uploader*

Response: Thanks for your careful review. We apologize for the spelling error and have revised it as shown in Fig 1. The last equipment of PCB assembly line, called as the unloader, is used to receive the completely assembled PCBs.

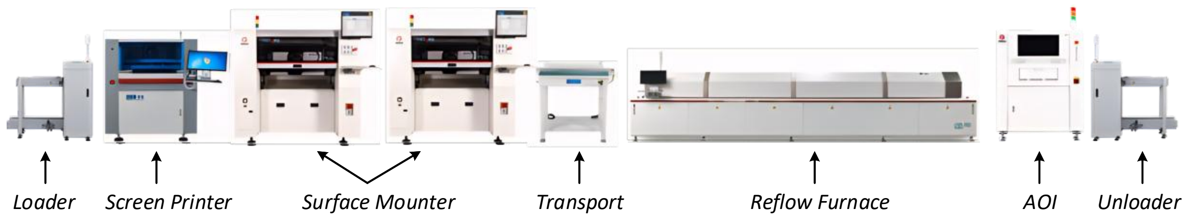

Fig. 1. PCB Assembly Line

2. *Surface mounters been the bottleneck for assembly efficiency, why*

Response: Thanks for your comment. We apologize for neglecting to explain this content since it has been discussed in related studies. According to the actual assembly lines, the time of screen printer for single board printing is about 10 seconds, the assembly efficiency of surface mounter is about 15,000 chips per hour, which means assembly 300 chips of boards usually takes more than 1 minute, the soldering time of the reflow soldering is about 1~2 minutes, but it can continuously and simultaneously heat up a number of boards, and the optical inspection time is 10~30 seconds, depending on the point's distribution. It should also be noted that in surface assembly lines, operators need to adjust the configuration of surface mounters, replenish the feeder components, calibrate the placement positions, which further increases the time-consuming of the production.

Surface mounter is the bottleneck in the production of equipment has been the industry consensus, and the relevant studies have explained the situation, for example:

[1] M. Ayob and G. Kendall, "The optimisation of the single surface mount device placement machine in printed circuit board assembly: a survey, "*Int. J. Syst. Sci.*, vol. 40, no. 6, pp. 553 – 569, Apr. 2007.

[2] A. Rong, A. Toth, O. S. Nevalainen, T. Knuutila, and R. Lahdelma, "Modeling the machine configuration and line-balancing problem of a PCB assembly line with modular placement machines, " *Int. J. Adv. Manuf. Tech.*, vol. 54, no. 1, pp. 349 – 360, Apr. 2011.

[3] O. Kulak, I. O. Yilmaz, and H.-O. Gunther, "A GA-based solution approach for balancing printed circuit board assembly lines, " *OR Spectrum*, vol. 30, no. 3, pp. 469 – 491, Jun. 2008.

We have cited the literatures above and added a re-analysis of equipment time consumption in INTRODUCTION of the production line, which is modified as follows:

~~The screen printer applies solder paste to the surface of PCBs. Surface mounters pick and place components on the PCB pads. The reflow furnace melts solder paste already pre-positioned on the PCB, before cooling it to create a permanent solder. Finally, the AOI looks for defects on the PCB to ensure assembly quality.~~ The screen printer applies solder paste faster, and reflow furnace puts PCBs continuously through the oven, which usually does not become a bottleneck as it's not affected by the previous process. Surface mounters, which need to accurately pick up and place hundreds of components, have a direct impact on production efficiency. Inspection equipment can take pictures of multiple placement points simultaneously, and the computation time for detection is negligible. Central to production control is the efficient use of machines, with surface mounters been the bottleneck for assembly efficiency [1-3].

3. *It is suggested to give the specific reasons for your mention that PCB assembly line scheduling has complex feasible domains.*

Response: Thanks for your comment. We are sorry that we did not give a specific reason why the problem has a complex feasible domain, whose complexity is mainly due to its property of being a combination of multiple optimization problems, and being constrained by the available tools, assembly priorities, etc. Therefore, we have discussed the complexity in ROBLEM FROMULATION as follows:

PCBALS can be regarded as a special type of assembly line optimization which is known to be NP-hard. It has a higher level of decision and greater complexity compared with single-machine. The production optimization of surface mounters can be viewed as a combination of warehouse locating, task assignment and route schedule problems. There are various combinations of component allocation between different machines. Specifically, each assembly component may be assigned to multi-candidate machines with different processing time, resulting in an exponential growth of the number of feasible solutions. … A variety of interdependent factors influence the assembly efficiency of a single surface mount machine, including number of cycles, pick-ups, nozzle changes, and placement points [5]. The result of component allocation affects the above multiple sub-objectives. In terms of available resources, the assembly tools limit the upper number of assembly machines for each component type, and the priority limits the assembly sequence. Due to resource coupling and conflicting sub-objectives, several local optimal solutions may exist in the feasible domain.

4. *In the subsection of Problem Formulation, it is recommended to use a figure to illustrate the characteristics of the scheduling problem at hand, i.e., the relations and constraints among component allocation, component assemble, machine type, and available tools etc.*

Response: Thanks for your advice. We fully agree that visual representation can enhance the clarity of the problem formulation. As recommended, a new Fig. 2 has been added to the revised manuscript (Section III - Problem Formulation).

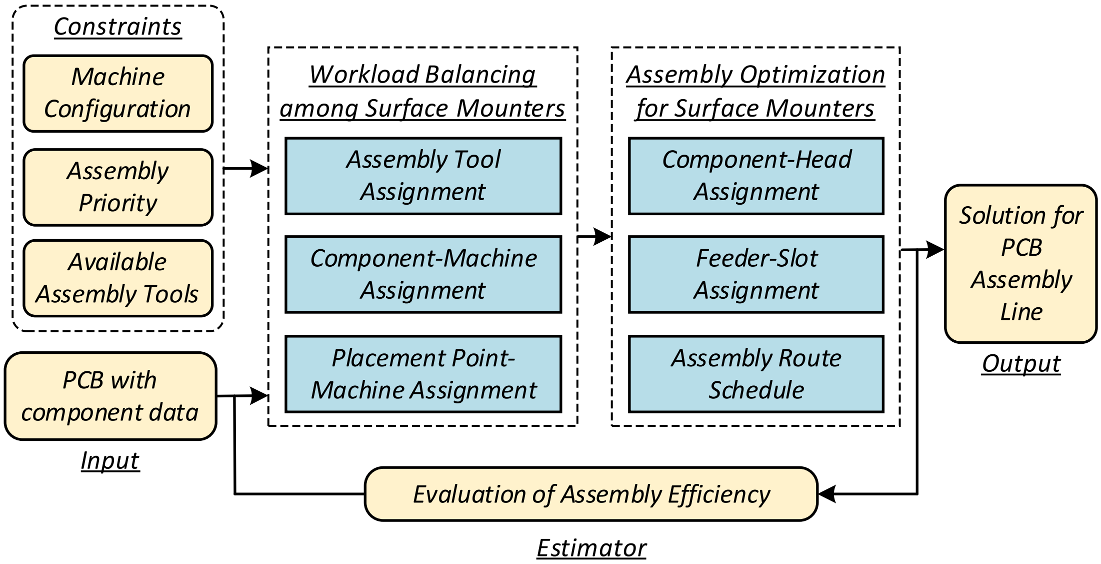

Fig. 2. Main optimization tasks and constraints in PCB assembly line optimization problems.

To illustrate the relationship of the research more clearly, we have made the following additions to the manuscript, based on Fig. 2 as:

The relationship of the PCB assembly line balancing is illustrated in Fig. 2, which is mainly composed of inputs, outputs, constraints, estimators and two optimization tasks. Among them, the inputs are the PCB to be assembled, which also includes the component information of the placement point; the constraints can be divided into machine configuration, assembly priority and available tools. The optimization task consists of two parts: line balancing and assembly process optimization of surface mounter, which have a coupled relationship; the former is generally regarded as the input of the latter, and the latter is used to evaluate the quality of the former solution. In the specific task allocation, the allocation of assembly tools and components for lines determines the head and feeder assignment of each component for surface mounter, which further determines the key performance indicators affecting the assembly efficiency; the assignment of placement points in load balancing affects the quality of the assembly route schedule of the surface mounter, which also has an impact on the overall assembly efficiency. The complexity of the assembly tasks determines that it is difficult to directly get the productivity; an estimator evaluates the actual assembly time based on the surface mounter's operating process and guides the line balancing.

5. *The specific relationship between single-machine optimization and line optimization needs to be more clearly described where appropriate.*

Response: Thanks for your insightful feedback. We appreciate your suggestion to further clarify their relationship.

Unlike traditional load balancing, where it is difficult to evaluate the productivity of the surface mounter directly based on the results of task (component) assignment, we need to fully optimize the surface mounter's production tasks to accurately obtain the assembly time. For optimization with a large number of feasible solutions, this is a rather time-consuming process. A hierarchical solution approach reduces the complexity of the problem and improves the efficiency of the search, and hence the quality of the solution, by employing approximation or estimation strategies in the single-machine optimization phase to eliminate poor solutions. Their relationship has been analyzed in the previous response in conjunction with Fig. 2, as

The optimization task consists of two parts: line balancing and assembly process optimization of surface mounter, which have a coupled relationship; the former is generally regarded as the input of the latter, and the latter is used to evaluate the quality of the former solution. In the specific task allocation, the allocation of assembly tools and components for lines determines the head and feeder assignment of each component for surface mounter, which further determines the key performance indicators affecting the assembly efficiency; the assignment of placement points in load balancing affects the quality of the assembly route schedule of the surface mounter, which also has an impact on the overall assembly efficiency.

The revised statements not only elaborate on the direct relationship between the two problems but also discuss the relevance of their sub-problems and their effect on assembly efficiency, further supporting the motivation for the hierarchical design of the proposed algorithm.

6. *The authors point out that the estimator's results may be affected by the point distribution, but how might this issue be resolved?*

Response: Thanks for your comment. We are grateful to you for your attention to the impact of the point distribution on the estimator results, but we apologize that from an algorithmic design point of view, we did not introduce it in this for the following reasons:

1) The object of low-level heuristics allocation is the grouped components, which only involves the type of components and the number of placement points, independent of the point distribution, which is difficult to encode.
2) The distribution of points mainly affects the movement path of the placement process, and its ratio in the overall assembly time is relatively small.
3) The proposed estimator has a high level of accuracy, and both the multi-population mechanisms and the point allocation strategy in the algorithm design can reduce the impact of the error.
4) As stated in the Experimental Setup section: the data with either sparse or concentrated

distribution can reduce the generalization performance of the estimator, therefore, we prepared the data with relatively uniformly distributed points, also to avoid the resulting large errors.

In the estimator design, we add statements on the effect of the point distribution as follows:

The object of LLHs allocation is the grouped components, which involves only the type of components and the number of placement points. This is independent of the point distribution, which is neglected due to its coding difficulty and small impact on efficiency.

Responses to Reviewer #3 Comments

1. *Hyper-heuristic optimizer is a commonly-used idea for solving the optimization problems with the similar feature with the one in this article. Thus, the novelty and advantages of the specially-designed parts in the proposed method suggests to be highlighted in Introduction.*

Response: Thank you for your comment. We agree that hyper-heuristic is a commonly-used idea and have gained prominence for their ability to automate heuristic selection across problems, reducing problem-specific engineering effort. Selective hyper-heuristics are more computationally efficient and are suitable for problems with complex feasible domains. However, it still somewhat relies on the problem related/knowledge-based design of low-level heuristics.

The optimization of PCB assembly lines presented in this manuscript is the first systematic study of load balancing for linear-aligned-head surface mounters. The special feature of this type of machine assembly task is that its efficiency is not only related to the number of points assembled but also the points attributes. The number of points, component types, nozzle types and the specific optimization algorithm all have a significant impact on the final assembly efficiency. In the framework of the existing hyper-heuristic algorithms, we incorporate several new technology and algorithm in the load balancing process and the evaluation of individual metrics to improve the quality of the solution. Experimental results also show further that our optimization results have outperformed mainstream research and industrial solvers under different production line configurations.

In summary, in addition to the existing presentation of the contribution in INTRODUCTION, we have added the following statements around the novelty of the proposed algorithm:

The algorithm design is tailored to the structural characteristics of the linear-aligned head surface mounters. The hyper-heuristic framework employs techniques with domain knowledge, which results in improved mechanisms for the search and evaluation process, achieving accuracy of solution evaluation, efficiency of the search process and balanced allocation of results. Compared to state-of-the-art algorithms and industrial solutions, the proposed HHO-MFFE enables higher assembly efficiency.

2. *LLHs are mainly employed to handle the constraints. Their effectiveness hopes to be analyzed by the experimental results and evaluated by the indicator, such as the ratio of them.*

Response: Thank you for your comment. Inspired by the reviewer's suggestion, we added two related experiments, the first one on the optimization effect of a single heuristic, and the second one on the percentage of each LLH invoked for the high-quality solution obtained during the hyper-heuristic search. For this, we have added a subsection of "Comparison of the Various Low-level Heuristics" to the EXPERIMENT to illustrate the role of LLHs in the hyper-heuristic search process.

First Experiment:

Ten PCBs are employed to compare the performances of various LLHs. Table VII shows the optimization results of load allocation, where A_p, A_c, A_n and A_r are target-driven LLHs, i.e., minimum points, component types, nozzle types and ratio, respectively; A_k, A_g and A_u is the target-driven LLHs; and *HH* is the result of the hyper-heuristic. Both minimum A_p and A_k achieve higher assembly efficiency by more balanced cycles and placement points. Results of LLHs that indirectly affect efficiency or single objective-related have low efficiency. All single-LLHs fail to achieve the hyper-heuristic effect.

TABLE VII ASSEMBLY LINE BALANCING SOLUTIONS OBTAINED BY VARIOUS LLHS

PCB	A_p	A_n	A_c	A_r	A_k	A_g	A_u	HH
2-1	10.06	10.26	9.52	9.88	9.72	9.79	10.70	**8.17**
2-2	15.38	18.28	16.12	19.97	14.75	17.66	16.01	**13.92**
2-3	20.46	20.48	20.00	23.06	20.10	22.81	19.18	**18.12**
2-4	18.98	25.97	19.87	26.24	21.17	27.06	22.84	**18.38**
2-5	22.36	28.25	26.14	29.64	21.13	32.34	22.94	**19.68**
2-6	28.81	35.23	28.79	38.40	28.78	33.84	27.69	**28.19**
2-7	46.21	45.29	40.47	51.13	42.57	45.42	43.27	**33.89**
2-8	52.07	59.06	50.44	59.39	51.73	63.46	49.05	**47.19**
2-9	66.93	67.80	65.82	84.64	65.98	68.50	65.42	**61.18**
2-10	135.68	143.67	143.01	168.83	139.76	146.01	149.82	**118.83**

Second Experiment:

Further, we compare the ratio of the number of each LLH using in the hyper-heuristic, as shown in Fig. 5. Balancing the number of placement points among surface mounters is the main task of optimization, and the ratio of target-driven operators is higher than data-driven ones in the remaining LLHs. Nozzle change-related A_g occurs relatively less frequently in the assembly process, thus for most of the data, the pickup-related A_u is more oriented in the search process.

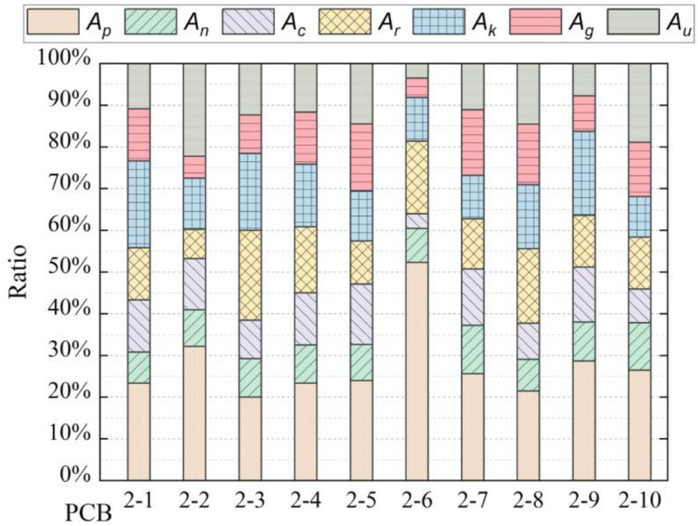

Fig. 5 Ratio of the number of each LLHs using in the hyper-heuristic.

3. *The computation complexity hopes to be further analyzed by theory and comparative experiment.*

Response: Thank you for your comment. We agree that it is necessary to analyze the computational complexity of such optimization problems with large-scale solution spaces and give an explanation in terms of theoretical analysis and comparative experiments.

In Problem Formulation, we analyze the complexity theoretically as:

PCBALS can be regarded as a special type of assembly line optimization which is known to be NP-hard. It has a higher level of decision and higher complexity compared with single-machine. The production optimization of surface mounters can be viewed as a combination of warehouse locating, task assignment and route schedule problems. There are various combinations of component allocation between different machines. Specifically, each assembly component may be assigned to multi-candidate machines with different processing time, resulting in an exponential growth of the number of feasible solutions.

In the EXPERIMENT, we compare the computational complexity of the proposed method, and the comparison experiments with the following analysis:

TABLE IX

COMPARISON OF THE SOLVING TIME OF THE PROPOSED LINE OPTIMIZERWITH STATE-OF-THE-ART ALGORITHMS

PCB	Hyper Heuristic			Hybrid Algorithm			Integrated Algorithm		
	*L*1	*L*2	*L*3	*L*1	*L*2	*L*3	*L*1	*L*2	*L*3
2-1	17.28	20.95	24.26	15.84	18.97	21.69	54.13	59.35	62.99
2-2	33.98	31.35	30.71	63.45	63.70	68.54	64.05	68.51	75.21
2-3	13.98	15.62	19.64	26.56	32.01	37.27	50.74	54.99	63.95
2-4	21.51	23.73	26.20	9.31	11.08	12.26	64.05	68.17	76.23
2-5	100.22	81.51	87.45	23.49	28.06	32.57	85.59	90.02	96.65

2-6	21.32	18.32	21.74	49.13	56.61	65.24	63.57	67.34	73.92
2-7	93.22	70.93	68.72	12.80	14.17	16.01	100.31	96.79	104.06
2-8	40.19	42.99	38.08	55.18	59.92	65.67	91.20	95.64	104.69
2-9	29.20	27.52	30.12	40.48	48.99	55.56	89.30	92.85	101.16
2-10	135.98	76.67	76.71	25.48	24.94	24.90	144.55	155.60	171.15

The genetic algorithm consists of relatively basic operators, which allow it to search quickly at the cost of solution quality. The hyper-heuristic and hybrid algorithms use a more complex time-fitting approach and account for component duplication, resulting in longer times than that of the genetic algorithm. The proposed hyper-heuristic is more efficient than the hybrid algorithm, and the quality of the solution it provides is higher. Evaluating the quality of the candidate solutions takes a large part of the solving time of the hyper-heuristic. PCB2-5 and PCB2-10 are more complex. Single-machine optimization takes longer for PCBs with larger number of components and nozzle types, resulting in relatively poor solving efficiency.

4. *The future work suggests to be supplemented in Conclusion.*

Response: Thank you for your comment. The vision of our research is to improve the efficiency of a production line consisting of linear-aligned-head surface mounters with multiple types of components to be assembled. In this manuscript, we study the optimization of production lines for a single type of PCB. However, with the rapid development of consumer electronics and other markets, manufacturers are faced with heavier tasks of high-mix, low-volume production, which require both higher production efficiency and stability. Based on this, we conclude with the future research as:

Future research can focus on load balancing optimization of flexible PCB assembly lines. For high-mix, low-volume PCB production tasks, its efficiency is affected by the configuration adjustments of surface mounters. This involves the optimization of the scheduling of dynamic production tasks, enhancing the efficiency of the feeder module changeover, etc., which is beneficial to shorten the productive cycle, reduce the storage cost, so that the small- and medium-batches can achieve profitability comparable to that of mass manufacturing, and improve the efficiency, robustness and stability of the assembly line.

5. *The paper should be thoroughly proof read for better language and grammatical errors.*

Response: Thanks for your advice. We have proofread the entire manuscript manually and with a professional grammar checker. The presentation including the part of INTRODUCTION, PROBLEM FORMULATION and ALGORITHM DESCRIPTION has been revised. Inaccurate or ambiguous descriptions have been modified, and the manuscript has also been proofread by a professional English speaker, who is also one of the authors.

6. *The primary distinction from previous research is that this paper focuses on optimizing the PCB assembly line for surface mounters with linear-aligned-heads. However, there is less description of the operating characteristics of this mounter (compared to other types of surface mounters).*

Response: Thanks for your advice. We apologize for the lack of description of the operating characteristics of linear-aligned-head surface mounters, which may prevent the readers from fully understanding the research. This type of surface mounter offers both efficiency and accuracy advantages when assembling various shapes of components. To illustrate its characteristics, we have added relevant expressions in the INTRODUCTION as:

Surface mounters with linear-aligned-head are widely applied in PCB assembly and consist of a stationary platform, two stationary feeder bases, and a moving gantry with multiple heads. The gantry moves between the PCBs and the base, and is fitted with heads assembled with suitable nozzles from an automatic nozzles changer for picking and placing different components. The linear-aligned design of the heads is spaced in integer multiples of the slot intervals so that heads can simultaneously pick up components from the feeders on different slots. Compared with the rotary-head type, the mechanical structure of linear-head is simple and reliable, with higher pickup efficiency, which can realize high-speed and high-precision assembly, and the applicable types of component packages are also more diversified.

7. *The literature review focuses more on rotary-head type.*

Response: Thank you for your comment. We recognize that the greater focus on rotary-head types in the review is because there is little relevant current research on linear-head type. In practice, the latter has a wider range of applications. The rotary-head type has an efficiency advantage in the placement of small-sized components, while the linear-head type studied in this manuscript is multi-function, considering the efficiency and accuracy of the assembly. We have listed in the introduction of the recent literature on the study of linear-head type:

Extensive research has been conducted on PCBALS and the optimization for a single machine has been thoroughly studied [5, 6].

[5] H. Gao, Z. Li, X. Yu, and J. Qiu, "Hierarchical multiobjective heuristic for PCB assembly optimization in a beam-head surface mounter, " IEEE Trans. Cybern., vol. 52, no. 7, pp. 6911－6924, Jul. 2021.

[6] G. Lu, X. Yu, H. Sun, Z. Li, J. Qiu, and H. Gao, "A scan-based hierarchical heuristic optimization algorithm for PCB assembly process, " IEEE Trans. Industr. Inform., vol. 20, no. 3, pp. 3609 – 3618, 2024.

In the LITERATURE REVIEW section, we have discussed component allocation algorithms for assembly lines categorized by optimization methods and review studies related to assembly time estimation. Although the related studies focus more on rotary-head type, their existing research is inspiring and is the basis of the framework designed in this manuscript (addressed in stages by allocation and evaluation). We have built on the established literature and combined the features of the linear-head type to reach good results and fill a gap in the field.