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Production Scheduling of Regional Industrial Clusters Based on Customization Oriented Smart Garment Ecosystem

Zhishuo Liu[1] ✉, Simeng Lin[1], and Han Li[1]

ABSTRACT

This paper presents the Smart Garment Ecosystem (SG-ECO) and enriches the garment customization production scheduling model theory. On the basis of SG-ECO, the author designs a regional collaborative production alliance (RCPA) based on the idea of collaborative production management and then establishes a flexible production scheduling model (FPSM) that is oriented to the RCPA model under multiple constraints and aims to maximize weighted cost savings. The RCPA model and research on FPSM can enrich the theoretical system of production scheduling research to a certain extent and provide new ideas for the latter's research on customized production scheduling. Although the calculation example proves that the genetic algorithm based on double-layer integer coding (DIC-GA) can effectively solve the FPSM problem, the feasible solution space of the algorithm increases when the order size increases, and the number of iterations and search time required gradually increase. An improved genetic algorithm with double-layer integer coding for processes and workshops is designed, which can not only ensure that each chromosome is a legal individual but also reduce the complexity of the algorithm. The crossover operation and compilation operation are designed based on the coding method to ensure that the genetic operations in the algorithm can produce feasible solutions.

KEYWORDS

garment customization; Smart Garment Ecosystem (SG-ECO); collaborative production scheduling; improved genetic algorithm (IGA)

China is a major country in the production, export, and consumption of clothing, but it cannot be regarded as a strong country in the clothing industry mainly because China is dominated by low-end clothing manufacturing. Moreover, its products are mainly labor-intensive products with low technical content. Another reason is that the apparel design link is weak and lacks innovation.

Made in China 2025[1] emphasizes the importance of design and innovation. Under the new situation, clothing design has gradually changed from product design to "Internet + product + service". In this paper, a new operating model for clothing customization, namely, the Smart Garment Ecosystem (SG-ECO), is constructed based on agile logistics and Internet thinking. The SG-ECO can be regarded as a complex multi-level economic community composed of multiple closely connected individuals or organizations (such as consumers, small- and medium-sized clothing brand companies, clothing manufacturers, logistics companies, investment institutions, and quality inspection departments).

1 Introduction

The main function of SG-ECO is to quickly respond to individual consumers' clothing customization needs; integrate clothing design, production, logistics, and sales; and provide consumers with diversified, fast production, and high-quality clothing customized products.

The SG-ECO is composed of three parts: front-end users, garment customization platforms (SG-GCPs), and multiple regional industrial clusters (RICs) centered on small- and medium-sized garment manufacturers. The SG-GCP is based on big data analysis and processing, and it makes intelligent and optimal decisions on several activities and plans in SG-ECO. RICs mainly use the information-sharing mechanism of SG-GCP to monitor the current inventory levels of materials in the cluster and the actual consumption and consumption trends of materials in real-time. Then, centralized purchases from various material suppliers are made and then distributed according to the actual demand of each production line.

However, two important problems in the RICs exist, namely, long production time and high prices. The main reason is that customized clothing cannot be mass-produced in large quantities, thereby losing the advantages of time and cost. Therefore, the first problem that needs to be solved in the RIC is how to efficiently organize and coordinate the available resources, formulate a production scheduling mechanism that can quickly respond to the individual needs of customers, and bring considerable benefits to small- and medium-sized clothing manufacturers and even the entire SG-ECO.

To this end, this paper designs a new type of regional collaborative production alliance (RCPA) for customized garment production based on the idea of collaborative production management. Then, it establishes a flexible production scheduling model for the RCPA mode under multiple constraints to maximize weighted cost savings. This work aims to provide consumers with fast, high-quality, and customized garment products with the hope of creating a new development model and provide a theoretical basis for the future development of the Chinese clothing industry.

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1 School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
Address correspondence to Zhishuo Liu, zhsliu@bjtu.edu.cn

2 Related Work

2.1 Multi-factory production scheduling

Since the 1990s, much research on multi-factory production scheduling has been conducted at home and abroad, mainly focusing on the collaborative scheduling problem between multiple factories in the supply chain environment.

Behnamian and Ghomi[2] studied the distributed parallel factory scheduling problem. Sun et al.[3] took the integrated scheduling of multi-product and multi-factory production and distribution as their research goal. Xiao et al.[4] and Zhang[5] proposed the concept of cloud manufacturing, which is a type of virtual manufacturing enterprise that has multiple factories located in different geographical locations.

Generally, the goal of a factory is to maximize profits or minimize production costs. Xiao et al.[4] considered the two aspects of supplier selection and production scheduling and derived four goals, namely, total scheduling cost, total scheduling time, idle production rate, and order delay; assigned different weight factors to each goal; and converted the multi-objective problem into a single-objective problem to be solved. Li[6] considered the individual interest demands of each factory and used the "input-output" matching principle and the deviation coefficient method to design a mathematical model that maximizes the overall income and minimizes the balance scale of individual interests of each factory.

2.2 Production scheduling in a supply chain environment

At present, two main aspects of research exist in the flexible production scheduling problem in the supply chain environment. One aspect involves considering the new characteristics of the production scheduling problem in the supply chain environment and flexible production conditions and improving and modeling the traditional single-objective, single-constrained production scheduling model and constraint conditions. The other involves studying the algorithm of the flexible production scheduling model.

In the aspect of the production scheduling model, Liu[7] comprehensively considered the on-time delivery principle and lean production requirements of orders in the supply chain and introduced the batch strategy and penalty function into the basic flow-shop model. Balaji and Porselvi[8] mainly studied the batch scheduling problem of multi-unit flexible manufacturing systems. Zhang[9] considered multiple constraints in production scheduling, such as production capacity constraints, inventory constraints, parts batch processing sequence constraints, machine occupancy, and component processing sequence constraints under the environment of multi-variety and small-batch products. Wang et al.[10] solved the flexible job shop scheduling problem by nesting it in a distributed scheduling method.

In terms of solving the algorithm, Karthikeyan et al.[11] designed a hybrid discrete firefly algorithm, using the discrete firefly algorithm to solve the machine assignment and operation sequence and then processing the new discrete function by constructing a continuous function as the appropriate transformation of attraction, distance, and motion. Mao et al.[12] took the production cycle, the reduction of machine idling time, and the improvement of product quality as scheduling goals and used an improved particle swarm algorithm to solve the problem. Zou et al.[13] designed a hierarchical ant colony genetic algorithm to solve the problem with the workpiece completion time and machine load as the objective functions. Ma and He[14] proposed an improved genetic algorithm, which aims to minimize the maximum completion time for the problems of multi-variety, small-batch, high degree of customer customization, and uncertainty in some production processes, establishing a flexible job shop scheduling model with the goal of minimizing the maximum completion time.

The above research indicates that some limitations remain in current domestic research on multi-factory production scheduling. For example, few studies have been conducted on machine scheduling problems at the process level in multiple factories, that is, specific task allocation and sequencing problems. Few studies are also available on formulating production plans and scheduling schemes that take into account the rapid response to customer needs and individual needs, especially collaborative production scheduling research for customized clothing production.

Therefore, under the multiple constraints of the RCPA model, this paper assigns weight factors to the production cost and time cost, establishes the flexible production scheduling model (FPSM), and designs an improved genetic algorithm based on double-layer integer coding (DIC-GA).

3 Structure of SG-ECO

The proposed SG-ECO is composed of three parts: front-end users, SG-GCP, and multiple RICs centered on small- and medium-sized clothing manufacturers. Its structure is shown in Fig. 1.

3.1 Front-end user

The front-end users of SG-ECO are composed of independent entities such as individual consumers, independent garment designers, small- and medium-sized clothing brand companies, and third-party professional organizations (such as clothing design software supply companies). They are independent and will not be described in detail in this paper.

3.2 Garment customization platform

The SG-GCP is the nerve center of SG-ECO. Research on SG-GCP is crucial to the construction and operation of SG-ECO. Through the construction of SG-GCP, the problems of

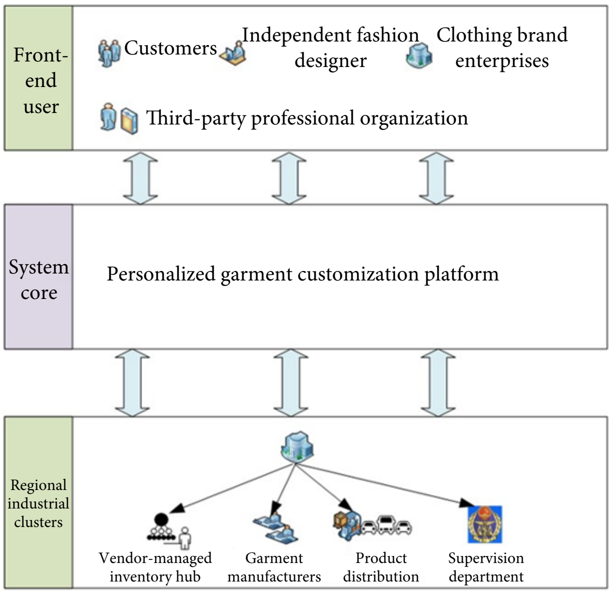

Fig. 1 Structure of SG-ECO.

interconnection and information sharing among heterogeneous information systems, people, and equipment in SG-ECO can not only be solved, but intelligent decisions on each autonomous entity, data information, and various activities can be made and organized.

SG-GCP is based on big data analysis and processing, making intelligent and optimal decisions on multiple activities and plans. The key business modules of SG-GCP are as follows:

(1) Massive order processing module

On the basis of intelligent collection technology, the information that SG-GCP obtains every day may be massive. As far as order data are concerned, due to the geographical characteristics of customer distribution and the individual needs of orders, reasonable classification and combination rules need to be formulated to maximize the use of available resources to meet the needs of each order. In SG-GCP, optimizing the order processing process, formulating a reasonable order execution plan, and managing and controlling the execution process can improve the fulfillment rate of clothing customization orders and greatly improve customer service and customer satisfaction. It can also reduce the total cost of the customized garment to a certain extent.

This module is a prerequisite for realizing the production of small-batch customized garment products using the cost advantages of mass production. Its core is to formulate execution plans for various orders and manage and control the execution process. Through this module, RIC resources can be efficiently used based on improving customer satisfaction, avoiding cross-regional scheduling and transportation, reducing environmental pollution, and making the entire SG-ECO more low-carbon and green.

(2) Intelligent scheduling decision module

Intelligent scheduling decision-making based on big data analysis is the most critical module in SG-GCP. It is the key to solving the cost and time problems of garment customization and quickly responding to the individual needs of consumers. Moreover, it is the basis for realizing small-batch and multi-category customized garment production.

In SG-ECO, various raw material suppliers, small- and medium-sized garment manufacturers, and logistics companies cooperate in the form of RIC, and the procurement of raw materials and the distribution of products are implemented around garment production activities. Therefore, focusing on formulating scientific and economic scheduling plans for the production links of the garment is necessary, and the following problems need to be solved:

(a) The selection mechanism and plan of the production and machines in each production process;

(b) The production time of different orders in each production process;

(c) Whether each order can complete all production tasks according to its delivery lead time.

The basis of this module is to establish a production scheduling decision-making model based on data analysis. The core goal is to organize and execute various production tasks oriented by massive orders.

(3) Partners benefit distribution module

The basis and key of this module are to formulate the principles and standards that need to be followed in the distribution of benefits, as well as to establish the benefit distribution model and solution algorithm. Its core task is to fairly distribute the benefits obtained from completing a certain task to each cooperative enterprise in SG-ECO that participates in the task by formulating an interest distribution mechanism.

(4) Transaction payment management module

To solve the credit and security issues in the transaction process and protect the interests of buyers and sellers, an intermediate link needs to be established between the buyer and the seller of funds. This module is composed of the buyer, seller, bank, or third-party payment tool and related payment agreements.

3.3 RICs

SG-ECO includes multiple RICs, each of which is built around a cluster of small- and medium-sized garment production enterprises, including multiple small- and medium-sized garment production enterprises, product distribution centers, vendor-managed inventory hubs (VMI-hubs), and quality supervision centers.

Small- and medium-sized garment manufacturers are responsible for the production tasks of orders. The product distribution center is responsible for packaging, sorting, and transporting the finished garments. The quality supervision center conducts quality inspections on every link in the industrial cluster, especially every link on each garment production line, to ensure the high-quality of finished garments and eliminate possible quality hazards from the source. A VMI-hub is the coordination center between raw material suppliers (such as surface accessories suppliers, button suppliers, and zipper suppliers) and small- and medium-sized garment manufacturers. It mainly uses the information-sharing mechanism of SG-GCP for real-time monitoring of the current inventory levels of materials in the cluster and the actual consumption and consumption trends of materials. Then, centralized purchases are made from various material suppliers and distributed according to the actual demand of each production line.

The relationship between market entities in RIC is shown in Fig. 2.

3.4 RCPA

In SG-ECO, the first problem that needs to be solved is how to efficiently organize and coordinate the available resources in RIC and develop a system of scheduling mechanism that can quickly respond to customers' individual needs while ensuring economic benefits to small- and medium-sized garment enterprises and the entire SG-ECO in RIC.

From the perspective of the production of a customized garment, the production of a piece of clothing may need to undergo complex processes, such as fabric processing, making samples, semi-finished products processing, sawing, nailing, and ironing. When consumers have more individual requirements, a single garment processing enterprise cannot complete the

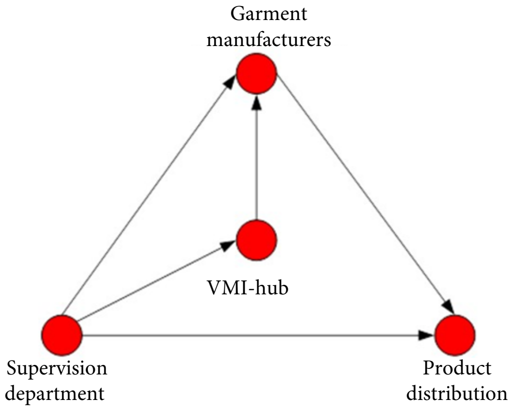

Fig. 2 Relationship among various market roles in RIC.

production task independently; otherwise, the cost will be high, and the production cycle will be long. To quickly respond to the individual needs of consumers and solve the problems of long production time and high costs, the traditional production mode of clothing manufacturers needs to be reformed. As a result, the production mode can complete the rapid production of the customized garments at a reasonable production cost.

On the basis of research on RIC in SG-ECO, this paper designs a new RCPA for customized clothing production based on the concept proposed according to the collaborative production management idea.

The massive order processing module in SG-GCP first classifies and combines garment customization orders obtained according to the customer's geographic location, order time, and personalized needs. SG-GCP has an optimization cycle of one day. The massive orders received every day can be divided into multiple order combinations of a certain scale. These order combinations will be assigned to multiple RICs, and the RICs will be responsible for a series of activities, such as fabric procurement, production, distribution, and quality inspection of these order combinations.

Some processes for different types of clothing can share the same production line, thus providing the possibility of massive production and modular production of customized garments. Therefore, according to the production process, this paper divides each garment manufacturer in an RIC into multiple production workshop modules that are responsible for different production processes. These modules mainly include cutting, sewing, printing, finishing, and other processes. Each workshop module contains multiple production and processing equipment.

In the RCPA mode, the production workshop modules and the processing machines divided by the various garment manufacturer in RIC are regarded as a shared resource library, which integrates the processing machines and production personnel in each workshop into the RIC factory. Then, a collaborative production management system interconnected with SG-GCP is established, and SG-GCP centrally manages and uniformly dispatches resources to complete the production tasks of the order combination in RIC.

On the basis of the idea of collaborative production management, the various modules in RCPA can cooperate to complete any customized garment production tasks that cannot be completed by the garment manufacturer, but the process is not economical.

The overall benefit obtained through collaborative production in this mode must be better than the sum of benefits in separate production. The organizational structure of the RCPA is shown in Fig. 3.

4 Establishing a Flexible Production Scheduling Model Oriented to RCPA Mode

4.1 Problem description

In the RCPA mode, the multi-factory collaborative production scheduling problem for customized garments can be regarded as a single-factory environment with multi-product, process, workshop, and machine flexible production scheduling problems.

The problem can be described as follows. The number of orders allocated to a certain factory after an order is I. A total of M processing machines participate in this scheduling task in this factory. The M processing machines are provided by different garment processing and production companies and are responsible for different production processes. The machines that are responsible for the same processes belong to the same type of workshop module.

The delivery lead time of each order is L_i. The garment products in each order must be processed by the prescribed and

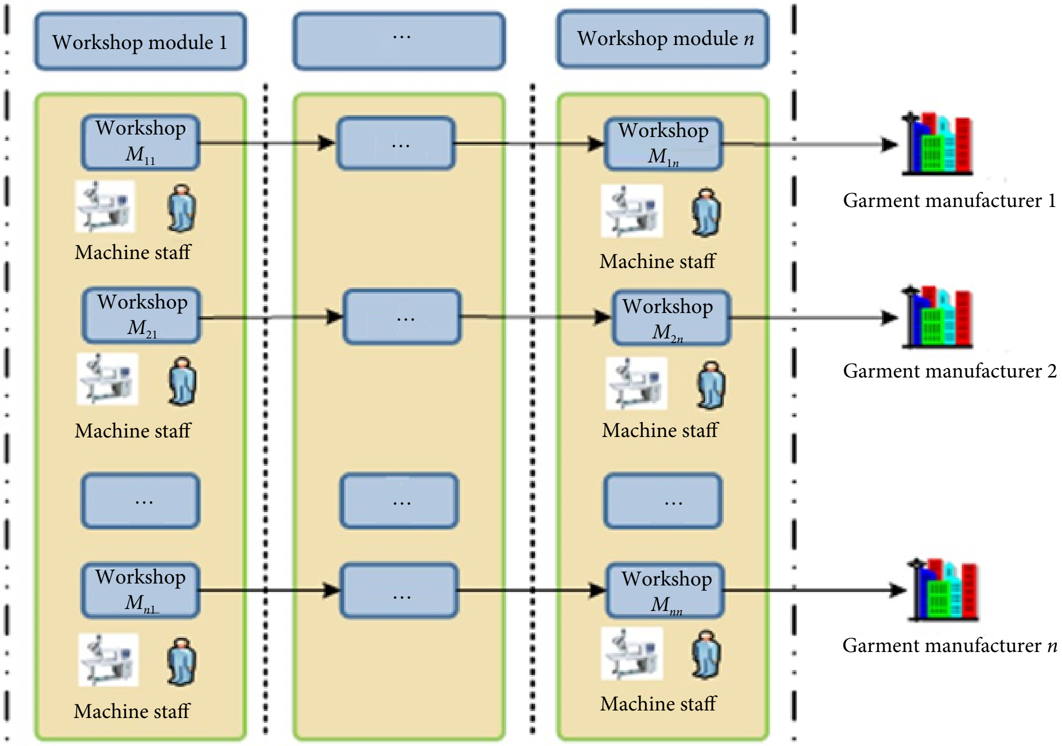

Fig. 3 Organizational structure of RCPA.

feasible process sequence, and the type and quantity of the production process (that is, the production workshop module in the factory) should not be the same.

With the limited available production capacity taken into account, the factory adopts a flexible production method for production; that is, at least one production machine exists in each process to provide processing services. To ensure that each batch of orders can be produced without delay, overtime is used to expand the production capacity at the process nodes where the production load exceeds the available production capacity. The *M* production machines in the factory all participate in the scheduling decision collaboratively to maximize the overall production benefit.

The following are the solutions to the above problems:

(1) The decision-making index and optimal objective function of the problem are determined;

(2) The selection plan of the processing machine for each order in every production process under the optimal objective function value is solved;

(3) The processing sequence and processing time of each order on the selected processing machine under the optimal objective function value are solved.

The production process diagram of *I* orders in RCPA mode is shown in Fig. 4.

4.2 Basic hypothesis

To facilitate the model construction and analysis, we made the following assumptions:

(1) Each order contains only one customized garment product;

(2) At least one production processing machine is available for production tasks in each process;

(3) Each machine can schedule only one production task at the same time;

(4) Once the process is performed, it cannot be interrupted;

(5) The production of customized garments is organized by adopting the make-to-order model;

(6) All production and processing machines can expand their production capacity by working overtime;

(7) The uncertain cost of each workshop is not considered, which means the processing time and production cost are known;

(8) Order delays are not allowed, and each batch of orders needs to be allocated as fully as possible according to the maximum production capacity;

(9) Data of the idle time, processing time, and cost of each workshop are shared;

(10) The supply of raw materials (fabric, parts, etc.) is sufficient; being out of stock is not allowed;

(11) The transportation cost within the factory is negligible.

4.3 Parameters and variables

On the basis of the above description and assumptions, we can define the relevant parameters and variables of the model as shown in Table 1.

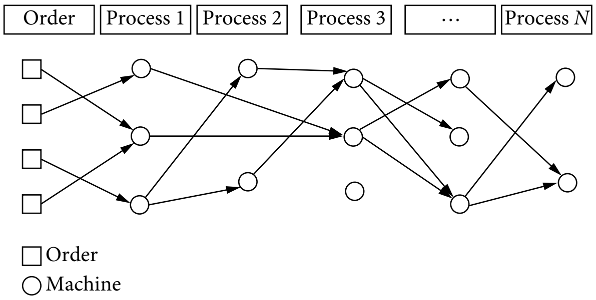

Fig. 4 Production process diagram of *I* orders in RCPA mode.

4.4 Function

(1) Cost saving

The production cost mainly includes the production cost incurred in the normal processing time of customized garments, the overtime cost incurred after the normal processing time in the workshop is exceeded, and the storage cost due to waiting in the production and processing. In terms of storage costs, before the products start the next process, the process where the product is currently located takes full responsibility for all the inventory costs. The cost function is shown in Eq. (1).

$$Z=\sum_{i=1}^{I}\sum_{j=1}^{J}\gamma_{j,sij}^{i}C_{sj,sij}^{i}+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{j=1}^{J}\gamma_{j,sij}^{i}y_{j,sij}^{i}C_{sj,sij}^{i}+ \\ \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{j'=1}^{J}x_{j,j'}^{i}C_{kj,sij}^{i}(ST_{j',sij'}^{i}-FT_{j',sij'}^{i}) \tag{1}$$

On the basis of cooperative production theory, a global optimal solution Z^* must be available for the FPSM problem when each production workshop adopts a cooperative mechanism, and the production cost corresponding to the optimal solution must be the least among all scheduling schemes. Then, we can obtain

Table 1 Parameters and variables.

Parameter and variable	Definition
I	Quantity of order
J	Quantity of processes
L	Order lead time
I_i	i-th order, where $i = 1, 2, \ldots, I$
L_i	Lead time of the i-th order, where $i = 1, 2, \ldots, I$
$ST_{j,s}^{i}$	Start time of the j-th process of the i-th order when the s-th workshop is selected
$FT_{j,s}^{i}$	Finish time of the j-th process of the i-th order when the s-th workshop is selected
C_s	Processing cost of completing the j-th process of the i-th order when the s-th workshop is selected
C_c	Variable processing cost of completing the j-th process of the i-th order when the s-th workshop is selected
C_k	Inventory cost (incurred due to the production completed ahead of schedule) of completing the j-th process of the i-th order when the s-th workshop is selected
C_j	Maximum production capacity of the j-th process, where $j = 1, 2, \ldots, J$
α_1, α_2	Cost factor/time factor, where $\alpha_1 \in (0,1), \alpha_2 \in (0,1)$, and $\alpha_1+\alpha_2=1$
j'	Post-process of the j-th process
i'	Previous order of the i-th order
$x_{j,j'}^{i}$	When j' is the post-process of j, the value is 1; otherwise, it is 0
$y_{j,s}^{i}$	When the processing time of the j-th process of the i-th order exceeds the normal processing time of the current workshop s, the value is 1; otherwise, it is 0
$\gamma_{j,s}^{i}$	When the i-th order selects the s-th workshop of the j-th process, the value is 1; otherwise, it is 0

$$Z^* = \text{Min}\left[\sum_{i=1}^{I}\sum_{j=1}^{J}\gamma_{j,sij}^{i}C_{sj,sij}^{i}+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{j=1}^{J}\gamma_{j,sij}^{i}y_{j,sij}^{i}C_{sj,sij}^{i}+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{j'=1}^{J}x_{j,j'}^{i}C_{kj,sij}^{i}(ST_{j',sij'}^{i}-FT_{j',sij'}^{i})\right] \tag{2}$$

With the assumption that some of the machines in the workshop do not cooperate, a non-cooperative feasible solution Z^0 can be obtained through the above model. The difference $|Z^* - Z^0|$ between the optimal value Z^* and the non-cooperative feasible solution Z^0 is the maximum production cost savings obtained by the alliance through cooperation.

(2) Time saving

No-delay delivery is one of the operational characteristics of the FPSM problem, which means each order must be delivered before the delivery date. Therefore, we consider only the product delivery time except for the transportation time here.

With the assumption that the product delivery time of an order is L_i, and the completion time of the last process of the order under the optimal strategy is $FT_{J,siJ}^{*i}$, then $(L_i - FT_{J,siJ}^{*i})$ is the time saved in producing the order, and $\sum_{i=1}^{I}(L_i - FT_{J,siJ}^{*i})$ is the total time saved.

On the basis of cost saving and time saving, this paper determines the objective function of FPSM. The objective function is a multi-objective problem and is thus transformed into a single-objective function form by assigning weight factors to reduce its dimensionality. The mathematical form of the objective function is shown in Eq. (3).

$$\text{Max}\,V(N) = \alpha_1(Z^0 - Z^*) + \alpha_2\left(\sum_{i=1}^{I}(L_i - FT_{J,siJ}^{*i})\right) \tag{3}$$

Constraints:

$$FT_{J,s_{iJ}}^{i} \leqslant L_i,\ \ i = 1,2,\ldots,I \tag{4}$$

$$\sum\nolimits_{i=1}^{I}\gamma_{j,s}^{i}\left(FT_{j,s_{ij}}^{i} - ST_{j,s_{ij}}^{i}\right) \leqslant C_j, i = 1,2,\ldots,I; j = 1,2,\ldots,J \tag{5}$$

$$\sum\nolimits_{i=1}^{I}\sum\nolimits_{j=1}^{J}\left(FT_{j,s_{ij}}^{i} - ST_{j,s_{ij}}^{i}\right) \leqslant \sum\nolimits_{j=1}^{J}C_j, i = 1,2,\ldots,I; j = 1,2,\ldots,J \tag{6}$$

$$ST_{j',s_{ij'}}^{i} \geqslant FT_{j,s_{ij}}^{i}, y_{j,j'} = 1 \tag{7}$$

$$ST_{j,s}^{i} \geqslant FT_{j,s}^{i'} \tag{8}$$

Formula (4) guarantees the timely delivery of orders.

Formula (5) constrains the maximum available capacity of each process, which means the number of orders for each round of optimization cannot exceed the maximum available capacity of the production cluster. Formula (6) represents the total processing time of all orders, which cannot exceed the sum of the maximum production capacity of all processes.

Formula (7) constrains the processing time between each process, and Formula (8) constrains the task distribution of each production machine.

5 Double Integer Coding Genetic Algorithm

The FPSM problem is an NP-hard problem that must be analyzed in detail. If the coding scheme of the standard genetic algorithm is directly applied to the scheduling problem, then a feasible solution may not be produced. Gen et al.[15] proposed a process-based coding scheme, which had the advantages of always obtaining a feasible scheduling solution after arbitrarily replacing chromosomes, avoiding deadlocks, and fully representing the docking space. However, due to the use of flexible production methods, the proposed FPSM problem needs to not only determine the processing sequence of the procedures but also arrange a suitable processing workshop for each procedure. The solution to this problem cannot be obtained by using only the coding based on the procedure.

Therefore, this paper improves the coding method of the standard genetic algorithm and related genetic operations and designs DIC-GA to solve the FPSGM problem.

(1) Genetic code

To address the two-layer goal of process sequence solving and machine arrangement, this paper divides the coding into two layers. The first layer is the code based on the process, which is used to determine the processing sequence of the order process; the second layer is based on the coding of each machine in the workshop, which is used to determine the processing machine in the workshop corresponding to each process.

To facilitate the process of determining its machine in each workshop and ensure that subsequent genetic operations can produce feasible solutions, the code based on the machine in the workshop represents the number of available workshops for the process.

The length of the chromosome is determined by the total number of orders and the processes of each order. If I orders exist and the number of order processes is J, then the length of the process code S is $K = I \times J$, and its genes are an array of $J_1, J_2, \ldots, J_I$. The m-th occurrence of order I in the sequence indicates that the j-th process of order I is at this position, and the corresponding machine code length is also $K = I \times J$.

With the assumption of I = 2 orders and J = 3 processes, the total length of the chromosome is 6. The available machines for the first process are M_1 and M_2; the available machines for the second process are M_3 and M_4; and the available machines for the third process are M_5, M_6, and M_7. Then, a legal chromosome can be expressed as

$$S = [2\,1\,1\,2\,1\,2],$$

$$M = [1\,2\,2\,1\,2\,3].$$

Through the correspondence, the processing sequence of the order in the chromosome is shown in Table 2.

(2) Select operation

This paper adopts the roulette selection strategy for selection operations. In roulette wheel selection, the probability of an individual being selected is proportional to its corresponding fitness value, where the probability of each chromosome being selected is the ratio of the sum of its corresponding fitness value to the fitness value of the individual in the entire population. If the population size is N and the fitness value of the i-th chromosome is $fitness_i$, then the probability of this chromosome being selected can be expressed as

Table 2 Actual processing sequence obtained by chromosome decoding.

Process No.	Workshop	
	Order 1	Order 2
1	M_2	M_1
2	M_4	M_3
3	M_6	M_7

$$P_i = \frac{fitness_i}{\sum_{i=1}^{N} fitness_i} \tag{9}$$

(3) Fitness function

The objective function is

$$\text{Max}\, V(N) = \alpha_1(Z^0 - Z^*) + \alpha_2 \left(\sum_{i=1}^{I} \left(L_i - FT_{J,siJ}^{*i} \right) \right) \tag{10}$$

The fitness function can be expressed as

$$fitness_i = V_i \tag{11}$$

where $fitness_i$ is the fitness value of the i-th chromosome, and V_i is the objective function of the i-th chromosome.

(4) Cross operation

In this paper, we designed two crossover operations, and chromosomes are randomly selected for crossover during the crossover. Specifically, the shuffle and crossover operations are used based on process coding, and two-point crossover operations are used based on machine coding.

(a) Shuffle crossover operation based on process coding

Two single-layer chromosomes S_1 and S_2 are selected randomly as the parent chromosomes for crossover operation, and the workshop machine code that corresponds to each process to the offspring is copied. The specific process is to randomly generate two natural numbers γ_1 and γ_2. The gene fragments between the two parent chromosomes are then exchanged to obtain two new offspring chromosomes $S_1'$and S_2', and the two new chromosomes obtained are revised to avoid conflicts. The revision method involves taking the complement of the cross segment and rearranging it to the non-cross segment after crossover.

For example, two parent chromosomes $S_1 = [2\,1\,1\,2\,1\,2]$ and $S_2 = [1\,2\,1\,2\,2\,1]$ are selected, two natural numbers $\gamma_1 = 2$ and $\gamma_2 = 4$ are randomly generated, two new offspring chromosomes $S_1' = [2\,2\,1\,2\,1\,2]$ and $S_2' = [1\,1\,1\,2\,2\,1]$ are obtained after crossover, and the new chromosomes are revised to obtain $S_1' = [2\,2\,1\,2\,1\,1]$ and $S_2' = [2\,1\,1\,2\,2\,1]$.

(b) Machine-based two-point crossover operation

Two chromosomes are selected randomly as the parent chromosomes, the processing sequence of the process is kept unchanged, and crossover operations are performed on the machine-based coding layer. The specific process is as follows: Two crossover points are selected randomly on individual genes, and then the genes are crossed over at these two points to obtain two new offspring.

(5) Mutation operation

On the basis of the two-layer coding scheme, this paper designs two mutation operations: a two-point reciprocal mutation operation based on process coding and a single-point mutation operation based on machine coding.

(a) Two-point reciprocal mutation based on process coding

A single-layer chromosome S is selected randomly, and two random natural numbers, γ_1 and γ_2, are generated as variant loci, $1 \leqslant \gamma_1 < \gamma_2 \leqslant (I \times J)$. The γ_1-th and γ_2-th genes in the chromosome are swapped, and the coding sequence of the workshop machine corresponding to the single-layer chromosome is kept unchanged. The offspring obtained using this mutation method must be feasible.

For example, a single-layer chromosome $S = [2\ 1\ 1\ 2\ 1\ 2]$, $\gamma_1 = 2$, and $\gamma_2 = 4$ are selected randomly, then the chromosome will produce new offspring after the mutation operation, $S' = [2\,2\,1\,1\,1\,2]$.

(b) Single-point mutation based on workshops

A single-layer chromosome M is selected randomly, a random natural number γ is generated as the mutated locus, and this point is mutated, where $1 \leqslant \gamma \leqslant (I \times J)$. To produce a feasible solution, when the point is mutated, the gene needs to be replaced according to other machines in the machine set of the corresponding process.

The coded chromosome is taken as an example, $M = [1\ 2\ 2\ 1\ 2\ 3]$. If a random number $\gamma = 6$ is generated, then the machine set of the corresponding process is first found as $\{M_5, M_6, M_7\}$, and a total of three machines are available. Therefore, the chromosome can be mutated into $M = [1\ 2\ 2\ 1\ 2\ 1]$ through single-point mutation, which means it changes from the original workshop M_7 to workshop M_5 at Process 3.

(6) Termination conditions

This paper uses the preset maximum iteration algebra *Maxgen* as the termination condition of the algorithm. When the number of iterations exceeds *Maxgen*, the algorithm ends. The output result can be expressed as a Gantt chart. The detailed solving process of the DIC-GA is shown in Fig. 5.

6 Details and Analysis of Simulation Experiments

To verify the effectiveness of the DIC-GA algorithm in solving the above FPSM problem, this paper designs three simulation examples with different order sizes. Simulation 1 is a small example composed of six orders, six procedures, and six workshops. Then, on the basis of simulation 1, the order is further expanded to 100 with six procedures and 16 workshops to verify the effectiveness of DIC-GA.

The assumption is that only one machine is available in each workshop, and 16 machines are provided by multiple small- and medium-sized garment manufacturers in RIC.

6.1 Simulation 1

In Simulation 1, we have six orders, all of which require a total of six processing steps: ① fabric processing → ② paper proofing → ③ cutting → ④ sewing → ⑤ special crafts → ⑥ finishing.

A workshop is arranged for each process to complete the processing tasks. These six workshops belong to different small- and medium-sized garment manufacturers in RIC, and each workshop has an intelligent processing machine (six in total).

The processes that each order needs to go through are not the same, and the processing time and cost in each process are also different.

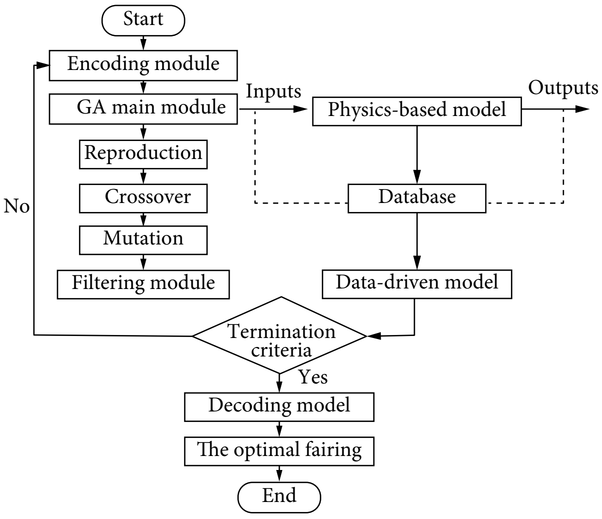

Fig. 5 Detailed solving process of DIC-GA.

Through the sorting of the processes that each order needs to go through and with the number and the type of processes referred to, the six orders can be divided into the following four order combinations:

(a) Order 1 goes through the process: ①→②→③→④→⑤→⑥;

(b) Orders 2 and 3: ②→③→④→⑤→⑥;

(c) Order 4: ①→②→③→④→⑥;

(d) Orders 5 and 6 : ②→③→④→⑥;

(1) Production delivery time of the order

In this example, the lead time for all orders is seven days. Considering that the delivery time includes not only the production cycle but also the transportation time, all orders must complete production tasks within three days to achieve the goal.

(2) Available production time of each process

Table 3 shows the available capacity time of the corresponding machines for each process.

(3) Unit processing cost and unit processing time

Tables 4 and 5 show the unit processing cost and unit processing time of the order on each machine in different workshops of each process, respectively, where (j, M_{j1}) means that process j uses machine $M_{j1} (j = 1, 2, \ldots, 6)$. In Table 4, the data outside the brackets represent the processing cost incurred during the normal processing time for each order, and the data in the brackets represent the unit processing cost during overtime.

The relevant parameters of the algorithm are set before the example is solved. Let *Popsize* = 40, *Maxgen* = 300, *GGAP* = 1, *pcross* = 0.7, *pmumation* = 0.2.

Table 3 Available capacity time.

Process	Machine	Available capacity time (h)	
		Normal	Overtime
1	M_{11}	20	5
2	M_{21}	21	5
3	M_{31}	18	4
4	M_{41}	22	5
5	M_{51}	24	5
6	M_{61}	20	3

Table 4 Unit processing costs.

Order	Unit processing cost (yuan/h)					
	$(1, M_{11})$	$(2, M_{21})$	$(3, M_{31})$	$(4, M_{41})$	$(5, M_{51})$	$(6, M_{61})$
1	18(20)	16(18)	19(23)	16(19)	27(30)	18(21)
2	17(19)	18(20)	16(19)	19(22)	26(29)	18(20)
3	15(17)	20(22)	19(21)	17(19)	30(32)	16(20)
4	18(20)	16(19)	15(18)	20(22)	28(30)	17(20)
5	16(19)	18(20)	19(21)	17(20)	27(29)	16(20)
6	17(19)	16(20)	18(20)	19(21)	28(31)	16(18)

Table 5 Unit processing time.

Order	Unit processing time (h)					
	$(1, M_{11})$	$(2, M_{21})$	$(3, M_{31})$	$(4, M_{41})$	$(5, M_{51})$	$(6, M_{61})$
1	0.6	1.0	1.0	0.8	1.4	0.8
2	0.8	0.8	0.7	0.9	1.3	0.9
3	0.5	1.0	0.7	1.0	1.2	1.0
4	0.9	0.6	0.8	0.7	1.2	0.5
5	0.9	0.6	0.6	0.6	1.1	0.8
6	1.0	0.6	1.0	0.6	1.2	0.9

On the basis of the algorithm and the related parameters established in this paper, DIC-GA is written by MATLAB to solve the above example. The value of the optimal solution is 8.53×10^{-4}, and the total convergence time of the algorithm is 11 s.

After the iteration is completed, the production scheduling Gantt chart is obtained through algorithm optimization, which indicates the optimal scheduling plan, as shown in Fig. 6.

6.2 Simulation 2

To further verify the effectiveness of DIC-GA, under the conditions of Simulation 1, the number of processes, workshops, and machines are kept unchanged; the order is expanded to 100; and the production lead time for all orders is set as two days.

The number and sequence of processes that these 100 orders need to go through are as follows:

(a) Orders 1 to 25 go through the process: ①→②→③→④→⑤→⑥;

(b) Orders 26 to 55: ②→③→④→⑤→⑥;

(c) Orders 56 to 85: ①→②→③→④→⑥;

(d) Orders 86 to 100: ②→③→④→⑥;

The unit processing cost and unit processing time are then input. Simulation 2 is solved by using MATLAB, the relevant parameters of the algorithm are set, and the number of iterations *Maxgen* = 1500. The other settings are the same as in Simulation 1.

The optimal scheduling scheme is shown in Fig. 7.

In summary, the results of two simulation examples of different scales show that the DIC-GA is effective for solving FPSGM. With the continuous expansion of the order scale, the convergence time and the number of iterations for the two examples increase gradually, but they can reach the global optimum in a relatively short period, and the optimal production scheduling scheme can be obtained.

7 Conclusion

In this paper, a new operating model for garment customization called SG-ECO, which is based on agile logistics, is constructed. To rapidly respond to the individual needs of consumers, an RCPA is designed based on the idea of collaborative production management, and a flexible production scheduling model for RCPA mode is established under multiple constraints to maximize the weighted cost savings. According to the characteristics of the FPSM problem, the DIC-GA based on double-layer integer coding is designed.

This article has some shortcomings. Research on SG-ECO is

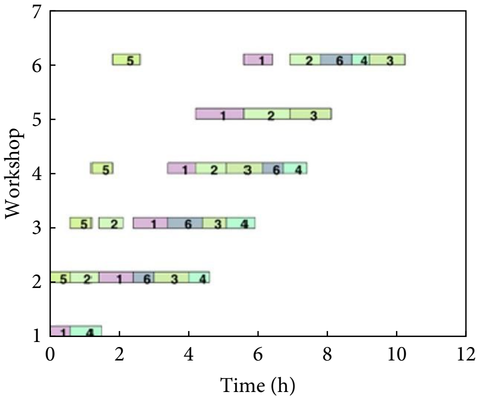

Fig. 6 Optimal scheduling plan of Simulation 1.

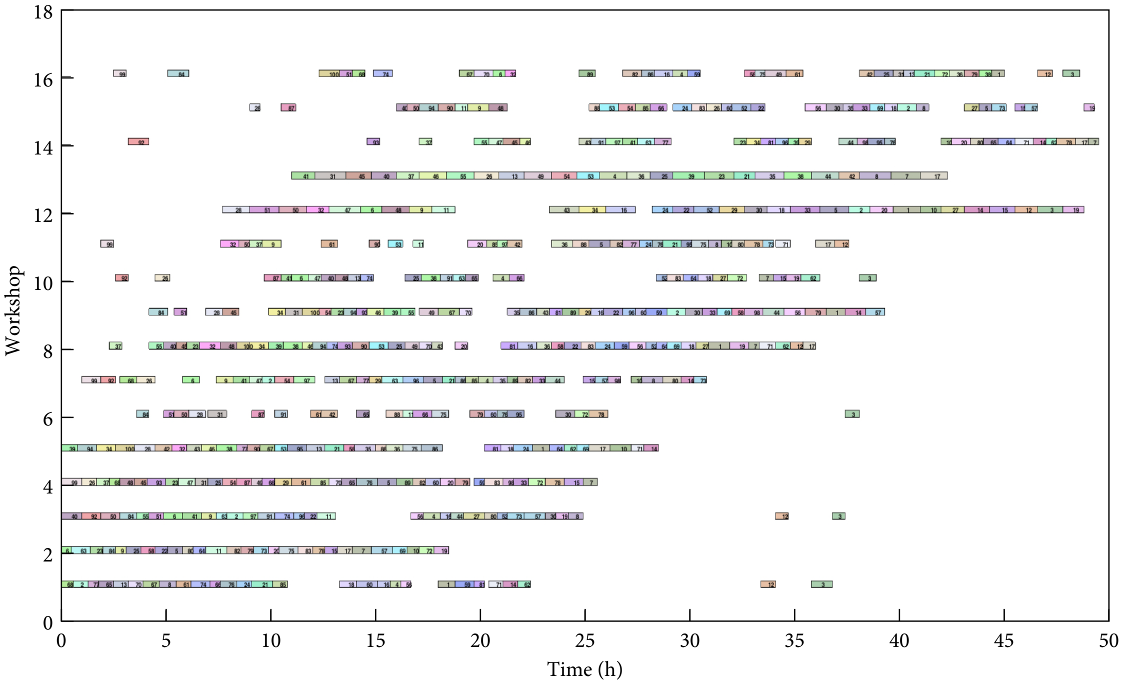

Fig. 7 Optimal scheduling plan of Simulation 2.

still in the exploratory period, and much valuable content is not involved, such as massive order processing. When the order size increases, the feasible solution space of DIC-GA increases, and the number of iterations and search time required accordingly increase gradually. This condition may affect the accuracy and efficiency of the FPSM model to a certain extent.

Dates

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References

[1] The State Council of the People's Republic of China, Made in China 2025, http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm, 2015.

[2] J. Behnamian and S. M. T. F. Ghomi, The heterogeneous multi-factory production network scheduling with adaptive communication policy and parallel machine, *Information Sciences*, vol. 219, no. 10, pp. 181–196, 2013.

[3] X. T. Sun, S. H. Chung, and F. T. S. Chan, Integrated scheduling of a multi-product multi-factory manufacturing system with maritime transport limits, *Transportation Research Part E: Logistics & Transportation Review*, vol. 79, pp. 110–127, 2015.

[4] Y. Y. Xiao, B. H. Li, C. H. Zhuang, X. D. Cha, and T. Y. Lin, Distributed supply chain scheduling oriented to multi-variety customization, *Computer Integrated Manufacturing System*, vol. 21, no. 3, pp. 800–812, 2015.

[5] X. Zhang, Research on parallel machine scheduling problem considering cost in cloud manufacturing environment, MS dissertation, School of Management, Hefei University of Technology, Hefei, China, 2016.

[6] Q. Li, Research on manufacturing/remanufacturing production planning in multi-factory collaborative environment, PhD dissertation, School of Management, Chongqing University of Technology, Chongqing, China, 2019.

[7] L. Liu, Research on enterprise production scheduling under the environment of supply chain, PhD dissertation, School of Information Science and Engineering, Shandong Normal University, Jinan, China, 2012.

[8] A. N. Balaji and S. Porselvi, Artificial immune system algorithm and simulated annealing algorithm for scheduling batches of parts based on job availability model in a multi-cell flexible manufacturing system, *Procedia Engineering*, vol. 97, pp. 1524–1533, 2014.

[9] N. J. Zhang, Research on sales forecasting and production scheduling for multi-variety and small-batch products, PhD dissertation, School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, China, 2016.

[10] S. C. Wang, D. B. Tang, H. H. Zhu, Q. Y. Nie, J. F. Pan, and L. Yang, Solving distributed multi-factory production scheduling problem based on improved particle swarm algorithm, *Machinery Manufacturing and Automation*, vol. 50, no. 4, pp. 9–13, 2021.

[11] S. Karthikeyan, P. Asokan, and S. Nickolas, A hybrid discrete firefly algorithm for multi-objective flexible job shop scheduling problem with limited resource constraints, *The International Journal of Advanced Manufacturing Technology*, vol. 72, nos. 9–12, pp. 1567–1579, 2014.

[12] Z. H. Mao, Y. Wang, and Z. C. Ji, Memetic non-dominated sorting particle swarm optimization algorithm for solving multi-objective flexible job shop scheduling problem, *Computer Systems & Applications*, vol. 24, no. 10, pp. 155–161, 2015.

[13] P. Zou, B. Li, J. Yang, S. Shi, and Y. Liang, Hierarchical ant-genetic algorithm-based multi-objective intelligent approach for flexible job shop scheduling, *China Mechanical Engineering*, no. 21, pp. 2873–2879 & 2884, 2015.

[14] X. Ma and F. He, Label printing production scheduling technology based on improved genetic algorithm, *Journal of Computer Applications*, vol. 41, no. 3, pp. 860–866, 2021.

[15] M. Gen, T. Tsujimura, and E. Kubota, Solving job-shop scheduling problem using genetic algorithms, in *Proc. 16th International Conference on Computers and Industrial Engineering*, Ashikaga, Japan, 1995, pp. 576–579.