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Integrated Manufacturing Cell Formation Technology Orienting Multi-product Type and Variant Volume Production

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Abstract: What is pursued by multi-product type and variant volume(MPTVV) production is rapid response and quick switching, so that structure of transferring line in manufacturing system is no longer unalterable. Cell formation(CF) algorithm is the key technology of cellular manufacturing system(CMS). Currently, CF methods are mainly extended on the idea of group technology(GT) that covers a lot on analysis of resource capability matching and its algorithm. Various constraints are considered, but seldom utilized comprehensively. Aimed to the problem of manufacturing cell(MC) formation under MPTVV production mode, integrated formation technologies for typical MC as group type of cell(GC), flow type of cell(FC) and inherited cell(IC) are presented based on technical analysis of CF. Oriented to practical production constraints like delivery time, product batch, equipment ability, key machine, key part and machine sharing, etc, an integrated formation model is constructed and internal interrelations of these constraints are analyzed synthetically. Ulteriorly, formation goals of types of MCs and their formation procedures under joint effect of formation constraints and rules are spread. In case study, three highly balanced GC are formed first; then FC formation are implemented based on the same data which indicate good balancing effect of cell load and flow-style production for key tasks; When task is adjusted, a new scheme is constructed on the result of FC configuration by using IC formation method, and more optimal performance of flow-style production is manifested. The proposed comparative study of different type of cells strongly explains the validation of integrated MC formation in support of rapid manufacturing resource transformation under MPTVV production mode.

Key words: multi-product type and variant volume production, cell formation, flow style manufacturing cell, inheriting manufacturing cell

1 Introduction*

Nowadays, multiple type and variable production mode has been an inevitable choice for most enterprises, which is a natural result in the course of adapting or being adapted to the ever changing needs of our society. As a mode positioned between few type and mass production of flowing dedicated production line and multiple type and small or medium production of discrete flexible production line, multiple type and variable production has both advantages of efficiency and flexibility targeting variability and rapid response of system. Cellular manufacturing is a form of production organization which can accommodate to such type of production mode, and well support rapid response of manufacturing system. The core of cellular manufacturing is the reorganization and reuse of manufacturing resources; manufacturing cell characterized with self-government, collaboration and flexibility is the core component. Therefore, technologies of cell formation and reconfiguration are also the keys in implementation of CMS.

Presently, technologies of cell formation(CF) are mainly focusing on its construction algorithm. Likely aspects of formation rules and constraints, such as multi-routes and equipment types, work time assignment, batch production, equipment sharing, balancing of unit and machine capacity, have all been involved, but there is an absence of integrated application of these factors. Researchers like YASUDA, et al[1] and GARBIE, et al[2] used similarity coefficient for cell analysis. To solve the problem of formation of clusters and cells under changing market, PILLAI, et al[3], proposed a robust design method based on demand forecast and the result cell structure turned out to be relatively stable. Intelligent algorithm was introduced for CF solving. Considering factors like part number, route, processing time, equipment capacity, equipment status and objectives of cell balancing and minimization of inter-cell moving, ASOKAN, et al[4], PRABHAKARAN, et al[5], and many other scholars adopted ant colony algorithm. VENKATARAMANAIAH, et al[6], constructed an unit configuration with exceptional elements using hybrid heuristic algorithm. MAHAPATRA, et al[7], concentrated on cell load balancing and minimization of inter-cell

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moving and employed GA for solution. MANSOURI, et al[8], studied constraints of bottleneck equipments, exceptional parts and equipment sharing using GA method. WON, et al[9], adopted fuzzy ART N-N algorithm to solve grouping problem of complicated parts and equipments. DEFERSHA, et al[10], introduced GA parallel arithmetic into CF, in which many practical restriction like cell configuration, substitute process, equipments sharing and capacity and load balancing or them, and production fees were taken into account. FTS, et al[11], cut CF procedure into two steps. Firstly, multi-objective function was constructed for scaling units, and then a single objective function was employed targeting optimization of moving within and between units. BAI, et al[12], paid their attention to FC formation theory and technique for emergency mobilization batch volume production. As a whole, above researches are mainly focused on static cell formation, while studies on sustainable dynamic formation are seldom, even not to say integrated formation of multi-cell types.

Main focus of this article will be on the problem of manufacturing cell(MC) diversification under multi-product type and variant volume(MPTVV) production mode. From the view of integrated construction of multi-type MCs, integrated formation model and method based on unified constraints, rules and algorithms will be studied, and decision-making tools will be developed.

2 Technical Challenge

Under MPTVV production mode, product type and volume is on constant change at different period of time or stages of different period stemming from market requirement change. So the direct reason bringing configuration change of manufacturing system is dynamic requirement. In cellular manufacturing system(CMS), such change will finally impute to cells formed, or be undertaken and realized by cells.

The essential of cell formation and reconfiguration is optimizing assignment of manufacturing resource. It is a kind of allocation or reallocation of ability of manufacturing resource. Resource assignment needs to tradeoff between extreme cases of “one machine is one cell” and “the whole line is also one cell”. Moreover, to realize rapid resource transformation, other than matching between task and resource, resource assignment and optimization under conditions like delivery time, batch, key machine, key part and equipment sharing have to be considered also. Important reason of unsuccessful implementation applying traditional CF technologies is in lack of comprehensive consideration.

The outcome of CF is logical cells, so there are no clear boundaries among cells and machines in cells have no fixed attribution. Machines may act as a standalone ”device unit” for scattered tasks, or they can share their capacity with other cells and accomplish tasks with other machines. In this case, it’s possible that discrete units will emerge. The result configuration is a plural structure composed by “complete” units and a discrete unit. Traditional analysis emphasizes independence of part family and cells too much that may result in unharmonious production. Thus, bottleneck operations and equipments will appear and requirement of mating production for assembly cannot be satisfied. Moreover, cell load distribution is uneven and machines cannot be shared among cells.

Cell types under MPTVV production mode should be flexible and various. In multi-product type and small volume or trial production, cell form of group type of cell(GC) is required, while in mass volume production, continuous production has to be realized. Furthermore, during different period, inheriting sustainable reconfiguration will be a basic demand. The direct reason of hard advancing of traditional group technology(GT) based technologies is that frequent layout adjustment due to rapid change of requirement is difficult to realize. As a rigid formation technology, too many efforts have to be cost on physical layout adjustment. Construction method based on similarity of equipments and parts only emphasizes adaptation of existed resources to requirements, but not fluency of production flow in the view of routes of tasks which is also an important problem consented by organizers. Flow line type running is also an important objective in MC formation. Against periodical changing requirements, to lessen cost and influence of machine adjusting, CF procedure has to inherit original production line. Existed CF analysis mainly focuses on GC, researches on type of cell(FC) and inherited cell(IC) are comparatively seldom, and same status presents in formation constraint analysis and unified construction of different types of MCs.

GC, FC and IC represent different objectives and targets of CF and are typical cell forms in manufacturing system. Technical analysis on integrate formation for multi-type cell will be carried out orienting them.

3 Integrated Model of MC Formation and its Constraints Analysis

MC is formed under multiple related constraints. During MC formation, external factors like production requirement, delivery time and internal ones as batch, processing time, machine ability, key equipment and selectable machine have to be considered together. Also, production goals in cycle time, cost, equipment utility have to be satisfied, thus the course of MC formation is again one multi-objective optimization procedure, in which no optimum but many suboptimum solution exists commonly. Here, constraints and goals are decomposed and their interrelations to different type of MCs are illustrated in Fig. 1.

Resource, route and task are three main data needed in CF, yet inherited CF has to use former configuration schemas as source data for comparing. CF rules include route selection, machine (type) selection and machine task assignment rules. Main CF constraints here are machine ability, batch, key or mass parts and key equipment. Output policies are composed of partition rules for cell and equipment and part family. In case of shortage of machine ability in resource assignment, three scenarios of overtime, outsource and equipment procurement can be selected. In the process of different types or even stages of MC formation, quantitative indexes including similarity coefficient, inter-cell operation number, cell load and takt time balancing have to be adopted. All these rules, constraints and goals construct formation constraints of multi-type cell. Most of them are sharable, but some are for special purpose. For example, for FC formation, there're rules that emphasize operation balancing of route and production takt time of equipment, and goals that stress takt balancing in cell.

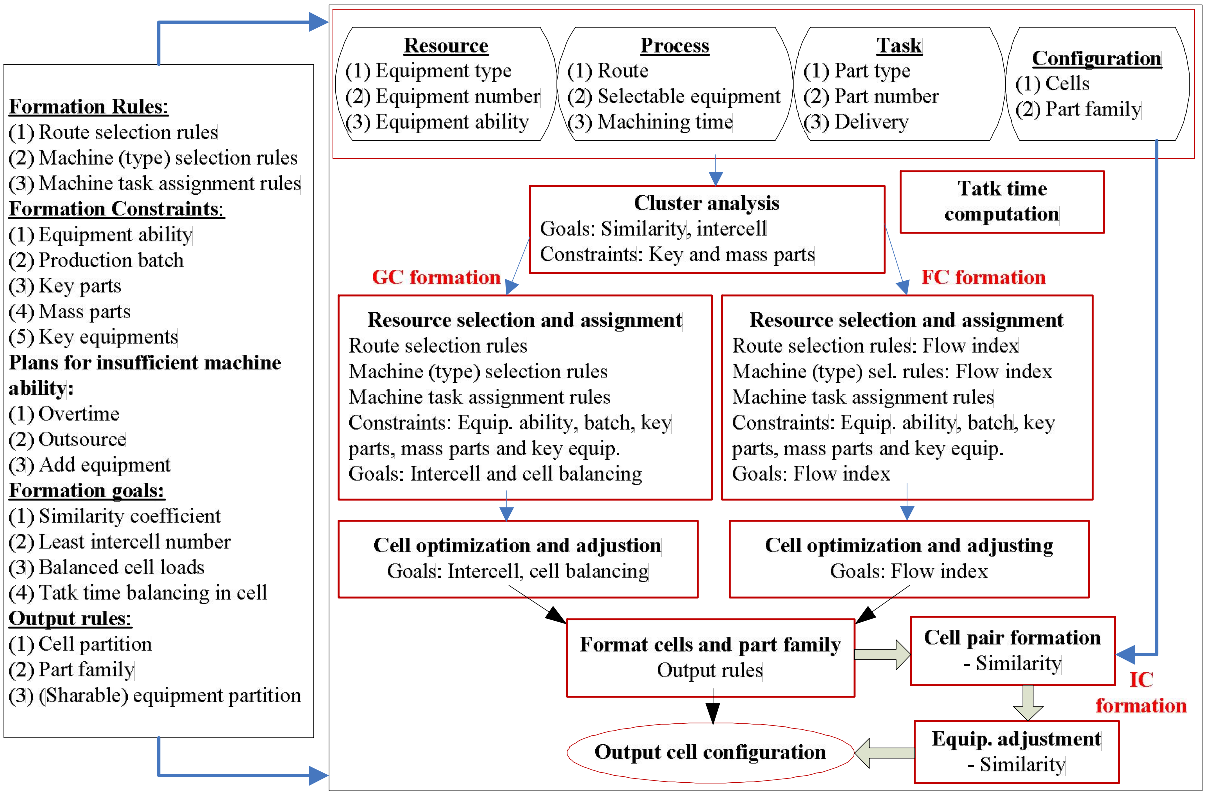


Fig. 1. Integrated model in MC formation and constraints analysis

Formation of three type of cell is not independent but interrelated, main stages: equipment cluster, resource selection and assignment, cell optimization and adjusting and cell output can all be reused. Cluster and output process are entirely universal, while assignment and optimization is different for different type of cell that rules, constraints and goals can be selected in demand.

According to Fig. 1, GC and FC are two basic cell (BC), and that FC is extended on GC and IC can be seemed as extension of BC. As a whole, GC constructs the constraints of FC like that BC to IC.

4 Objective and Procedure of Integrated Formation

For convenience, the flowing symbols are taken to express constraints in Fig. 1.

(1) Base data set: $S_0=\{D_1, D_2, D_3, D_4\}$. D_1 denotes production tasks; D_2 denotes part routes; D_3 denotes equipment resources; D_4 denotes configuration schemas.

(2) Formation rules set: $S_1=\{E_1\{e_{11}, e_{12}, e_{13}, e_{14}, e_{15}\}, E_2\{e_{21}, e_{22}\}, E_3\{e_{31}, e_{32}\}\}$. E_1 denotes routes selection rules, including; e_{11} denotes the first route; e_{12} denotes least machine type; e_{13} denotes shortest machining time; e_{14} denotes least inter-cell operation time; e_{15} denotes highest balancing index of operations. E_2 denotes machine (type) selection rules; e_{21} denotes current machine type; e_{22} denotes shortest machining time; e_{23} denotes machining time limited by takt time. E_3 denotes machine task assignment rules; e_{31} denotes task dispersed and average use of machines; e_{32} denotes task concentrated and focus use of machines.

(3) Formation constraints set: $S_2=\{F_1, F_2, F_3, F_4, F_5\}$. F_1 denotes machine ability; F_2 denotes batch; F_3 denotes key parts; F_4 denotes mass parts; F_5 denotes key equipment.

(4) Output rules set: $S_3=\{G_1,G_2,G_3\}$. G_1 denotes cell partition rules; G_2 denotes part partition rules; G_3 denotes sharable equipment partition rules.

(5) Formation goals set: $S_4=\{H_1\{h_{11}, h_{12}\}, H_2, H_3\{h_{31}, h_{32}\}, H_4\}$. H_1 denotes similarity coefficient, h_{11} denotes similarity coefficient; h_{12} denotes un-similarity coefficient. H_2 denotes least inter-cell operation number; H_3 denotes cell load balancing; h_{31} denotes cell load ratio; h_{32} denotes

ratio of balanced cell load. H_4 denotes takt time balancing in cell.

(6) Treatment set for shortage of equipment: $S_5=\{I_1, I_2, I_3\}$. I_1 denotes overtime; I_2 denote outsource; I_3 denote equipment procurement.

(7) Four steps of CF are described as follows: STEP1 denotes equipment cluster; STEP2 denotes resource assignment; STEP3 denotes cell optimization and adjusting; STEP4 denotes schema output.

In this paper, four steps with different constraints and objectives are marked out clearly, so that heuristic algorithm with stepped objective would be the most suitable problem solving method.

4.1 Objectives and procedure of GC formation

STEP1 is cluster of machine types, so single index of similarity or un-similarity coefficient is applied with flowing objective:

$$\max Z_{\text{step1}}=\max(h_{11}), \tag{1}$$

or

$$\min Z_{\text{step1}}=\min(h_{12}). \tag{2}$$

Where Z is formation objective of different formation steps. $\max(h_{11})$ denotes the max similarity coefficient(SC) of cells under all cell configurations, while $\min(h_{12})$ is the min un-similarity coefficient(UC) with relation of $h_{11}+h_{12}=1$, that is, the total of SC and UC is 1. Here, we adopt max SC index for cluster.

Resource selection in STEP2 and cell optimization in STEP3 both take compositive objectives with index of least inter-cell operation number and least cell load ratio:

$$\min Z_{\text{step23}}=w_{h2}\frac{H_{2\min}}{H_2}+w_{h3}\frac{h}{h_{31\max}}, \tag{3}$$

where w_{h2} and w_{h3} denote weight of inter-cell operation number and cell load ratio, which can be set as needed. $H_{2\min}$ denotes the minimum of total inter-cell operation number in all cell configurations. $H_2=\sum^{p}H_{2i}v_i$ is total inter-cell operation number of one configuration. H_{2i} denotes moving times of part i between different cells in its selected route, v_i denotes machining number of part i, and p is cell number of current cell configuration. $h=h_{\min}/h_{\max}$ denotes the min cell load ratio of one configuration. $h_{\min}$ is load of the min load cell and $h_{\max}$ is the max one. $h_{31\max}$ denotes the maximum of min cell load ratio in all configurations.

Then, formation procedure of GC is given (Fig. 2).

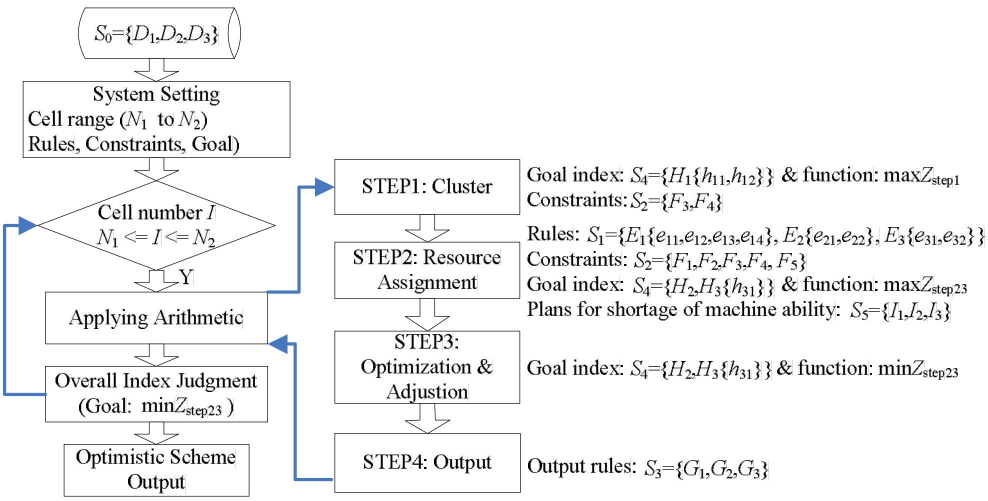


Fig. 2. Formation procedure of GC

First, according to settings of cell number (I) or range (N_1-N_2), rules, constraints and goals, formation algorithm is applied to each number of cells; then objective indexes are collected for all number of cells; At last, the configuration under a certain cell number corresponding to the optimum index is output.

In STEP1, resource of machine type needed is searched first; then similar machine type is clustered using $\max Z_{\text{step1}}$ as formation objective until cell number decreases to I. That is, the original cell configuration is formed. Adjusting of original configuration is then implemented under constraints selected: non key and important parts are kicked out to improve similarity; machines are reassigned to reduce inter-cell number of key or mass parts.

In STEP2, machining equipment for part operations is selected, and at the same time tasks of equipment are determined. In case of shortage of equipment ability, relevant plans have to be given. First, route selection rules $E_1\{e_{11}, e_{12}, e_{13}, e_{14}\}$ for main route and machine type selection rules $E_2\{e_{21}, e_{22}\}$ for main machine type is applied. Unto equipment selection, constraints $\{F_3, F_4, F_5\}$ are used: key machines are selected for key and mass parts preferentially. According to machine task assignment rules $E_3\{e_{31}, e_{32}\}$, spare machines have precedence under condition of average use of machines, while selected machines have precedence when constraint of focus use of machine is set, namely, spare ability of machine is reassigned.

Machine ability and batch $\{F_1, F_2\}$ are important constraints in resource assignment. Before machine selection for part operations, machinable part number of certain operation allowed by machine ability is computed first to assure that part load on machine must not exceed its ability. After each assignment, remaining machining ability of the machine has to be recomputed for equipment selection of other parts' operations. For each part operation, machines of the first machine type is selected preferentially, and in ability shortage, machine of other types takes the position. If machine ability is still on shortage, corresponding user plans $S_5=\{I_1, I_2, I_3\}$ will be presented. Assigned machine will enter relevant machine type in cells of STEP1. The whole process is targeted under index of inter-cell machining number H_2 and cell load balancing $H_3(h_{31})$ and objective of $\min Z_{\text{step23}}$ (Fig. 3).

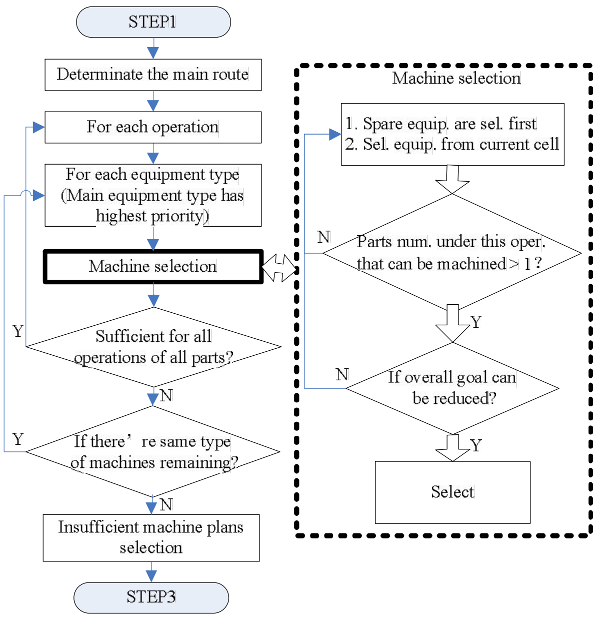


Fig. 3. Resource selection and task assignment in STEP2

STEP3 is a step of global optimization and adjusting which objective is consistent with STEP2: $\min Z_{\text{step23}}$. Options include inter-cell adjusting and cell load balancing. Detailed adjusting process will be given at section 4.4.

At the last step, output rules $S_3=\{G_1, G_2, G_3\}$ is employed to generate the final cell configuration.

4.2 Objectives and procedure of FC formation

To realize effect of continuous production of flow line, operation machining time in cells have to be balanced in FC formation to assure machining time of operations is same in the rough. Furthermore, as FC is formed upon GC, its objective includes not only cell similarity, minimum of inter-cell number, but goals toward continuous production, like load balancing between cells $H_3(h_{32})$ which is mainly made for assembly mating and takt time balancing of cell H_4 for realization of continuous production, so we get a compositive objective:

$$\min Z_f = \min Z_{\text{step23}} + w_{\text{h32}}\sqrt{\frac{\sum_{c=1}^{C}(L_{\max}-L_c)^2}{C}} + w_4\sum_{c=1}^{C}\left(\frac{L_c}{L}\times\sum_{i=1}^{N_c}\frac{Q_{ic}}{Q_c}\times\frac{T_{ic\max}-T_{ic\min}}{CT_i}\right), \tag{4}$$

where w_{h32}, w_4 denote weight of cell load balancing and cell takt time balancing, respectively. L_c denotes load of cell c. $L=\sum_{c=1}^{C} L_c$ denotes total load of the whole production line. $L_{\max}=\max_c(L_c)$ denotes load of the max load cell. c denotes cell index (c=1, 2,$\cdots$, C); and C denotes MC numbers. $T_{ic\max}$ denotes the max machining time by single machine of all operation types of task i in cell c. $T_{ic\min}$ denotes the min machining time by single machine of all operation types of task i in cell c. $CT_i=F/Q_i$ denotes takt time of task i. F is virtual work time and Q_i is part number in task i. Q_{ic} denotes the machining part number of task i in cell c and Q_c denotes the machining part number of all tasks in cell c. N_c denotes operation type number of in cell c.

Formation procedure of FC is similar to GC. Differentials exist in the following aspect: (1) Computation of takt time of (key) parts in tasks and equipment requirement by takt time that will be as constraints for machine selection. (2) Objective $\min Z_f$ leans to cell load balancing $H_3(h_{32})$ and takt time balancing H_4. Inter-cell factor H_2 is also considered. Ratio of cell load h_{31} in GC is substituted by load balancing rate h_{32}. (3) In STEP2, operation balancing index e_{15} is added to E_1 and takt time related rule e_{23} is added to E_2. (4) STEP3 mainly applies adjusting option of takt time balancing for key tasks. The adjusting procedure will be detailed in section 4.4.

4.3 Objectives and procedure of IC formation

As stated above, formation of IC is based on BC (GC and FC), so realization of IC will be constructed on objectives of BC. From the view of different period, evolvement of MC is sustainable that IC formation has to exhibit such transformation and employ similarity as its basic theory to seek relation between original and new configuration. Thus, procedure of IC formation can be simply divided into two phases: formation and adjusting phase that formation of BC being borrowed to construct the new configuration and inheriting adjusting phase which is implemented between two configurations.

Constraints and goals of basic cell are utilized for new configuration at formation. Because that stable suboptimum solution has be gained at the first phase, so inheriting adjusting have to be at cost of partial objective index and balance between two configurations.

$$Z'_{\text{step23}} = Z_{\text{step23}} - r(Z_{\text{step23}} - Z_{\text{org}}),\ \text{if}\ Z_{\text{step23}} > Z_{\text{org}},$$
$$Z'_{\text{step23}} = Z_{\text{step23}} - r(Z_{\text{org}} - Z_{\text{step23}}),\ \text{if}\ Z_{\text{step23}} > Z_{\text{org}}, \quad (5)$$

where r denotes inheriting scale with default as 80%; Z_{org} denotes objective of the inherited configuration; Z_{step23} denotes objective of the new configuration; Z'_{step23} denotes balanced objective.

Overall formation procedure is shown in Fig. 4.

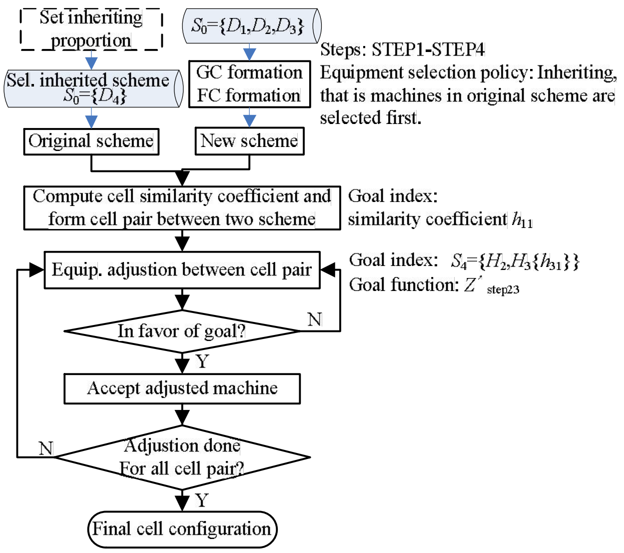


Fig. 4. Formation procedure of IC

In the first phase, new configuration is generated using formation of BC, and then at machine selection, equipments adopted in original configuration will be accepted preferentially.

Second phase can be divided into two levels of task and resource again. Task level is mainly to inherit cell configuration of historical tasks, while at resource level adjusting of machines and their ability sharing schema will be carried out. In task level, cell similarity coefficient h_{11} is used to find the most similar cell pair between configurations. Machine adjusting is a little more complex. Fig. 5 will be presented for better understanding.

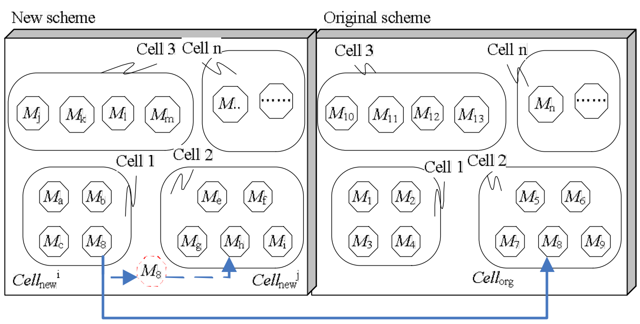


Fig. 5. Machine adjusting in IC formation

For each pair of cells of the original and new configuration: $Cell_{\text{org}}$ (Cell2) and $Cell_{\text{new}}^i$ (Cell1), equipment adjusting is going on as follows.

(1) For each machine, in cell of new configuration $Cell_{\text{new}}^i$, M8 for example, search the same machine from original configuration.

(2) If same machine exists, then record its attributive cell in original configuration $Cell_{\text{org}}$ indexed with j and turn to step (3), otherwise turn to step (1) for the next machine.

(3) Transfer this machine between cells of the new configuration from $Cell_{\text{new}}^i$ to $Cell_{\text{new}}^j$.

(4) Compute objective function value. If it is profitable for overall objective, then this time of machine adjusting is accepted, and turn to step (1) for the next machine, or it will be roll backed.

4.4 Optimization and adjusting in CF algorithm

4.4.1 Inter-cell adjusting

Try to reassign machines to other cells and compute objective function value Z and inter-cell operation number of each cell configuration. If it is favor of goals, then actual inter-cell number is recorded, or an infinite value is recorded. At last, configuration having min inter-cell number is accepted.

4.4.2 Cell load balancing

In GC and FC formation, cell load balancing algorithm (Fig. 6) will adopt cell load ratio, that is the ratio of min and max cell load.

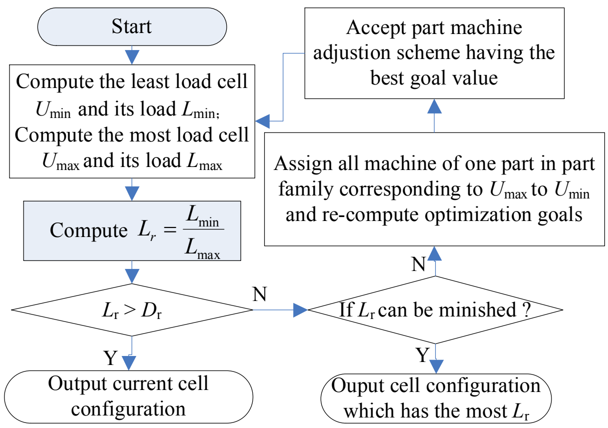


Fig. 6. Cell load balancing algorithm in GC formation

Here, D_r denotes the standard cell load ratio which value is often between 0.3–0.8. Higher value means more load balance is to be gained. But if it is too low, balance of cells cannot be achieved, and too high value will lead that no cells can be formed.

If L_r is lower than D_r then adjust cells that all used machines of one part from corresponding part family of the max load cell are all moved to the min load cell. Compute the result objective value Z and assignment schema with minimum value will be adopted. Re-compute L_r and iterate for each part and each cell until initializing value of D_r is met.

4.4.3 Takt time balancing of tasks

Here in FC formation, takt time balancing H_4 of key tasks is emphasized, so that cell production limitation is broke and continuous production of key task can be obtained, which also conforms to the thought of equipment sharing. When constraints of F_3 or F_4 are selected, only takt time and balancing index of key or mass parts is computed, that is only to ensure continuous production of these tasks, and others have to put into production at free time of machines.

Try to assign machines to other cells. If objective value Z is lowered, then the assignment is accepted, or it is rolled back. Iterate the operation until objective value cannot be lowered through assignment.

5 Case Study

Above heuristic algorithm has been realized in VC++ environment. Case study uses task data in Table 1 and equipment resource data in Table 2. It is noted that in Table 1 the number in bracket after part is part number in our task; sequence number of part operation is composed of route and its operation number; three parts P_2, P_8, P_{11} have selectable route, and they're marked out using shadow; machining time uses minute as unit. Delivery time of this task is two months.

5.1 Result and analysis of GC formation

Overall parameter settings are integrated in interface Fig. 7. Work shift is set to normal single shift, and when adding policy is selected in case of machine ability shortage, overtime single shift will be used. One shift has 8 h, and one week has 5 workdays. Default time utility ratio is 95%. Cell number is set to range from 2 to 4. Rule set of resource selection is $S_1=\{E_1\{e_{12}\}, E_2\{e_{22}\}, E_3\{e_{32}\}\}$ as being shown.

Table 1. List of task resource

Task	Operation of part route	Machine
P_1(80) Key part	1-1(Turn)	M_1(15), M_2(20)
	1-2(Benchwork)	M_3(20)
	1-3(Cylindric grind)	M_8(60)
	1-4(Grindout)	M_{10}(5)
P_2(80)	1-1(Turn)	M_1(40), M_2(30)
	1-2(Fine turn)	M_7(50)
	1-3(Fine mill)	M_6(50)
	1-4(Top grind)	M_9(60)
	1-5(Grindout)	M_{10}(40)
	2-1(Fine turn)	M_7(70)
	2-2(Fine mill)	M_6(50)
	2-3(Top grind)	M_9(60)
	2-4(Grindout)	M_{10}(40)
P_3(160) Key part	1-1(Mill)	M_4(30), M_5(25)
	1-2(Benchwork)	M_3(15)
	1-3(Cylindric grind)	M_8(32)
	1-4(Fine mill)	M_6(40)
P_4(160)	1-1(Turn)	M_1(30), M_2(35)
	1-2(Mill)	M_4(26), M_5(30)
	1-3(Fine turn)	M_7(32)
	1-4(Fine mill)	M_6(45)
	1-5(Cylindric grind)	M_8(25)
P_5(180)	1-1(Turn)	M_1(30), M_2(35)
	1-2(Mill)	M_4(25), M_5(30)
	1-3(Fine turn)	M_7(27)
	1-4(Fine mill)	M_6(35)
	1-5(Cylindric grind)	M_8(32)
P_6(180)	1-1(Turn)	M_1(25), M_2(15)
	1-2(Fine turn)	M_7(30)
	1-3(Fine mill)	M_6(35)
	1-4(Top grind)	M_9(20)
	1-5(Grindout)	M_{10}(25)
P_7(180)	1-1(Mill)	M_4(35), M_5(30)
P_7(180) Key part	1-3(Cylindric grind)	M_8(28)
	1-4(Fine mill)	M_6(45)
P_8(160)	1-1(Turn)	M_1(18), M_2(20)
	1-2(Mill)	M_4(25), M_5(30)
	1-3(Fine turn)	M_7(25)
	1-4(Fine mill)	M_6(40)
	1-5(Cylindric grind)	M_8(30)
	2-1(Furn)	M_1(18), M_2(20)
	2-2(Fine turn)	M_7(25)
	2-3(Fine mill)	M_6(80)
	2-4(Cylindric grind)	M_8(30)
P_9(160)	1-1(Turn)	M_1(25), M_2(20)
	1-2(Fine turn)	M_7(25)
	1-3(Fine mill)	M_6(30)
	1-4(Top grind)	M_9(25)
	1-5(Grindout)	M_{10}(20)
P_{10}(160)	1-1(Mill)	M_4(25), M_5(20)
	1-2(Benchwork)	M_3(10)
	1-3(Cylindric grind)	M_8(22)
	1-4(Fine mill)	M_6(38)
P_{11}(100)	1-1(Nenchwork)	M_3(15)
	1-2(Turn)	M_1(25), M_2(30)
	1-3(Mill)	M_5(27)
	2-1(Benchwork)	M_3(15)
	2-2(Mill)	M_5(60)
P_{12}(100) Key part	1-1(Mill)	M_4(25), M_5(30)
	1-2(Top grind)	M_9(50)
	1-3(Grindout)	M_{10}(70)
	1-4(Turn)	M_1(40), M_2(38)
	1-5(Cylindric grind)	M_8(50)
P_{13}(100) Key part	1-1(Turn)	M_1(45), M_2(30)
	1-2(Fine turn)	M_7(30)
	1-3(Cylindric grind)	M_8(60)

Key part	1-2(Benchwork)	M_3(15)	1-4(Fine turn)	M_7(30)

Table 2. List of equipment resource

Type	No.	Type name	Key machine
M_1	$M_{1\text{-}1}$	Turn	Non-key machine
	$M_{1\text{-}2}$	Turn	Non-key machine
M_2	$M_{2\text{-}1}$	Turn	Non-key machine
M_3	$M_{3\text{-}1}$	Drill	Non-key machine
M_4	$M_{4\text{-}1}$	Mill	Non-key machine
M_5	$M_{5\text{-}1}$	Mill	Non-key machine
M_6	$M_{6\text{-}1}$	Fine mill	Key machine
	$M_{6\text{-}2}$	Fine mill	Key machine
	$M_{6\text{-}3}$	Fine mill	Key machine
M_7	$M_{7\text{-}1}$	Fine turn	Key machine
M_8	$M_{8\text{-}1}$	Cylindric grind	Key machine
	$M_{8\text{-}2}$	Cylindric grind	Key machine
M_9	$M_{9\text{-}1}$	Top grind	Key machine
M_{10}	$M_{10\text{-}1}$	Grind out	Key machine

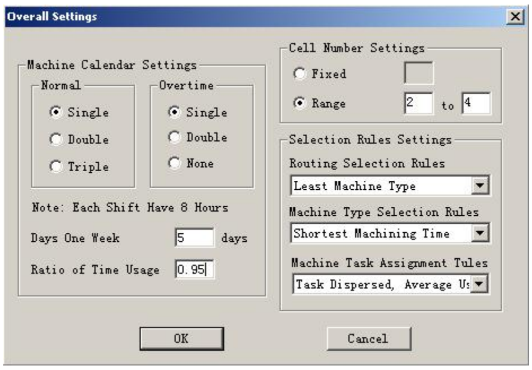


Fig. 7. Overall settings of CF

Phase constrain and goal settings are collected in Fig. 8. Here, constraints for all type of cell are same as $S_2=\{F_3, F_5\}$. Kick out operation will be carried out for non-key parts with kick out ratio being set to 0.1. Optimization options include adjusting of cell load and inter-cell. Standard cell load ratio is $D_r=0.75$, and compositive objective with weight of $w_{h3}=0.85$ and $w_{h2}=0.15$ will be used. The motive is to emphasize balancing of cell load. Too high weight value of inter-cell will induce machine cluster to seldom cells.

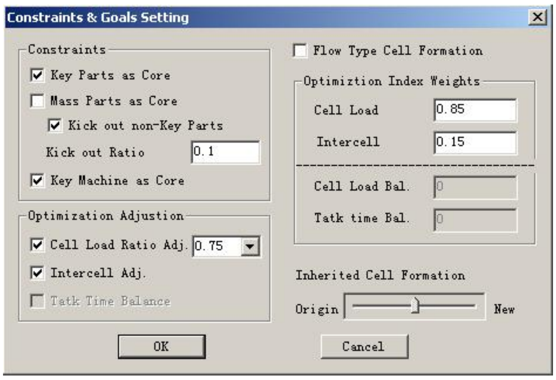


Fig. 8. Constraint and goal settings of CF

In the process of automatic formation, ability shortages of fine turn operations 1 and 2 of P_6 are prompted, so we let M_7 work for an extra shift. Finally 3 cells are formed (Table 3). P_{10} is kicked out so that it is not in part families.

Table 3. Configuration result of GC

Cells	Part family
$M_{2\text{-}1}$, $M_6\{M_{6\text{-}2}, M_{6\text{-}3}\}$, $M_{7\text{-}1}$	P_2, P_8, P_9, P_{13}
$M_{1\text{-}2}$, $M_{4\text{-}1}$, $M_{6\text{-}1}$, $M_{8\text{-}2}$, $M_{9\text{-}1}$	P_4, P_5, P_{12}
$M_{1\text{-}1}$, $M_{3\text{-}1}$, $M_{5\text{-}1}$, $M_{8\text{-}1}$, $M_{10\text{-}1}$	P_1, P_3, P_6, P_7, P_{11}

The left figure in Fig. 9 illustrates distribution of machine load and sharing information of machines in cells (Table 4). The right figure is our contrastive case for impact analysis of task assignment rules. This time, rule of "Task concentrated and focus use of machines" is adopted. It is showed that in contrastive case $M_{2\text{-}1}$ is not selected and load of other machines becomes more concentrated and thus higher utility is achieved.

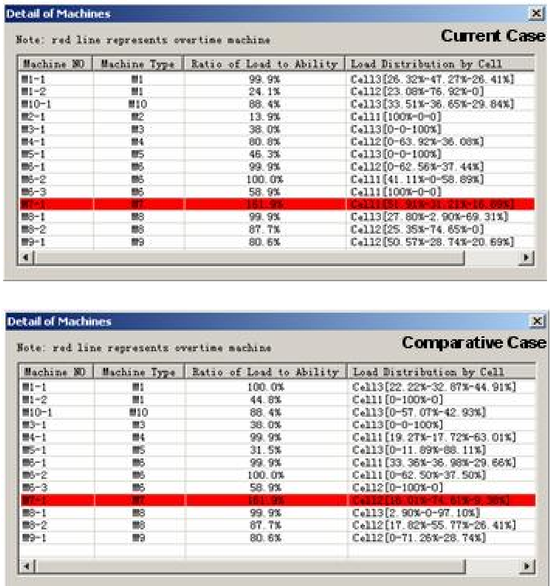


Fig. 9. Distribution of machine loads and impact analysis of task assignment rules

Table 4. Details of machine sharing in cell1 (%)

Machine No.	Load in main cell	Load in the first sharing cell	Load in the second sharing cell
$M_{2\text{-}1}$	100	0	0
$M_{6\text{-}2}$	41.11	0	58.89
$M_{6\text{-}3}$	100	0	0
$M_{7\text{-}1}$	51.91	31.21	16.89

Machining details of overtime machine $M_{7\text{-}1}$ is displayed in Fig. 10.

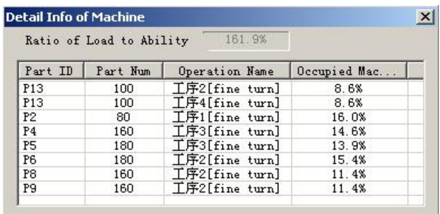


Fig. 10. Detail information of machine $M_{7\text{-}1}$

Fig. 11 illustrates the graphical route of all parts. Parts with multi-routes $\{P_2, P_8, P_{11}\}$ are all going along the route having least machine type. Operations with selectable machine types are all using the machine type having shortest machining time. They are all decided by resource selection rules.

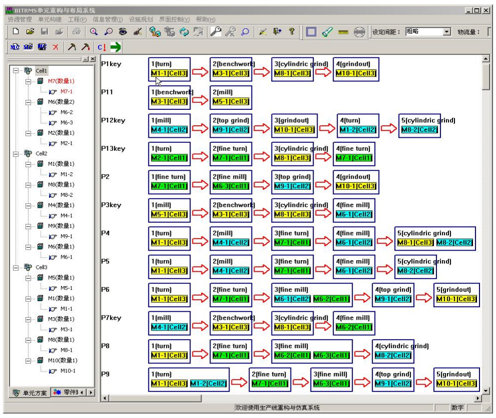


Fig. 11. Result machining route of all parts

Pie chart of cell ability, cell load and histogram of their ratio (Fig. 12) shows three cells have near load and load balancing is very well, that is consistent with setting of high cell load ratio and high cell load weight. Inter-cell statistics is given in Fig. 13. Thus, we can see that achievement of high degree of cell load balancing is at cost of inter-cell performance.

5.2 Result and analysis of FC formation

In overall settings, fixed cell number of 3 and route selection rule "first route" are set. And, in phase settings, we select the "FC formation" so that adjusting option of "takt time balance" and corresponding weight settings are active.

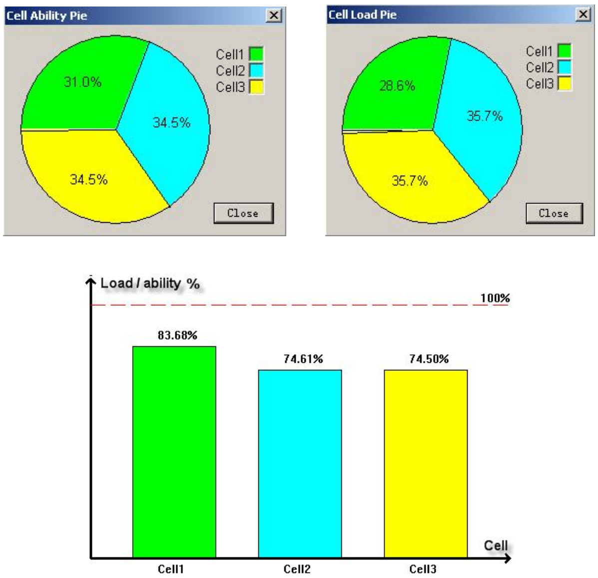


Fig. 12. Pie chart of cell ability, cell load and histogram of their ratio

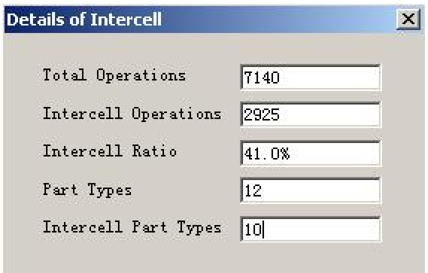
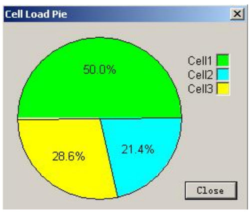
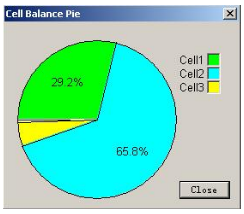
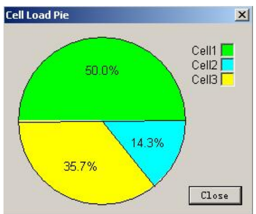
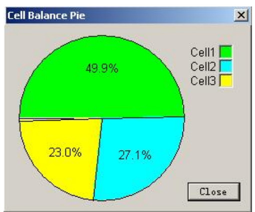
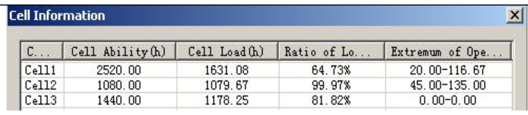


Fig. 13. Statistics of inter-cell production

Comparative case study will show us the effect of FC formation (Table 5).

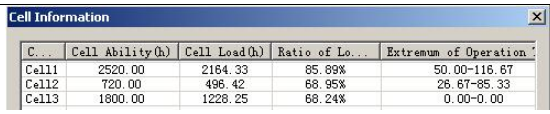
Table 5. Contrastive case study of FC formation

Item	CASE1		CASE2	
Index weight	Cell formation: 0.25 for cell load ratio and 0.75 for inter-cell; Optimization: 0.4 for cell load balancing and 0.6 for cell takt time balancing		Cell formation: 0.25 for cell load ratio and 0.75 for inter-cell; Optimization: 0.2 for cell load balancing and 0.8 for cell takt time balancing	
Configuration	Cell	Part family	Cell	Part family
	$M_1\{M_{1\text{-}1}, M_{1\text{-}2}\}, M_{2\text{-}1}, M_{5\text{-}1}, M_{8\text{-}1}, M_{9\text{-}1}, M_{10\text{-}1}$	$P_1, P_2, P_3, P_6, P_9, P_{12}$	$M_1\{M_{1\text{-}1}, M_{1\text{-}2}\}, M_{5\text{-}1}, M_{6\text{-}2}, M_{7\text{-}1}, M_{9\text{-}1}, M_{10\text{-}1}$	$P_2, P_6, P_8, P_9, P_{12}, P_{13}$
	$M_{3\text{-}1}, M_{6\text{-}2}, M_{7\text{-}1}$	P_7, P_8, P_{11}, P_{13}	$M_{3\text{-}1}, M_{8\text{-}1}$	P_1, P_3, P_7, P_{11}
	$M_{4\text{-}1}, M_6\{M_{6\text{-}1}, M_{6\text{-}3}\}, M_{8\text{-}2}$	P_4, P_5	$M_{2\text{-}1}, M_{4\text{-}1}, M_6\{M_{6\text{-}1}, M_{6\text{-}3}\}, M_{8\text{-}2}$	P_4, P_5
Cell load pie Cell balance pie (All tasks)				
Cell load distribution				



Cell Information

C...	Cell Ability(h)	Cell Load(h)	Ratio of Lo...	Extremum of Ope...
Cell1	2520.00	1631.08	64.73%	20.00-116.67
Cell2	1080.00	1079.67	99.97%	45.00-135.00
Cell3	1440.00	1178.25	81.82%	0.00-0.00



Cell Information

C...	Cell Ability(h)	Cell Load(h)	Ratio of Lo...	Extremum of Operation
Cell1	2520.00	2164.33	85.89%	50.00-116.67
Cell2	720.00	496.42	68.95%	26.67-85.33
Cell3	1800.00	1228.25	68.24%	0.00-0.00

In above weight settings, CASE1 and CASE2 have higher index of cell load balancing and takt time balancing respectively. Their formation result indicates that CASE1 is more balancing in cell load distribution than CASE2, while CASE2 has higher task balancing performance than CASE1. Further more, in CASE2, Cell2 and Cell3 gains more task balancing for key parts than Cell1. And, extreme difference of machining time of certain operation type in cell averagely allocated to single machine in CASE2 is relatively small, which denotes better operation balancing of key parts in CASE2. Besides, due to selection of "key parts" as one of constraints, takt time balancing is only applied to key parts during formation procedure. The difference in Cell3 is zero for that parts in part family $\{P_4,P_5\}$ relevant to Cell3 are all non- key parts.

Table 6 is detailed analysis of CASE2, the outcome demonstrates well balancing of cell load and key tasks.

Table 6. Balancing analysis of key parts in machine cells min

Part (part number)	Cell1						
	$M_{1\text{-}1}$	$M_{1\text{-}2}$	$M_{5\text{-}1}$	$M6\text{-}2$	$M_{7\text{-}1}$	$M_{9\text{-}1}$	$M_{10\text{-}1}$
$P_1(80)$	15×80	–	–	–	–	–	15×80
$P_3(160)$	–	–	25×160	–	–	–	–
$P_7(180)$	–	–	–	45×180	–	–	–
$P_{12}(100)$	–	40×100	–	–	–	50×100	70×100
$P_{13}(100)$	–	–	–	–	30×100 30×100	–	–
Total machine load	1 200	4 000	4 000	8 100	3 000×2	5 000	7 120
Cell load	35 420						
Average machine load	15	40	25	45	30	50	39.56
Difference	50−15=35						
Part (part number)	Cell2			Cell3			
	$M_{3\text{-}1}$	$M_{8\text{-}1}$	$M_{2\text{-}1}$	$M_{4\text{-}1}$	$M_{6\text{-}1}$	$M_{6\text{-}3}$	$M_{8\text{-}2}$
$P_1(80)$	20×80	60×80	–	–	–	–	–
$P_3(160)$	15×160	32×160	–	–	40×160	–	–
$P_7(180)$	15×180	28×180	–	35×180	–	–	–
$P_{12}(100)$	–	–	–	25×100	–	–	50×100
$P_{13}(100)$	–	60×100	30×100	–	–	–	–
Total machine load	6 700	20 960	3 000	8 800	6 400	–	5 000
Cell load	27 660			23 200			
Average machine load	16	40.3	30	31.4	40	–	50
Difference	40.3−16=24.3			50−30=20			

5.3 Result and analysis of IC formation

On period of task change, inheriting formation is introduced. New task is founded on original task that P_1 and P_2 is taken out, part number of P_8, P_9, P_{10} decrease to 100 from 160, and two parts P_{14}, P_{15} (Table 7) are added. This time, IC formation is based on FC configuration of CASE2 in section 5.2. Constraints will not be changed, but flow type index is improved that weights of cell load balancing and cell takt time balancing are 0.1 and 0.9 separately. Inheriting scale is set to 80% (Fig. 8). During construction, adding machine policy is adopted for shortage of fine turn machine. Result is showed in Table 8, where framed equipment denotes differential machines of cell pairs.

Obviously, due to IC formation policy and high inheriting scale. Only position of $M_{6\text{-}3}$ has to be adjusted and one new machine M_7 (Add_1) be procured in the new configuration. Beside, new configuration indicates well flow performance (Figs. 14–15) which is the co-effect of new task and improved flow index.

Table 7. Added tasks

Task	Operation of part route	Machine
$P_{14}(110)$	1-1 (Turn)	$M_1(30)$, $M_2(40)$
	1-2 (Fine mill)	$M_6(50)$
	1-3 (Top grind)	$M_9(45)$
$P_{15}(110)$	1-1 (Benchwork)	$M_3(45)$
	1-2 (Mill)	$M_5(50)$
	1-3 (Fine mill)	$M_6(40)$
	1-4 (Grindout)	$M_{10}(30)$

Table 8. Comparative analysis of configurations

Original cell	Cell1	Cell2	Cell3
Original configuration	$M_{1\text{-}1}$ $M_{1\text{-}2}$ $M_{5\text{-}1}$ $M_{6\text{-}2}$ $M_{7\text{-}1}$ $M_{9\text{-}1}$ $M_{10\text{-}1}$	$M_{3\text{-}1}$ $M_{8\text{-}1}$	$M_{2\text{-}1}$ $M_{4\text{-}1}$ $M_{6\text{-}1}$, $M_{6\text{-}3}$ $M_{8\text{-}2}$
New configuration	$M_{1\text{-}1}$ $M_{1\text{-}2}$ $M_{5\text{-}1}$ $M_{6\text{-}2}$ $M_{6\text{-}3}$ $M_{7\text{-}1}$ $M_{9\text{-}1}$ $M_{10\text{-}1}$	$M_{3\text{-}1}$ $M_7(Add_1)$ $M_{8\text{-}1}$	$M_{2\text{-}1}$ $M_{4\text{-}1}$ $M_{6\text{-}1}$ $M_{8\text{-}2}$
New cell	Cell1	Cell3	Cell2

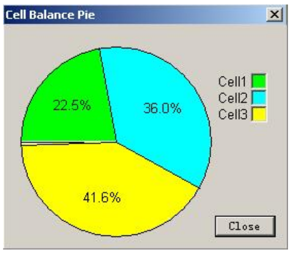
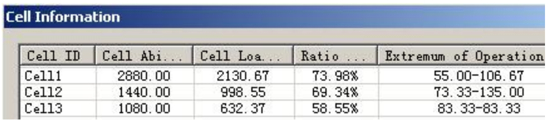


Fig. 14. Pie of takt time balancing of cell in new IC configuration


Cell Information

Cell ID	Cell Abi...	Cell Loa...	Ratio ...	Extremum of Operation
Cell1	2880.00	2130.67	73.98%	55.00-106.67
Cell2	1440.00	998.55	69.34%	73.33-135.00
Cell3	1080.00	632.37	58.55%	83.33-83.33

Fig. 15. Distribution of cell load in new IC configuration

6 Conclusions

(1) Integrated Model of MC formation is constructed and formation constraints are analyzed. MC formation is impacted by internal or external factors that it is the outcome of multiple interrelated constraints. Its objective can be easily extended to make it an optimization problem of multi “more” objectives. MC formation of different type is impact each other and their formation procedures are interlinked. At different stage of cell formation, different constraints and rules are put into effect gradually.

(2) Objectives and procedure of integrated formation are presented. Cell formation constraints are denoted by mathematic symbols and for different stages of types of cells. Formula description for formation goals is given. Application process of such constraints and goals is also detailed.

(3) Case study shows that integrated MC formation is a valuable method adaptive to MPTVV production mode.

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