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Optimization of Line Configuration and Balancing for Flexible Machining Lines

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Abstract: Line configuration and balancing is to select the type of line and allot a given set of operations as well as machines to a sequence of workstations to realize high-efficiency production. Most of the current researches for machining line configuration and balancing problems are related to dedicated transfer lines with dedicated machine workstations. With growing trends towards great product variety and fluctuations in market demand, dedicated transfer lines are being replaced with flexible machining line composed of identical CNC machines. This paper deals with the line configuration and balancing problem for flexible machining lines. The objective is to assign operations to workstations and find the sequence of execution, specify the number of machines in each workstation while minimizing the line cycle time and total number of machines. This problem is subject to precedence, clustering, accessibility and capacity constraints among the features, operations, setups and workstations. The mathematical model and heuristic algorithm based on feature group strategy and polychromatic sets theory are presented to find an optimal solution. The feature group strategy and polychromatic sets theory are used to establish constraint model. A heuristic operations sequencing and assignment algorithm is given. An industrial case study is carried out, and multiple optimal solutions in different line configurations are obtained. The case studying results show that the solutions with shorter cycle time and higher line balancing rate demonstrate the feasibility and effectiveness of the proposed algorithm. This research proposes a heuristic line configuration and balancing algorithm based on feature group strategy and polychromatic sets theory which is able to provide better solutions while achieving an improvement in computing time.

Keywords: flexible machining line, line balancing, line configuration, constraints model, optimization

1 Introduction

In modern mechanical and automobiles manufacturing for mass production, the automatic machining line, often called a transfer line, is widely used to realize efficiency, high quantity and economic production. The line is composed of a set of workstations and automatic transfer of work units between workstations. Each workstation carries out one identical set of machining operations every cycle time. The automatic machining line for a given part family is a significant investment, and requires a long period for its design. In today's competitive business environment, it is vitally important for machine tool manufacturers to design the line more effectively and efficiently according to a wider variety of customer demands. The manufacturer should quickly offer a complete preliminary design solution for the corresponding line in terms of line architecture, number of machines, etc, and an approximate line cost. Line configuration and balancing is an important issue to be considered in the preliminary design stage for the automatic machining lines.

The automatic machining line configuration and balancing is selection of the type of machining line and the resolution of the balancing problem, i.e., the allocation of machining operations and machines to workstations in order to obtain the necessary production rate meeting demand while achieving the quality required. It is imperative to consider here all the constraints among the features, operations, setups and workstations.

Historically, the line configuration and balancing problem was first stated for assembly lines. Exhaustive studies have been made by many researchers in the past 50 years, with many interesting applications covered. The problem of machining line configuration and balancing is rather recent. SZADKOWSKI[1] was the first to consider such a problem. DOLGUI, et al[2], first called it transfer line balancing problem(TLBP). Until the mid-1990s almost all the production systems in the global powertrain industry had dedicated transfer lines that could produce only a single product at low cost when produced at large quantities[3]. Most of the previous studies of the machining line configuration and balancing problems were related to dedicated transfer lines equipped with multi-spindle heads machines. Several exact and approximate methods have been proposed[4–7].

With the advancement of machine technologies over the past decade, the production of medium-to-high volume,

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large size mechanical parts, such as automotive powertrain components, has undergone a transformation. Dedicated transfer lines with dedicated machine workstations are being replaced with flexible machining line composed of multiple parallel CNC machining centers, with all machines performing exactly the same machining operations[8]. Such configurations of parallel identical machines in each workstation, with material transfer between the workstations improve throughput and reduce work-in-process inventories. Methods for selecting the optimal configurations were suggested by DOU, et al[9–10]. Recently, the other TLBP problem which is called flexible machining line balancing problem, FMLBP is researched.

XU, et al[11] and LI, et al[12], proposed different particle swarm algorithms to solve the line balancing problem in one certain line configuration. ESSAFI, et al[13], developed an exact method based on a mixed linear programming model for this problem. Precedence, inclusion and exclusion constraints are respected and sequence dependent set-up times are specified. However, experiments showed that only small sized instances could be solved within a reasonable calculation time. As a consequence, several heuristic approaches have been suggested to deal with larger industrial instances. A greedy heuristic, two metaheuristics based on ant colony principles and on a greedy randomized adaptive search procedure were presented[14–16]. BORISOVSKY, et al[17], proposed a genetic algorithm with a heuristic decoder, mutation operator for handling the inclusion constraints and a MIP model for a local improvement of the solutions. In addition, BORISOVSKY, et al [18], presented a new exact solution approach on the base of a set partitioning type model which combines several solution techniques: the dynamic programming, the MILP modeling, the constraint generation and the branch and cut method with parallel computing. The above researches treated the problem as operations sequencing and assignment problem. The constraints consist of order relations between operations and assignment relations between operation sets and workstation. Solution time for large problems is long.

DAS, et al[19] and OSMAN, et al[20], decomposed the problem into two sub problem: a features assignment problem and an operations sequencing problem. OSMAN, et al[20], applied benders decomposition and ant colony optimization techniques to solve the two sub problem. This method had fewer computing time. However, in industrial instances, operations of one feature may be assigned to different workstations.

Our motivation is to develop an efficient solution for the FMLBP which concerns selecting number of workstations as well as setup sequence, number of paralleling identical machines allocation, grouping and sequencing of operations. We consider the objectives of minimizing cycle time and number of total machines. In this paper, we propose the mathematical model and heuristic algorithm based on feature group strategy and polychromatic sets theory. The feature group strategy and polychromatic sets theory are used to establish constraint model.

The paper is organized as follows: section 2 details the problems; section 3 defines the problem model; section 4 presents the optimization method; section 5 discusses an actual case; the conclusion is presented in section 6.

2 Problem Statement

In this paper, we consider a problem of configuring and balancing flexible machining lines for complex boxy parts, for example, automotive engine cylinder block. Fig. 1 shows the process of line configuration and balancing. The features are located at various faces of the part and, as such, are processed on flexible manufacturing machines by changing their orientation through a fixture. Each feature requires one or more machining operations for its completion. The set of all operations determined by the process plans are executed at the flexible machining line.

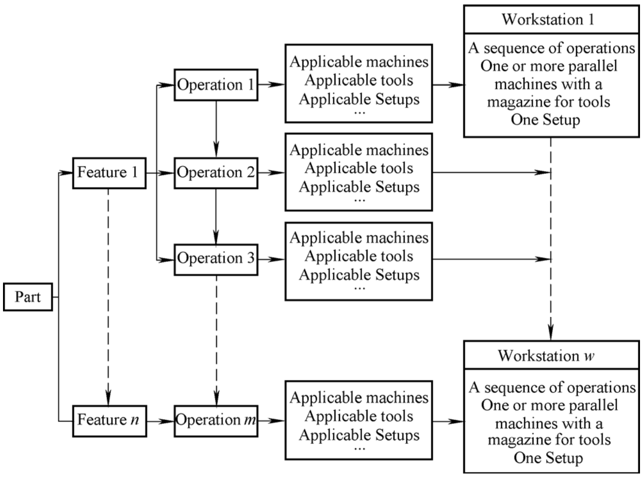


Fig. 1. Representation of a line configuration and balancing

The machining line is composed of sequentially arranged workstations. Each workstation consists of one or more parallel CNC machining centers with identical setup and operation assignment. Each CNC machining center contains one spindle and a magazine for tools. Each machining operation requires its own specific type of tool, which is placed in the limited capacity tool magazine. The capability of a machine is different when allocated with a different set of tools. A part to be machined will pass through a sequence of workstations in the order of their installation. Only one setup is allowed to be assigned to one workstation. Each workstation is associated with a sequence of operations, and is provided with at least one machine which carries out the operations during the line cycle time. The line configuration and balancing problem is allocation operations and machines to workstations in order to obtain the necessary production rate. A proper line configure for machining these features is vital in achieving efficient and high-quality manufacture of the part.

A feasible line configuration must subject to the various technological constraints. There are four kinds of technological constraints.

(1) **Precedence constraint**: Precedence constraint induces a partial order between operations which means that operation *j* cannot be done until operation *i* has been done before. This constraint is the most important constraint in operation sequencing. It includes first basic reference and last others part, first face machining, last hole machining, first rough machining, last finish machining, first main machining, last subordinate machining, etc. Precedence constraint has two situations. One is that two operations belong to the same feature. The other is that two operations belong to the different features.

(2) **Clustering constraint:** Clustering constraint means some sets of operations must be executed on the same workstation. It signifies that two operations *i* and *j* that belong to the same machining stage must be handled together (i.e., these operations must be done with one setup), such as the constraints that refer to a datum: parallelism, perpendicularity, angularity, concentricity, circular run-out, total run-out, symmetry and the like. For clustering constraint, the order is unimportant.

(3) **Accessibility constraint:** Accessibility constraint is related to the position of the part and the setup on the machine. The part is mounted on the machine with a fixture in a given position, some sides and elements of the part are not accessible for machining even after the part displacement or rotation. For every part position and setup there corresponds a set of features which can be machined. In order to enable the cutting tool to reach all faces of the part, fixing position change takes place. In the considered machining line, only one part fixing position which is called one setup is defined for each workstation. The part repositioning is made between two workstations.

(4) **Capacity constraint:** Capacity constraint is related to the workstation, the machine and the cutting tool. Each workstation has an upper limit on the local workload time which is equal to the number of parallel machines multiplied by the given cycle time. Each machine has an accuracy that can be achieved. Each machine' tool magazine contains a specific number of tool slots that cannot be violated.

In addition, sequence dependent set-up times have to be considered. Workload time of a workstation is composed of fixed machining time of each operation and non-machining time (NMT) associated with two sequential operations. The NMT represents the orientation change time, the tool change time and the tool displace time. The NMT required for the execution of two sequential operations is not equal to the sum of their times but depends also on the order in which they are done because the NMT needed for the displacement/change of tool and part rotation is different.

3 Problem Formulation

We formulate a mathematical model to solve the FMLBP. The model specifies the number of machines in each workstation, the machining operations assigned to each workstation and the sequence of operations in each workstation. The objective of the model is to reduce line cycle time and total machine numbers, increase line balancing rate. The model involves precedence constraint, clustering constraint, accessibility constraint and capacity constraint mentioned earlier. The constraints are imposed to distribute operations and machines to workstations. The proposed mathematical model is discussed in the following section.

In this section, we will introduce the notations and formulate the main assumptions of the problem considered. The set of features for one type of part and their machining operations is to be executed at the line. Machining time of each operation is known. A part to be machined will pass through a sequence of workstations. Each workstation is associated with a setup and a sequence of operations. When the total time of a workstation exceeds the line cycle time, parallel and identical machines can be installed. In this case, the local cycle time is equal to the number of parallel machines multiplied by the line cycle time. All machines of the same workstation execute the same operations. The description of the input data and the problem requirements are given as below.

Indices

g—Index set of feature group, $g=1, 2, \cdots, G$,

w—Index set of workstations, $w=1, 2, \cdots, W$,

Parameters

F—Set of features to be machined,

FG—Set of feature groups, $FG=\{FG_1, FG_2, \cdots, FG_G\}$,

O—Set of operations to be performed. Each operation must be assigned to exactly one workstation,

SP—Set of setups. Only one setup is allowed to be assigned to one workstation,

m_g—Number of operations in feature group g,

m_w—Number of operations on workstation w,

n_g—Number of features in feature group g,

F^g—Set of features in feature group g,

$F^g = \{F_1^g, F_2^g, \cdots, F_{n_g}^g\}$,

O^g—Set of operations in feature group g,

$O^g = \{O_1^g, O_2^g, \cdots, O_{m_g}^g\}$,

ST—Set of workstations, $ST = \{ST_1, \cdots, ST_W\}$,

N_w—Number of machines on workstation w,

N_w^0—Maximum number of machines allowed in workstation,

N_w^{mtool}—Number of tools needed on each machine of workstation w,

N_0^{mtool}—Tool magazine size on each machine,

T_w—Workload time for workstation w, it is equal to the sum of the machining times of all operations assigned to this workstation plus sequence-dependent non-machining times for the change or displacement of tools, part rotation.

CT_0—Objective line cycle time,

CT—Line cycle time,

LB—line balancing rate.

3.1 Objective function

The optimization problem consists in designing a machining line as a sequence of workstations, where for each workstation a number of machines and a sequence of operations and tools are assigned so that the described constraints are fulfilled. The objective is to determine the configuration of the line and operations sequence to minimize the line cycle time and the total number of machines and to maximize the line balancing rate.

The objective function is calculated as follows.

(1) Minimize the line cycle time:

$$\text{Minimize}\left(\text{MAX}\frac{T_w}{N_w}\right). \tag{1}$$

(2) Minimize the total number of machines:

$$\text{Minimize}\left(\sum_{w=1}^{W} N_w\right). \tag{2}$$

(3) Maximize the line balancing rate:

$$\text{Maximize}\left(\sum_{w=1}^{W} T_w \bigg/ \text{MAX}\left(\frac{T_w}{N_w}\right)\times\sum_{w=1}^{W} N_w\right). \tag{3}$$

3.2 Constraint model

3.2.1 Group features of the part

The considered machining line must perform all operations with respect to various constraints. Each feature requires one or more machining operations which are performed in an order without violating the precedence constraints. The features may have precedence relationship among themselves, such as precedence of basic reference feature and other features. Each feature can be machined in several alternative setups. Accessibility constraint often exists between features and setups. Cluster constraint exists between operations and workstation. Each workstation has one setup. As the line configuration and balancing problem involves various interdependent constraints, it is very difficult to formulate and solve this problem.

In order to simplify the description of interdependent constraints, the first and basic task is to group features of the part. In a typical complex boxy part there are six basic planar faces. There are a number of face features and hole features located at different basic planar faces. Whenever a feature is processed and the next feature is to be processed on a different basic planar face, the part is rotated to change orientation. The time required for this non-value added activity is non-productive. It is required to be kept at a minimum. Thus, the features can be grouped together with the objective of minimizing NMT. The features located at the same basic planar face tend to have the same setups. According to the characteristics of boxy part, we group all the features into datum feature group, special feature group, basic feature group and oblique feature group. Number of datum feature groups is related to setups. Each feature group must be executed after setup is applied. There are six basic feature groups corresponding to six basic planar faces. Hole features perpendicular to certain basic planar face and face features parallel to certain basic planar face are grouped into one basic feature group. Features inclined to the basic planar face at the same angle are grouped into one oblique feature group. Special feature group is relate to special machining requirement, for example, features must be machined on the same workstation are grouped into one special feature group. Intersecting hole features, it should be first long hole machining and last short hole machining, can be grouped into one special feature group. Fig. 2 shows grouping of features in groups.

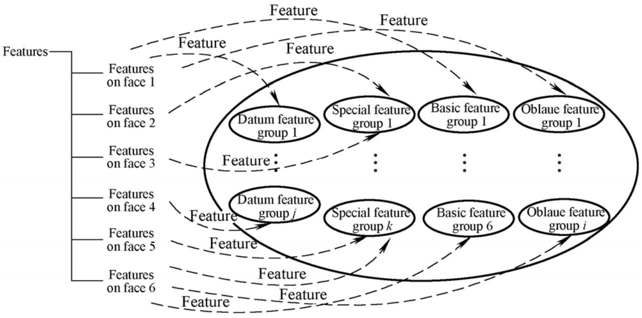


Fig. 2. Allocation of feature to groups of feature

3.2.2 Polychromatic sets theory

In order to describe these complex constraints, matrix based polychromatic sets theory is used. Polychromatic sets theory is a brand new mathematical tool which is used to describe the relationship between different technical index of complex mechanical system, such as property, attribute, characteristic and parameter. The theory not only describes the characteristics of sets and elements, but also describes the relationship of elements and entireties.

For polychromatic set $A=(a_1,\cdots,a_i,\cdots,a_n)$, the element colour set $F(a_i)=(f_1,\cdots,f_i,\cdots,f_k)$ corresponds to every element $a_i\in A$ and the colour set $F(A)=(F_1,\cdots,F_i,\cdots,F_m)$ corresponds to the entirety of A. They are included in a unified colour set,

$$F\supseteq F(A);\,F(a_i);\,i=1,2,\cdots,n.$$

When an object is represented in terms of polychromatic sets, its colour corresponds to jth characteristic of the object or the element. The relationship between element and unified colour can be represented by $A\times F(A)$, the relationship between individual colour and unified colour can be represented using $F(a)\times F(A)$.

3.2.3 Feature-operation constraint matrix

To simplify the computation and clarify the presentation of the relations between features and operation, we build the “feature-operation” constraint matrix based on polychromatic sets theory shown in Eq. (4). In the matrix, the operation methods are regarded as basic elements. Element OM_1 to OM_m respectively represents operation method. Operation Methods $=$ {milling, semi finish milling, finish milling, drilling, gun drilling, core drilling, rough boring, semi finish boring ,finishing boring, rough reaming, finish reaming, tapping}. And feature is looked as unified color. Unified color F_1^g to $F_{n_g}^g$ respectively represent machining feature in feature group g. Each feature has a unique identification code and each operation has a unique identification code:

$$\begin{array}{c|ccccc|} & F_1^g & \cdots & F_j^g & \cdots & F_{n_g}^g \\ OM_1 & b_{11} & \cdots & b_{1j} & \cdots & b_{1n_g} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ OM_i & b_{i1} & \cdots & b_{ij} & \cdots & b_{in_g} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ OM_m & b_{m1} & \cdots & b_{mj} & \cdots & b_{mn_g} \end{array}, \tag{4}$$

When $b_{ij} = 0$, the operation isn’t executed; When $b_{ij} > 0$, the operation is executed. b_{ij} is operation code. When $b_{ij} < 0$, the operation has predecessor face feature. ($-b_{ij}$) is equal to feature code.

We can find out the relative machining method and machining feature from the row name and the column name based on value of b_{ij} and its position in feature-operation matrix. Feature-operation matrix can be put into two-dimension array $b[m][n_g]$.

3.2.4 Feature group- station constraint matrix

The part is mounted on the machine in an orientation through a fixture. In order to enable the cutting tool to reach all faces of the part, there are several possible setups. Only one of these setups is chosen for each workstation; a setup defines the accessibility constraints for the part. For every setup there is a set of feature groups which can be machined. Suppose several feasible setup sequences in the line are known according to the process plans, we can build the “feature group-station” constraint matrix shown in Eq. (5). Element FG_1 to FG_G respectively represents feature group, unified color ST_1 to ST_W respectively represents workstation:

$$\begin{array}{c|ccccc|} & ST_1 & \cdots & ST_j & \cdots & ST_W \\ FG_1 & d_{11} & \cdots & d_{1j} & \cdots & d_{1W} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ FG_i & d_{i1} & \cdots & d_{ij} & \cdots & d_{iW} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ FG_G & d_{G1} & \cdots & d_{Gj} & \cdots & d_{GW} \end{array}, \tag{5}$$

where

$$d_{ij} = \begin{cases} 1, \text{Feature group can be machined} \\ \quad \text{in this workstation,} \\ 0, \text{Feature group can not be machined} \\ \quad \text{in this workstation.} \end{cases}$$

3.2.5 Capacity constraints

Capacity constraints of the model are given by Eqs. (6)–(9).

Eq. (6) demonstrates that workload time of each workstation composed of machining time and non-machining time (NMT) should not exceed its time capacity. t_i represents machining time for operation i. t_{ij} denotes NMT for operation i when operation j is processed directly after operation i on the same workstation. The NMT for performing one operation in a workstation is represented by the three terms that appear on the right hand side of Eq. (7). t_{ij}^1 denotes time for part orientation change to performing an operation j after completing an operation i. t_{ij}^2 denotes time for replacing tool after performing an operation i while performing an operation j. t_{ij}^3 denotes time for tool fast-moving in the operation i. The available time in a workstation is given by the cycle time multiplied by the number of machines existing in the workstation.

$$\sum_{i=1}^{m_w} (t_i + t_{ij}) \leqslant CT_0 \times N_w, \tag{6}$$

$$t_{ij} = t_{ij}^1 + t_{ij}^2 + t_{ij}^3. \tag{7}$$

Eq. (8) shows that, for each workstation, the total tool slots occupied in a machine’s magazine should not exceed the tool magazine capacity.

$$N_w^{mtool} \leqslant N_0^{mtool}. \tag{8}$$

Restriction on the number of machines in each workstation is satisfied by Eq. (9)

$$N_w \leqslant N_w^0. \tag{9}$$

4 Solution Algorithm

In this section, we discuss the solution algorithm developed to solve the FMLBP. The objective is to assign operations to workstations and find the sequence of execution that satisfies the precedence, cluster, accessibility and capacity constraints and to minimize the line cycle time and the total number of machines. Fig. 3 shows the process of the solution algorithm.

Step 1: Sequence operations in each feature group.

Step 1.1: Put the first nonzero element of each column in array $b[m][n_g]$ into one-dimensional array $c[]$. Put the column name of selected element into array $d[]$ and the row name into array $e[]$. There are p ($p \leqslant n_g$) elements in $c[]$.

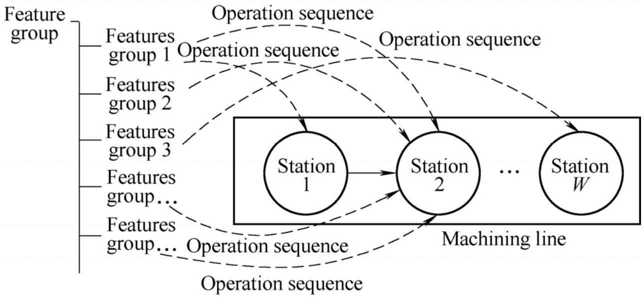


Fig. 3. Allocation of operations to stations

Step 1.2: Randomly select k from 0 to p–1. If $b[0, d[k]]<0$, the feature $d[k]$ is hole, then go to step 1.4, else, the feature $d[k]$ is face, then go to step 1.3.

Step 1.3: Put $c[k]$ into new operation set, $b[e[k], d[k]]=0$, go to step1.5.

Step 1.4: If machining operations on feature $(-b[0, d[k]])$ haven't been processed, go to step 1.1. Put $c[k]$ into new operation set, $b[e[k], d[k]]=0$, go to step 1.5.

Step 1.5: Repeat above steps until obtaining new operation sequence which consists of m_g operations.

After finishing step 1, we can obtain an operation sequence O_g meeting precedence constraint in each feature group:

$$O_g = (O_1^g, O_2^g, \cdots, O_{m_g}^g).$$

Step 2: Assign operation to workstation for each feature group.

Step 2.1: According to the feature group-station constraint matrix, compute the distributable workstation number K_g:

$$K_g = \sum_{j=1}^{W} d_{gj}. \tag{10}$$

Step 2.2: Generate $K_g - 1$ random numbers $I_g \in [1, m_g]$ and sort from smallest to largest. The cut points set O_g' to split operation sequence O_g is obtained:

$$O_g' = (I_1, I_2, \cdots, I_j, \cdots, I_{k_g - 1}).$$

Step 2.3: Allocate operations in feature group g to workstations according to cut points set O_g'. For example, the segment of O_g from start to $O_{I_1}^g$ is allocated to the first workstation which may be assigned to. The assignment result is represented by a_g:

$$a_g = \{\underbrace{O_1^g, O_2^g, \cdots, O_{I_1}^g}_{ST_{y_1}}, \underbrace{O_{I_1+1}^g, \cdots, O_{I_2}^g}_{ST_{y_2}}, \underbrace{O_{I_2+1}^g \cdots, O_{I_{K_g-1}}^g}_{\cdots}, \underbrace{O_{I_{K_g-1}+1}^g, \cdots, O_{m_g}^g}_{ST_{y_{K_g}}}\}.$$

where $y_1, \cdots, y_{k_g}$ is respectively the index number of workstation which feature group FG_g may be assigned to.

Repeat step 2, all operations in each feature group are allocated to workstations.

Step 3: Calculate target value.

Step 3.1: Calculate the workload time of every workstation according to Eq. (6).

Step 3.2: Compute the total number of machines.

The total number of machines on each station is

$$N_w = \mathrm{INT}\left(\frac{T_w}{CT_0}\right) + 1. \tag{11}$$

The machine number configure N_{st} on the line is

$$N_{st} = \{N_1, N_2, \cdots, N_W\}.$$

The total number of machines $N_{machine}$ is

$$N_{machine} = N_1 + N_2 + \cdots + N_W. \tag{12}$$

The line cycle time is

$$CT = \mathrm{MAX}\left(\frac{T_w}{N_w}\right). \tag{13}$$

The line balancing rate is

$$LB = \frac{\sum_{w=1}^{W} T_w}{N_{machine} \times CT}. \tag{14}$$

Step 4: Select and retain the best solution using the Pareto optimal solution set.

Step 5: Repeat Step 1 to Step 4 until satisfying update times of the best solution in optimal solution set.

5 Case Study and Discussions

This section presents a case study that we conducted with our industry partners to examine and validate the proposed approach. The case selected is the machining process of a diesel engine cylinder block. There are 84 features on the part, which has 20 face machining operations and 143 hole machining operations. The objective line cycle time is 640 s. The machines used for all workstations are four-axis CNC machining centers which are capable of completing all the machining operations. Fig. 4 shows the part and Fig. 5 shows the machine. Each operation machining time is known, and the total time needed for the machining is 5024 s. It takes 4.2 s for the machining center to change tool each time. Each worktable rotation time is related to rotary angle of the worktable between two operations. Rapid movement time for each operation is related to traveling distance of the tool from a certain location in the machining center to the processing area along three coordinate axes.

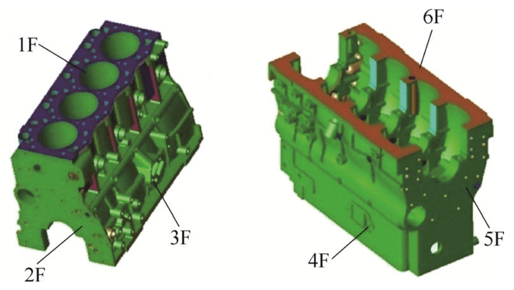


Fig. 4. Diesel engine cylinder block

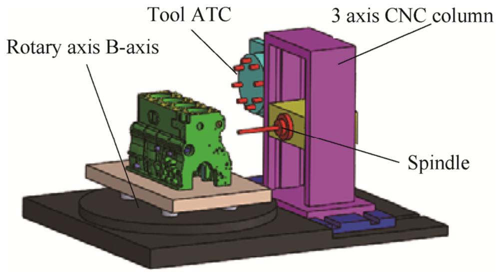
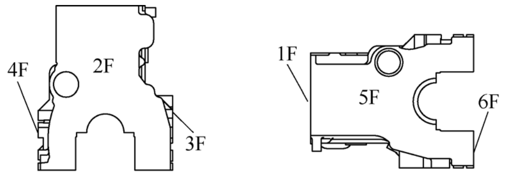
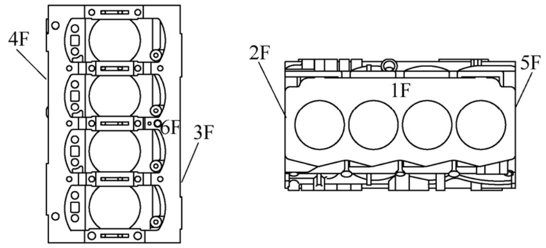


Fig. 5. Machine configuration

The cylinder block is mounted on the machine through a fixture. There are four feasible setups that depend on the part process plan to enable the cutting tool to reach all faces of the cylinder block, as depicted in Fig. 6. A feasible line configuration must be associated with a feasible setup sequence. There are three types of setup sequences, the first one with six stations is {Setup 1, Setup 2, Setup 3, Setup 3, Setup 2, Setup 4}, the second one with five stations is {Setup 1, Setup 2, Setup 3, Setup 2, Setup 4}, and the third one with 4 stations is {Setup 1, Setup 2, Setup 3, Setup 4}.



Setup 1, accessible to 2F, 3F, 4F, 5F Setup 2, accessible to 2F, 5F, 1F, 6F



Setup 3, accessible to 3F, 4F, 1F, 6F Setup 4, accessible to 1F, 2F, 5F

Fig. 6. Feasible setups

Fig. 7 shows present enterprise's line configuration and their line balancing result. The letter over the OP number represents the setup scheme defined in Fig. 6. Line cycle time is 636.97 s. Line balancing rate is 91.5%.

We apply the proposed method to this case study. The total 84 features are grouped into 16 feature groups which consist of 3 datum feature groups, 6 basic feature groups, 4 oblique feature groups and 3 special feature groups. According to setups and feature groups, we build the feature group-station constraint matrix. In each group, the feature-operation constraint matrix is created. Besides precedence, clustering, accessibility constraints, the maximum number of machines to be installed in a workstation is 3. The tool magazine size on each machine is 40. We execute the procedure until obtaining 20 solutions with line balancing rate bigger than 97% in optimal solution set. The results of our experiments are presented below.

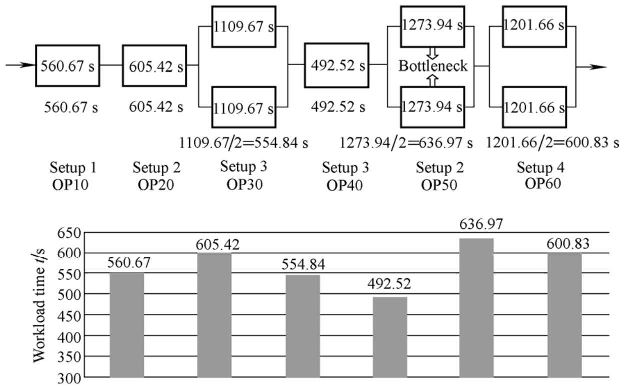


Fig. 7. Enterprise's solution

Fig. 8 gives optimal solution with six stations. Line cycle time is 604.43 s. Line balancing rate is 97.4%. Most of the runs get the similar solution. Compared with present enterprise's line balancing result, this solution has same number of machines, shorter cycle time and higher line balancing rate. It takes about two hours to get the optimal solution. Compared to the large solution space, $3^6 \cdot 4^{163}$ (obtained from the following facts: each workstation can choose 1 to 3 machines, each operation can perform at about 4 workstations), the algorithm is much more efficient.

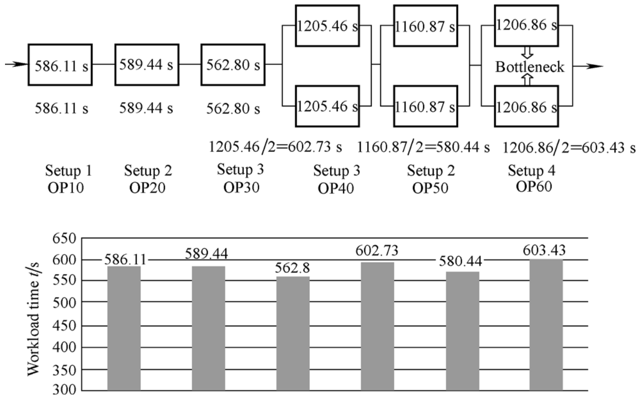


Fig. 8. Optimal solution with six stations

Fig. 9 gives optimal solution with five stations. Line cycle time is 599.98 s. Line balancing rate is 98.4%. Fig. 10 gives optimal solution with four stations. Line cycle time is 597.30 s. Line balancing rate is 98.7%. For the two setup sequences, the minimum machine number is 9. Short parallel systems have the shortest cycle time and highest line balancing rate.

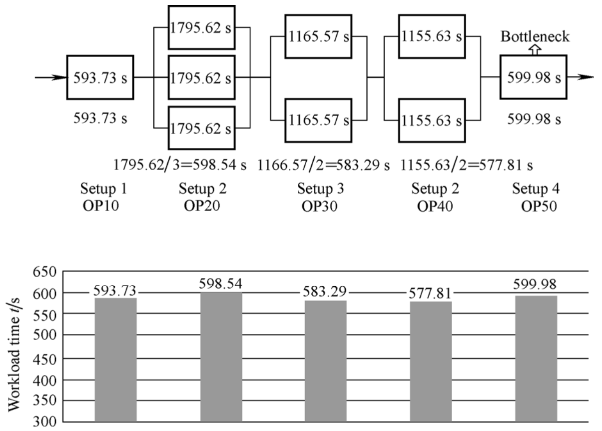


Fig. 9. Optimal solution with five stations

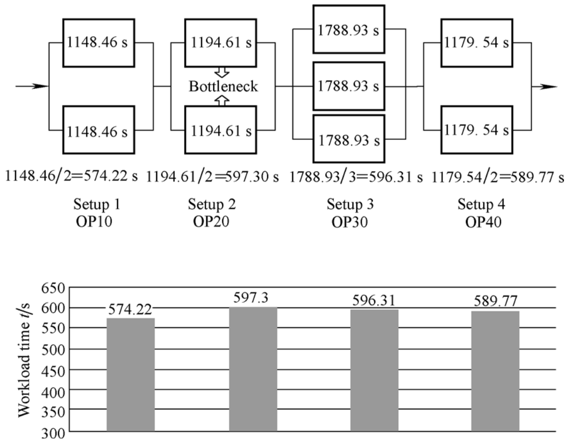


Fig. 10. Optimal solution with four stations

Finally, we compare the developed algorithm and evaluate the solutions. LI, et al[12], gave an optimal line balancing solution for similar industrial case, and the solution was only for certain line configuration. But the selected line configuration is not necessarily the best one. The proposed approach can obtain optimal solutions in different line configurations, which would be helpful to a FML designer in selecting the best configuration. In addition, our computing time is shorter. It takes about 2 h for the approach to solve the problem with 84 features, 163 operations, 6 workstations. However, it takes about 21 h to solve similar question which has 30 features, 96 operations, 6 stations in Ref. [16]. The experimental result demonstrates that the approach is more efficient for solving problem instances of industrially relevant size.

6 Conclusions

(1) Feature group strategy and the polychromatic sets theory are used to establish constraint model. According to the characteristics of boxy part, all the features are grouped into datum feature group, special feature group, basic feature group and oblique feature group. The “feature-operation” constraint matrix and the “feature group-station” constraint matrix are used to describe constrains.

(2) The heuristic algorithm is developed for the FMLBP, which consists of two steps: sequence operations in each feature group, assign operations to workstation for each feature group.

(3) The proposed approach is validated through a real industrial case. Experimental results show that the proposed approach can address the problem effectively and efficiently. It helps designers to explore different scenarios and possibilities.

(4) Setup plan has significant effect on line configuration and balancing. In order to improve performance of a line economically and competitively, further research can concentrate on the integration of setup planning and line balancing.

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