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Solving dual flexible job-shop scheduling problem using a Bat Algorithm

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A B S T R A C T

For the flexible job-shop scheduling problem with machine selection flexibility and process sequence flexibility in process design, types and characteristic of machine selection and process sequence flexibility are analyzed. The mathematical model of dual flexible job-shop scheduling problem is established, and an improved bat algorithm is proposed. For purpose of expressing the relationship effectively between the process and the bat population, a new method of encoding strategy based on dual flexibility degree is proposed. The crossover and mutation operation are designed to strengthen the searching ability of the algorithm. For purpose of overcoming the shortcomings of the fixed parameters in bat algorithm, the value of the inertia weight was adjusted, and a linear decreasing inertia weight strategy was proposed. We carried out experiments on actual examples, it can be seen from the experimental results that the robustness and optimization ability of the algorithm we proposed are better than Genetic Algorithm (GA) and Discrete Particle Swarm Optimization algorithm (DPSO). This shows that the proposed algorithm is more excellent in solving the flexible job-shop scheduling problem, and it is an efficient scheduling algorithm.

A R T I C L E I N F O

Keywords:
Flexible job-shop scheduling
Optimization
Process sequence flexibility
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1. Introduction

Dual Flexible Job-shop Scheduling Problem (DFJSP) based on machine selection flexibility and process sequence flexibility is an extension of the classical Job-shop Scheduling Problem (JSP) and the Flexible Job-shop Scheduling Problem (FJSP). It overcomes the problems of the fixed step sequence and uniqueness of machine selection, and increases the flexibility of scheduling problem, making it closer to an actual production environment. DFJSP needs to consider not only the processing sequence of the work, but also the problems of assigning operations to machines, which are a more complicated NP-hard problem [1]. Therefore, research on DFJSP has theoretical significance and application value.

At present, researches on FJSP are mainly focused on two aspects. The first involves assigning operations to machines. Yuan et al. [2] proposed a hybrid harmony search algorithm for solving FJSP, they converted the continuous vector to the discrete vector and introduced heuristic and random strategies for a resentful initialization scheme. Zhao et al. [3-4] proposed a hybrid genetic algorithm to solve FJSP. Luan et al. [5] proposed a new genetic algorithm to solve FJSP, in which they optimize the performance by minimizing the data sizes of the constrained model and reduced the time and space complexity of GA. The second involves processing sequence flexibility. A model is defined by Saygin[6] , which combines flexible process design and production scheduling. Huang et al. [7] proposed an improved genetic algorithm for solving JSP based on process sequence flexibility. Ba et al. [8] proposed a new model of multi-resource flexible job shop scheduling problem, and designed a new genetic algorithm for solving this problem. Moreover, Modrák et al. [9] proposed an algorithm that can convert a multi-machines problem to a two-machines problem, and experiments show that the algorithm is effective in solving n-jobs and m-machine problems.

Bat Algorithm (BA) is a materialistic optimization algorithm developed by Yang [10] in 2010. Since its proposed the algorithm has caught the attention of scholars in different fields. It has been used in the study of power system stability by Ali [11]. Shi et al. [12] has applied BA to WSN position. Chen et al. [13-14] proposed a mind evolutionary bat algorithm which is applied to feature selection of mixed gases infrared spectrum. Besides its relevance to practical application BA is applied to the function optimization problem [15], pattern recognition [16] and optimization of engineering problems [17]. In area of workshop scheduling, there are a lot of articles concerning the influencing factors since the BA was presented. Marichelvam el al. [18-19] has applied the BA to the hybrid flow shop scheduling problem (FSP) in 2013, and it shows BA was more effective than genetic algorithm and particle swarm optimization in solving this problem through the simulation results. Luo et al. [20] proposed a discrete BA solution for permutation flow shop scheduling problem (PFSP) in 2014 and it also shows that BA was effective in solving PFSP through the simulation results. Zhang et al. [21] proposed an improved BA for solving PFSP, the simulation results show that the improved BA is feasible and effective. La et al. [22] proposed a hybrid BA to solve the two stages hybrid FSP and the result shows that the hybrid BA is better than the classical BA.

Be seen from the above, the studies of FJSP are primarily focused on the single FJSP. DFJSP is less researched. Although BA is applied to various fields, few investigators utilize it to solve DFJSP. Therefore, this paper establishes a model for DFJSP and proposes an improved bat algorithm for solving it.

2. Definition and formalization problem

Assumptions of notations for DFJSP are as follows:

- Let $J = J_\mathrm{i}$, $1 \leq i \leq n$, indexed i, be a set of n jobs.
- Let $M = M_\mathrm{j}$, $1 \leq j \leq m$, indexed j, be a set of m machines.
- Each job J_i consists of several operations. Certain jobs consist of unfixed process sequence. The operations of each job are not fixed numbers. Each operation can be processed for a given set of machines.

Some symbols used throughout the paper are as follows:

n	Total number of jobs
m	Total number of machines
λ	Total number of operations
λ_i	Number of operations of job J_i
O_{ij}	j-th operation of job J_i
S_{ij}	Total number of alternative machines of operation O_{ij}
W_{ijk}	j-th operation of job J_i on machine M_k
M_{ij}	Set of alternative machines of operation O_{ij}
T_{ijk}	Processing time of O_{ij} on machine M_k

In the actual production process there are many kinds of flexibility, such as machine selection flexibility and process sequence flexibility and so on. Descriptions of two of these flexibilities are described as below in details.

Process sequence flexibility

Process sequence flexibility is a kind of flexibility where there is not a fixed process sequence among operations for a job. Assume job J_i need λ_i operations to be finished. If order of operations from k_1-th to k_2-th $(k_1 < k_2)$ is unfixed, then it is regarded as flexible operations, and $< O_{ik_1}, O_{ik_2} >$ is denoted as the flexible process sequence span of job J_i. Flexible operation is classified into two types as follows: (1) Partial flexible operation: An operation which belongs to a flexible process sequence span can be inserted into any arbitrary position of the span. (2) Total flexible operation: An operation can be inserted into any arbitrary position of the process sequence.

Machine selection flexibility

The machine selection flexible scheduling problems can be classified into two main groups according to the relation between set M_{ij} and set M. (1) Total machine selection flexible scheduling problem: Each operation can be processed on any machine among the set M_{ij}, where $M_{ij} = M$. (2) Partial machine selection flexible scheduling problem: Each operation can be processed on any machine among the set M_{ij}, where $M_{ij} \subset M$. The partial machine selection flexible scheduling problem suits better than the total machine selection flexible scheduling problem in the practical manufacturing environments. But compared to the total machine selection flexible scheduling problem, the partial machine selection flexible scheduling problem has the disadvantages of great search space, great computation and difficulties solution.

Table 1 An example of processing time table of partial machine selection flexible scheduling problem

Job	Operation	M_1	M_2	M_3	M_4
J_1	O_{11}	2	7	—	6
	O_{12}	6	—	4	5
	O_{13}	—	3	2	4
J_2	O_{21}	3	1	6	3
	O_{22}	1	3	—	3

Table 2 An example of processing time table of total machine selection flexible scheduling problem

Job	Operation	M_1	M_2	M_3	M_4
J_1	O_{11}	2	7	2	6
	O_{12}	6	3	4	5
	O_{13}	4	3	2	4
J_2	O_{21}	3	1	6	3
	O_{22}	1	3	4	3

Examples of partial machine selection flexible scheduling problem and a total machine selection flexible scheduling problem are shown in Table 1 and Table 2 respectively. Processing time of each operation on the corresponding machine is indicated in the table. In Table 1, the tag "—" means that a machine cannot execute the corresponding operation.

Assumptions used throughout the DFJSP are as follows:

- In flexible process sequence span, each operation has the same priority.
- Each operation, once started, cannot be interrupted.
- Each machine can process only one job at the same time.
- Arrival time of a job is included in the processing time.
- When machines are available for re-scheduling when the corresponding operations are completed, machines can choose to stop or no-load running.

The task of DFJSP is to seek an appropriate schedule which cost minimum time to complete all operations. The makespan T_{max} can be calculated by the formula:

$$T_{max} = \max\{T_{max}^j \mid j = 1,2,\dots,m\} \tag{1}$$

where T_{max}^j is time of completion of last job on machine j.

3. The improved bat algorithm

To effectively avoid the bat algorithm from prematurity and to improve the global search capability and search precision, in this paper the following improvements of BA are made: (1) In order to express the relationship between the process flexibility, process sequence and bat population, a new coding strategy based on dual flexibility is proposed. (2) To enhance the ability of neighborhood search, the corresponding operations like crossover and mutation are designed. (3) A linear decreasing inertia weight strategy is adopted to effectively control the local and global search capability of BA during the optimization procedure.

3.1 Coding strategies

Coding is to abstract and specify the research problem, and then to develop mathematical model. Finally, it realizes the mapping between the solution space of feasible solution and the exploration space of BA. This is the key step in BA solving, and also the primary problem to be solved.

Classical JSP only needs to code based on the process sequence. But DFJSP need not only to code based on process sequence, but also need to select the corresponding machine for each operation. Therefore, the coding strategy needs to be done in the following three points: (1) The coding strategy should reflect machine selection flexibility and process sequence flexibility. (2) The coding strategy should show the sequence of operations for each job. (3) It has to show the corresponding processing machine that each job need for each operation.

Thus, we design three coding strategy based on above requirements:

A coding strategy base on the sequence

In the bat algorithm, all processes are required to be added to the code, present with vector $X_1 = (x_{11}, x_{12}, \dots, x_{1\lambda})$, the length is λ, among those vector elements, x_{11} indicates the first process of the first job, x_{12} indicates the second process of the first job. By that analogy, the total number of t is the operation of the i-th job characters of j-th job. In vector X_1, the order of the i-th corresponds to the order of processing sequence of each process. The advantages of this coding strategy are the high flexibility and always generate the feasible schedule after an exchange of the processing sequence.

A coding strategy base on the process sequence flexibility

In the DFJSP, after the coding based on sequence, it is needed to mark and determine the priority of each job with flexible process sequence span, here we use vector $X_1 = (x_{21}, x_{22}, \dots, x_{2\lambda})$ to present, the length is λ. Among them, the default initialization for x_{2i} is 0 or 1, 0 indicates that the process sequence is not flexible, to 1, indicates the opposite.

A coding strategy base on the machine selection flexibility

In the bat algorithm, we use vector $X_3 = (x_{31}, x_{32}, \dots, x_{3\lambda})$ to present machine selection. The length is λ. Among them, each variable is a positive integer which represents the position in the selected machine set. The advantage of this coding strategy is to ensure that generate the feasible schedule after the operation, and it can be applied to either totally FJSP or partially FJSP.

3.2 Bat algorithm and its improvement

Assume search space is a d-dimensional space, $v_i(t-1)$ and $x_i(t-1)$ denote the velocity and location of bat i at the time step t-1. The location $x_i(t)$ and velocity $v_i(t)$ at the time step t are as follows:

$$F_i = F_{min} + (F_{max} - F_{min})\beta \tag{2}$$

$$v_i(t) = v_i(t-1) + (x_i(t-1) - x^*)F_i \tag{3}$$

$$x_i(t) = x_i(t-1) + v_i(t) \tag{4}$$

$$x_{new} = x_{old} + \varepsilon A^{t-1} \tag{5}$$

$$A^t(i) = \alpha A^{t-1}(i) \tag{6}$$

$$R^t(i) = R^0(i)[1 - \exp(-\gamma(t-1))] \tag{7}$$

where F_i is the update frequency of bat i, F_{min} and F_{max} represent the minimum and maximum value of the update frequency. $\beta \in [0,1]$ and $\varepsilon \in [-1,1]$ are random numbers. Here x^* is the current global optimal solution, x_{old} is an optimal solution from a random selection of the optimal solution set, $A^{t-1}(i)$ is the average loudness at the time step $t-1$. For any $0 < \alpha < 1$ ($\alpha \in R$) or $\gamma > 0$ ($\gamma \in R$), we have,

$$A^t(i) \to 0, R^t(i) \to R^0(i), \text{as } t \to \infty \quad (8)$$

The standard bat algorithm flow is presented in Fig. 1.

Begin
Step 1. Initialize parameters such as bat population x_i, velocity v_i, loudness $A(i)$, pulse rates $R(i)$ and so on
Step 2. Define pulse frequency F_i
Step 3. Calculated fitness value fit_{min} and the current global optimal solution x^*
Step 4. While (t < Max number iterations)
Step 5. For ($i = 1$ to pop size)
Step 6. Generate new solutions by adjusting frequency, and updating velocities and locations via Eq. 2 to Eq. 4
Step 7. If (rand>$R(i)$)
Step 8. Select a solution among the optimal solution set
Step 9. Generate a new solution via Eq. 5
Step 10. end if
Step 11. Calculated fitness value fit_{new}
Step 12. If (fit_{new}<$fit(i)$&rand< $A(i)$)
Step 13. Accept the new solutions
Step 14. Update $A(i)$ and $R(i)$
Step 15. end if
Step 16. end for
Step 17. Find the current optimal fitness value fit_{new} and the current optimal x^*
Step 18. end while
End

Fig. 1 The standard bat algorithm flow

BA was proposed for solving the constrained optimization problem of a continuous domain. Then, a binary bat algorithm (BBA) was proposed by Mirjalili et al. [23] in 2014 for solving the optimization problem of a discrete domain. Although DFJSP is a discrete combinatorial optimization problem, but BBA cannot be applied to DFJSP directly. Therefore, according to the characteristics of DFJSP and optimization mechanism of BBA, we designed the related operators for solving DFJSP. To use bat algorithm to solve DFJSP, doing the following:

In order to explain the jobs, process sequence, machines, processing time, processing order and the status of processing and other information, the following definitions are given based on the rule of encoding and decoding. Example is taken from table 1 for understanding of the following definitions.

Definition 1: The correlation matrix of job and operation, JO

The correlation matrix of job and operation (JO) represents the relationship between jobs and operations. According to the data in Table 1, a matrix can be obtained as follows:

$$JO = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 2 & 2 \\ 1 & 3 & 3 \\ 2 & 4 & 1 \\ 2 & 5 & 2 \end{bmatrix}$$

JO is a λ-by-3matrix. The first column indicates job number; the second column indicates operation number of all operations; the third column indicates the order of the operation for the corresponding job. For example, the first line (1,1,1) indicates that the operation 1 is the first operation of the job 1; the second line (1,2,2) indicates that the operation 2 is the second operation of the job 1. By that analogy, the last line (2,5,2) indicates that the operation 5 is the second operation of the job 2.

Definition 2: The matrix of processing of job, *PJ*
The matrix of processing of job (PJ) represents the working state of each job under process. According to the data in Table 1, a matrix can be obtained as below:

$$PJ = \begin{bmatrix} 1 & 3 & 1 & 0 \\ 2 & 2 & 2 & 1 \end{bmatrix}$$

PJ is a n-by-4matrix. The first column indicates the job number; the second column indicates the number of operations corresponding to the jobs; the third column indicates the processing progress, the default initialization is 0; the fourth column indicates processing state of the job with four status 0, 1, 2, 3, status 0 indicate job is before process, status 1 indicate job is under process, status 2 indicate job is waiting for process, and status 3 indicate job is after process. For example, the first line (1,3,1,0) indicates that machine 1 has 3 processes and first operation of machine 1 is before process; the second line (2,2,2,1) indicates that machine 2 has 2 process and second operation of machine 1 is under process.

Definition 3: The matrix of temporary resource pool, *TRP*
The matrix of temporary resource pool (TRP) represents the process state of each job under process. According to the data from Table 1, a matrix can be obtained as follows:

$$TRP = \begin{bmatrix} 1 & 1 & 2 & 1 & 1 & 2 \\ 3 & 1 & 1 & 2 & 1 & 6 \end{bmatrix}$$

TRP is a n-by-6matrix. The first column indicates machine number; the second column indicates operation number for corresponding job; the third column indicates the operation number for corresponding job; the fourth column indicates job number; the fifth column indicates the order of the operation for corresponding job; the sixth column indicates the processing time on the machine for corresponding job. For example, the first line (1,1,2,1,1,2) indicates that two jobs need to be processed on the machine 1 and the processing time is 2 for the first operation of the job 1 on machine 1; the second line (3,1,1,2,1,6) indicates that one job need to be processed on the machine 3 and the processing time is 6 for the first operation of the job 2 on machine 3.

Definition 4: The matrix of resource state, *RS*
The matrix of resource state (RS) represents the status of each machine. According to the data from Table 1, a matrix can be obtained as below:

$$RS = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 2 & 1 & 2 & 1 \end{bmatrix}$$

RS is a m-by-4matrix. The first column indicates the machine number; the second column indicates the availability of the machine which has two processing status represented by 0 and 1 respectively, status 0 indicates that the machine is available to be used, status 1 indicates the machine is not usable because of occupation or out of order; the third column indicates job number; the fourth column indicates the operation number for corresponding job. For example, the first line (1,0,1,1) indicates that the machine 1 is available and the first operation of job 1 can be processed on machine 1; the second line (2,1,2,1) indicates that the machine 2 is not usable and the first operation of job 2 cannot be processed on machine 1.

To make the current optimal individual of bat population get a better solution, four neighborhood search operators such as inserting, reversing, crossover and mutation are adopted. Detailed definitions of operators are provided below.

Definition 5: Neighborhood search operator
Exchanging operator: We use exchanging operator (i, j) to exchange the two elements i, j of the sequence. Take data from Table 1 as an example, assuming that the coding sequence is (4,1,2,3,2) based on operation sequencing, after the exchanging operator (2,4), the coding sequence becomes (4,3,2,1,2).

Inserting operator: The goal of inserting operator (i, j) is to insert element i next to element j. Take data of Table 1 as an example, assuming that the coding sequence is (4,1,2,3,2) based on operation sequencing, after the inserting operator (2,4), the code sequence becomes (4,2,3,1,2).

Reversing operator: Reversing operator (i, j) reverse the subsequence between element i and element j. Take data from Table 1 as an example, assuming that the coding sequence (4,1,2,3,2) is based on operation sequencing, after the reversing operator (2,5), the code sequence becomes (4,2,3,1,2).

Crossover operator: Assume a current sequence X, crossover operator choose randomly one sequence Y of bat population, and generate a new sequence Z by replacing the elements i, j of current sequence X with the elements i, j of sequence Y. Take data of Table 1 as an example, assuming that the current sequence (4,1,2,3,2) and randomly selected sequence (1,4,2,1,4) are both based on process sequence, after the crossover operator (2,4), the code sequence becomes (4,4,2,1,2).

Mutation operator: After each iteration, if the current optimal solution is no better than the population optimal solution, then the current optimal solution should be mutated. The number of variations cannot be more than the 1/4 of the total number of population. The mutation operator <i,j> means to mutate the selection of O_{ij} by value from M_{ij}.

Updating process of position and velocity in bat algorithm is similar to the updating process of PSO algorithm [24]. The inertia weight$w$ is introduced to balance the local searching and the global searching via equation (9) [25]. In order to enhance the algorithm's ability of global searching at prophase of evolution, the weight exponential decline strategy is applied as shown in equation (10).

$$v_i(t) = wv_i(t-1) + (x_i(t-1) - x^*)F_i \tag{9}$$

$$w = \frac{T-t}{T}(w_{max} - w_{min}) + w_{min} \tag{10}$$

Where, t is the current number of iterations and T is maximum number of iterations; w_{max} and w_{min} are the maximum and minimum values of the inertia weight.

To summarize, the basic steps of the improved bat algorithm for solving DFJSP can be described as follows in Fig 2.

Step 1.	Initialize parameters, include the size of bat population $PopSize$, loudness $A(i)$, pulse rates $R(i)$, maximum inertia weight w_{max}, minimum inertia weight w_{min} and so on
Step 2.	The coding sequence is generated based on these three coding strategies
Step 3.	Calculate fitness value
Step 3.1	Load the information of all jobs into *PJ* and *TRP*
Step 3.2	Every job is processed in the beginning from the first operation by *PJ.* Firstly, judge by *RS* whether the machine which the first operation needing is processed is used by another operation. If not, then the job is into the processing status. Meanwhile, record the corresponding numbers of the job and the operation. Otherwise, the job is flagged as waiting for processing in *PJ*.
Step 3.3	The first job starts to be processed in *PJ* and *TRP*, which judge by *TRP* is being processed. If it is and the rest time of processing is greater than zero, the processing of the job is going on. If not, judge whether all operations of the job are finished. If the job is accomplished, make the machines free by *RS*. Otherwise, add the information of the next operation into *PJ* and *TRP.*
Step 3.4	If all jobs are already processed by *PJ*, go to *Step 3.5*; otherwise, go to *Step 3.2*
Step 3.5	Output fitness value
Step 4.	If the termination criterion is reached, go to S*tep 10*; otherwise, go to *Step 5*
Step 5.	Generate new solutions by adjusting frequency, and updating velocities and locations via Eqs. 2, 9 and 10
Step 6.	If rand>$R(i)$, select a solution from optimal solution set and generate a local solution x_{new} around the selected optimal solution via Eq. 5
Step 7.	Calculate fitness value fit_{new} of corresponding x_{new}
Step 8.	If $fit_{new} < fit(i) \& rand < A(i)$, accept the new solutions, update $A(i)$ and $r(i)$ via Eq. 6 to Eq. 7; otherwise, do neighborhood search operator
Step 9.	Go to step 4
Step 10.	Post process results and visualization

Fig. 2 The improved bat algorithm flow

4. Case simulation and analysis

4.1 Experimental parameter settings

The improved bat algorithm is coded in Matlab platform and run on an Intel core i7-5500U, 3.0 GHz and 12.0 GB RAM PC. The parameters of three algorithms are as follows:

Table 3 Parameter settings of three algorithms

Parameter	Value		
	Improved bat algorithm	GA	DPSO
$PopSize$	100	100	100
T	500	500	500
F_{max}	1	—	—
F_{max}	0	—	—
α	0.9	—	—
γ	0.9	—	—
A	0.25	—	—
w_{max}	0.96	—	—
w_{min}	0.36	—	—
Pc	—	0.7	—
Pm	—	0.08	—
w	—	—	0.9
c_1	—	—	2
c_2	—	—	2

The *PopSize* represent the size of the bat population and T is the maximum number of iteration.

4.2 Experimental dates

To verify the efficiency and feasibility of the improved bat algorithm for solving DFJSP, this paper used the actual data of manufacturing enterprise which is the problem 6×8. Problem 6×8 is a DFJSP instance that consists of 6 jobs of 27 operations that can be implemented on 8 machines. The data of the machine selection flexibility, process sequence flexibility and processing time are as follows:

Table 4 The data of machine selection flexibility

Job	Job number	Flexible process span
J_1	6	<2,3>, <5,6>
J_2	3	—
J_3	5	<3,5>
J_4	3	<2,3>
J_5	6	<3,4>
J_6	4	—

The tag "—" means that the job does not have a flexible process span.

Table 5 Data of process sequence flexibility and processing time (min)

Job	Operation	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
J_1	O_{11}	—	12	—	9	14	—	20	—
	O_{12}	18	—	—	19	—	15	11	—
	O_{13}	—	12	14	9	—	17	—	—
	O_{14}	—	11	—	—	9	—	—	12
	O_{15}	15	—	—	8	—	—	—	18
	O_{16}	12	—	9	—	—	11	—	—
J_2	O_{21}	—	—	12	19	14	—	—	—
	O_{22}	8	—	—	9	11	—	15	—
	O_{23}	16	7	—	—	—	9	—	—
J_3	O_{31}	—	—	—	11	10	—	—	13
	O_{32}	—	—	12	18	—	—	14	—
	O_{33}	9	—	—	15	7	—	12	—
	O_{34}	—	12	—	15	—	7	—	9
	O_{35}	3	—	—	4	—	8	—	—
J_4	O_{41}	—	19	—	—	7	—	13	—
	O_{42}	—	—	8	—	11	—	—	16
	O_{43}	9	11	—	8	—	—	18	—
J_5	O_{51}	6	—	—	12	—	—	14	9
	O_{52}	—	—	—	22	—	12	17	—
	O_{53}	—	18	—	—	11	—	—	9
	O_{54}	9	—	12	—	—	—	—	7
	O_{55}	—	11	—	—	—	9	14	—
	O_{56}	8	—	—	12	6	—	—	9
J_6	O_{61}	—	—	11	—	17	—	—	18
	O_{62}	5	—	12	—	—	—	7	9
	O_{63}	—	11	—	—	—	8	13	7
	O_{64}	19	—	13	7	—	15	—	—

4.3 Experimental results and comparisons

This paper used the improved bat algorithm, discrete particle swarm optimization [26] (DPSO) and genetic algorithm [27] (GA) to solve the DFJSP. And the experimental results are compared and analyzed.

To obtain meaningful results, we run each algorithm fifty times on the above instance. The experimental results of these three kinds of algorithms are shown in Table 6 and Table 7.

The optimum solution, average solution and standard deviation of three algorithms in 50 experiments are shown in Table 6. The optimum solution obtained by this paper is 55, which is obviously better than 65 obtained by GA and 62 obtained by DPSO. Furthermore, the average value and standard deviation are also better than both GA and DPSO. In a conclusion, the algorithm in this paper is obviously better than GA and DPSO in searching performance.

Table 6 Makespan comparison between three algorithms

Algorithm	Optimum solution	Average solution	Standard deviation
GA	65	70.72	4.25
DPSO	62	65.56	3.15
Improved bat algorithm	55	57.32	2.24

Table 7 Distribution of 50 calculation results

Interval / Algorithm	Interval				
	[55,60)	[60,65)	[65,70)	[70,75)	[75,80)
GA	0	0	23	14	13
DPSO	0	23	19	8	0
Improved bat algorithm	40	10	0	0	0

The distribution of experiments results in each interval for running 50 times is presented in Table 7. It is clear from the table, the results of the improved bat algorithm are comparatively concentrated, which are mainly in the range of [55, 60], whereas the results of GA and DPSO algorithm are relatively distributed. Thus, the improved bat algorithm in terms of solving DFJSP is more robust than GA and DPSO algorithm. Figs. 3, 4, and 5 shows the Gantt charts of optimal scheduling concerning three kinds of algorithms.

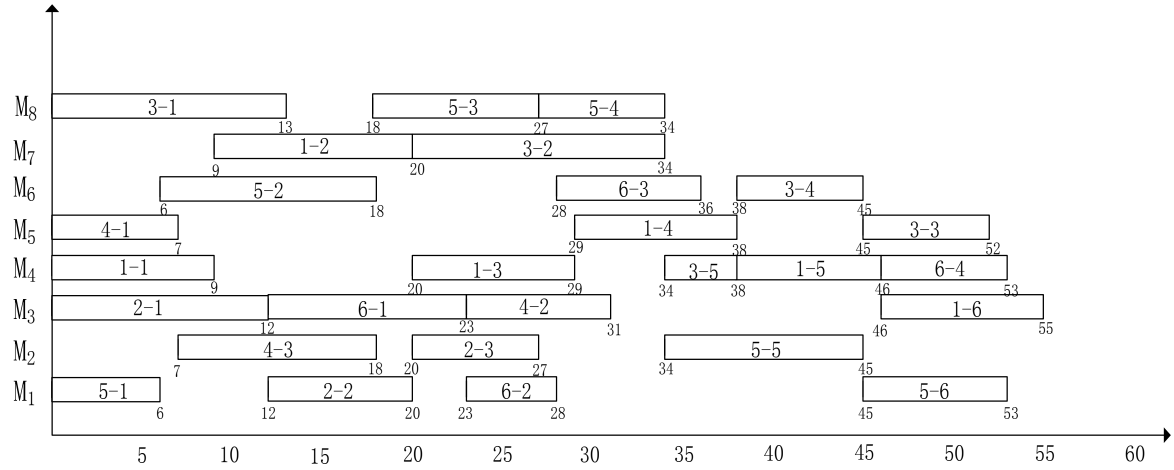

Fig. 3 The Gantt chart of optimal scheduling of the improved bat algorithm

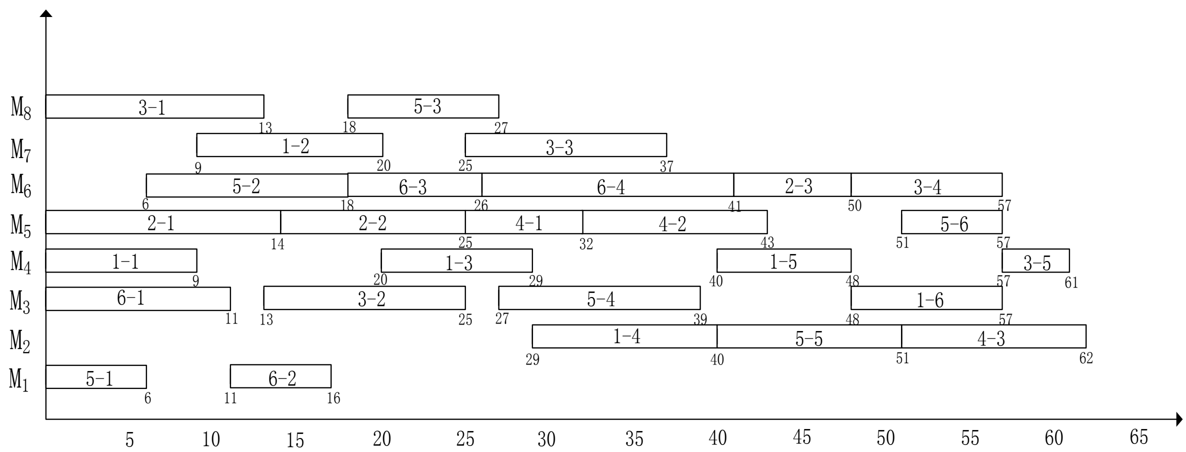

Fig. 4 The Gantt chart of optimal scheduling of DPSO algorithm

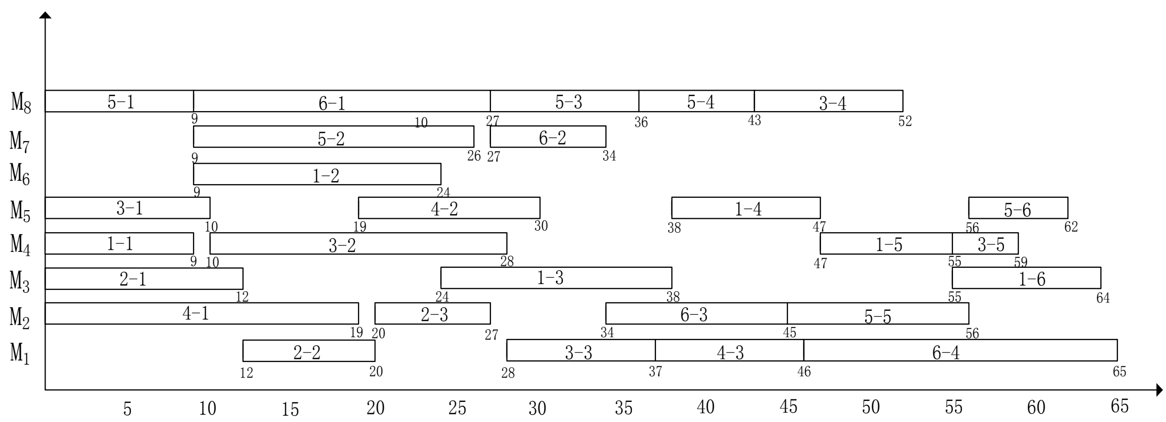

Fig. 5 The Gantt chart of optimal scheduling of GA

5. Conclusion

According to dual flexible job shop scheduling problems, we established a mathematical model based on process sequence flexibility and machine selection flexibility, and an improved bat algorithm is presented to solve it. The premise of BA used in DFJSP is to realize the mapping between operations and bat populations. Therefore, we proposed a dual flexible encoding strategy. In order to intensify neighborhood searching ability of the algorithm, several operations are designed such as crossover and mutation. Furthermore, a linear decreasing inertia weight strategy is put forward to effectively avoid the algorithm of premature convergence and to intensify the global searching ability and the precision of the algorithm. Aiming at solving actual job-shop scheduling problems, we set up the scheduling model and designed the detailed algorithm. Experimental results indicate that the improved bat algorithm for solving DFJSP is feasible and effective, which provides a new way to solve such problems. It is a further research direction to use the improved algorithm to solve multi-objective DFJSP and construct new dispatching rules.

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Performance modelling based on value analysis for improving product development process architecture

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A B S T R A C T

Improving the architecture of product development process (PDP) is an effective approach to improve PDP performance. However, performance is difficult to model because the criterion of performance such as development cost, time and product quality are usually contradictory. The objective of this paper is to use process value as the evaluation indicator of PDP performance. The process value of PDP, as well as the ratio of process function and process cost, is discussed and its quantitative method is proposed. The process function is defined as the process effectiveness which considers the importance of each activity of PDP, and its evaluation methods based on rework theory and quality function deployment (QFD) are given. The simulation method is used to illustrate the proposed model and analyze the relation between architecture and process value of PDP, and an optimization model for PDP architecture is provided. With the model, we can get a suitable PDP architecture to balance the cost and product function during product development.

A R T I C L E I N F O

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1. Introduction

Product development process (PDP) refers to the entire set of activities to convert customers' needs into a technical and commercial solution [1, 2]. The activities and their relationships are described by the process architecture (or network). Analyzing and optimizing the architecture is helpful to build a PDP with high performance, which implies low development cost, short lead time and high product quality [3, 4]. However, these criterions are usually contradictory. For example, higher product quality may mean that the development time is longer or cost is higher. In addition, high performance is an elusive notion [5].

There have been relevant studies on performance measurement in PDP. Huang and Fu [6] proposed a quantitative model based on signal flow graphs (SFG), assessing process from the aspects of time, cost, quality and robustness. Pun et al. [7] proposed a self-assessment model of new product development performance (NPD) using analytical hierarchy process (AHP). Syamil et al. [8] researched the relationships between product development process and process performance, and provided a model of process performance at project level. The cost estimating [9], development quality [10], product performance [11], feasibility [12] and uncertainty [13] etc. have also been studied by some other researchers, which can reflect or affect the performance of PDP. So many measures and evaluation methods for PDP performance lead to an ambiguous definition of performance in above literatures. In addition most works focused on performance at project or program level.

O'Donnell and Duffy [14] considered that the overall performance in design is determined both by performance of the design solution (related to the product design parameters or product quality), and the performance of the process (related to the duration or cost). In their model, efficiency and effectiveness are as fundamental elements of performance. Efficiency is seen as the relationship between the knowledge that an activity gained and the used resources; while effectiveness is related to the degree how the outputs of knowledge meet the goals of activities. The model provides an improved perception of performance measurement, but the relationship between efficiency and effectiveness is not direct, because their focuses (efficiency focuses on process, and effectiveness focuses on solution or product) are different. Accordingly in some cases it is difficult to achieve combination of the two variables.

With successful application and good effects in manufacturing process, lean thinking has been gradually extended to development field in enterprises. Many works have been reported recently [15-17]. Value is the core concept in lean product development (LPD). The essential of value is to guide improvement processes [18]. Some scholars have tried to improve the performance of PDP through the value analysis method [19] or value stream method [20, 21]. Browning [22] pointed out that value is a function of both the product recipe and the process that produces it. That is to say both the effectiveness of the product and the efficiency of the process affect value.

However, there are two types of value in product development, product value and process value according to Chase [23]. Unfortunately, most of researches in this field have ignored the difference between them, and mainly focused on product value. Different from the product value which is defined as a capability provided to a customer at the right time at an appropriate price, process value is defined as the ability to perform with maximum quality at minimum cost. The quality is related to effectiveness, while the cost is related to efficiency, and waste in PDP can be understood as inefficiency and ineffectiveness [18], so the process value provides a new way to evaluate and improve the performance of PDP.

This paper is concerned with performance modelling by building the evaluation method of process value. The proposed model that describes the process value of PDP integrates the performance parameters, such as development time, process cost and product quality or function. It involves the factors such as process structure, rework constraints, customer requirements and so on. In the model, we extend O'Donnell and Duffy's [14] concept of effectiveness. In our work, the process effectiveness of one activity is evaluated by its rework. The rework evaluation method based on Design Structure Matrix (DSM) and the creation goal evaluation method based on Quality Function Deployment (QFD) are introduced to the model. Through the optimization of the process value, PDP can be improved from different aspects, such as resource allocation, process architecture improvement, requirement optimization, etc. In this study we focus on improving PDP from the aspect of process architecture improvement.

The remainder of this paper is organized as follows. Section 2 discusses the process value and its quantitative method. In section 3 the relationship between architecture and performance of PDP is verified by simulation based on a sample, and a new optimization model for PDP architecture is proposed. An example and some discussions are given in section 4. Finally, the conclusions and some extended research are presented in section 5.

2. Performance modelling based on value analysis

2.1 Process value

The importance of one activity in PDP describes the role that the activity plays during developing product, which can be considered as the process creation goal of the activity divided from the overall process creation goal of PDP. We use g to denote the creation goal of an activity and G to denote the overall process creation goal of PDP. The relationship between them can be expressed as Eq. 1.

$$G = \sum_{i=1}^{n} g_i \tag{1}$$

Here n indicates the number of activities. Whether an activity is able to achieve its goals or play its role in PDP depends on the effectiveness of the activity. In our method, the process effectiveness refers to the degree of the relevance between the creation and the goal of the process or activity. The effectiveness of the activity is denoted by e, while the effectiveness of the PDP is denoted by E. The process function can be considered as the actual creation of activity or PDP. The process function of an activity denoted by f and the process function of PDP denoted by F can be calculated as Eq. 2 and Eq. 3.

$$f = g \cdot e \tag{2}$$

$$F = G \cdot E \tag{3}$$

In addition, f and F have the following relationship:

$$F = \sum_{i=1}^{n} f_i \tag{4}$$

In our model the process value is defined as the capability to achieve the process creation goal under appropriate cost. The process value of an activity represented by the letter v, and the process value of the PDP represented by the symbol V^{proc}, are formulated as Eq. 5 and Eq. 6.

$$v = \frac{g \cdot e}{c} \tag{5}$$

$$V^{proc} = \frac{G}{\alpha_1 \cdot C + \alpha_2 \cdot T} \cdot E \tag{6}$$

The cost of PDP includes both resource consumption C and time consumption T. In Eq. 6, α_1 and α_2 respectively represent the weight of the cost and development time. The performance model of PDP with effectiveness and process value is expressed in Fig. 1.

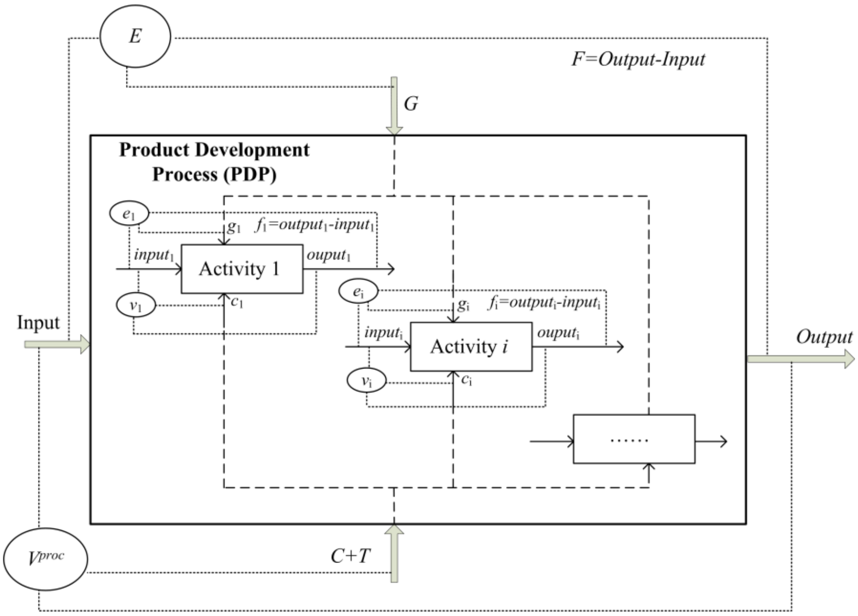


Fig. 1 Effectiveness and process value

The first part $\frac{G}{\alpha_1 \cdot C + \alpha_2 \cdot T}$ reflects the different development modes and development methods. The second part E reflects the uncertainties in a PDP, such as the different architectures, reworks and so on. So we can select suitable product development type and improve the architecture of PDP according to Eq. 6. This paper only studies the improvement of architecture under a fixed product development type. The parameters G and C can be considered as the static information, which can be obtained through prediction. Non-dimensional treatment for them is produced in analysis process. The cost C is the accumulation of the cost of all activities in PDP in normal executing case. It is the expected cost, rather than the actual cost of execution, and can be calculated according to Eq. 7.

$$C = \sum_{i=1}^{n} (c_i \cdot d_i) \tag{7}$$

Here c_i is the expected cost of unit time of activity i, and d_i is the expected working time of activity i. Generally, coefficient of C is 1.

The development time T is affected by the development process architecture. Assume that the development time on critical path of a PDP is T_{min}, the coefficient of T can be calculated by Eq. 8.

$$T = \frac{T_{min}}{T_{expected}} \tag{8}$$

Here $T_{expected}$ is the expected time of the product development project, and can be considered as a constant.

In Fig. 1 input and output of activity or PDP are indeterminate and difficult to evaluate, so in the next section we will explore the decomposition of G and evaluate E.

2.2 Decomposing of process creation goal

G of PDP is the performance or function of product that must be created. As a broad concept, it reflects the extent of how much the product to meet the customer requirements, including technical parameters, quality and other attributes. So that is to say, it is based on the customer requirements and will not be changed during development. In other words, it can be seen as a constant. However, g of an activity is decomposed from G of PDP based on its importance during the development, and difficult to quantify. The coefficient of activity (COA) is used to express the importance of an activity during development.

Customer requirement is the start to evaluate process. On referring to Quality Function Deployment (QFD) method, which considers that meeting customer requirement is the ultimate goal of product development, this paper establishes the mapping matrix from customer requirement to product function, and the mapping matrix from product function to activities. Through these matrices the COA can be evaluated.

Because the QFD has been quite mature, it is assumed that the customer requirements and all of the mapping matrices are able to be estimated or set by experienced engineers. The customer requirements can be expressed by $CR = [CR_1, CR_2, \dots, CR_l]$, where l is the total number of customer requirements, and $\sum_{k=1}^{l} CR_k = 1$.

The mapping matrix from product requirements to product function is

$$RF = \begin{bmatrix} rf_{11} & \cdots & rf_{1m} \\ \vdots & \ddots & \vdots \\ rf_{l1} & \cdots & rf_{lm} \end{bmatrix},$$

where rf_{ks} indicates the importance coefficient of product function s to realize the customer requirement k. The sum of every row in RF is 1. The weight of product functions W is expressed by $[W_1, W_2, \dots, W_m]$. So the evaluation coefficient of product functions (COF) expressed by vector $[COF_1, COF_2, \dots, COF_m]$ can be calculated with Eq. 9.

$$COF = (CR \cdot RF) \times W \tag{9}$$

Similarly, the matrix

$$FA = \begin{bmatrix} fa_{11} & \cdots & fa_{1m} \\ \vdots & \ddots & \vdots \\ fa_{n1} & \cdots & fa_{nm} \end{bmatrix},$$

with sum of every column being 1, expresses the mapping matrix from product function to development process, and fa_{is} indicates the importance coefficient of activity i to realize the product function s. So the evaluation coefficient of product function target of activities (COA) expressed by vector $[COA_1, COA_2, \dots, COA_n]$, can be calculated with Eq. 10.

$$COA = COF \cdot FA^{\mathrm{T}} \tag{10}$$

Then the decomposing formula of G is given as Eq. 11.

$$g_i = G \times COA_i \tag{11}$$

2.3 Effectiveness evaluating based on R-DSM

The effectiveness reflects the degree of completing the process creation goal. If the creation goal cannot be fully completed by the PDP or the activity, the part that has not been completed can be considered as ineffective, which should be retrieved by rework process. So we can evaluate the effectiveness of activity through its rework.

We suppose that the completion degree of the process function of the activity is related to the cost and time the activity consumed. As shown in Fig. 2, if the consumed time and cost is c and the process creation goal is g, it will get the process function $f = g \cdot e$. In other words, there will be $g - f$ process function left to be reworked, which is expressed as rg. Similarly, in order to get the process creation goal $g - f$ function which can be the process creation goal of the rework, the consumed time and cost (rc) will be $\frac{(g-f)\cdot c}{g}$, which is the rework effort. So the rework rate of an activity can be calculated as $r = \frac{g - g\cdot e}{g} = 1 - e$. Therefore the activity effectiveness can be represented and calculated simply by the rework rate of activity as Eq. 12.

$$e = 1 - r \tag{12}$$

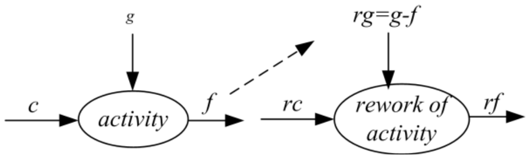


Fig. 2 Example of rework

Reworks can improve product quality or functions, but probably it will increase the development cost and time. We explain the rework probability, rework impact and rework workload using design structure matrix (DSM) method, which is similar with Browning and Eppinger's [24].

Rework probability is a measure of uncertainty of one certain PDP architecture. Fig. 3 shows the rework probability, impact and rate through the DSM representation.

- Rework Probability Design Structure Matrix (RP-DSM): $RP(i,j)$ represents the probability that activity $i$reworks due to activity j for $i,j = 1,2,\cdots,n$ and $i \neq j$. $RP(i,j)$ represents the rework probability of the activity i due to the change of information outside the PDP, such as changes of customer requirements.

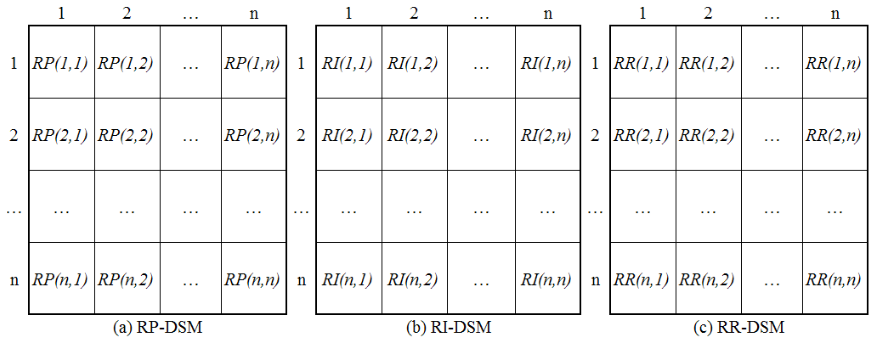


Fig. 3 DSM of rework probability, impact and rate

- Rework Impact Design Structure Matrix (RI-DSM): $RI(i,j)$ represents the rework percentage of completed work of activity i when it is due to activity j or other reasons outside the PDP.
- Rework Rate Design Structure Matrix (RR-DSM): $RR(i,j)$ represents the actual rework effort of activity i affected by activity j or other reasons outside the PDP. It is product of $RP(i,j)$ and $RI(i,j)$, as Eq. 13.

$$RR(i,j) = RP(i,j) \times RI(i,j) \quad i,j = 1,2,\cdots,n \tag{13}$$

Suppose there are two activities. Activity 1 is the predecessor activity of activity 2, and the two activities have information interaction with each other. According to the architecture, activity 1 is executed without any information from activity 2, because activity 2 must be executed after activity 1. After activity 2 is completed, activity 1 would be caused to rework, and the rework rate is $RR(1,2)$. So the rework effort of activity 1 caused by activity 2 is $c_1 \cdot RR(1,2)$. In other words, the rework rate of activity 1 is $r_{1,2} = RR(1,2)$. Because activity 2 is successor activity of activity 1, and its rework is caused by the change of activity 1. The change quantity is $c_1 \cdot RR(1,2)$, therefore, the rework effort of activity 2 is $\frac{c_1 \cdot r_1}{c_1} \cdot c_2 \cdot RR(2,1)$, equivalent to $c_2 \cdot r_1 \cdot RR(2,1)$. In other words, the rework rate of activity 2 is $r_{2,1} = r_1 \cdot RR(1,2)$.

Similarly, if activity 1 and activity 2 are parallel, they will be executed without any information provided by another activity. So rework rate of activity 1 is $r_{1,2} = RR(1,2)$, while rework rate of activity 2 is $r_{2,1} = RR(2,1)$.

From the above analysis, the following conclusions can be drawn:

(1) If activity i is the upstream activity of activity j for $i,j = 1,2,\cdots,n$, the rework rate of activity i is $RR(i,j)$, and the rework rate of activity j is $r_i \cdot RR(j,i)$.

(2) If activity i and activity j are parallel, the rework rate of activity i is $RR(j,i)$, and the rework rate of activity j is $RR(j,i)$.

Use a_{ij} to show the precedence relationship between activity i and j. If activity i is the upstream activity of activity j, $a_{ij} = 1$. Otherwise, $a_{ij} = 0$. And for all $i,j = 1,2,\cdots,n$, $a_{ij} + a_{ji} \leq 1$ and $a_{ii} = 0$. So the above conclusions can be expressed as:

$$r_{i,j} = RR(i,j) \cdot (1 - a_{ji}) + r_j \cdot RR(i,j) \cdot a_{ji} \quad a_{ji} = 1 \text{ or } 0 \;\&\; a_{ij} + a_{ji} \leq 1 \tag{14}$$

In addition, the RR-DSM only expresses the rework rate of one activity when it is directly affected by other activities. However, in practice an activity usually is influenced by multiple activities and some activities indirectly. Therefore, it is necessary to determine a total rework rate (r) of an activity under a specific PDP architecture.

Suppose that there are three activities 1, 2 and 3, and the rework rate of activity 1 caused by activity 2 and 3 are $r_{1,2}$ and $r_{1,3}$ respectively. Thus the rate that activity 2 doesn't cause activity 1 to rework is $1 - r_{1,2}$, while the rate that activity 3 doesn't cause activity 1 to rework is. That's to say, the rate that activity 1 doesn't rework is $(1 - r_{1,2}) \cdot (1 - r_{1,3})$. In other words, the total rework rate (r_1) of activity 1 is $1-(1-r_{1,2})\cdot(1-r_{1,3})$. So the effectiveness of activity i can be expressed as Eq. 15 and Eq. 16.

$$r_i = 1 - \prod_{j=1}^{n}(1-r_{i,j}) \quad i,j = 1,2,\cdots,n \tag{15}$$

$$e_i = \prod_{j=1}^{n}(1-r_{i,j}) \quad i,j = 1,2,\cdots,n \tag{16}$$

According to Eq. 1, Eq. 2, Eq. 3, Eq. 4 and Eq. 11, we can get the calculation process for the effectiveness of one PDP as $E=\frac{F}{G}=\frac{\sum_{i=1}^{n} f_i}{\sum_{i=1}^{n} g_i}=\frac{\sum_{i=1}^{n}(g_i\cdot e_i)}{\sum_{i=1}^{n} g_i}=\frac{\sum_{i=1}^{n}(G\cdot COA_i\cdot e_i)}{\sum_{i=1}^{n}(G\cdot COA_i)}$. Because G is a constant and $\sum_{i=1}^{n} COA_i = 1$, so we can get the formula for E as Eq. 17.

$$E = \sum_{i=1}^{n}(COA_i \cdot e_i) \tag{17}$$

3. Optimization model for PDP

3.1 Computational study

An illustrative sample is presented for demonstrating the value of PDP analysis. The sample has three customer requirements, four product functions and five activities. The required input data are listed in Fig. 4. The reworks due to reasons outside of PDP are not considered. For simplicity, assume that both G and C are 1, and all the costs and process creation goals of activities are evaluated with the standardized coefficient. Both the weight of the cost and the weight of development time are 0.5. The expected lead time of the product development is 30.

Customer requirements

Requirement ID	Evaluation coefficient of requirements
CR_1	0.3
CR_2	0.5
CR_3	0.2

Mapping matrix RF

PF_1	PF_2	PF_3	PF_4
0.3	0.4	0.3	0
0.2	0	0.4	0.4
0	0.5	0.5	0

Product functions

Function ID	Weight of function
PF_1	0.1
PF_2	0.3
PF_3	0.5
PF_4	0.1

Activity information

Activity ID	Time(expected)	Cost of unit time
P_1	6	6
P_2	10	2
P_3	8	4
P_4	12	1
P_5	8	1

Mapping matrix FA

PF_1	PF_2	PF_3	PF_4
0.3	0.4	0.3	0
0.2	0	0.4	0.4
0	0.5	0.3	0
0.5	0	0	0.2
0	0.1	0	0.4

RP-DSM

P_1	P_2	P_3	P_4	P_5
0	0.5	0.8	0.2	0
0.6	0	0.4	0	0.5
0.3	0.5	0	0	0.4
0.3	0.5	0.5	0	0
0	0.6	0.2	0.4	0

RI-DSM

P_1	P_2	P_3	P_4	P_5
0	0.6	0.5	0.5	0
0.5	0	0.5	0	0.4
0.2	0.2	0	0	0.5
0.5	0.5	0.1	0	0
0	0.2	0.4	0.5	0

Fig. 4 Example of rework

All possible PDP process architectures are constructed and the process values are calculated. And the process simulations are carried out for all the architectures. Each of PDP process architectures is simulated by 1000 times, and the mean value of these simulation results is used as the final simulation of the architecture. All of the simulation programs are implemented in MATLAB 7.0.

Fig. 5 shows the simulation results of all the different process architectures. The process values are calculated by the formula (6)-(17), and the costs and duration are obtained by simulation. The figure depicts both cost and duration show decreasing trend with the increasing of process value. This concludes that the PDP architectures with high process value have better performance. So development process can be improved by optimizing the PDP architecture based on the value analysis.

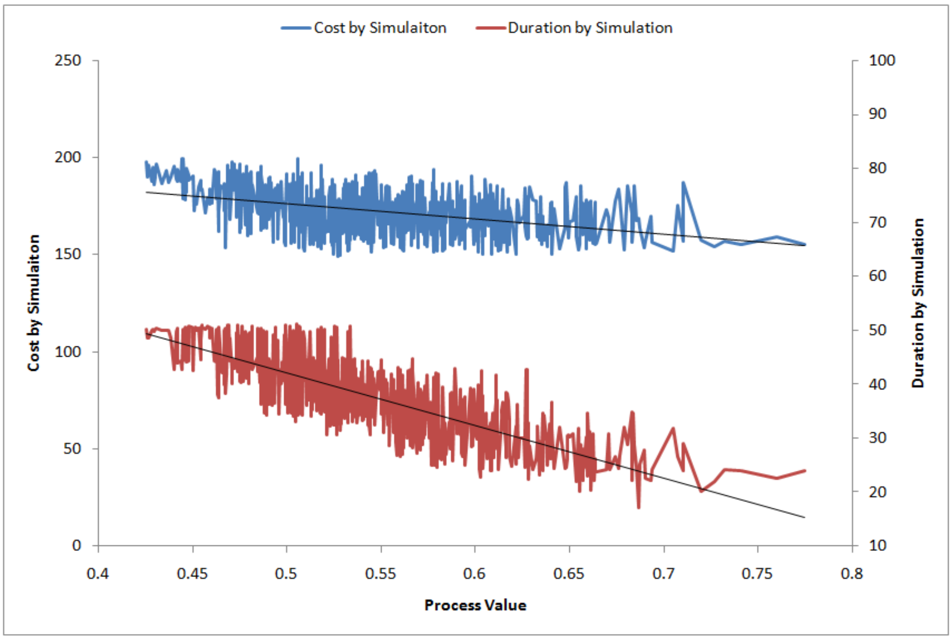


Fig. 5 Simulation results analysis of the computational study

3.2 Optimization model for PDP

Based on the elements discussed above, we propose the optimization model for PDP architecture as follows:

$$\max: V^{proc} = \frac{G}{\alpha_1 \cdot C + \alpha_2 \cdot T} \sum_{i=1}^{n} (COA_i \cdot e_i) \tag{18}$$

subject to Eq. 8, Eq. 9, Eq. 10, Eq. 13, Eq. 14, Eq. 15, Eq. 16 and

$$a_{ij} + a_{ji} \leq 1 \quad i,j = 1,2,\cdots,n \tag{19}$$

$$a_{ji} = 1 \; or \; 0 \quad i,j = 1,2,\cdots,n \tag{20}$$

The optimization model focuses on the effects of PDP architecture on the process value which can express the performance of PDP. In the model, the resource requirements are assumed static and unlimited, and the customer requirements, process goals, rework probability and activity duration can be estimated. The optimization variables are a_{ij}, for all $i,j = 1,2,\cdots,n$ and $i \neq j$. All parameters are summarized in Table 1. Eq. 19 shows that there is no circuit in the network of PDP.

4. Example application

In order to verify the feasibility of the proposed optimization model, the development process of a refrigerator is studied as an example. The PDP of the refrigerator has 18 activities and its detailed information is given in Fig. 6. Through analysis, we sorted out the customer requirements and the product functions, shown in Fig. 7. Fig. 8(a) gives the initial architecture of the PDP. With the increasing of competitive pressure it is necessary to shorten the development cycle and reduce the cost. The expected lead time is 200 days.

Table 1 Model parameters

Parameters	Definition and Description
V^{proc}	Process value of PDP
G	Overall process creation goal of PDP, which can be decomposed into the process creation goals of activities (g). If g_i is evaluated with the standardized coefficient, G would be 1.
C	Expected total cost of PDP, which is the sum of the cost of each activity (c). If c_i is evaluated with the standardized coefficient, C would be 1.
T	Development time that expressed with the standardized coefficient.
T_{min}	The development time on critical path of a PDP.
$T_{expected}$	The expected lead time of the product development project.
α_1	The weight of PDP cost.
α_2	The weight of PDP duration.
E	Effectiveness of the PDP, which is the degree to what the creation during the process relates to the overall process creation goal of the PDP.
F	Process function of the PDP, which is the actual creation of the PDP.
COF_s	The evaluation coefficient of product functions s.
CR_k	The evaluation coefficient of customer requirement k
W_s	The weight of product function s.
COA_i	The coefficient of activity i which is used to express the importance of an activity.
RF	The mapping matrix from product requirements to product function.
FA	The mapping matrix from product function to development process.
g_i	Creation goal of the activity i and evaluated with the standardized coefficient.
c_i	Cost of the activity i. Sometimes it can be evaluated with the standardized coefficient.
d_i	Duration of activity i.
e_i	Effectiveness of activity i
f_i	Process function of activity i, which is the actual creation and calculated using $e_i \cdot g_i$.
$RR(i,j)$	The actual rework effort of activity i affected by activity j for $i,j = 1,2,\cdots,n$.
$RP(i,j)$	If $i \neq j$, it is the probability that activity i is reworked affected by activity j for $i,j = 1,2,\cdots,n$, and else it is the rework probability of the activity i caused by the change of information outside the PDP.
$RI(i,j)$	The rework percentage of completed work of activity i, when activity i is reworked affected by activity j, or other reasons outside the PDP.
r_i	The total rework rate of activity i under a specific PDP architecture.
$r_{i,j}$	The rework rate of activity i affected by activity j or other reasons outside under a specific PDP architecture.
m	Total number of activities.
n	Total number of product functions.
l	Total number of requirement.

It can be seen from Fig. 6, some activities interact with each other. There are two main coupling activities groups, one is (5,6,10,14), and the other is (4,9,13). The mapping matrix FAs of them shown in Fig. 9 are obtained by Analytic Hierarchy Process (AHP). The optimization models are established for the two coupled activities groups, and the improved architectures shown in Fig. 8(b) is obtained.

Using the given parameters, the process simulation for the architectures before and after the improvement is performed. The simulation runs 1000 times for each architecture. The simulation results are given in Table 2.

Activity information

Activity ID	Activity description	Activity duration	Cost of unit time
1	General Design	7	17.1
2	Appearance Preliminary Design	14	7.8
3	Technical Specifications Determine	14	7.1
4	Body Preliminary Design	5	14
5	Appearance Modeling	10	14
6	Body Detailed Design	20	11
7	Body Trial-produce	25	25.6
8	Body Test	30	13
9	Refrigerating System Preliminary Design	10	9
10	Refrigerating System Detailed Design	30	10
11	Refrigerating System Trial-produce	40	16.5
12	Refrigerating System Test	35	12
13	Control System Preliminary Design	10	10
14	Control System Detailed Design	25	16
15	Control System Trial-produce	56	15
16	Control System Test	35	13.7
17	Assembling	21	12.9
18	Assembly Test	14	15.7

RP-DSM

Activity ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	1	1	0.3	0	0	0	0	0.6	0	0	0	0.7	0	0	0	0	0
5	0	0	0	1	0.2	0.8	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.3	0.3	0	0	0	0.6	0	0	0	0.6	0	0	0	0
7	0	0	0	0	0	1	0.2	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0.3	0	0	0	0	0	0	0	0	0	0
9	0	1	1	0.5	0	0	0	0	0.3	0	0	0	0.6	0	0	0	0	0
10	0	0	0	0	0	0.8	0	0	1	0.3	0	0	0	0.5	0	0	0	0
11	0	0	0	0	0	0	0	0	0	1	0.3	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	1	0.2	0	0	0	0	0	0
13	0	1	1	0.4	0	0	0	0	0.8	0	0	0	0.2	0	0	0	0	0
14	0	0	0	0	0	0.4	0	0	0	0.8	0	0	1	0.7	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.4	0	0
17	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0.3	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3

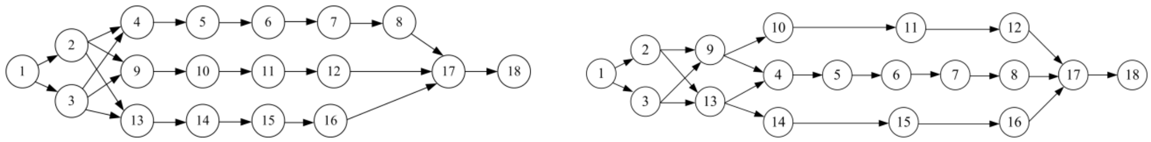
RI-DSM

Activity ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0.6	0.4	0.5	0	0	0	0	0.5	0	0	0	0.6	0	0	0	0	0
5	0	0	0	0.6	0.7	0.6	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.3	0.6	0	0	0	0.7	0	0	0	0.6	0	0	0	0
7	0	0	0	0	0	0.4	0.6	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0
9	0	0.4	0.5	0.6	0	0	0	0	0.6	0	0	0	0.5	0	0	0	0	0
10	0	0	0	0	0	0.6	0	0	0.5	0.7	0	0	0	0.5	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.6	0.7	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0.4	0.5	0	0	0	0	0	0
13	0	0.3	0.2	0.5	0	0	0	0	0.5	0	0	0	0.5	0	0	0	0	0
14	0	0	0	0	0	0.5	0	0	0	0.5	0	0	0.6	0.7	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.7	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.6	0	0
17	0	0	0	0	0	0	0	0.5	0	0	0	0.4	0	0	0	0.3	0.8	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.9

Fig. 6 Detailed information of the refrigerator development

Customer requirements			Mapping matrix RF								Product functions		
Requirement ID	Requirement description	Evaluation coefficient of requirements	PF_1	PF_2	PF_3	PF_4	PF_5	PF_6	PF_7	PF_8	Function ID	Function description	Weight of function
CR_1	Fast Refrigeration Speed	0.176	1	0	0	0	0	0	0	0	PF_1	Refrigerating Capacity	0.07
CR_2	Low Energy Consumption	0.118	0	0.28	0	0.28	0	0.1	0.1	0.26	PF_2	Energy Consumption	0.124
CR_3	Small Noise	0.118	0	0.17	0.5	0.17	0	0	0.2	0	PF_3	Noise Level	0.093
CR_4	Environmental	0.176	0	0.2	0.2	0	0	0	0.6	0	PF_4	Thickness of Insulation Layer	0.109
CR_5	Appearance Style	0.059	0	0	0	0.1	0.9	0	0	0	PF_5	Dimension of Body	0.07
CR_6	Multi-function	0.118	0	0	0	0	0	0	0	1	PF_6	Temperature Control Method	0.116
CR_7	Low Price	0.118	0	0.06	0	0.06	0	0.2	0.2	0.52	PF_7	Cooling Method	0.209
CR_8	Simple Operation	0.118	0	0	0	0	0	0.5	0.5	0	PF_8	Input Power	0.209

Fig. 7 Customer requirements and the product functions



(a) Initial architecture (b) improved architecture

Fig. 8 Architectures of PDP

Activity ID	PF_1	PF_2	PF_3	PF_4	PF_5	PF_6	PF_7	PF_8
5	0. 06	0. 14	0. 14	0. 22	0. 32	0. 06	0. 05	0. 09
6	0. 22	0. 18	0. 18	0. 49	0. 54	0. 10	0. 15	0. 26
10	0. 59	0. 35	0. 35	0. 25	0. 09	0. 34	0. 59	0. 53
14	0. 13	0. 33	0. 33	0. 04	0. 05	0. 50	0. 21	0. 12

Activity ID	PF_1	PF_2	PF_3	PF_4	PF_5	PF_6	PF_7	PF_8
4	0. 24	0. 48	0. 16	0. 69	0. 77	0. 09	0. 14	0. 53
9	0. 68	0. 47	0. 58	0. 22	0. 16	0. 32	0. 57	0. 33
13	0. 08	0. 05	0. 26	0. 09	0. 07	0. 59	0. 29	0. 14

Fig. 9 Mapping matrix FAs of the two coupling activities groups

Table 2 Simulation results

Item	Initial scheme	Improved scheme
Process value	0.748	0.793
Cost by simulation	9,099	8,730
Duration by simulation	210	194

Compared with the initial scheme, the cost of the improved scheme is reduced by 369,000 RMB (1 US $ = 6.86 RMB), and the development time is shortened by 16 days.

The performance of PDP and the value concept have received considerable attention in the previous literatures. However, no one has studied these two together. This study concludes that the PDP with maximum process value has good performance because of its lower cost and shorter development period. The V^{proc} as a comprehensive indicator is not only related to the process cost, process time and product quality, but also related to the customer requirement, rework probability and the product development process architecture. Under the goal of maximizing process value, we can improve PDP from different aspects by different optimization variables.

The proposed model is suitable for improving PDP of products like refrigerator from the process architecture aspect. These products have strong market characteristics, and have mature and stable development technology. Their development process goals are certain, and their development resources are relatively fixed. The customer requirements can be obtained through market research, while the rework probability and impact between activities can be obtained through statistical analysis based on historical data. Enterprises that produce these products must develop and launch new products rapidly in order to occupy the market, and also need to implement low-cost strategy in order to maximize profitability.

The optimization model can also be used to solve other improvement problem by adjusting constrains and optimization variables. For example, in the engineering to order (ETO) enterprises like mould enterprises, shipyards, etc., multiple products usually are being developed simultaneously, and this causes competition of sharing resource. In such situation, the optimization goal is still maximizing the process value, but the variables and constraints should be changed. Variables that represent resource allocation will be added to the model as an optimization variable, and the variables represent process architecture (a_{ij}) will be used as constraints. Thus, the changed model can be used to solve the resource allocation problem.

5. Conclusion

The research studies the performance modelling of PDP based on value analysis. The proposed process value of PDP used to express process performance is a comprehensive indicator of cost, time and function. In the specific quantitative method of the process value, process function is evaluated by process creation goal and effectiveness. To estimate the effectiveness of activities, an evaluation method of rework is introduced, and to estimate the process creation goal of activities, a method referring to QFD is used. We demonstrate the analyzing procedure of process value and verify the relationship between architecture and value of PDP by simulation method based on an example. The simulation results show that the PDP architectures with high process value, have low development cost and short development time. To improve the PDP architecture, an optimization model is provided. Through the model, we improve a refrigerator development process.

Although studies such as this paper have led to a deeper thinking and understand of the process value and performance of PDP, the empirical research of the value evaluation method and optimization model should be carried out, and simulation and genetic algorithm should be further studied in the future.

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The impact of information and communication technologies (ICT) on agility, operating, and economical performance of supply chain

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ABSTRACT

Information and communication technologies (ICT) are widely used in supply chain (SC) due to their effects on both economic performance and operational agility. This paper proposes a structural equation model integrating 17 items into four latent variables: ICT, SC agility, operating performance, and economic performance. Data analysed in the model were gathered through a questionnaire administered to 306 managers of Mexican maquiladoras. Likewise, we used statistical software WarpPLS 5.0®, which is based on partial least squares algorithms, to assess the six hypotheses established in the model. Such hypotheses were validated with a 95 % confidence level, and values were standardized to avoid problems regarding the measurement scale. Findings demonstrate that ICT have a positive direct impact on the other three analysed latent variables, which together account for 63 % of the variability of SC economic performance. Similarly, we found that ICT can explain up to 40 % of the variability of SC agility.

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1. Introduction

1.1 General

The recently emerged concept of globalization usually refers to a process in which a product is manufactured in one part of the world but includes components sub-assembled in other countries, while it can be consumed in another remote area. Consequently, globalized companies require large logistics systems to transport all these materials and components. Moreover, the process involves multiple actors sharing information, materials, and above all, financial resources [1]. This set of activities is commonly called supply chain (SC).

To improve SC metrics, companies currently rely on a wide range of information and communication tools, which are traditionally categorized into two groups: communication technologies and information technologies [2]. It is common, however, to include both concepts in one, and thus refer to them as information and communication technologies (ICT).

Mexico currently caters for 5,074 foreign-owned assembling plants, also known as maquiladoras, whose parent companies are headquartered overseas and provide them with specialized *ICT* to comply with production orders. The maquiladora program became attractive after Mexico, the US, and Canada signed the North American Free Trade Agreement (NAFTA). The treaty created an appealing and convenient free trade zone for these countries, which enabled

US and Canadian companies to import raw materials in Mexico and export finished products at preferential tariffs. As a result, maquiladoras became a key industry in Mexico, especially along the Mexico-US border.

In Ciudad Juárez, a border city located in the state of Chihuahua, the maquiladora industry is represented by 326 manufacturing companies, directly offering 222,040 jobs. These maquiladoras belong to a globalized SC, whose performance can be compromised by many factors, such as ICT. Therefore, to contribute to the discussion on the impact of ICT on supply chain performance, this paper seeks to measure the effects of *ICT* on SC *Agility*, *Operating Performance* and *Economic Performance*, thereby looking to support decision-making in Mexican maquiladoras on ICT implementation. More specifically, results here provided may help executives identify the most important activities to gain certain benefits. Note that similar studies have been conducted in other industrial sectors by Garcia-Alcaraz et al. [3] and Martinez-Loya et al. [4].

1.2 Information and communication technologies in supply chain

In the industrial sector, *ICT* are mainly used to monitor and control the flow of materials in supply chains. From this perspective, benefits gained from *ICT* implementation are vast and varied; the most illustrative examples include:

- *SC visibility*: *ICT* enable to monitor the material flow along the SC at any time, and sometimes with remote access [5]. Visibility has been studied from several SC perspectives, such as inventory control [6], risks visibility from cash break down, information, or materials flow [7], and visibility as a result of interaction and collaboration among SC partners [8, 9], among others.
- *SC agility*: Research has reported agility as one of the major *ICT* benefits [10]. However, because SC agility is one of the four variables studied in this paper, we will not provide further details on this element in this section.
- *SC flexibility*: It refers to the way companies make necessary changes to meet customer demands. Flexibility must be designed and planned [11] from the supplier evaluation phase [12], although lack of flexibility can be improved with appropriate plant localization [13] and proper use of *ICT* [14]. In fact, *ICT* generate predictive models that stimulate flexibility and facilitate decision-making based on metrics and their analysis [15].

1.3 Supply chain agility

SC agility usually refers to how fast production processes and material flows are [16], although it is frequently confused with flexibility. Since SC agility has been studied from many different points of view, many models have been proposed to measure it [17]. Agility is thus a strategy deserving serious management, since undoubtedly, companies with agile SCs have greater competitive potential [2]; however, in order to achieve agile SCs, firms require solid integration among SC members, which is often reached with *ICT* implementation [18].

Nevertheless, agility is not merely an *ICT* product or the result of SC members' integration. Agility also and mainly derives from the effort and dedication of people involved in the SC [10], and it offers attractive advantages to customers. Such benefits later translate into economic benefits, which obviously reflect on increased financial profits [19]. From this perspective, recent studies have reported that *Agility* in wineries is gained through *ICT* implementation [3], and under such argument, we propose the first working hypothesis of this study, H_1: In the maquiladora industry, *ICT* implementation along the SC has a positive direct effect on *Agility*.

1.4 Operating performance

In order to improve a process, it is necessary to know its current state and then make a comparative analysis. In other words, *Operating Performance* must be monitored to be improved. Nowadays, several indices and indicators serve this purpose, and when *Operating Performance* is improved (maximize or minimize), sooner or later results are converted into profits. Currently, companies rely on a wide range of internal *ICT* to assess and enhance *Operating Performance*. Some of these *ICT* include Enterprise Resource Planning (ERP) [20], Warehouse Management

System (WMS), bar codes, and Radio Frequency Identification (RFID) [21]. One benefit of using these kinds of *ICT* is SC risks reduction [22].

One of the most important performance indices is cycle times. Short time cycles imply that products spend a little time in inventory and are rapidly manufactured and delivered to customers [23]. However, cycle times are affected by inventory policies and the company's ability to make appropriate demand forecasts [24]. Also, cycle times can be reduced through SC members integration and information sharing [25]. In this sense, the use of mobile technologies has become a trend [26].

Although cycle time reduction must be priority, ensuring unrejected deliveries is equally important, as they imply customer satisfaction [27]. This means that managers must focus on guaranteeing short and fast cycle times without lowering product quality. In this sense, cycle times must be supervised using *ICT* along the SC to guarantee visibility [4], whereas customer complaints do require another SC *Operating Performance* metric. To find a relationship between *ICT* and SC *Operating Performance* in the maquiladora context, we propose the second working hypothesis, H_2: In the maquiladora industry, *ICT* implementation has a positive direct effect on SC *Operating Performance*.

Operating Performance indices can have several improvement sources, such as proper *ICT* integration; however, they can also be enhanced through *Agility* [28] and proper SC alignment with the corporate vision and mission [29]. For instance, by using factor and cluster analyses, authors in Kisperska-Moron and Swierczek [30] grouped a set of polish companies according to SC agility, whereas an empirical study conducted by Ngai et al. [31] reported the effects of SC *Agility* on productivity indices. Therefore, to analyse the impact of SC *Agility* on SC *Operating Performance*, we propose the third working hypothesis as follows, H_3: In the maquiladora industry, SC *Agility* has a positive direct effect on SC *Operating Performance*.

1.5 Economic performance in supply chain

Companies implement production, quality, and management methodologies, techniques, procedures, and technologies in SC to increase profits, which is why research on SC benefits has different origins and purposes. From this perspective, some of the studies associating *ICT* with SC performance have focused on the use of ERP, one of the most popular methods for materials handling. Also, Kanellou and Spathis [32] evaluated SC performance in terms of financial impact, whereas research in [33] analysed the same phenomenon in Chinese companies. Furthermore, the study in Teittinen et al. [34] reported that *ICT* implementation in SC was vital for companies in emerging countries. Hence, in order to contribute to the discussion on the economic benefits of ICT implementation for SCs, we propose the fourth working hypothesis as follows, H_4: In the maquiladora industry, *ICT* implementation has a positive direct effect on *Economic Performance*.

Another source of profits is SC *Agility*, since it guarantees customer satisfaction through rapid deliveries [19] and allows companies to quickly and efficiently adapt to the needs of these clients. Unfortunately, as mentioned in Silvestre [35], senior managers generally but incorrectly associate agility with high production costs. However, a study conducted by Yang [36] using path analysis showed that by using *ICT*, Chinese manufacturing companies could increase *Agility* and achieve greater *Economic Performance*, whereas authors in Yusuf et al. [37] reported similar results in the petroleum industry in the United Kingdom. Therefore, in the context of Mexican maquiladoras, we can propose the following working hypothesis to assess the effects of SC *Agility* on *Economic Performance*, H_5: In the maquiladora industry, SC *Agility* has a positive direct effect on *Economic Performance*.

SC *Operating Performance* can quickly turn into economic benefits. From this perspective, product quality, low costs, and fast deliveries are top priorities, because they are synonyms of satisfied customers [38] and a rapid and continuous material flow, and thus they demonstrate effective SC integration [39]. Similarly, short cycle times are always beneficial from an economic point of view [40], whereas quick setups may allow for product customization, which is often profitable. Considering thus the impact of SC *Operating Performance* on the *Economic Performance* of companies, we propose the sixth working hypothesis for the maquiladora industry, H_6:

In the maquiladora industry, SC *Operating Performance* has a positive direct effect on *Economic Performance*.

Fig. 1 depicts the proposed model to test the six hypotheses discussed above.

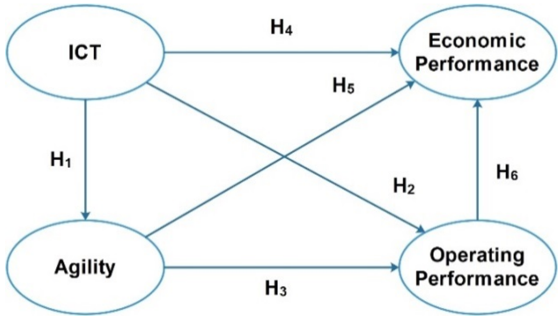

Fig. 1 Proposed model

2. Methodology

2.1 Questionnaire design

As data collection instrument, we designed a questionnaire to assess the four latent variables and their corresponding items. Latent variable *ICT* included seven items, while SC Agility was composed of three items; *Operating Performance* was formed of five items, and *Operating Performance* was assessed by two items. Table 1 lists the assessed items for each latent variable and references justifying their study.

The questionnaire had to be answered using a five-point Likert scale for subjective assessments, where the lowest value (1) indicated that an activity had never been performed or a benefit had never been obtained. On the other hand, the highest value (5) implied that an activity had always been performed or a benefit had always been gained.

Table 1 Analysed Latent Variables and Items

ICT	*Operating Pperformance*
Effective use of the Internet in B2B commerce [41].	In-full and on-time deliveries [5].
Effective use of the Internet for business management [42].	Customer satisfaction (no claims or warnings) [39, 43].
Use of the Internet for product customization and collaboration [42].	Short supplier-customer time cycle [44].
Displayed information and inter-organizational coordination [41, 45].	SC visibility [5, 46].
Use of Intra-Organizational Information Systems for SC coordination and integration [42, 47].	High-levelled product customization [39, 43].
SC optimization through ECR [48].	*Agility*
Removal of SC intermediaries [49].	Fast re-engineering process [50, 51].
Economic performance	Ability to respond to unexpected customer demands [45, 51].
SC costs reduction [39].	Ability to respond to high market fluctuations [35].
SC performance contributes to cash flow [29, 52].	

2.2 Data collection process

To collect information, we stratified the sample by focusing on 306 companies established in Ciudad Juárez (Mexico), which have mature SCs. Then, we invited potential participating companies to schedule a survey administration meeting, depending on their availability. For companies that did not respond to the first invitation, a second request was emailed two weeks later; however, after three unsuccessful attempts, the case was discarded. As regards the survey administration process, we conducted face-to-face interviews with SC managers and personnel directly involved in the materials flow process.

2.3 Data capture and questionnaire validation

Collected data were analysed using statistical software SPSS 21®. However, before any data validation process, we conducted statistical tests to identify missing values and outliers. Missing values were replaced by the median value of items, as long as they did not exceed 10 % in each survey, while outliers were solved by standardizing values [54]. Similar procedures have been followed in other SC studies [55].

As for data validation, we first computed the Cronbach's alpha and composite reliability indices for every latent variable to test internal validity and consistency, setting 0.7 as minimum acceptable value [53]. Then, since removing items from latent variables can improve their reliability, we ran additional tests, relying on five indices: Average Variance Extracted (AVE), Variance Inflation Factors (VIF), Q-Squared, R-Squared, and Adjusted R-Squared. This procedure has been used in previous SC research to validate other data collection instruments [29, 52].

AVE was used to measure discriminant validity of latent variables, setting 0.5 as the minimum acceptable value [56], while we relied on VIF as collinearity measure, whose maximum value was set to 3.3 [57]. Finally, since we dealt with ordinal data, we computed Q-squared index as measure of nonparametric predictive validity, and R-squared and Adjusted R-Squared as measures of parametric predictive validity. We expected to obtain similar values in both R-squared and Adjusted R-Squared indices.

2.4 Descriptive analysis of items

Following the data validation process, we conducted a descriptive analysis of items to find measures of central tendency and data dispersion. We estimated the median or 50-th percentile as measure of central tendency and the interquartile range (IQR) as measure of data dispersion. On one hand, high median values suggested that an activity was always performed or a benefit was always gained in the Mexican maquiladora industry, whereas low values indicated that an activity was never performed or a benefit was never gained. On the other hand, high IQR values indicated low consensus among respondents as regards the median value of an item, whilst low values suggested high consensus [58].

2.5 Structural equation modelling

To test hypotheses depicted in Fig. 1 and discussed in the introduction section, we employed Structural Equation Modelling (SEM). SEM is a multivariate analysis technique widely used in SC research to statistically validate causal relationships between latent variables. For instance, a SEM-based study conducted by [59] reported the impact of JIT on SC performance, whereas authors in [60] assessed the effects of uncertainty on SC financial performance by means of a structural equation model. Likewise, SEM-based research by [61] reported the effects of green SC management on competitiveness and market incentives.

In this research, the structural equation model was run on WarpPLS 5.0® software. More specifically, we employed WarpPls3 PLS algorithm, since partial least squares (PLS) algorithms are widely recommended for small-sized samples or when using non-ordinal data [62]. Then, to validate the model, we computed three model fit and quality indices, proposed by [62] and used by [63] in SC environments: Average Path Coefficient (APC), Average R-Squared (ARS), and Average block Variance Inflation Factor (AVIF).

APC and ARS were used to measure the model's general efficiency and predictive validity, respectively. In both cases, we computed the P-values to determine statistical significance of parameters, setting 0.05 as the threshold, and thus testing null hypotheses APC = 0 and ARS = 0, versus alternative hypotheses: APC≠0 and ARS≠0. As for AVIF, we computed it as internal collinearity measure, accepting any value lower than 5.

Once indices were estimated, we measured and validated three types of effects between latent variables: direct, indirect, and total effects. Direct effects are depicted in Fig. 1 as arrows directly connecting two latent variables, whereas indirect effects occur through mediator variables, and total effects are the sum of direct and indirect effects for every relationship. For every effect, we estimated a P-value to determine its statistical significance, setting 0.05 as the threshold, thus implying that validated effects were significant at a 95 % confidence level. Finally, for each dependent latent variable we decomposed the value of R^2 into all the effect sizes caused by independent latent variables.

3. Results

3.1 Sample description

As previously mentioned, we validated 306 surveys administered in Mexican maquiladoras from Ciudad Juárez. As regards the sample characteristics, Table 2 compares participant's gender with length of work experience. As can be observed, 233 males and 73 female managers were surveyed. Also, most respondents had from one to two years of work experience in their current position, although 57 people had more than ten years of work experience.

Table 2 Gender and job experience (years)

Gender	Experience (years)				Total
	1-2	2-5	5 - 10	>10	
Male	90	64	25	54	233
Female	36	20	14	3	73
Total	126	84	39	57	306

Table 3 shows surveyed industries and their size, measured by number of employees. Note that only 278 of the 306 participants reported such information. In this sense, the table shows that 93 automobile and electronics manufacturers were surveyed, while 51 of the studied maquiladoras belonged to the aeronautics sector. However, the medical or surgical sector was the least prominent industry, with only 21 reported cases. As regards company size, all surveyed maquiladoras can be considered large, since they reported more than 500 employees in operation.

Table 3 Industrial sector and size of companies surveyed

Industrial sector	Number of employees					Total
	1-50	51-100	101-200	201-500	>501	
Automotive	3	3	6	9	72	93
Electronics/Electrical	7	8	8	17	53	93
Plastic	1	0	1	3	10	15
Packaging	1	0	1	1	2	5
Aeronautics	15	8	8	5	15	51
Medical	0	21	0	0	0	21
Total	27	41	24	35	152	278

3.2 Questionnaire validation

For data validation, we measured reliability of latent variables using seven indices as described in the methodology section. Results from this data validation process are shown in Table 4. Values obtained for R-squared and adjusted R-squared indices demonstrated that latent variables had enough predictive validity. Likewise, since values of the composite reliability index and the Cronbach's alpha were above 0.7, we concluded that all latent variables had sufficient internal consistency. Also, we found enough discriminant validly and no collinearity problems in data, since AVE values were above 0.5 and VIF values were below the threshold (3.3). Finally, since we obtained Q-squared values similar to their corresponding R-squared values, we demonstrated that all latent variables showed predictive validity from both parametric and non-parametric perspectives.

Table 4 Statistical validation of latent variables

Index	Latent variable			
	ICT	*Agility*	*Operating performance*	*Economic performance*
R-squared		0.397	0.627	0.459
Adjusted R-squared		0.395	0.624	0.455
Composite reliability	0.933	0.889	0.916	0.874
Cronbach's alpha	0.916	0.813	0.817	0.819
AVE	0.667	0.729	0.846	0.581
VIF	1.757	2.142	2.691	2.718
Q-squared		0.400	0.627	0.453

3.3 Descriptive analysis of items

Table 5 shows results from the descriptive analysis of items, which are sorted in descending order based on their median values. According to participants, item *Effective use of the Internet in B2B commerce* is the most important *ICT* activity (median value = 4.26). However, in terms of SC *Agility*, the most valuable feature is *Ability to respond to unexpected customer demands* (median value = 4.38). In the case of SC *Operational Performance*, managers from Mexican maquiladoras considered item *In-full and on-time deliveries* as the most important activity, with a median value of 4.39. Finally, as for *Economic Performance*, the sample reported *SC costs reduction* as the most important element (median value = 4.2).

Table 5 Descriptive analysis of items

ICT	**Median**	**IR**
Effective use of the Internet in B2B commerce.	4.26	1.39
Effective use of the Internet for business management.	4.26	1.32
Displayed information and inter-organizational coordination.	4.18	1.49
Intra-organizational Information Systems for SC coordination and collaboration.	4.18	1.37
Removal of SC intermediaries.	4.18	1.47
Use of the Internet for product customization and collaboration.	4.15	1.45
SC optimization through ECR.	4.10	1.45
Agility		
Ability to respond to unexpected customer demands.	4.38	1.26
Ability to respond to high market fluctuations.	4.31	1.38
Fast re-engineering process.	4.16	1.44
Operating performance		
In-full and on-time deliveries.	4.39	1.21
Customer satisfaction (no claims or warnings).	4.26	1.34
High-levelled product customization.	4.18	1.35
Short supplier-customer time cycle.	4.14	1.43
SC visibility.	4.12	1.37
Economic performance		
SC costs reduction.	4.2	1.39
SC performance contributes to cash flow.	4.12	1.35

3.4 Direct effects and hypotheses validation

Figure 2 shows the model evaluated as described in the methodology section. Every effect includes a beta (β) value and a P-value; the former is a measure of dependency, whereas the latter was used to determine statistical significance of effects at a 95 % confidence level. Note that all P-values are below 0.05, demonstrating that all beta parameters were statistically significant and had to remain in the model. The figure also shows the percentage of explained variance in every dependent latent variable (R^2). In this sense, we found that *Economic Performance* was 63 % explained by the three other latent variables, since $R^2 = 0.63$. Similarly, *Operating Performance* was 46 % explained by SC *Agility* and *ICT*, since in this case $R^2=0.46$.

As regards model fit and quality indices, we obtained the following results: Average Path Coefficient (APC) = 0.396 (with $P < 0.001$); Average R-Squared (ARS) = 0.572 (with $P < 0.001$); Average Adjusted R-Squared (AARS) = 0.571 (with $P < 0.001$); and Average block VIF (AVIF) = 2.234 (ideally <= 3.3). Since these indices demonstrated model's adequacy, we could formulate accurate conclusions on the sixth hypotheses proposed in the introduction section. Such conclusions are presented in Table 6, where based on β-values, the highest positive direct effect occurred from *ICT* on *Agility*, implying that when the former increased its standard deviation by one unit, the latter increased by 0.63 units (β = 0.63).

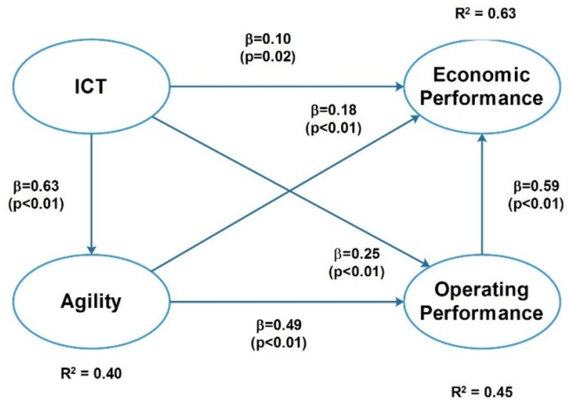

Fig. 2 Evaluated model

Table 6 Direct effects – tested hypotheses

Hypothesis	Independent variable	Dependent variable	β- and P-values	Conclusion
H_1	*ICT*	*Agility*	0.63 (P < 0.01)	Accepted
H_2	*ICT*	*Operating performance*	0.25 (P < 0.01)	Accepted
H_3	*Agility*	*Operating performance*	0.49 (P < 0.01)	Accepted
H_4	*ICT*	*Economic performance*	0.10 (P = 0.02)	Accepted
H_5	*Agility*	*Economic performance*	0.18 (P < 0.01)	Accepted
H_6	*Operating performance*	*Economic performance*	0.59 (P < 0.01)	Accepted

3.5 Total indirect effects

Indirect effects occur through mediator variables using two or more model segments; they are important, since they can explain relationships that initially seemed to be statistically non-significant. In this research, Table 7 shows the sum of indirect effects between latent variables, including statistical validation given by P-values, and the effect size, ES. ES is similar to R^2 of direct effects, and it expresses the percentage of explained variance in dependent latent variables. As can be observed, *ICT* have strong indirect effects on both *Economic Performance* and *Operating Performance,* with values β = 0.447 and β = 0.307, respectively.

Table 7 Indirect effects

To	From	
	ICT	*Agility*
Economic performance	0.447 (p < 0.001) ES = 0.247	0.29 (p < 0.001) ES = 0.172
Operating performance	0.307 (p < 0.001) ES = 0.172	

3.6 Total effects

Total effects are the sum of direct and indirect effects. Table 8 introduces total effects found in each relationship between latent variables, which based on the P-values, were all statistically significant. Also, it was found that *ICT* had high total effects on all the other latent variables, thereby demonstrating the importance of *ICT* implementation in SC. Also, note that the highest ICT effect occurred on SC *Agility* (β = 0.63 units), whereas *ICT* impact on *Operating Performance* seemed a little lower (β = 0.561). Also, we found that SC *Agility* had significant total effects on *Operating Performance* (β = 0.488) and *Economic Performance* (β = 0.47).

Table 8 Total Effects

To	From		
	ICT	*Agility*	*Operating performance*
Agility	0.63 (p < 0.001) ES = 0.397		
Economic performance	0.547 (p < 0.001) ES = 0.303	0.47 (p < 0.001) ES = 0.300	0.594 (p < 0.001) ES = 0.457
Operating performance	0.561 (p < 0.001) ES = 0.315	0.488 (p < 0.001) ES = 0.316	

4. Conclusions, industrial implications, and future work

In this research, we provided quantitative dependency measures to demonstrate that ICT implementation has effects on SC agility and operating and economic performance. These findings look trivial and with common sense, but those dependence values represent the main contribution given in this paper. Results introduced in Fig. 2 thus validated the six hypotheses as statistically significant, and they can thus support decision-making in Mexican maquiladoras on ICT implementation as a profitable strategy.

Findings here reported also support *ICT* implementation as a source of competitiveness, since they allow companies to increase SC *Agility* and visibility, which both impact on *Operating Performance* and *Economic Performance*. In this sense, we found that the *ICT* effects on *Economic Performance* only increased when SC *Agility* and *Operating Performance* were present, since the indirect effect in this relationship was higher than the direct effect (β = 10 vs. B = 0.447). Similar results were reported in the wine industry by Garcia-Alcaraz et al. [3] and Martínez-Loya et al. [4].

Similarly, this study argues that *ICT* allow for a faster response to customer needs by streamlining changes resulting from demand uncertainty. This argument is supported by the relationship found between *ICT* and *Agility*, which showed the highest direct effect (β = 0.63), and in which the former explained 40 % of the variance of the latter ($R^2 = 0.40$).

In this research we found that indirect effect from *ICT* on *Operating Performance* given through *Agility* was higher (β = 0.307) than the direct effect (β = 0.25), and total effects equalled 0.561 units. Similar findings were obtained in the relationship between *Agility* and *Economic Performance*, in which the direct effect was 11 units below the indirect effect (β = 0.18 vs. B = 0.29) given through *Operating Performance*. Such results entail the following industrial implications*:*

- Company executives and SC managers must encourage ICT implementation to meet SC and corporate demands. However, it is equally important to properly plan *ICT* implementation, and provide adequate training on the use of ICT, since their success impact on SC *Agility* and *Operating Performance.*
- SC visibility is key to the production processes, since it supports companies in making on-time decisions and rapid production process changes.
- Managers must pursuit all operating benefits provided by *ICT* and SC *Agility*, since both elements guarantee proper *Operating Performance*, and thus increase *Economic Performance*.

Finally, as future research, we will seek to provide full explanation for explained variance of latent variables, since R^2 obtained in this study did not reach the unit. To achieve this goal, we will analyse technological levels and updates of *ICT*, as well as the role of support and maintenance equipment in SC performance.

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Fuzzy Delphi and hybrid AH-MATEL integration for monitoring of paint utilization

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A B S T R A C T

This study investigates the unattended aspects of paint utilization selection criteria in industries. In today competitive business environment almost all companies focus towards sustainable manufacturing. The utilization evaluation and selection criteria for paint and its consumption reduction is the top priority for industry. Especially in automotive industries, paint shop stands as a centre for hazardous waste due to wastage of paint and thinner during the painting process. This research work focuses on optimizing consumption of paint by finding most important criteria affecting paint consumption and optimizing the same to achieve maximum paint yield. The study uses the routes of Delphi technique in a fuzzy environment to find out the most important criteria for paint utilization selection, so that maximize utilization and minimize consumption reduction of paint has been achieved. An integrated approach of AHP and DEMATEL methods has been implemented to prioritize the criteria and to familiarize the relationship within criteria. The outcomes of the study substantiate and prove that this study is the best way to select particular paint utilization selection criteria for the paint shop and also to anticipate the optimal level of paint utilization.

A R T I C L E I N F O

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1. Introduction

In this modern era, intense competition and globalization are the main approaching criteria for many organizations. Every industry aims to provide best services to the customers by providing after sales service, warranty, repair services besides selling the product. The first and foremost characteristic which attracts the customer is the appearance of a vehicle. This appearance of vehicles comes from the design, finishing, paint, etc. Out of which, painting process plays a centre role in providing not only good appearance to vehicles but also prevents corrosion. That's why all the companies prioritize the painting process in assembly. As the painting process involves in investing more money, it is necessary to understand and investigate the suitability of paints on vehicles. Painting process also requires the use of costly and harmful chemicals and other resources and to enhance the profitability, the consumption of paint has to be reduced. Therefore, the selection of a particular paint supplier needs a lot of scrutinizes, and there are many factors which should be considered before selecting one. This study is an attempt to understand experts' views in the evaluation of paint utilization selection criteria so that they can use their supplier accordingly and how it can help in paint consumption reduction.

Many researchers across the globe explored various multi criteria decision making (MCDM) approaches in manufacturing [6], for supplier selection [11], supply chain [10], transportation and logistics [13]. However, no attempt has been found in selecting paint utilization criteria. After scrutinizing the available literature and identifying the gaps, objectives have been set. The primary objective of this study work is to investigate the main criteria points for paint utilization criteria consumption in a manufacturing plant, prioritizing criteria and establish an interrelationship in assembly and targeting paint suppliers accordingly. To achieve the objectives of the study, three MCDM techniques have been used. Out of these, the first one is Delphi in a fuzzy environment has been used to capture the ambiguity of the expert opinion during criteria selection; secondly, Analytical Hierarchy process (AHP) has been put into use to assist in quantifying relative priorities for the given set of evaluation criteria. Thirdly for confirmation and as a final check of interrelation among the criteria, DEMATEL method was later put into use.

The rest of the study has been organized in different parts. In the first part, introduction to the study has been given followed by the required basic preliminaries. The procedure for finalizing criteria for best paint utilization criteria has been given in the third part. Prioritizing of criteria and construction of a network relationship map has been discussed in the fourth part. Discussion and concluding remarks have been given in discussion and conclusion parts.

2. Preliminaries

2.1 Fuzzy sets

The some important definitions of fuzzy sets which we employed in this study are given below:

Def. 1. A fuzzy set $\tilde{A}$ is a subset of the universal set X, with mapping $\mu_{\tilde{A}} : X \rightarrow [0,1]$, where For the fuzzy set $\tilde{A}$ the function value of $\mu_{\tilde{A}}\ (x)$ is called the 'membership value' of x in $\tilde{A}$ representing the degree of truth that x is an element of the fuzzy set $\tilde{A}$.

Def. 2. the triangular fuzzy number (TFN) of fuzzy set defines as follows.

$$\mu_{\tilde{N}}(x) = \begin{cases} 0, & x < l, \\ (x-l)/(m-l), & l \leq x \leq m, \\ (r-x)/(r-m) & m \leq x \leq r, \\ 0, & x > r, \end{cases}$$ which can be denoted as a triplet (l, m, r).

2.2 Fuzzy Delphi method

This section describes the procedure of fuzzy Delphi technique using triangular fuzzy number to capture experts' opinions by using Eq. 1.

$$\widetilde{W}_k = (l_k, m_{k,}, r_k) \tag{1}$$

$\tilde{W}_k$ represents the fuzzy number for the criteria k. l_k, m_k, and r_k can be represented as the minimum, average, and maximum number of experts opinions. The center-of-gravity method is used to calculate the value of S_k by using Eq. 2.

$$S_k = (l_k + m_k + r_k)/3 \tag{2}$$

The principles for final selection of the criteria as follows: (1) If $S_k \geq \lambda$ accept criterion k; (2) If $S_k < \lambda$ omit criterion k.

Once the paint selection criteria is selected, the evaluation of each criteria against others criteria is done by experts for this AHP is employed and further to find the interrelationship, DEMETAL is utilized. In the earlier studies, AHP method has been used to find weight of criteria and all criteria are considered independent and is not considered to find cause-effect relationship within the criteria and DEMATEL method has been used for not only capturing the importance but also reveals the cause-effect relation within criteria [3, 7, 19]. A brief description of both the methods is described below.

2.3 Analytical hierarchy process (AHP) method

AHP is power full tool for handling multi-criteria factors in decision making, developed by Saaty [20]. If there are n criteria through then $n\times(n-1)/2$ mutually comparisons can do with help of this method. 1-9 point scale is used to obtain expert's preferences about the selected criteria. A pairwise comparisons is formed as a matrix shows in Eq. 3.

$$\mathrm{A} = (a_{ij}) = \begin{bmatrix} a_{11} & a_{12} & . & . & . & a_{1n} \\ a_{21} & a_{22} & . & . & . & a_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a_{n1} & a_{21} & . & . & . & a_{nn} \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & . & . & . & a_{1n} \\ 1/a_{12} & a_{22} & . & . & . & a_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & a_{n-1n} \\ 1/a_{1n} & 1/a_{2n} & . & . & 1/a_{n-1n} & 1 \end{bmatrix} \quad (3)$$

a_{ij} is preference comparison the criterion i with criterion j.

Eigenvalues and eigenvectors with Eq. 4, are used to calculate the relative weights of the criteria.

$$Aw = \lambda_{max} w \quad (4)$$

Here eigenvector and largest eigenvalue of matrix A, are represented by w and λ_{max}. With the help of Eq. 5 and Eq. 6, the reliability of the judgments of experts has been checked.

$$\text{Consistency Index } (CI) = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

$$\text{Consistency Ratio } (CR) = \frac{CI}{RI} \quad (6)$$

RI represents Random Index and n criteria. The value of RI against the number of criteria is given in Table 1.

If $CI \leq 0.1$, it shows the consistency of the pairwise matrix and can proceed to calculate final weight of the criteria, otherwise, matrix has to be revised.

Table 1 Random index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.45

2.4 Decision making trial and evaluation laboratory (DEMATEL) method

For better understanding and examining the dependent criteria for an INRM ((Influential Network Relationship Map), DEMATEL technique is generally put into use [8]. Cause computation and each constituent requires proper utilization of the matrix, the structural model and the related mathematical theories in the DEMATEL and thus complex problems are solved easily [18]. Complex and intertwined problem groups are easily solved by the DEMATEL [17]. DEMATEL is generally applied to get a better view of the specific problem and catalyse to the detection of feasible solutions by which we can find out the interdependence between the elements of a system with the help of a casual diagram. The casual diagram portrays the interdependence between the elements within a system. The causal diagrams show contextual relationships rather than graphs without direction and also the strengths of the influence between the elements. The different mathematical steps for DEMATEL as follows:

Step 1: Experts have been asked to rate the relationship among the criteria with the scale of 0-5, 0-no effect and 5-high effect. The average of experts' opinion has been calculated by Eq. 7.

$$A = [a_{ij}] = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^{k} \quad (7)$$

Step 2: The matrix normalization has been achieved by Eq. 8.

$$F = m \times A, \tag{8}$$

where,

$$m = \min \left[\frac{1}{max_i \sum_{i=1}^{n} a_{ij}}, \frac{1}{max_j \sum_{j=1}^{n} a_{ij}} \right], i, j \in \{1, 2, \ldots, n\} \tag{9}$$

Step 3: Eqs. 10-11 have been utilized to estimate total relation matrix *T*.

$$T = \lim_{m \to \infty} (F^1 + F^2 + \cdots + F^m) = \sum_{m=1}^{\infty} F^i \tag{10}$$

where,

$$\begin{aligned} \sum_{m=1}^{\infty} F^i &= F^1 + F^2 + \cdots + F^m \\ &= F(I + F^1 + F^2 \ldots + F^{m-1}) \\ &= F(I - F)^{-1}(I - F)(I + F^1 + F^2 \ldots + F^{m-1}) \\ &= F(I - F)^{-1}(1 - F)^m \\ T &= F(I - F)^{-1} \end{aligned} \tag{11}$$

After identifying matrix *T*, *r* and *c* with help of Eq. 12 and Eq. 13 are calculated.

$$r = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij} \right]_{n\times 1} \tag{12}$$

$$c = [c_i]_{1\times n} = \left[\sum_{i=1}^{n} t_{ij} \right]_{1\times n} \tag{13}$$

Step 4: Eq. 14 had been used to calculate the threshold value (α) and avoid minor effects.

$$\alpha = \sum_{i=1}^{n} \sum_{j=1}^{n} [t_{ij}] / N \tag{14}$$

where, *N* elements in the matrix *T*.

3. Paint utilization selection criteria

The fuzzy Delphi technique creates better criteria solutions [2, 5, 14] and used to finalize for paint utilization selection criteria. This concept has been implemented to measure the importance of the criteria by using linguistic scales in the form of TFN [9, 16] as mentioned in Table 2.

Table 2 The linguistic scales

Linguistic scales	Extremely important			Important			Normal			Unimportant			Extremely unimportant		
TFN	0.7	0.9	0.9	0.5	0.7	0.9	0.3	0.5	0.7	0.1	0.3	0.5	0.1	0.1	0.3

Table 3 Best paint utilization selection criteria

Criteria	S
Transfer Efficiency (C_1)	0.72201
Solid Content of Paint (C_2)	0.67320
Conductivity of Paint (C_3)	0.65402
Hiding Power (C_4)	0.72041
Technical Support (C_5)	0.62430
Paint Workability (C_6)	0.69831
Thinner Intake (C_7)	0.76343
Supply Viscosity (C_8)	0.65340

After using this method, the important criterion is generally shifted from the evaluation result and the shifting threshold value effects the number of criteria. This study adopts a threshold value of 0.6. 12 production managers from paint assembly automotive have been interview about paint utilization selection criteria and after using Eq. 1 and Eq. 2, and principles selection criteria are shown in Table 3.

Both qualitative and quantitative criteria are considered in evaluation and selection of the best paint utilization criteria and a brief description of each criterion as follows.

3.1 Transfer efficiency

Transfer efficiency of a painting process is the comparison of amount of paint deposited on component to the amount of total paint sprayed through the painting gun. This is commonly described as the % of weight of solids sprayed to the weight of solids increased by the component. As an illustration, 70 % transfer efficiency means that 50 % of the weight of the solids in the material that was sprayed actually touched the component and the remaining 30 % was lost during the spray finishing process. With help of formula below, we can calculate transfer efficiency easily.

$$\text{Transfer efficiency} = \frac{\text{Actual paint deposited on component}}{\text{Total paint sprayed on component}}$$

Transfer efficiency of a painting system plays major role to optimize paint consumption, as we can't achieve paint consumption beyond the transfer efficiency of the painting system by all means.

3.2 Solid content of paint

A conventional paint is a mixture of resins, solvents, pigments and additives. When a paint is applied over a surface of any solid portion, a dry or solid portion is left over when the paint is completely dried. The volume of the paint that is left over is represented in terms of volume solid. The volume solid of a coat is the ratio of the volume of non-volatile components to its total wet volume. The figure is generally articulated as percentage. Awareness of Volume Solids provides many benefits: 1) It helps to compare and understand the true cost of different paints, 2) It helps to determine and predict how much paint is actually required to be applied to obtain adequate coverage, and 3) It helps to control the actual quality of the painting.

3.3 Thinner intake of paint

Thinner intake of paint is the thinner volume essential to achieve desired viscosity from supplied viscosity. Paint is transported from manufacturing plants to automotive paint shop in with a viscosity ranging from 0.14-0.21 Pa·S but paint cannot be applied on parts with the supplied viscosity by any paint applicator whether it is manual painting or electrostatic spraying. For ease of paint application, viscosity is required in the range of 0.03-0.05 Pa·S depending on the paint and application technique and to reduce the viscosity of paint thinner is added.

$$\text{Thinner intake (\%)} = \frac{\text{Volume of thinner added (L)}}{\text{Volume of raw paint (L)}}$$

3.4 Paint conductivity

Paint Conductivity is the measure of charge carrying capacity of paint, it plays major role in electrostatic painting application where painting is achieved due to potential difference between paint and substrate. Electrostatic painting is based on Coulomb's Law i.e. oppositely charged particle attracts each other. In electrostatic painting, paint is given negative charge and substrate is earthed through conveyor. Paint conductivity is measured by resistivity of paint, which is opposite of paint conductivity. An optimum value of paint conductivity is required to achieve maximum transfer efficiency of an electrostatic painting system.

$$\text{Paint conductivity} = 1/\text{Paint resistivity}$$

3.5 Hiding power of paint

Hiding power of paint is actually the capability of a particular coating to hide the surface on which coating is used. The thumping power is directly linked to the method by which the film is actually applied and also the film thickness. The hiding power of the coating is influenced by the pigments in the binder media. A coating with strong hiding power develops the pigment particles scatter the light so strongly that they hardly reach the substrate. Thus, hiding power is selected as an important parameter for selecting a paint.

3.6 Supply viscosity

Viscosity is described as the internal resistance of a fluid to flow and may be considered as a measure of fluid friction. In paint manufacturing and application industry, the very first information available about paint is its viscosity. Paint supplier supplies paint in a relatively high viscous condition.

3.7 Technical support

In an automotive paint shop, the process of painting is carried out inside a spraying chamber. This spraying chamber is an effective pressurized enclosed environment, which is generally used to paint parts of a vehicle loaded in a well-designed hangers fixed on a moving conveyer. For maintaining efficient working conditions, the spray booths are equipped with air supply units, air exhaust blowers, LNG heating system and continuous waster scrubber. During the painting process a lot of these parameters are generally required to be optimized by the paint shop in charge or the engineer, on the other hand some parameters related to paint are optimized by the technical support staff of the concerned paint supplier during the painting process.

3.8 Paint workability

Paint workability is defined as the ability of paint to spread over the surface and provide uniform thin layer of paint after baking.

4. Prioritization and network relationship map (NRM)

To get the weight of criteria, AHP is used and data has been synthesized in excel and then analysed. Let $C = \{C_j | j= 1, 2,..., n\}$ is the decision criteria set. The data of the available pair wise comparison of n criteria can actually be summarized into an (n x n) evaluation matrix named A in which each element a_{ij} ($i, j = 1, 2, ...,n$) is of weights of the criteria. We would have (n x n) matrixes for every expert, then the geometric mean of all the matrixes was taken to form a geometric mean matrix [4]. The geometric mean has been taken as more ratio properties are involved [1].

$$G_{ij} = \left[\prod_{i=1}^{n} x_{ij}\right]^{\frac{1}{n}} \quad \forall\, i,j \tag{15}$$

By using Eq. 15, matrix shown in Table 4 has been formed by averaging all the corresponding ranking of each pairwise comparison of all experts/respondents.

Table 4 Average matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
C_1	1.00	0.33	3.00	5.00	5.00	3.00	3.00	5.00
C_2	3.00	1.00	3.00	5.00	3.00	3.00	5.00	5.00
C_3	0.33	0.33	1.00	3.00	3.00	3.00	5.00	7.00
C_4	0.20	0.20	0.33	1.00	1.00	3.00	3.00	5.00
C_5	0.20	0.33	0.33	1.00	1.00	0.33	1.00	3.00
C_6	0.33	0.33	0.33	0.33	3.00	1.00	3.00	5.00
C_7	0.33	0.20	0.20	0.33	1.00	0.33	1.00	1.00
C_8	0.20	0.20	0.14	0.20	0.33	0.20	1.00	1.00

For normalization matrix shown in Table 5, is obtained by dividing column by the sum of the corresponding column. As a process of cross verification sum of each column is checked if it was 1 or not and the same has been confirmed.

Table 5 Normalization matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
C_1	0.34	0.11	0.36	0.32	0.29	0.22	0.14	0.16
C_2	0.54	0.18	0.36	0.32	0.17	0.22	0.23	0.16
C_3	0.11	0.06	0.12	0.19	0.17	0.22	0.23	0.22
C_4	0.07	0.04	0.04	0.06	0.06	0.22	0.14	0.16
C_5	0.07	0.06	0.04	0.06	0.06	0.02	0.05	0.09
C_6	0.11	0.06	0.04	0.02	0.17	0.07	0.14	0.16
C_7	0.11	0.04	0.02	0.02	0.06	0.02	0.05	0.03
C_8	0.07	0.04	0.02	0.01	0.02	0.01	0.05	0.03

The average of each row has been taken to find the weight, by doing this the individual weightage of each criteria and rank has been derived and is shown in Table 6. The degree of consistency (CI) and consistency ratio (CR) has been calculated by routes given by Saaty [20] with Eq. 5 and Eq. 6. The CR value obtained is less than 0.1 and it substantiates the acceptability of matrix M.

Table 6 Weightage

Criteria	Weightage	Percentage (%)	Rank
Transfer Efficiency (C_1)	0.221	22.1	2
Solid Content of Paint (C_2)	0.291	29.1	1
Conductivity of Paint (C_3)	0.165	16.5	3
Hiding Power (C_4)	0.097	09.7	4
Technical Support (C_5)	0.059	05.9	6
Paint Workability (C_6)	0.096	09.6	5
Thinner Intake (C_7)	0.041	04.1	7
Supply Viscosity (C_8)	0.030	03.0	8

To check the interdependent among selected criteria, DEMATEL technique has been utilized. Firstly, the average matrix A is constructed by Eq. 7 as displayed in Table 7. The normalized influence matrix is calculated by Eq. 8 and Eq. 11 the total influence matrix T. In last the NRM is constructed by Eq. 12 and Eq. 13 as displayed in Fig.1.

According to step 2, by using Eq. 8 and Eq. 9, we got m is 0.053 and the nominalization matrix F as follows

Table 7 Average matrix

A =

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	Sum
C_1	0.000	3.000	3.833	2.000	1.000	1.000	2.083	0.083	13.000
C_2	1.000	0.000	1.750	3.000	1.000	2.000	3.000	2.000	13.750
C_3	1.917	2.000	0.000	2.000	1.000	2.667	2.917	2.000	14.500
C_4	2.917	3.000	2.000	0.000	2.000	2.833	2.000	2.000	16.750
C_5	1.000	1.000	1.000	2.000	0.000	2.000	1.000	2.000	10.000
C_6	2.000	2.917	2.917	1.000	1.000	0.000	1.000	2.000	12.833
C_7	2.000	3.000	2.083	2.000	2.917	3.000	0.000	3.833	18.833
C_8	1.000	2.917	2.000	1.000	1.000	2.000	3.917	0.000	13.833
Sum	11.83	17.83	15.58	13.00	9.917	15.50	15.917	13.917	--------

$$F = \begin{bmatrix} 0.000 & 0.159 & 0.204 & 0.106 & 0.053 & 0.053 & 0.111 & 0.004 \\ 0.053 & 0.000 & 0.093 & 0.159 & 0.053 & 0.106 & 0.159 & 0.106 \\ 0.102 & 0.106 & 0.000 & 0.106 & 0.053 & 0.142 & 0.155 & 0.106 \\ 0.155 & 0.159 & 0.106 & 0.000 & 0.106 & 0.150 & 0.106 & 0.106 \\ 0.053 & 0.053 & 0.053 & 0.106 & 0.000 & 0.106 & 0.053 & 0.106 \\ 0.106 & 0.155 & 0.155 & 0.053 & 0.053 & 0.000 & 0.053 & 0.106 \\ 0.106 & 0.159 & 0.111 & 0.106 & 0.155 & 0.159 & 0.000 & 0.204 \\ 0.053 & 0.155 & 0.106 & 0.053 & 0.053 & 0.106 & 0.208 & 0.000 \end{bmatrix}$$

According to step 3, by using Eq. 11 matrix T is calculated and given as follows

$$T = \begin{bmatrix} 0.250 & \mathbf{0.499} & \mathbf{0.493} & 0.373 & 0.262 & 0.374 & \mathbf{0.431} & 0.306 \\ 0.319 & 0.389 & \mathbf{0.421} & \mathbf{0.427} & 0.280 & \mathbf{0.441} & \mathbf{0.492} & \mathbf{0.416} \\ 0.367 & \mathbf{0.498} & 0.352 & 0.393 & 0.284 & \mathbf{0.477} & \mathbf{0.499} & \mathbf{0.422} \\ \mathbf{0.437} & \mathbf{0.581} & \mathbf{0.486} & 0.332 & 0.349 & \mathbf{0.518} & \mathbf{0.497} & \mathbf{0.450} \\ 0.240 & 0.329 & 0.293 & 0.299 & 0.159 & 0.339 & 0.302 & 0.319 \\ 0.331 & \mathbf{0.483} & \mathbf{0.442} & 0.314 & 0.247 & 0.304 & 0.375 & 0.374 \\ \mathbf{0.424} & \mathbf{0.626} & \mathbf{0.524} & \mathbf{0.459} & \mathbf{0.417} & \mathbf{0.568} & \mathbf{0.448} & \mathbf{0.572} \\ 0.314 & \mathbf{0.524} & \mathbf{0.432} & 0.343 & 0.281 & \mathbf{0.441} & \mathbf{0.535} & 0.325 \end{bmatrix}$$

Bold component of matrix are > α.

Using Eq. 6 to Eq. 7, Table 8 is found out.

Table 8 Cause and effect

Crietria	r_i	c_j	$r_i + c_j$	$r_i - c_j$	**Impact**
Transfer Efficiency (C_1)	2.989	2.681	5.671	0.308	Cause
Solid Content of Paint (C_2)	3.185	3.929	7.114	-0.744	Effect
Conductivity of Paint (C_3)	3.292	3.442	6.735	-0.149	Effect
Hiding Power (C_4)	3.651	2.942	6.593	0.709	Cause
Technical Support (C_5)	2.280	2.280	4.560	-0.001	Effect
Paint Workability (C_6)	2.871	3.463	6.334	-0.593	Effect
Thinner Intake (C_7)	4.038	3.580	7.618	0.457	Cause
Supply Viscosity (C_8)	3.196	3.185	6.380	0.011	Cause

A threshold value has been set up to obtain the Network Relation Map (Fig.1). The threshold value (α) has been computed by Eq. 14 and that threshold value is also used to remove some minor effects elements in matrix T.

In matrix T the values of t_{ij} have been calculated, if element of matrix T greater than threshold value α (0.398) that element shown in bold in matrix T e.g. the value of $t_{12}(0.499) > \alpha$ (0.398), the arrow in the digraph is drained from C_1 to C_2. The network relationship map for all the eight criteria is built as depicted in Fig. 1.

$$\alpha = \sum_{i=1}^{n}\sum_{j=1}^{n}[t_{ij}]/N \quad = 25.50/64 = 0.398$$

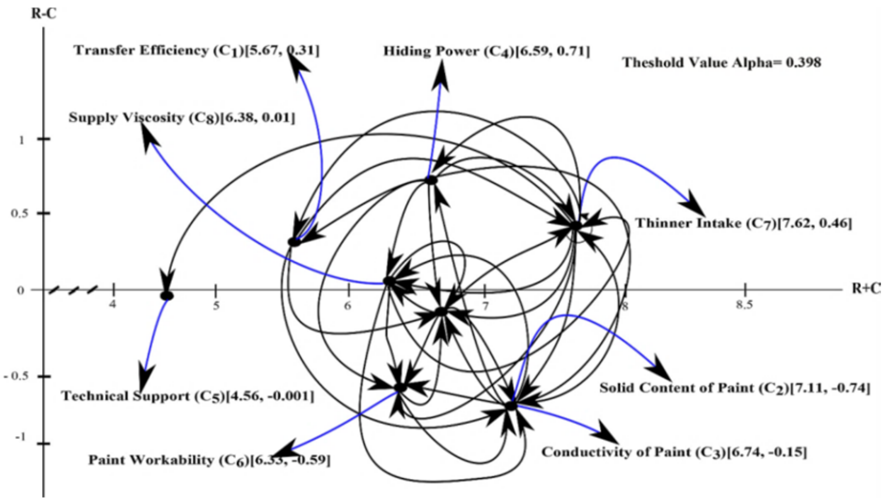

Fig.1 Network relation map (NRM) within criteria

5. Discussion

It is well known acceptable fact that all the components of paints are required, but all of them don't have the same priority. In many cases, decisions are made upon giving crisp values, but all these crisp values are not such an accurate reflection of what is exactly happening in the real world. The need for fuzzy set theory arose from the fact that human judgments about preferences are always unclear and are hard to estimate from numerical values. To handle such situations which are complex and uncertain Delphi method was first applied in the fuzzy environment to finalize the selection criteria of paint selection. AHP was used to prioritize and from the results derived from AHP. DEMATEL technique has been employed to find out the interrelationship relationship between criteria and to identify the interrelationship within the criteria. AHP analysis shows that the criteria solid content of paint has the first rank with the weightage value of 29.1 followed by transfer efficiency, conductivity of paint with the weightage value of 22.1 and 16.5. Hiding power (9.7), paint workability (9.6), technical support (5.9), thinner intake (4.1), and supply viscosity (0.3) are contained the rank four to eight. The oval prioritization of criteria is as $C_2 > C_1 > C_3 > C_4 > C_6 > C_5 > C_7 > C_8$.

On the basis of (r-c) values all eight criteria have been divided into two group, i.e., (i) cause group and (ii) effect group.

(i) Those criteria has (r-c) has positive value, there are in net cause group and affect the rest criteria, high value shows major impact. The criteria: Transfer Efficiency (C_1), Hiding Power (C_4), Thinner Intake (C_7), and Supply Viscosity (C_8) are in this group and having 0.3088, 0.7098, 0.4573 and 0.0110 values. The analysis shows that Hiding Power (C_4) is the most critical criteria on the others followed by Thinner Intake (C_7), Transfer Efficiency (C_1), and Supply Viscosity (C_8). The analysis shows that mutual interaction between Transfer Efficiency (C_1) and Thinner Intake (C_7) has also the mutual interaction with t_{17}(0.4313) and t_{71}(2.2757), t_{17}(0.4242) values and all are greater than α (0.3985).

(ii) If (r-c) has negative value, say it is net receive and all net receive criteria. The current study, Solid Content of Paint (C_2), Conductivity of Paint (C_3), Technical Support (C_5), and Paint Workability (C_6) are categorized in the effect group, with the (r-c) values of -0.7442, -0.1499, -0.0001 and -0.5925. The criteria Thinner Intake (C_7) is impacting all other criteria followed by Hiding Power (C_4), Supply Viscosity (C_8), and Transfer Efficiency (C_1).

6. Conclusion

Paint suppliers optimization and choosing them is a major challenge for any automobile industry. It is important because they have to sustain themselves in the competitive environment and to do that they are always on a look out to upgrade their selection criteria of paint suppliers so that they can achieve their maximum utilization of paint that they usually consume. It has been observed that solid content of paint is the most important criteria and supply viscosity of Paint is the least important dimension for the paint supplier selection. The outcomes of DEMATEL results validates that the thinner intake is the most influential and has the strongest connection to other criteria. The criteria Transfer Efficiency is at rank two with weight 22.1 %, and comes in cause group, which has a direct effect on the criteria i.e. Solid Content of paint, Conductivity of Paint, and Thinner Intake, this the most suggested criteria according analysis of the study for paint supplier selection. The criteria Hiding Power ranks four with weightage 9.7 % and has a direct relationship with Transfer Efficiency, Solid Content of paint, Conductivity of Paint, Paint Workability, Thinner Intake, and Supply Viscosity. Thinner Intake is also in cause group and directly affected by all the other criteria Transfer Efficiency, Solid Content of paint, Conductivity of Paint, Hiding Power, Technical Support, Paint Workability, Thinner Intake, Supply Viscosity. The last criteria, which comes in cause group is Supply Viscosity and affected to Solid Content of paint, Conductivity of Paint, Hiding Power , Paint Workability, Thinner Intake.

The current work is having a great future scope and more detailed investigations of criteria's that effects the utilization of paint consumption and its selection criteria. Further artificial intelligence techniques could be employed to optimize the various paint utilization criteria.

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Reconsidering production coordination: A principal-agent theory-based analysis

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A B S T R A C T

Production coordination is a common phenomenon in supply chains. Unlike the existing literature, we examine the production coordination problem from the perspective of asymmetric information: how a manufacturer (leading firm) coordinates the relationships with its subsidiary firm(s) and, subsequently, how market returns influence the leading firm's expected utilities, agency cost and the subsidiary firm's expected incomes. We develop an incentive contract model with asymmetric information based on principal-agent theory. Comparative analysis and simulations are conducted to test the model. Results show that the leading firm's expected utilities and agency cost and the subsidiary firm's expected incomes are significantly affected by the subsidiary firm's capability, cost coefficient, absolute risk aversion factor and output variance (common factors); sharp differences among the leading firm's expected utilities and agency cost and the subsidiary firm's expected incomes were found due to different market returns. Thus, the proposed approach (incentive contract model) can help leading firms apply incentives to optimize production modes to obtain production coordination while considering common factors; market returns differences are included in the new model, in contrast to previous approaches.

A R T I C L E I N F O

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1. Introduction

Production coordination is related to demand, inventory status, production plan, production time, promotion plan, demand forecast and sharing transportation routes (Lee, 2000) [1]. With the development of the supply chain, production coordination will become increasingly complex, and production activities of the supply chain cannot be achieved until bodies of resources (the principal: leading firm, and agent: subsidiary firm) are motivated. Therefore, the problem of production coordination urgently needs to be solved. An optimizing algorithm and tools have been developed to solve the production coordination problem; for example, Matičević, et al. (2007) used the theory of ERP (enterprise resource planning) to achieve internal supply chain coordination for production[2]; Gong, et al. (2015) created a mathematical model and performed a simulation for the resource sharing model's impact on supply chain efficiency[3]; Galić, et al. (2016) put forward multiple criteria solver (MCS) optimizations to solve an asphalt supply chain problem, and simulation results justified that the proposed model can eliminate the lack of an original model [4].

Incentive theory is an important way to solve the production coordination problem. With the background of the global manufacturing network, Jiao, You and Kumar (2006) established an agent-based (leading firms and subsidiary firms involved in production coordination) and contracted-based (market demand) model, which is a useful method to address the production coordination problem[5]. Sahay (2003) believed that the mechanism design was important for the production coordination, and the sharing of information, risk and revenue was essential [6]. With the help of cooperative game theory, Nagarajan and Sosˇic´(2008) analyzed the integration problem of production coordination and proposed the theory of 'vision', which provided a new mode of production coordination[7]. Brintrup (2008) established an agent-based, target-based and role-based model to select suppliers to reduce transaction time and increase corporate revenue[8]. In order to meet customers' needs, Akanle and Zhang (2008) proposed optimizing the configuration for production coordination, so they built an agent-based model to coordinate bidding and obtained the optimum based on a genetic algorithm[9]. Yi, et al. (2016) combined put options and selective returns in a proposed contract model and constructed a two-echelon supply chain to analyze risk coordination in supply chains[10]. By applying bargaining theory, Saha, et al. (2014) found that inventory-level and retail-price-dependent demand can play an important role in supply chain coordination contracts[11]. Xu, et al. (2015) analyzed consumer return behavior's effect on buy-back contracts in order to coordinate a robust supply chain[12].

To some extent, the focus of production coordination is principal-agent. In production coordination, principal-agent theory can be developed to cope with the contract relations problem. Principal-agent theory is derived from rational choice model, in which the principal's initial actions are available for agent(s) as incentives to help them make decisions that the principal prefers. Principal-agent theory focuses on the responsive decisions of the agents to to the principal's goal and on how the responsive decisions can be mediated by their actions. In order to operate an effective production coordination network, the leading firm should conduct a comprehensive analysis of actors' (agents') decisions (Compte and Jehiel, 2008) [13]. For the analysis of principal-agent problems in the production coordination network, we focus on the understanding of different roles and their power positions (Kulp, 2002) [14]. In the view of adaptive contract design, Ho, et al. (2016) considered Bandit algorithms to solve repeated principal-agent problems in crowd-sourcing markets[15]. When there exists asymmetric information between the principal and agent, the agent must try its best to achieve his own maximum benefit. With asymmetric information, a distinct strategy should be determined due to the agent's hidden intentions. Consequently, adverse selection and moral hazard arise (Herwig and Sascha, 2011) [16]. Therefore, there is a need to formulate proper conduct regulations for production coordination in business activities (Keser and Willinger, 2007) [17]. Rubin, et al. (2016) focused on the principal–agent algorithm itself, and the results of a gift-exchange experiment showed that the introduction of shocks can significantly reduce the likelihood that the agent will fulfill the contract[18].

To sum up, existing literatures focus mainly on resource configuration, production management, the trust mechanism and the agent model, and the full qualitative descriptions of the principal-agent problem (Herwig and Sascha, 2011) [16]. A wide spectrum of goals, such as wages and premiums, are used as the utility function of the principal and agents (Mukherji et al., 2007) [19]. However, there is a gap in the literature related to production coordination and market returns' effect, that is, in asymmetric information, how a manufacturer (leading firm) coordinates the relationships with its subsidiary firm(s) and, subsequently, how market returns influence the leading firm's expected utilities and agency cost and the subsidiary firm's expected incomes.

In this paper, based on principal-agent theory, the incentive contract model is constructed in the context of asymmetric information. Additionally, a comparative analysis and simulations are carried out for the leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost. Thus, this chapter is organized as follows: we first conduct a comprehensive review that forms the theoretical foundation of this study. Section 2 discusses applications of principal-agent models to production coordination. Section 3 discusses solutions of principal-agent models for production coordination. Section 4 presents the simulations. Section 5 concludes.

2. Principal-agent model of production coordination

2.1 The factors related to the model

The principal-agent theory focuses on the rational choice model in which the agent has several tasks to fulfill for the principal. In order to fulfill the tasks, the agent has free access to several means and tools. However, the principal expects the agent to make decisions that the principal prefers. Inevitably, objective conflicts between the principal and agent often arise, and both of them want their maximum benefit; in particular, opportunistic practices of deceit and fraud are possible. Mechanism design is effective way of tackling the principal-agent problem by looking for the common factors related to both the principal and the agent in the context of asymmetric information (Lal and Srinivasan, 1993) [20]. The factors related to both actors consist of the leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost. In this paper, one leading firm is assumed (the principal), and one subsidiary firm is assumed (the agent).

(1) The leading firm's expected utilities

The leading firm provides products or services to its departments, the subsidiary firm is responsible for the provision of products or services, and the total utilities that the product or service brings about will be owned by the leading firm. In order to stimulate the subsidiary firm, the leading firm needs to pay for the subsidiary firm, which is called remuneration. Therefore, the leading firm's utilities are obtained by deducting from the total utilities. The leading firm is risk neutral, and its utilities can be made by market sales (considering the service price only) or profits (considering the service cost and service price), but the market profit method is more scientific.

(2) The subsidiary firm's expected incomes

The subsidiary firm can obtain incomes by gaining market share or other ways; at the same time, it must pay a certain cost, including economic cost and risk cost, so the subsidiary firm is risk averse, and it will not make enough efforts to conduct innovation due to the structure of income; thus, it is not conducive to the leading firm's utilities.

(3) The leading firm's agency cost

The subsidiary firm possesses private information, and it will avoid making efforts. Therefore, the leading firm needs to monitor the subsidiary firm, thus guaranteeing that the subsidiary firm makes as much effort as possible to increase the utilities of its products or services. However, the monitoring will inevitably increase the leading firm's agency cost, which includes the risk cost and the incentive cost (referring to the different utilities that the subsidiary firm brings about in the context of symmetric information and asymmetric information).

In the production coordination process, the leading firm wants to increase its own utilities and decrease its agency cost, and the subsidiary firm tries its best to avoid working but wants to gain market share. The goal of cooperative production is to look for the common factors related to the leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost. Based on common factors, the leading firm creates industry policy to realize cooperative production (Fig. 1).

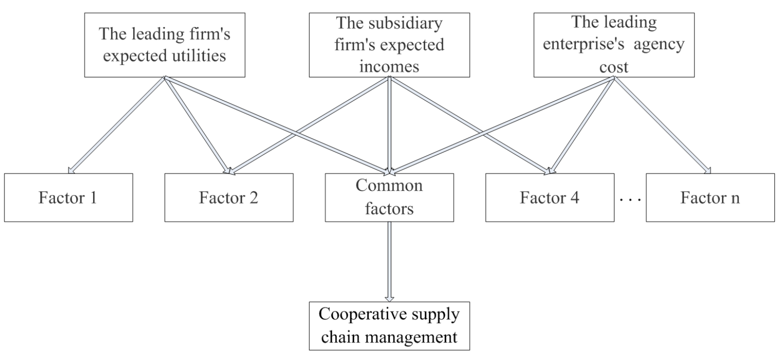

Fig. 1 The common factors

In Fig. 1, many factors affect the leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost in production coordination. The common factors related to the leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost can be calculated based on a mechanism design.

2.2 The improved model

(1) Market returns model 1 (the price p and cost c are not considered)

The utilities U (that yield Q) are the market gains when the subsidiary firm provides products or services to the users with a certain level of effort, and U is subjected to the subsidiary firm's ability, market prosperity and market randomness. Therefore, $U = Af(e) + B + \theta$,where A is the subsidiary firm's ability ($A > 0$); e is the effort, $f(e)$is the function, and $f'(e) > 0$, which means that marginal yields are positive and that yields are positive with subsidiary firm ability; $f''(e) < 0$, which means that the rate of yields is decreasing; The constant B is market prosperity; θ is market randomness，and $\theta \sim N(0, \sigma^2)$($\sigma^2$is the output variance).

Theorem 1: The linear relation of the model is still reasonable when $f(e) = e$.

Proof: If $f(e) = e^{r1}$， where $0 < r1 < 1$，equation $f(e) = e^{r1}$ is consistent with the restrictions above. Supposing $E = e^{r1}$, so $U = AE + B + \theta$. Additionally, we can see the full linear relations in expression $e^{r1} \to E \to U$, so $U = Af(e) + B + \theta$ is simplified as $U = Ae + B + \theta$ when $f(e) = e$.

The subsidiary firm generates sales with a certain level of effort, so the leading firm needs to pay for the subsidiary firm's work $s(U) = \alpha + \beta U$,where α is the fixed income, β is the user's share gains.

Theorem 2: The subsidiary firm and the leading firm will obtain the same market gain share β when the gain in market share is normally distributed.

Proof: The leading firm wants β_f, while the subsidiary firm wants β_u ($\beta_f<\beta_u$), the third party could supposedly decide the reasonable market share gain β when knowing $\beta_f$and β_u. By differentiating $\beta_f$and β_u, we can obtain

$$F\left(\frac{\beta_f{}^* + \beta_U{}^*}{2}\right) = 1/2, \beta_U{}^* - \beta_f{}^* = 1/f\left(\frac{\beta_f{}^* + \beta_U{}^*}{2}\right) \tag{1}$$

And $\beta \sim N(\mu, \sigma^2)$, so

$$\frac{\beta_f{}^* + \beta_U{}^*}{2} = \mu, \beta_U{}^* - \beta_f{}^* = 1/\ f(\mu) = \sqrt{2\pi}\sigma \tag{2}$$

The optimum market share gain for the subsidiary firm and the leading firm will be

$$\beta_u{}^* = \mu + \sqrt{\frac{\pi}{2}}\sigma, \beta_f{}^* = \mu - \sqrt{\frac{\pi}{2}}\sigma \tag{3}$$

Finally, the subsidiary firm and the leading firm will gain the same market share μ ($\sigma = 0$). Therefore, the leading firm's expected utilities are

$$E(U - s(U)) = -\alpha + E(1-\beta)U = -\alpha + (1-\beta)(Ae + B) \tag{4}$$

The subsidiary firm's direct cost is $C(e)$ when providing products or services, and $C^{'}(e) > 0, C^{''}(e) \geq 0$. We set $C(e) = me^{r2}$， where $m > 0, r2 > 1$，and $E = e^{r1}$, so $C(e) = mE^{r3}$ ($r3 = r2/r1 > 1$). $C(e) = mE^{r2}$ is consistent with the restrictions above, so $C(e) = mE^{r3}$ can be simplified as $C(e) = be^2/2$ when $m = b/2, r3 = 2$, where b is the cost coefficient.

In addition, the subsidiary firm must pay the risk cost when participating in collaborative incentive contracts, and the subsidiary firm's certainty equivalent profits (I) can reflect its actual income. Set the utilities $u = -e^{rI}$ (exponential distribution) for the subsidiary firm, where r is the absolute risk aversion factor, and $r > 0, z \sim N(m, n^2)$. The subsidiary firm's expected utilities are

$$E(u)=\int_{-\infty}^{+\infty}-e^{-rz}\frac{1}{\sqrt{2\pi}n}e^{-\frac{(z-m)^2}{2n^2}}dz=-e^{-r(m-\frac{rn^2}{2})} \tag{5}$$

$E(u)=u(I)$, so $-e^{-r(m-\frac{rn^2}{2})}=-e^{r(I)}$, $I=m-\frac{rn^2}{2}$. $\theta\sim N(0,\sigma^2)$, so random variable $I_1=\alpha+\beta(Ae+B+\theta)-be^2/2$ obeys a normal distribution, and the subsidiary firm's expected profits are

$$EI_1=\alpha+\beta(Ae+B)-be^2/2 \tag{6}$$

The variance of the subsidiary firm's profits is $DI_1=\beta^2\sigma^2$, and in equation $I=m-\frac{rn^2}{2}$, m is the mean (EI_1), $n$is the variance(DI), so the subsidiary firm's certainty equivalent profits are

$$I=\alpha+\beta(Ae+B)-be^2/2-r\beta^2\sigma^2/2 \tag{7}$$

Where $r\beta^2\sigma^2/2$ is the risk cost. s is the lowest profit that the subsidiary firm requires, and the subsidiary firm will not participate in an incentive contract when the equivalent profit is less than s. Therefore, the prerequisite that the subsidiary firm participates in the incentive contract is

$$\alpha+\beta(Ae+B)-be^2/2-r\beta^2\sigma^2/2\geq s \tag{8}$$

Combined with our previous research [21], the production coordination model based on principal-agent theory is

$$E\big(U-s(U)\big)=\max\{-\alpha+(1-\beta)(Ae+B)\}$$
$$s.t.\begin{cases}\arg\max\{\alpha+\beta(Ae+B)-be^2/2-r\beta^2\sigma^2/2\}\\ \alpha+\beta(Ae+B)-be^2/2-r\beta^2\sigma^2/2\geq s\end{cases} \tag{9}$$

(2) Market returns model 2 (the price p and cost c are considered)

In model 1, the utilities U are calculated by yield Q; in this model, p is the price of products or services,$(p-c)Q$ is the user's returns, and therefore, leading firm utilities are

$$E(U)=E((p-c)Q-s(Q))=-\alpha+(1-\beta)(p-c)(Ae+B) \tag{10}$$

The subsidiary firm's certainty equivalent profits are

$$I=\alpha+\beta(p-c)(Ae+B)-be^2/2-r(p-c)^2\beta^2\sigma^2/2 \tag{11}$$

Additionally, the production coordination model based on principal-agent theory is

$$E\big(U-s(U)\big)=\max\{-\alpha+(1-\beta)(p-c)(Ae+B)\}$$
$$s.t.\begin{cases}\arg\max\{\alpha+\beta(p-c)(Ae+B)-be^2/2-r(p-c)^2\beta^2\sigma^2/2\}\\ \alpha+\beta(p-c)(Ae+B)-be^2/2-r(p-c)^2\beta^2\sigma^2/2\geq s\end{cases} \tag{12}$$

3. The solution for the production coordination model

3.1 Market returns model 1 (the price p and cost c are not considered)

(1) Symmetric information

The leading firm can monitor the subsidiary firm in the case of symmetric information, and the leading firm will not motivate subsidiary firm. At the same time, the leading firm must pay the least even if the subsidiary firm wants the most. Based on the game relations, the subsidiary firm will gain the least in the end (s). Therefore, the cooperative production coordination model including the leading firm and the subsidiary firm changes as follows:

$$E\big(U - s(U)\big) = \max\{-\alpha + (1-\beta)(Ae+B)\}$$
$$s.t.\ \ \alpha + \beta(Ae+B) - be^2/2 - r\beta^2\sigma^2/2 = s \tag{13}$$

The differentiation for e yields

$$\{\alpha + \beta(Ae+B) - be^2/2 - r\beta^2\sigma^2/2 - s\}' = 0 \tag{14}$$

So $e_1^* = \frac{A\beta}{b}$.In the case of symmetric information, market share gains β cannot change regardless of whether the subsidiary firm works hard or not, and the leading firm will not motivate the subsidiary firm to gain market share, and the subsidiary firm will obtain unchanged revenue in the end. So, $e_1^* \approx e^* = A/b$, β is neglected. Then, $\alpha_1^* \approx \alpha^* = s + A^2/2b$.

(2) Asymmetric information

In the case of asymmetric information, the subsidiary firm will try its best to increase s when (α, β) is given. Do differentiation for e,

$$\{\alpha + \beta(Ae+B) - be^2/2 - r\beta^2\sigma^2/2 - s\}' = 0 \tag{15}$$

so $e = A\beta/b$. Then, the leading firm takes actions to increase its expected utilities when observing e, that is,

$$E\big(U - s(U)\big) = \max\{-\alpha + (1-\beta)(Ae+B)\}$$
$$s.t. \begin{cases} \alpha + \beta(Ae+B) - be^2/2 - r\beta^2\sigma^2/2 = s \\ e = A\beta/b \end{cases} \tag{16}$$

The differentiation for β yields

$$\{-\alpha + (1-\beta)(Ae+B)\}' = 0 \tag{17}$$

so,

$$\beta_1 = (A^2 - Bb)/2A^2 \tag{18}$$

Actually, a rational subsidiary firm will obtain s at most, that is,

$$\alpha + \beta(Ae+B) - be^2/2 - r\beta^2\sigma^2/2 = s \tag{19}$$

Both the subsidiary firm and the leading firm will determine β, and market share gain β is known by the leading firm and the subsidiary firm. The differentiation for β yields

$$\{\alpha + \beta(Ae+B) - be^2/2 - r\beta^2\sigma^2/2\}' = 0 \tag{20}$$

so,

$$\beta_2 = Bb/(rb\sigma^2 - A^2) \tag{21}$$

And $\beta_1 = \beta_2$, $B = (A^2 - 2A^2\beta_1)/b$, therefore,

$$\beta = 1/(1 + rb\sigma^2/A^2) \tag{22}$$

$$\alpha = s + be^2/2 + r\beta^2\sigma^2/2 - \beta(Ae+B) \tag{23}$$

$$e = A\beta/b \tag{24}$$

And $s(U) = s + be^2/2 + r\beta^2\sigma^2/2$. Eventually, the leading firm's expected utilities (α, β are known) are

$$E\big(U - s(U)\big) = B - s + A^2/2b(1 + rb\sigma^2/A^2) \tag{25}$$

The subsidiary firm's expected incomes (α, β are known) are

$$E\big(s(U)\big) = s + A^2/2b(1 + rb\sigma^2/A^2) \tag{26}$$

The subsidiary firm's expected profits must be s regardless of whether it works hard or not, and the leading firm should motivate the subsidiary firm through expected incomes instead of expected profits, so this paper will discuss the subsidiary firm's expected incomes. In the case of asymmetric information, the principal cannot observe the agent's effort. Therefore, there are two additional kinds of agency costs compared with symmetric information: one is the risk cost; another is the incentive cost. In the case of symmetric information, the leading firm's risk cost is 0; in the case of asymmetric information, the leading firm's risk cost is

$$R = \frac{r\beta^2\sigma^2}{2} = \frac{r\sigma^2}{2\left(1 + \frac{rb\sigma^2}{A^2}\right)^2} \tag{27}$$

The incentive cost refers to the difference between high expected revenue with symmetric information and low expected revenue with asymmetric information. For this reason, the subsidiary firm works harder in the case of symmetric information than in the case of asymmetric information. Therefore, the leading firm's expected utilities will decrease in the case of asymmetric information. Therefore, the leading firm's incentive cost is

$$E(L) = \big(Ae^* + B - C(e^*)\big) - \big(Ae + B - C(e)\big) == \frac{br^2\sigma^4/A^2}{2(1 + rb\sigma^2/A^2)} \tag{28}$$

Then, the leading firm's agency cost is

$$TC = R + E(L) = \frac{r\sigma^2}{2(1 + rb\sigma^2/A^2)} \tag{29}$$

3.2 Market returns model 2 (the price p and cost c are considered)

Similarly, the leading firm's expected utilities are

$$E\big(U - s(U)\big) = (p - c)B - s + \frac{(p - c)^2A^2}{2b(1 + rb\sigma^2/A^2)} \tag{30}$$

The subsidiary firm's expected incomes are

$$E\big(s(U)\big) = s + \frac{(p - c)^2A^2}{2b(1 + rb\sigma^2/A^2)} \tag{31}$$

The leading firm's agency cost is

$$TC = R + E(L) = \frac{(p - c)^2r\sigma^2}{2(1 + rb\sigma^2/A^2)} \tag{32}$$

4. The simulation

In order to clarify the factors' relations, the paper conducts a mathematical simulation of the leading firm's expected utilities $E\big(U - s(U)\big)$, the subsidiary firm's expected incomes $E\big(s(U)\big)$ and the leading firm's agency cost TC $(A, b, r, B, s, \sigma^2 > 0)$ based on MATLAB.

4.1 The simulation of the leading firm's expected utilities $E(U - s(U))$, the subsidiary firm's ability A and the absolute risk aversion factor r

(1) Market returns model 1 (the price p and cost c are not considered)

The simulation setting is shown below: cost coefficient $b = 0.5$, output variance $\sigma^2 = 20000$, market prosperity $B = 10000$, subsidiary firm lowest profit $s = 100000$.The MATLAB simulation procedure is as follows: Initialization (B, s, the interval for A: $i \in [1000{,}11000]$, the interval for r: $j \in [0{,}10000]$, array computations (input i, j and function), the interval check (if $i < Max(i)$ and $j < Max(j)$, computing continues, otherwise computing ends) The code for the function is as follows (others omitted):

$$Sf(i,j) = ((a(1,i) * a(1,i))/(1 + \left(10000 * \frac{b(1,j)}{a(1,i)} * a(1,i)\right))) + (x - y) \tag{33}$$

The relations between $E(U - s(U))$, A and r are shown in Fig. 2.

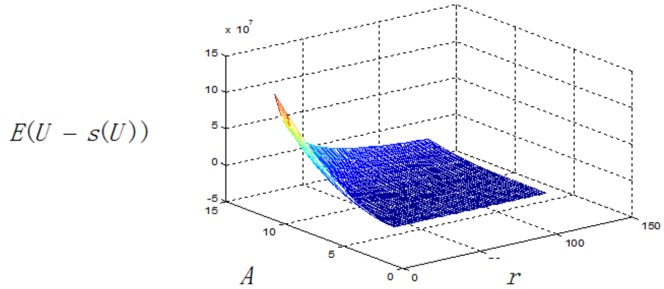

Fig. 2 The relations between $E(U - s(U))$, A and r (1)

Fig. 2 indicates that $E(U - s(U))$ is positive with A; $E(U - s(U))$is negative with r.

(2) Market returns model 2 (the price p and cost c are considered)

The simulation setting is shown below: $p = 100$, $c = 50$; the others are the same as above. The code for the function is as follows (others omitted):

$$Sf(i,j) = (2500 * (a(1,i) * a(1,i))/(1 + \left(10000 * \frac{b(1,j)}{a(1,i)} * a(1,i)\right))) + ((50 * x) - y) \tag{34}$$

The relations between $E(U - s(U))$, A and r are shown in Fig. 3. In Fig. 3, the results are similar to those in Fig. 2, but the magnitude of relations between $E(U - s(U))$, A and r is times greater in Fig. 4 compared with Fig. 3, so p and c affect the model most.

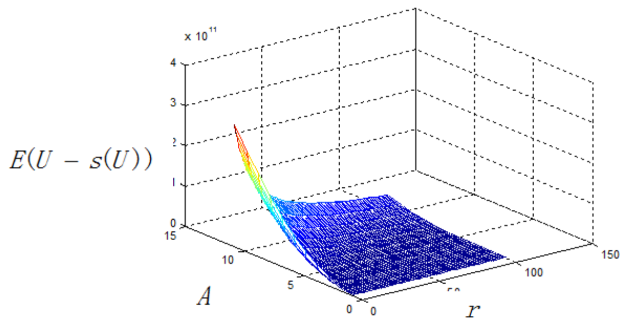

Fig. 3 The relations between $E(U - s(U))$, A and r (2)

4.2 The simulation of the leading firm's expected utilities $E(U - s(U))$, cost coefficient b, and market prosperity B

(1) Market returns model 1 (the price p and cost c are not considered)

The simulation setting is shown below: subsidiary firm ability $A = 5000$, output variance $\sigma^2 = 20000$, subsidiary firm absolute risk aversion factor $r = 500$, subsidiary firm lowest profit $s = 100000$.The code for the function is as follows (others omitted):

$$Sf(i,j) = (25000000/(2 * b(1,j) * (1 + 0.4 * b(1,j))) + (a(1,i) - 100000) \quad (35)$$

The relations between $E(U - s(U))$, B and b are shown in Fig. 4.

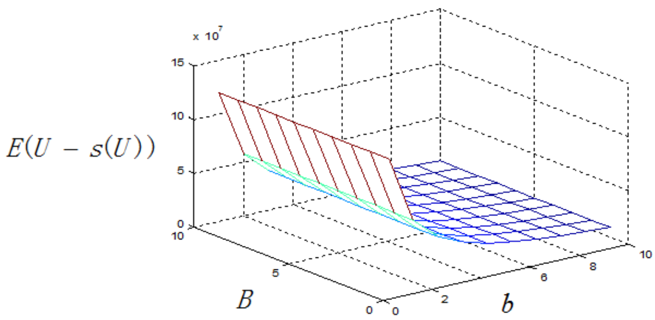

Fig. 4 The relations between $E(U - s(U))$, B and b (1)

Fig. 4 indicates that $E(U - s(U))$ is negative with b; $E(U - s(U))$ is positive with B.

(2) Market returns model 2 (the price p and cost c are considered)

The simulation setting is shown below: $p = 100$, $c = 50$; the others are the same as above. The code for the function is as follows (others omitted):

$$Sf(i,j) = (2500 * 25000000/(2 * b(1,j) * (1 + 0.4 * b(1,j))) + (50 * a(1,i) - 100000) \quad (36)$$

The relations between $E(U - s(U))$, B and b are shown in Fig. 5. In Fig. 5, the results are similar to those in Fig. 4, but the magnitude of relations between $E(U - s(U))$, B and b is 10^4 times greater, so p and c affect the model most. Additionally, we find that $E(U - s(U))$is negative with s; $E(U - s(U))$ is negative with σ^2; and p and c affect the model most. Based on the analysis above, the relations between factors $(A, b, r, B, s, \sigma^2)$, $E(s(U))$ and TC can be calculated as well.

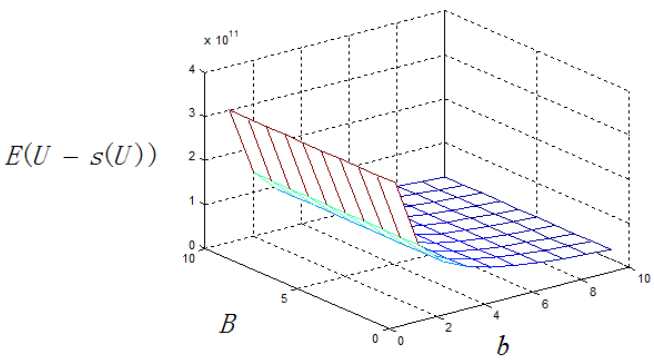

Fig. 5 The relations between $E(U - s(U))$, B and b (2)

To sum up, the leading firm's expected utilities $E\big(U - s(U)\big)$, the subsidiary firm's expected incomes $E\big(s(U)\big)$ and the leading firm's agency cost$TC$are all affected by the subsidiary firm's ability A, the cost coefficient b, the absolute risk aversion factor r and the output ance σ^2; $E\big(U - s(U)\big)$, $E\big(s(U)\big)$ and TCdiffer $(p - c)^2$ times due to the market returns model 1 (the price p and cost c are not considered) compared with the market returns model 2 (the price p and cost c are considered).

5. Conclusion

Production networks are an effective way to realize production coordination. The leading firm and the subsidiary firm comprise production networks and enhance production networks' core competencies if parties are united. In the production networks, the leading firm has a special market position due to its access to critical resources. Additionally, the leading firm greatly determines the goals followed by the subsidiary firm in production networks. Inevitably, objective conflicts between the principal and agent often arise, as both of them want their maximum benefit, and in particular, opportunistic practices of deceit and fraud are possible.

Mechanism design is an effective way to tackle the principal-agent problem by looking for the common factors related to both the principal and the agent in the case of asymmetric information. The paper develops a principal-agent theory for production coordination. The goal of the principal-agent theory is to analyze the problems occurring between the leading firm and the subsidiary firm and to find the common factors of production coordination, develop solutions for these problems, and the needs of incentive contracts to fulfill the leading firm's requirements and the subsidiary firm's profit. The findings of the simulation help to illuminate the potential behavioral uncertainties between the leading firm and the subsidiary firm and to apply the optimal kinds of measures in production coordination. The leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost are all affected by the subsidiary firm's ability A, cost coefficient b, absolute risk aversion factor r and output variance σ^2. The leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost differ thousands of times due to the different market returns (the price p and cost c are considered or not). The common factors related to both actors are the leading firm's expected utilities, the subsidiary firm's expected incomes and the leading firm's agency cost; in particular, the difference in market returns is included in the new model, in contrast to previous approaches. Thus, the proposed approach (incentive contract model) can help the leading firm apply incentives to optimize production modes to achieve production coordination while taking into account these common factors and market returns.

In the model of Pareto loss, the leading firm and the subsidiary firm will make efforts to renegotiate jointly to increase the effort e $(e = \beta A/b)$; in Pareto improvement, the utilities for the leading firm and the subsidiary firm will increase. Therefore, we should improve the subsidiary firm's ability, reduce the subsidiary firm's cost coefficient, lower the subsidiary firm's absolute risk aversion, and pay attention to random market factors. The leading firm can take on incentive measures to optimize production coordination based on the common factors.

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A genetic regulatory network-based sequencing method for mixed-model assembly lines

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A B S T R A C T

Mixed-model sequencing to minimize work overload at stations is regarded as one of the most concerned optimization problems in assembly lines manufacturing a variety of product models simultaneously. A novel sequencing method based on the genetic regulatory network is proposed to solve this problem. First, genes, gene regulation equations and gene expression procedures are developed in the network based on its similarity with the mixed-model sequencing problem. Each two-state gene represents a binary decision variable of the mathematical model. The gene regulation equations describe decision variable interactions in the constraints and objectives. The gene expression procedure depends on the regulation equations to generate solutions, in which the value of each decision variable is indicated by the expression state of the related gene. Second, regulatory parameter optimization in the regulation equations minimizes the work overload at stations. The effectiveness of the proposed method is validated through experiments consisting of reference instances and industrial instances. The experimental results demonstrate that this method outperforms other methods in large-scale instances.

A R T I C L E   I N F O

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1. Introduction

Mixed-model assembly lines (MMALs) are widely applied to the industrial engineering world because they can assemble various models of products in a facultative sequence while reducing setup times [1]. Although it is possible to implement any model sequence, the model sequence causes different economic impacts in the actual environment [2]. For instance, different models require diverging processing times at stations to complete the specific assembly operations that realize customized function requirements [3]. The cycle time defines the standard time to process a product at a station, which is typically the average of the processing times of different models weighted by the model demands [4]. The processing times required in complex operations are thus greater than the cycle time, while those required in simple operations are less than the cycle time [5, 6]. If some complex operations are processed continuously by using a specific station, then assembly tasks may not be completed before the operators have reached the down-stream station border, which is regarded as a work overload situation. Although utility workers or line stoppages are adopted to deal with the work overload situation, these lead to additional costs [7]. The mixed-model sequencing (MMS) problem is thus addressed to minimize the work overload at stations, in which different models of products are arranged by performing alternately complex operations and simple ones at each station [8].

The MMS problem has attracted a lot of attention because of its complexity and practical value. Various types of MMS methods including exact solution procedures, heuristic procedures and meta-heuristics have been proposed by scholars. However, the existing methods can hardly achieve high-quality solution when the problem is from large-scale instances and requires acceptable computational time. This study aims to fill in this gap by proposing a novel method based on the genetic regulatory network (GRN). In a GRN, gene states are the same as decision variable values in the MMS problem. Gene regulations describe the interconnection between genes, which have an analogous function with constraints. The gene expression procedure governed by gene regulations determines gene states iteratively, which is similar to a heuristic sequencing procedure. Based on these similarities, genes are first defined in the GRN to represent decision variables. Second, gene regulation equations are developed to express not only hard constraints in the mathematical model, but also soft constraints derived from certain sequencing rules. The importance of soft constraints is weighted by regulatory parameters in the equations. Third, the gene expression procedure is designed to indicate a heuristic procedure that is specified by regulatory parameters. Finally, the regulatory parameters are optimized to obtain the optimal solutions with minimum work overload at stations.

Thereupon, the key contribution is the extension of GRN applications to assembly line scheduling. A series of computational experiments are conducted to validate the effectiveness of this GRN-based method. The remainder of this paper is organized as follows. A relevant literature review of MMS methods and GRNs is offered in Section 2. A mathematical model of MMS problems is presented in Section 3. A GRN-based sequencing method is given in Section 4. Section 5 contains the experimental results and discussions. Conclusions and future research directions are discussed in Section 6.

2. Literature review

2.1 Mixed-model sequencing problem

In terms of sequencing in MMALs, Boysen et al. [9] provided an integrated review to discuss three fundamental approaches, i.e., MMS, car sequencing and level scheduling. Of these approaches, the MMS methods aim at minimizing sequence-dependent work overload based on a detailed scheduling in MMALs, which have been widely investigated by researchers [10]. These MMS methods can be further classified into four major classes: branch-and-bound computation, exact solution procedure, heuristic procedure, and meta-heuristic [11-13]. The focus of the existing literature was on heuristic procedure and meta-heuristic because it is impractical to implement other methods for large-scale instances [14-16]. For instance, Cano et al. [17] used a scatter search method that selects from 20 priority rules to generate hyper heuristic procedures. Gujjula et al. [18] proposed a heuristic method based on Vogel's approximation method to address large-scale MMS problems. Cortez and Costa [19] developed a set of fast constructive heuristics, two local search procedures and a meta-heuristic to deal with a specific problem featured with worker-dependent processing times. Well-known meta-heuristics such as genetic algorithm and ant colony algorithm have also been employed to solve a variety of MMS problems [20-25]. In general, most heuristic methods used greedy priority rules to construct rapidly a model sequence by appending iteratively alternative models into it. These methods chose products with minimum objective function values at each iteration, which led to intensive increases of the work overload in the last part of the model sequence. Hence, these approaches based on heuristic procedures could obtain good solutions rather than optimal ones. Although other heuristic methods were considered to improve the solution quality (e.g., the work overload increases caused by remaining model copies were taken into account at each iteration), they resulted in the computational effort to be dramatically increased for large-scale problems. Alternatively, meta-heuristic methods could find optimal solutions or near-optimal solutions by globally searching among all the feasible ones. However, the global search caused the computational effort to be increased with the number of model copies as well as the number of stations.

Consequently, it is difficult to generate a near-optimal model sequence with an acceptable computational effort for real large-scale instances in the actual manufacturing environment. In this paper, we propose a novel GRN-based method to solve MMS problems. The critical factors of this method include the description of the MMS problem by using a GRN and the integration of certain validated sequencing rules in the GRN. Based on such a GRN, the proposed method can solve the MMS problem more efficiently than meta-heuristics without compromising the solution quality, especially for large-scale instances.

2.2 Genetic regulatory network

The GRN is a structured network that describes the regulation of gene expression in cells [26]. It has been widely applied by biologists to investigate the dynamic changes of cell morphologies, and has become a hot topic in the past few years. A GRN has at least the following three elements in common: genes, gene regulations and gene expression procedure [27]. Each gene has two alternative states (i.e., the expressed state and the unexpressed state). If a gene is in the expressed state, it has regulatory effects on the states of other genes, which is the primary form of gene regulations. Based upon these regulations, gene expression procedure iteratively converts certain genes in the unexpressed state into ones in the expressed state if there are enough positive regulatory effects on these genes. Since a cell is mainly composed of copied components (e.g., mRNAs and proteins), gene expression procedure finally determines the cell's morphology in accordance with genes in the expressed states [28]. Various formalisms have already been employed to describe GRNs, for instance, Bayesian networks, directed graphs, partial differential equations, Boolean networks, qualitative differential equations, stochastic equations, and rule-based formalisms [29].

3. Problem description

The following assumptions are taken into consideration when constructing the mathematical model:

- The assembly line is a 'moving line' in which the conveyor moves at a constant speed;
- The length of a station is a fixed one (measured by the product passing time), and neighboring stations do not overlap;
- Products are equi-spaced on the line by launching each other after a constant time interval, which is equivalent to the cycle time;
- The operation processing time at a station is not longer than the length of this station;
- The impact of unfinished works on operations at succeeding stations is not taken into consideration;
- Operators return with infinite velocity to the subsequent product;
- The model changeover time is included in the operation processing time;
- To facilitate the presentation, the notations listed in Table 1 are used in the development of the mathematical model. The mathematical model takes the following form.

$$\text{Minimize} \sum_{t=1}^{T}\sum_{k=1}^{K} w_{tk} \tag{1}$$

$$\text{S.T.} \sum_{t=1}^{T} x_{tm} = d_m \quad \forall m \tag{2}$$

$$\sum_{m=1}^{M} x_{tm} = 1 \quad \forall t \tag{3}$$

$$s_{1k} = 0 \quad \forall k \tag{4}$$

$$s_{tk} \geq 0, w_{tk} \geq 0 \quad \forall t, k \tag{5}$$

$$w_{tk} \geq s_{tk} + \sum_{m=1}^{M} x_{tm} p_{mk} - l_k \quad \forall t, k \tag{6}$$

$$s_{t+1,k} \geq s_{tk} + \sum_{m=1}^{M} x_{tm} p_{mk} - w_{tk} - c \quad \forall t, k \tag{7}$$

Table 1 Problem's notations

Notations		Definitions
Sets		
	$\{1, \dots, t, \dots, T\}$	Set of products in the model sequence
	$\{1, \dots, k, \dots, K\}$	Set of stations
	$\{1, \dots, m, \dots, M\}$	Set of models
Parameters		
	d_m	Demand for model m in the production plan
	c	Cycle time
	T	Total demand for products, $T = \sum_{m=1}^{M} d_m$
	l_k	Length of station k (time unit)
	p_{mk}	Operation processing time of model m at station k
Variables		
	s_{tk}	Starting time for assembling the tth product at station k
	w_{tk}	Extra operation processing time for the t-th product at station k (work overload time)
	x_{tm}	Binary variable: 1, if the t-th product belongs to model m; 0, otherwise

The objective of the mathematical model is to minimize the total work overload at stations. The constraints in Eq. 2 ensure that the model sequence satisfies the demand for each model. Eq. 3 makes sure that a station cannot process more than one product at the same time within each production cycle. Eq. 4 represents the initial state of stations. Eq. 5 and Eq. 6 ensure that all the operations should be processed within boundaries of their related stations. If operations on a product cannot be finished within boundaries of their related stations, then a work overload occurs. Eq. 7 makes sure that operators at station k can start processing product $(t + 1)$ after they have completed the operations on product t or product t has left station k.

4. Genetic regulatory network-based sequencing method

4.1 Mapping between the mathematical model and the genetic regulatory network

In the mathematical model presented in Section 3, the binary decision variables, the constraints and the solution are similar to the genes, the gene regulations and the gene expression procedure in a GRN, respectively. Based on these similarities, the model can be represented by using a GRN (shown in Fig. 1): (1) each gene represents a decision variable; (2) gene regulations describe constraints; (3) gene expression procedure generates solutions.

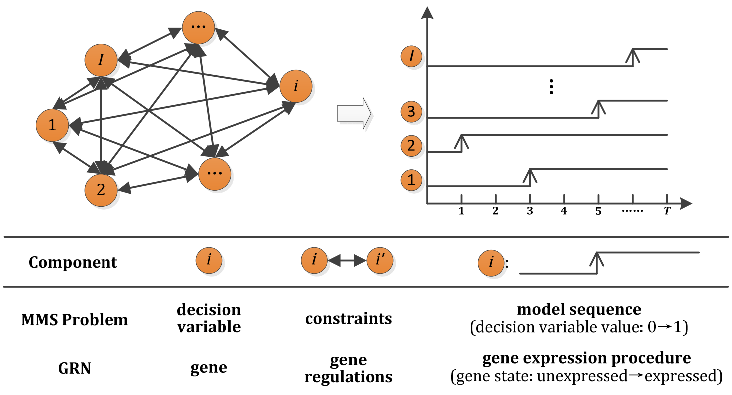

Fig. 1 Mapping between the MMS problem and the GRN

In general, the differential equation method is the most suitable method to develop gene regulation equations because it can represent gene regulations in a quantitative form. In the GRN, first, regulation equations are used to describe all the constraints, and the gene expression procedure is developed based upon the regulation equations to obtain feasible solutions. Second, some soft constraints related to sequencing rules are integrated in the regulation equations to decrease work overload at stations. Third, regulatory parameters are optimized to integrate reasonable sequencing rules and thus minimize work overload at stations. Consequently, as shown in Fig. 2, the GRN-based method contains two parts:

- A GRN is developed based on the mathematical model and certain sequencing rules;
- Regulatory parameters are optimized by using a genetic algorithm in order to minimize the work overload.

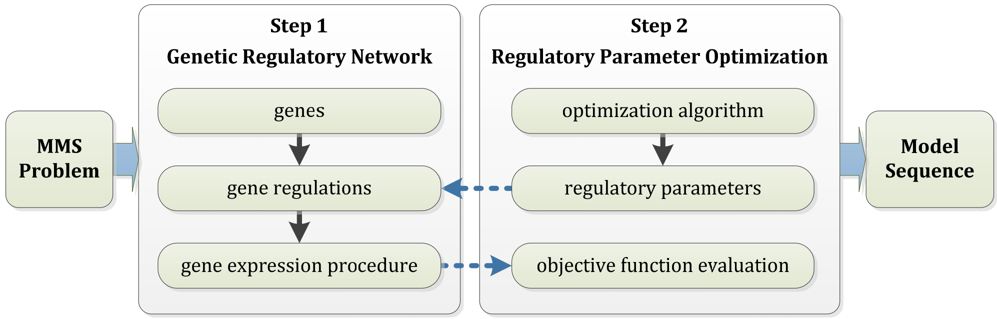

Fig. 2 Outline of the GRN-based method

4.2 Genetic regulatory network establishment

According to decision variables of the mathematical model, genes $\{\theta_{tm} \mid t = 1,2,\dots,T, m = 1,2,\dots,M\}$ are generated. Each gene θ_{tm} indicates that a product of model m is assigned to the tth position of the model sequence. Moreover, the regulation equation in Eq. 8 is developed to express constraints.

$$v_i = f_i(x_1(t), x_2(t), \cdots, x_I(t), \varepsilon_1, \varepsilon_2, \cdots, \varepsilon_E) \tag{8}$$

where I represents the number of genes in a GRN, $x_i(t)\ \forall i \in \{1,2,\cdots,I\}$ is a binary variable that is equal to 1 if gene θ_i is in the expressed state at time t, otherwise, it is equal to 0, $f_i\colon \mathbb{R}^{(I+E)} \to \mathbb{R}$ is a nonlinear function, v_i represents the inhibition coefficient to convert gene θ_i to the expressed state, $\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_E$ are regulatory parameters. In terms of Eq. 2 and Eq. 3, the regulation equation first describes following constraints of each position in the model sequence:

(1) A model can be selected when other models have not been selected yet.
(2) A model can be selected when the demand for this model has not been satisfied at former positions.

Moreover, soft constraints related to the study of Cano et al. [17] and the study of Dörmer et al. [30] are also included in the regulation equation:

(3) A model can be selected if it causes the least work overload at stations.
(4) A model can be selected if it leads to the least idle time at stations.
(5) A model can be selected if its production ratio best matches its demand ratio in the production plan.

No sequencing procedure could satisfy all the soft constraints completely, and each unsatisfied case might increase the work overload at stations. The regulation equation of gene θ_{tm} is thereby developed as follows:

$$v_{tm} = \varepsilon_1 \sum_{k=1}^{K} \phi(s_{tk} + p_{mk} - l_k) + \varepsilon_2 \sum_{k=1}^{K} \phi(c - s_{tk} - p_{mk})$$

$$+\varepsilon_3 K^{\varepsilon_4} \left| \frac{\sum_{t=1}^{T} x_{tm} + 1}{\sum_{t=1}^{T} \sum_{m=1}^{m} x_{tm} + 1} - \frac{d_m}{T} \right| + H\left(\sum_{m=1}^{M} x_{tm}\right) + H\left(\sum_{t=1}^{T} x_{tm} + 1 - d_m\right) \tag{9}$$

where v_{tm} represents the inhibition coefficient to gene θ_{tm}, $H(x)$ is a step function satisfying $H(x) = 0\ (x < 0)$ and $H(x) = +\infty\ (x \geq 0)$, $\phi(x)$ is a piecewise function satisfying $\phi(x) = 0\ (x < 0)$ and $\phi(x) = x\ (x \geq 0)$, ε_1, ε_2, ε_3, ε_4 represent regulatory parameters that combine regulation segments derived from different constraints. The first three terms of the right side of Eq. 9 indicate the inhibition to gene θ_{tm} owing to soft constraints (3) to (5), respectively. The last two terms of the right side of Eq. 9 describe constraints (1) and (2), respectively. Constraints in Eq. 4 to Eq. 7 are embodied in the calculation of s_{tk}:

$$s_{t+1,k} = \begin{cases} 0 & \text{if} \quad s_{tk} + \sum_{m=1}^{M} x_{tm} p_{mk} \leq c \\ s_{tk} + \sum_{m=1}^{M} x_{tm} p_{mk} - c & \text{if} \quad c < s_{tk} + \sum_{m=1}^{M} x_{tm} p_{mk} \leq l_k \\ l_k - c & \text{if} \quad l_k < s_{tk} + \sum_{m=1}^{M} x_{tm} p_{mk} \end{cases} \tag{10}$$

Based on the regulation equation, the expression procedure of gene θ_{tm} is also developed. As shown in Table 2, at each discrete time $t \in \{1, 2, \cdots, T\}$, the inhibition coefficient v_{tm} is calculated for genes $\{\theta_{tm} \mid m = 1, 2, \ldots, M\}$ and the gene with minimum v_{tm} is converted to the expressed state. When $t > T$, the model sequence is obtained based on the gene states $\{x_{tm} \mid t = 1, 2, \ldots, T, m = 1, 2, \ldots, M\}$.

Table 2 Pseudo codes of gene expression procedure

```
//initialization
for t ← 1 to T do
  for m ← 1 to M do
    x_tm ← 0              //all the genes are initialized in the unexpressed state
  next;
next;

//gene expression circulation
for k ← 1 to K do
  s_1k←0                  // initialization of stations
next;
for t ← 1 to T do         //discrete time
  m_0 ← 1, v_0 ← +∞       //index of the gene with minimum v_tm
  for m ← 1 to M do
    calculate v_tm in Eq. 9     //calculate inhibition coefficients
    if v_tm < v_0 then          //compare inhibition coefficients
      m_0 ← m             //update index
      v_0 ← v_tm          //update the minimum inhibition coefficient
    end if;
  next;
  x_tm0 ← 1               //convert the gene with minimum v_tm to the expressed state
  for k ← 1 to K do
    calculate s_t+1,k in Eq. 10    //update station status
  next;
next;
```

4.3 Regulatory parameter optimization

Based on the GRN established in Section 4.2, a solution to the MMS problem is obtained when regulatory parameter values are determined. In the genetic algorithm illustrated in Fig. 3, first, the initial population is formed by N individuals that are generated randomly. Each individual represents a feasible solution to the MMS problem. A chromosome is a sequence of real numbers to indicate these regulatory parameters (i.e., ε_1, ε_2, ε_3 and ε_4). Letting the current generation to be r, the individuals from the current population $P(r)$ are then selected based on their fitness values. The selected ones will receive the operations of crossover and mutation to generate new individuals. During these operations, each individual has a specific possibility (denoted by *PMutation*) to reinitialize the value of a randomized position in its chromosome, whereas each pair of individuals have a possibility denoted by *PCrossover* to change values of first two positions between their chromosomes. The new population $P(r+1)$ for the next generation $r+1$ is then formed by the newly generated individuals. If the best fitness value in current generation is not better than that in the previous generation, then the search process is terminated.

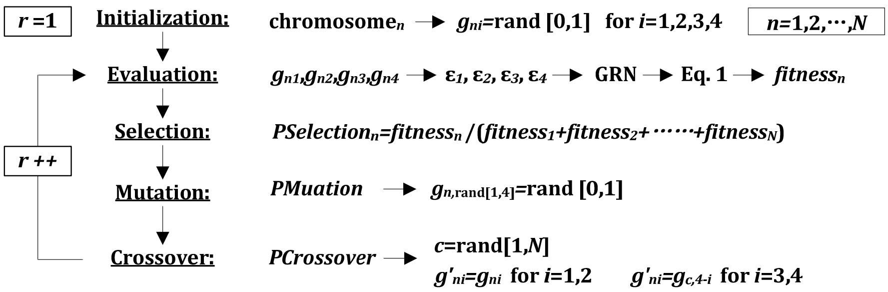

Fig. 3 Regulatory parameter optimization by using a real coded genetic algorithm (RCGA)

5. Computational experiment

In this section, the GRN-based method is applied to reference instances [31] in order to validate its effectiveness. Table 3 presents the processing time structures. These five structures provide processing times as well as station lengths at four stations. Table 4 lists production plans included in these instances. These 45 production plans declare the demand for products of four models, and are divided into five blocks based on models' demand ratios. In addition, the GRN-based method is also applied to industrial instances collected from a powertrain plant [32]. This line is composed of 21 stations that are with the same station length. Table 5 presents processing times of nine engine models at these stations. Forty-six production plans composed of different demand structures are listed in Table 6. These production plans are divided into two blocks based on their total demands.

In addition, an integer coded genetic algorithm (ICGA) [34, 35], a Cplex v11.1 solver and the scatter search based hyper-heuristic (HH) method proposed by Cano et al. [17] are also used to solve these problems. The ICGA encodes the model sequence directly by using a sequence of integer numbers $g_{n1}g_{n2}, \cdots, g_{nT}$, in which g_{nt} ($\forall t \in \{1,2,\cdots,T\}$) represents the model of the tth product in the model sequence. Basic steps of this ICGA are illustrated in Fig. 4. The Cplex solver uses a single-processor license to obtain optimal solutions for small-scale instances. To avoid unpredictable computational times for large-scale instances, its CPU time is limited to 7200 s. The HH method uses the HH2-IP10% procedure because it obtains the best results in a series of comparative experiments in Cano et al. [17]. Because the GRN-based method, the ICGA and the HH method depend on the stochastic search procedure, they are repeated 30 times for each instance to obtain the mean results of objective function values and CPU times.

Table 3 Processing time structures in reference instances

Structure		m=1	m=2	m=3	m=4	l_k	Structure		m=1	m=2	m=3	m=4	l_k
1	k=1	92	97	103	108	108		k=3	85	100	115	110	115
	k=2	103	98	104	95	105		k=4	82	94	119	115	120
	k=3	101	105	99	95	106	4	k=1	113	114	82	95	115
	k=4	95	104	96	105	106		k=2	119	113	85	87	120
2	k=1	91	80	107	114	115		k=3	115	112	84	94	115
	k=2	120	105	88	87	120		k=4	116	118	87	81	120
	k=3	90	113	117	100	120	5	k=1	115	104	89	95	115
	k=4	100	107	86	114	115		k=2	99	119	98	87	120
3	k=1	111	114	83	98	115		k=3	104	100	114	85	115
	k=2	120	113	85	87	120		k=4	96	102	87	118	118

Table 4 Production plans in reference instances

Block		d_1	d_2	d_3	d_4
1	P_1	13	1	1	1
	P_2	1	13	1	1
	P_3	1	1	13	1
	P_4	1	1	1	13
2	P_5	7	7	1	1
	P_6	7	1	7	1
	P_7	7	1	1	7
	P_8	1	7	7	1
	P_9	1	7	1	7
	P_{10}	1	1	7	7
3	P_{11}	5	5	3	3
	P_{12}	5	3	5	3
	P_{13}	5	3	3	5
	P_{14}	3	5	5	3
	P_{15}	3	3	5	5
	P_{16}	3	3	4	4
	P_{17}	4	4	4	4
4	P_{18}	5	5	5	1
	P_{19}	5	5	1	5
	P_{20}	5	1	5	5
	P_{21}	1	5	5	5
5	P_{22}	1	3	5	7
	P_{23}	1	3	7	5
	P_{24}	1	5	3	7
	P_{25}	1	5	7	3
	P_{26}	1	7	3	5
	P_{27}	1	7	5	3
	P_{28}	3	1	5	7
	P_{29}	3	1	7	5
	P_{30}	3	5	1	7
	P_{31}	3	5	7	1
	P_{32}	3	7	1	5
	P_{33}	3	7	5	1
	P_{34}	5	1	3	7
	P_{35}	5	1	7	3
	P_{36}	5	3	1	7
	P_{37}	5	3	7	1
	P_{38}	5	7	1	3
	P_{39}	5	7	3	1
	P_{40}	7	1	3	5
	P_{41}	7	1	5	3
	P_{42}	7	3	1	5
	P_{43}	7	3	5	1
	P_{44}	7	5	1	3
	P_{45}	7	5	3	1

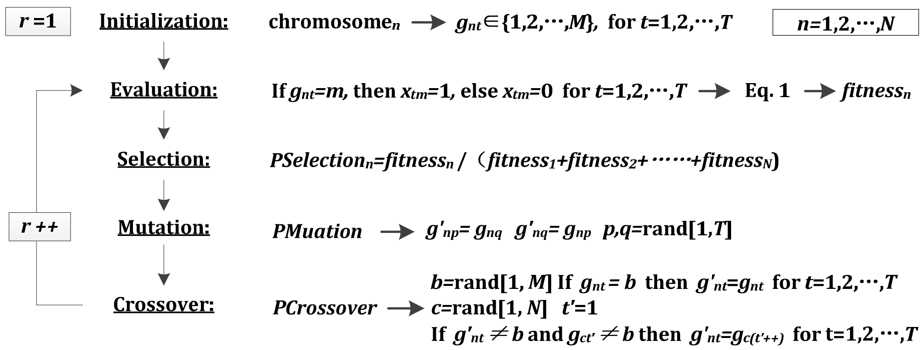

Fig. 4 Basic steps to solve the MMS problem by using an ICGA

Table 5 Processing times in industrial instances

	m=1	m=2	m=3	m=4	m=5	m=6	m=7	m=8	m=9	l_k
k=1	104	100	97	92	100	94	103	100	101	195
k=2	103	103	105	107	101	108	106	102	110	195
k=3	165	156	164	161	148	156	154	164	155	195
k=4	166	175	172	167	168	167	168	156	173	195
k=5	111	114	114	115	117	117	115	111	111	195
k=6	126	121	122	124	127	130	120	121	134	195
k=7	97	96	96	93	96	89	94	101	92	195
k=8	100	97	95	106	94	102	103	102	100	195
k=9	179	174	173	178	178	171	177	171	174	195
k=10	178	172	172	177	178	177	175	173	175	195
k=11	161	152	168	167	167	166	172	157	177	195
k=12	96	106	105	97	101	100	96	104	96	195
k=13	99	101	102	101	99	101	96	102	99	195
k=14	147	155	142	154	146	143	154	153	155	195
k=15	163	152	156	152	153	152	154	156	156	195
k=16	163	185	183	178	169	173	172	182	171	195
k=17	173	179	178	169	173	178	174	175	175	195
k=18	176	167	181	180	172	173	173	168	184	195
k=19	162	150	152	152	160	151	155	148	167	195
k=20	164	161	157	159	162	160	162	158	157	195
k=21	177	161	154	168	172	170	167	149	169	195

Table 6 Production plans in industrial instances

Block		d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	d_9
6	P_1	30	30	30	30	30	30	30	30	30
	P_2	30	30	30	45	45	23	23	22	22
	P_3	10	10	10	60	60	30	30	30	30
	P_4	40	40	40	15	15	30	30	30	30
	P_5	40	40	40	60	60	8	8	7	7
	P_6	50	50	50	30	30	15	15	15	15
	P_7	20	20	20	75	75	15	15	15	15
	P_8	20	20	20	30	30	38	38	37	37
	P_9	70	70	70	15	15	8	8	7	7
	P_{10}	10	10	10	105	105	8	8	7	7
	P_{11}	10	10	10	15	15	53	53	52	52
	P_{12}	24	23	23	45	45	28	28	27	27
	P_{13}	37	37	36	35	35	23	23	22	22
	P_{14}	37	37	36	45	45	18	18	17	17
	P_{15}	24	23	23	55	55	23	23	22	22
	P_{16}	30	30	30	35	35	28	28	27	27
	P_{17}	30	30	30	55	55	18	18	17	17
	P_{18}	60	60	60	30	30	8	8	7	7
	P_{19}	10	10	10	90	90	15	15	15	15
	P_{20}	20	20	20	15	15	45	45	45	45
	P_{21}	60	60	60	15	15	15	15	15	15
	P_{22}	20	20	20	90	90	8	8	7	7
	P_{23}	10	10	10	30	30	45	45	45	45
7	P_{24}	60	60	60	60	60	60	60	60	60
	P_{25}	60	60	60	90	90	45	45	45	45
	P_{26}	20	20	20	120	120	60	60	60	60
	P_{27}	80	80	80	30	30	60	60	60	60
	P_{28}	80	80	80	120	120	15	15	15	15
	P_{29}	100	100	100	60	60	30	30	30	30
	P_{30}	40	40	40	150	150	30	30	30	30
	P_{31}	40	40	40	60	60	75	75	75	75
	P_{32}	140	140	140	30	30	15	15	15	15
	P_{33}	20	20	20	210	210	15	15	15	15
	P_{34}	20	20	20	30	30	105	105	105	105
	P_{35}	47	47	40	90	90	55	55	55	55
	P_{36}	74	73	73	70	70	45	45	45	45
	P_{37}	74	73	73	90	90	35	35	35	35
	P_{38}	47	47	40	110	110	45	45	45	45
	P_{39}	60	60	60	70	70	55	55	55	55
	P_{40}	60	60	60	110	110	35	35	35	35
	P_{41}	120	120	120	60	60	15	15	15	15
	P_{42}	20	20	20	180	180	30	30	30	30
	P_{43}	40	40	40	30	30	90	90	90	90
	P_{44}	120	120	120	30	30	30	30	30	30
	P_{45}	40	40	40	180	180	15	15	15	15
	P_{46}	20	20	20	60	60	90	90	90	90

An Intel(R) Core(TM) i7-2720QM CPU @ 2.20 GHz and 8 GB RAM based notebook computer is used to conduct the computational experiments. Table 7 presents genetic algorithm parameters used in the GRN-based method and the ICGA method. Table 8 lists the average objective function values (*Obj*) obtained and the average CPU times (T_{CPU}) spent by the GRN-based method, the ICGA, the HH method and the Cplex solver in each block. In this table, the number of feasible solutions for each instance is evaluated based on Eq. 11 [33].

$$N_f = \left(\sum_{m=1}^{M} d_m\right)! / \prod_{m=1}^{M} (d_m!) \tag{11}$$

d_m is the demand for model m in the production plan. The average number of feasible solutions in each block (N_{fb}) is calculated and also presented in this table as the indicator of problem scales.

Table 7 Genetic algorithm parameters in different methods

Method	Population size	Maximum generation	PMutation	PCrossover
RCGA	50	30	0.1	0.8
ICGA	200	50	0.1	0.8

Table 8 Experimental results of different blocks

Block	N_{fb}	GRN-based		ICGA		HH method		CPLEX solver	
		Obj	T_{CPU}, s	Obj	T_{CPU}, s	Obj	T_{CPU},s	Obj	T_{CPU}, s
1	3.4×10^{3}	247.7	0.4	245.2	0.6	248.6	0.5	245.2	4.2
2	8.2×10^{5}	136.4	0.5	136.7	0.7	137.1	0.6	135.0	39.3
3	3.8×10^{7}	64.5	0.6	68.3	0.9	64.6	0.8	64.3	281.3
4	1.2×10^{7}	100.4	0.6	96.5	1.2	100.7	1.1	96.2	190.8
5	5.8×10^{6}	114.6	0.6	115.2	0.9	114.7	1.5	113.2	112.2
6	5.8×10^{247}	403.3	107.5	497.2	297.2	419.4	138.1	238410.5	7200
7	7.8×10^{505}	856.0	201.1	924.6	578.4	875.6	216.5	245774.1	7200

As shown in Table 8, based on 'N_{fb}' column, two scenarios are considered. Block 1, 2, 3, 4 and 5 are composed of small-scale reference instances and Block 6 and 7 are composed of large-scale industrial instances.

In the small-scale reference instances, the Cplex solver obtains the best results, and the other methods obtain results close to the best ones. Specifically, the results in Block 1 reveal that the GRN-based method and the HH method cannot generate the optimal solutions in some instances owing to the predetermined sequencing rules, while the ICGA can obtain the optimal ones through global searching procedure when there are a few feasible solutions. However, the results in Block 2, 3, 4 and 5 reveal that ICGA fails to obtain the optimal solutions for some instances when the number of feasible ones is increased, while the GRN-based method and the HH method generate better solutions than the ICGA. This is because the sequencing rules integrated in the GRN enable the RCGA to search among good solutions rather than all the feasible ones in the regulatory parameter optimization procedure. Similarly, the HH method uses the scatter search to select from different combinations of sequencing rules and thus searches among good solutions too. However, the GRN-based method achieves better results because its weighted integration of commonly-used sequencing rules enables better searching capacity than the random combination of 20 priority rules in the HH method.

For the large-scale instances, the Cplex solver fails to obtain good results in the limited CPU time, while the other methods achieve better ones in a reasonable time. The results in Block 6 and 7 reveal that the ICGA can hardly find even near-optimal solutions in an enlarged solution space, while the GRN-based method and the HH method are better than the ICGA. In addition, the results also demonstrate the GRN-based method saves the CPU time. In comparison with the ICGA method, the GRN-based method optimizes four regulatory parameters rather than the whole model sequence to decrease computational effort. This regulatory parameter optimization also demonstrates better efficiency than the scatter search on 20 priority rules in the HH method.

Fig. 5 illustrates how the computational time of different methods changes with the increase of problem sizes. The CPLEX solver finds out the optimal solution by using a traversal procedure, for which the computational time increases significantly with a larger problem size. The GRN-based method, the HH method and the ICGA are based on random searching procedures that demonstrate lower increasing rates than the CPLEX solver. Moreover, the ICGA searches among all feasible solutions, whereas the GRN-based method and the HH method search among good solutions owing to the predetermined sequencing rules. For this reason, these two methods save the computational time than the ICGA.

Consequently, it can be noted that the GRN-based method provides an effective means to solve the MMS problem, especially for large-scale instances. In addition, this method is also potentially applied for MMS problems in the dynamic environment by using the predictive-reactive strategy. In this strategy, the GRN-based method first provides a production plan with the minimum work overload before line production, and gives the reactive schedule within a rolling window (containing 10~20 products) once the predetermined plan is interrupted by dynamic events such as machine failures or processing time variations. Because the small-sized MMS problems are regularly solved within 1 s by using the GRN-based method, this reactive schedule realizes real-time responses for the dynamic events. In this way, by using a predictive schedule to ensure the overall performance and employing reactive schedules to make quick responses, the GRN-based method will realize efficient production in the dynamic environment.

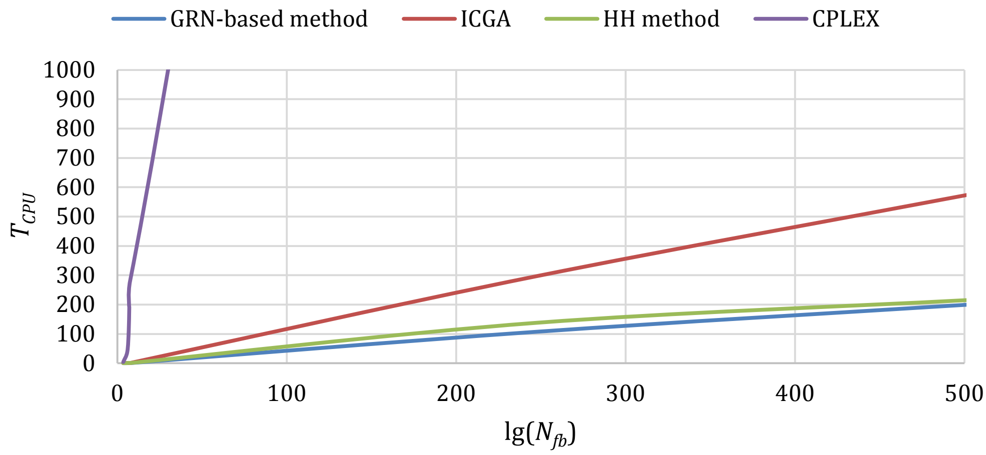

Fig. 5 Computational time with different problem sizes

6. Conclusion

This paper deals with the MMS problem in assembly lines to minimize work overload at stations. In terms of similarities between MMS and GRN, a novel MMS method based on the GRN is proposed. This method is applied to reference instances as well as industrial instances to validate its effectiveness. A Cplex solver, an ICGA and a HH method are used to benchmark the results. It is demonstrated that the GRN-based method realizes higher solution quality than other methods by integrating the sequencing rules reasonably, especially for large-sized problems. However, due to the regulatory parameter optimization that uses GA, rather than some well-designed mechanisms, the efficiency of this method requires further improvements. Thereupon, we will investigate a new parameter optimization mechanism in our future work. In addition, some other optimization problems also have the validated rules to determine its binary decision variables. The proposed method is thus potentially used for the problems in other areas, including the production scheduling problem in other manufacturing systems, the transportation scheduling problem in logistics industry and the medical device scheduling problem in healthcare industry. In our future work, we will develop new scheduling methods by extending the GRN-based approach to these areas.

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Influence of the production fluctuation on the process energy intensity in iron and steel industry

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A B S T R A C T

This paper mainly studies how the production fluctuation affects the process energy intensity in iron and steel industry. First of all, the production state is divided into five conditions according to the production volatility. Meanwhile, the process energy intensity model is constructed. And model analysis showed that operating rate and qualification rate are two key parameters that represent the production volatility. A case study showed that the process energy intensity is inversely proportional to the normal production operating rate and qualification rate, but proportional to the operating rate in the other production states. Moreover, the production halt operating rate and normal production qualification rate significantly influence the process energy intensity in terms of production volatility. And then, some management suggestions were introduced on how to reduce the fluctuation of the process production. The application of the model is quantitative analysis methods, which can describe influence of production fluctuation on the process energy intensity. Based on this, corresponding measures are adopted for reducing energy consumption, including adjustment of production planning and strategy etc.

A R T I C L E I N F O

Keywords:
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1. Introduction

The iron and steel industry, which is the basic raw materials industry, influences the operation of national economy directly [1]. The crude steel production of the world increased from 750 Mmt (Million metric ton) in 1996 to 1545 Mmt in 2012. This is mainly because the crude steel production of China is continuously at the top in the world for a dozen years since 1996, which correspondingly enlarges the energy demand. Take Chinese steelmakers, the energy consumption increased from 168 Mtce (Million ton coal equivalent) in 2000 to 597 Mtce in 2012. The energy consumption of six energy-intensive sectors- excavating industry, chemicals, non-metallic industry, iron and steel, non-ferrous metals, petroleum – accounts for 71.4 % of total industry energy consumption as shown in Fig. 1. It depicts the ratio of energy consumption in each sector to total energy consumption in 2012, with the iron and steel industry having the largest share at 23.6 %. Heavy energy-consuming of the iron and steel industry will inevitably lead to increasing of energy costs and aggravation of the ecological environment.

1) Energy expense challenges

The energy cost of iron and steel making accounts for up to 20 % of the total production costs [2]. Coal and electricity are the primary energy source of the iron and steel industry. Meanwhile,

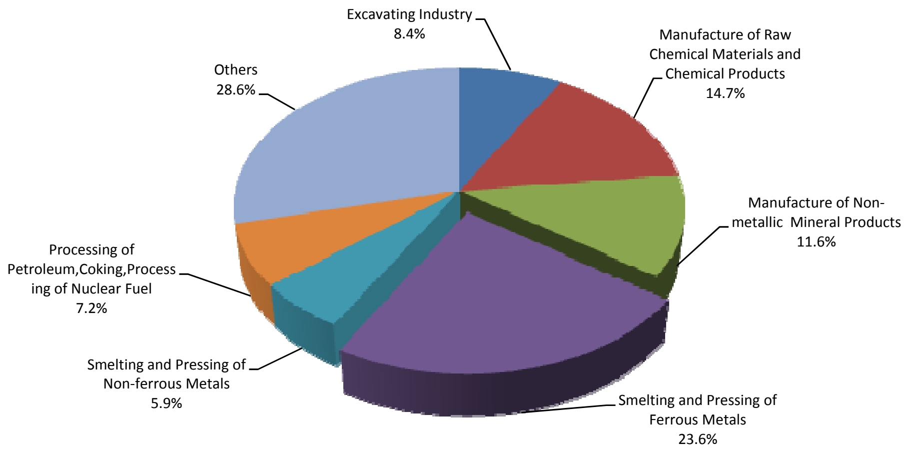

Fig. 1 Energy consumption ratio of each sector (Date source: CHINA STATISTICAL YEARBOOK 2012)

due to governmental macro-control, energy prices of coal and electricity have been increasing dramatically since 1980 in China; so high energy consumption and high energy price raises the energy expense of steel making [3]. So energy cost reduction is a very important factor in reducing the total cost.

2) Ecological challenges

In terms of ecological challenges, the first issue is carbon dioxide (CO_2) emissions. The energy efficiency has a direct impact on overall energy consumption and related CO_2 emissions [4].In 2009, the CO_2 emission from the Chinese iron and steel sector amounted to 1.17 billion metric tons, which is 16.29 % of the total Chinese CO_2 emissions and is nearly equal to 50 % of the world's steel industry's CO_2 emissions [5]. And the CO_2 emissions from energy (fuel) consumption accounts for 95 % of the total CO_2 emissions by the steel industry, which illustrates the important influence of energy (fuel) consumption on CO_2 emissions [6]. Meanwhile, GHG emissions problems of steel industry exist widely in other countries as well [7-9]. Secondly, the pollution problem of the steel industry, such as SO_2 and NOx, cannot be ignored either [10-12].

Facing the challenges from globalization, enhancing enterprise competitiveness and efficiency by applying new technology and new management means, improving energy efficiency, and reducing production costs is desperately needed.

2. Literature review

Currently, energy conservation research works performed in the steel industry have primarily concentrated on three aspects: equipment process improvement, process optimization, and energy conservation through management.

1) Equipment process improvement

Equipment process improvement refers mostly to replacing outdated, low-efficiency equipment by advanced, high-efficiency equipment. Early energy conservation efforts were primarily concentrated on the optimization and alteration of individual equipment.

Equipment scale enlargement is one of the important measures in energy conservation. For example, blast furnaces are process equipment that have the most concentrated material and energy flow in the iron and steel industry production process [13]. And through a comparison of a 5576 m^3 blast furnace from Shougang Jingtang Steel and a 4080 m^3 blast furnace from QianAn steel, Zhu et al. [14] discovered that constructing two 5576 m^3 blast furnaces can obtain similar yields as constructing three 4080 m^3 blast furnaces; however, the former has clear advantages in terms of investment reduction and energy conservation. Meanwhile, large-scale sintering machines and scale enlargement of a coke oven have low energy consumption and a high technical economic index.

Meanwhile, advanced production technology and equipment can improve energy efficiency. Pulverized coal injection technology (PCI) and continuous casting technology (CCT) are effective energy saving technology. The wide use of advanced combustion equipment [15] and power equipment [16] can promote energy efficient utilization. And the use of the spark plasma sintering (SPS) technology allowed for an energy saving in the order of 90-95% [17]. COREX process displays many energy and ecological advantages [18]. The surface of blast furnace tuyere was cooled by using cooling air instead of cooling water, which could reduce the energy taken away by the cooling water [19]. In addition, Tiago et al. [20] analyzed the feasibility of the biomass energy utilization to the EAF steelmaking process. Moreover, the recovery and utilization of residual energy and heat (RUREH) plays an important role for energy saving and CO2 emission reduction [21-22].

2) Process optimization

As technology continues to progress, room for energy savings through process equipment improvement becomes smaller, and thus, process optimization comes into play.

The issues of the steel industry studied in process optimization are the internal process function match and coordinated operation; the goal is to achieve continuous, compact production to reduce energy consumption during the production process. Examples of process optimization include technologies such as increasing the continuous casting ratio, long process flow (blast furnace - converter) to short process flow (electric arc furnace steel – continuous casting short process), continuous thin slab casting and rolling processes (CSPs), and rolled steel billet hot charging technology. Since the 1990’s, China’s steel industry per ton overall energy consumption declined significantly; among which, 48 % of the energy savings was due to the process restructuring and optimization [23].

Lu et al. [24] studied how the way ferrite flows in the iron and steel production process influences energy consumption and proposed important concepts, such as the base operating energy consumption graph. Thereafter, Chen et al. [25] and Yu et al. [26] used relevant concepts to calculate the influence of material flow structure change on energy consumption intensity in an actual production process and searched for an optimized production organization mode that minimized energy consumptions. Moreover, with the development of Circular Economy, industry ecosystem is gradually concerned. Dong et al. [5] agreed with a great potential for implementing circular economy in steel industry, and mode of future steel enterprises in circular economy society was discussed. Song et al. [27] and Chao et al. [28] thought that industry ecosystem is beneficial to itself, economy and environment.

3) Energy conservation through management

Energy waste issues in the operation process of the steel industry brought by “evaporating, emitting, dripping, or leaking” and disorderly management have become increasingly prominent. One of the most promising means of reducing energy consumption and related energy costs is implementing an energy management [29]. Wang et al. [30] noted that the potential of energy management system and industrial energy saving policies by transiting steel industry energy flow from “disorderly” to “orderly” is extremely large. Jean-Christian et al. [31] noted when sound energy management practices are included, the participants assessed the cost-effective energy conservation potential to be 9.7 %, which was 2.4 % higher than the potential for solely adopting cost-effective technologies. Tang et al. [32] thought that energy management of steel industry is basically in the safety and insurance mode of production-oriented, leading to inefficient energy management, high energy consumption and great loss of benefits. Therefore, it is necessary to establish a systematic energy efficiency management system oriented by quality and value of energy. Liu et al. [33] pointed out various environmental managements have been taken by the companies, including certain proactive efforts such as conducting cleaner production audit, pursuing ISO 14001 certification and the implementation of ESAs.

Because the steel industry production is influenced by factors, such as market demand, up-downstream process linkage, and equipment operation conditions, the production fluctuation changes greatly [23]; this change greatly influences the process energy intensity. When implementing lean energy management, the influence of production volatility on the process energy intensity should be fully considered. However, quantitative research on this aspect has rarely been reported. For this reason, this paper takes "process" as the starting point and explores and extracts the primary factors of influence of production fluctuation on the process energy intensity. Chen et al. [34] put forward there were six states in a production process, and process energy intensity formula was constructed. Combined with (E-P) method of cleaner production [35], production states were re-defined and re-divided taken into account this principle of division in this paper, process energy intensity formula was re-established. And the model is further verified using actual examples. And then, some suggestion and management measures were introduced.

3. Study object

With the view of process structure, iron and steel enterprise possesses the characteristics of the up-downstream processes are connected in series, and each unit is connected in parallel in the same work procedure. Therefore, When production fluctuations occurs in a unit, it will inevitably bring the production fluctuations of up-downstream processes or other units of the same procedure, thus affecting the energy intensity. In this paper, a unit in the production process is selected as study object (shown in Fig. 2). And then, the influence of production fluctuation on the process energy intensity is discussed. Meanwhile, measures of reducing production volatility, which can reduce impact on process energy intensity, are proposed under different production disposition.

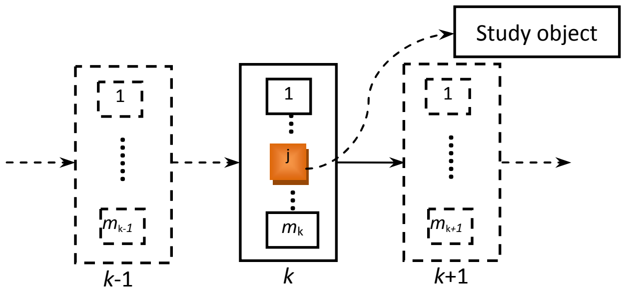

Fig. 2 The relationship between study object and it's up-downstream

Fig. 2. is the production process flow diagram. In which, k – the k-th procedure; k-1, k+1 – the up-downstream processes, respectively; j – the j unit of the k-th procedure.

4. Methodology

4.1 Production state description

Based on (E-P) method of cleaner production, the steel industry total process energy consumption, process production, and the process energy intensity have the following relationship:

$$E = E_0 + K \cdot P \tag{1}$$

$$e = E_0/P + K \tag{2}$$

In which, E – total process energy consumption within the statistical cycle, tce (ton coal equivalent); E_0 – energy consumption not directly related to production within the statistical cycle, such as energy consumed by the company general service, tce; P – process production within the statistical cycle, t; K – the normal production state energy intensity, tce/t; e – the process energy intensity within the statistical cycle, tce/t.

Fig. 3. is the process energy production graph (E-P graph), where the total process energy consumption increases as production increases, whereas the process energy intensity decreases in an inversely proportional manner. When the production is zero (stop production), equipment used for the company general service still consumes energy; therefore, the total process energy

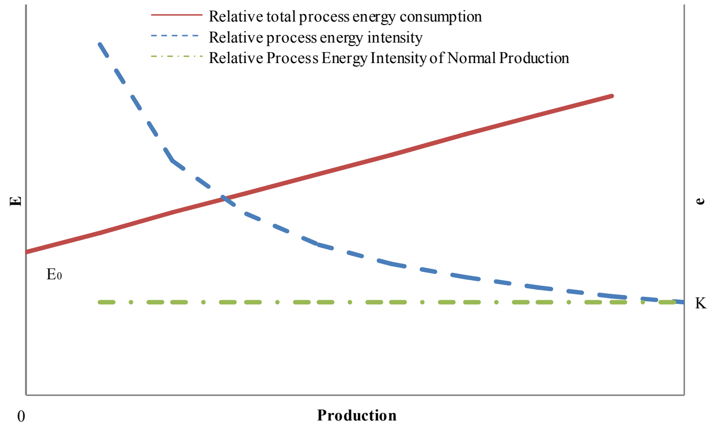

Fig. 3 Relationship between energy consumption and production of process

consumption is not zero, and thus, the process energy intensity is infinite in this situation. When the process production is relatively low (abnormal production), despite the total process energy consumption being low, due to the low production amount, the process energy intensity is extremely high. With the gradual increase in production, the total process energy consumption increases correspondingly; however, the process energy intensity decreases significantly; also, when production increases to the designed capacity (normal production), the process energy intensity approaches a stable state.

Therefore, this paper divides the process production state into three conditions of stop production, abnormal production, and normal production. Additionally, transitional states must exist between these three states, as shown in Fig. 4. The processes of transitional states (4), (5), and (6) belong to production decrease; the energy consumption is relatively low and thus, will not be considered. Moreover, the occurrence probability of the direction transition from normal production to abnormal production process (process (1) in Fig. 4.) is extremely low and therefore, will not be considered. Transitional states (2) and (3) are processes from low production volume to high production volume, in which the majority of the equipment in the process is at a start-up stage, and the energy consumption is relatively high. So it is adequate to only consider process transitional states (2) and (3). Here, state (2) is defined as a stop production transition, and state (3) is defined as an abnormal production transition.

Combined with Fig. 2, the relationship between the total energy consumption and the process energy intensity for each production state can be obtained, as shown in Fig. 5. While, the total process energy consumption in normal production is highest, but the process energy intensity is lowest; the total process energy consumption in stop production is lowest; however, because the production volume is zero, the process energy intensity is infinite.

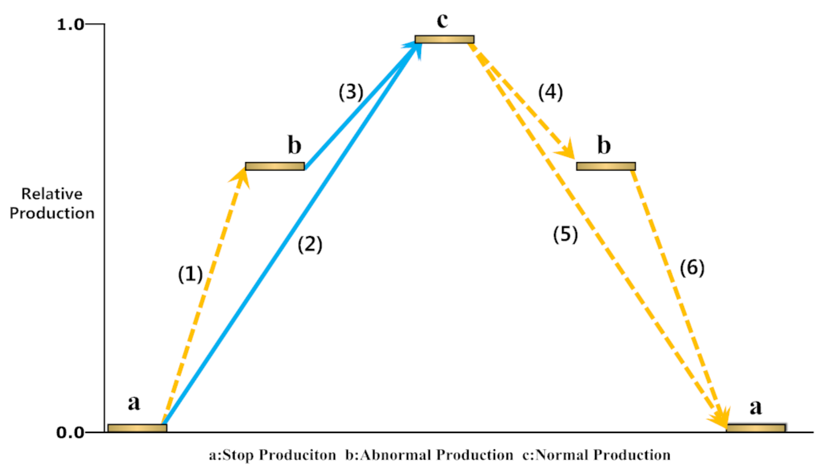

Fig. 4 Illustration of the production state

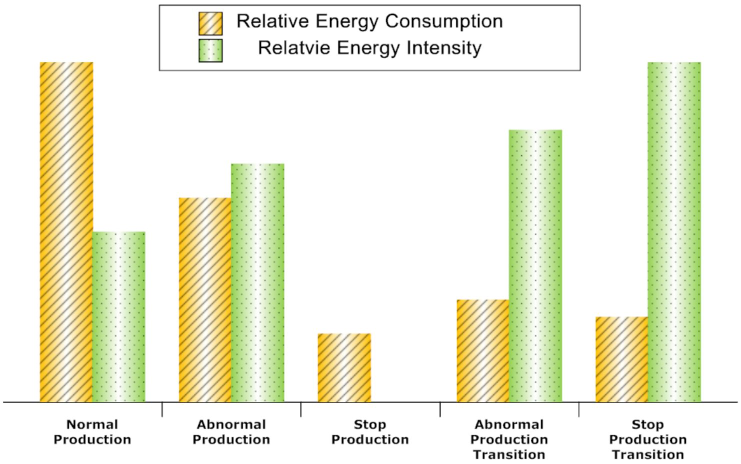

Fig. 5 Relationship of all production states between the relative energy consumption and relative energy intensity

4.2 Mathematical model

The concept of the statistical average of energy and material flow is introduced. Energy flow is the ratio of the total energy flow amount in the i^{th} state and time duration, Shown in Eq. 3.

$$E_i = \sum_{l=1}^{n_i} \int_0^{t_{i,l}} E_{i,l}(t)\, dt \,/ \sum_{l=0}^{n_i} t_{i,l} \tag{3}$$

In which, i – subscript, i =1, 2, 3, 4, 5, which represents normal production, abnormal production, stop production, abnormal production transition, and stop production transition, respectively; E_i – statistical average of energy flow in i-th production state, tce/h; n_i – number of times the i-th production state occurred; $E_{i,l}$ – instantaneous energy flow in the l-th occurrence of i-th state, tce/h; $t_{i,l}$ – time of l-th occurrence of i-th state, h.

By the same principle, the material flow statistical average can by expressed by Eq. 4:

$$M_i = \sum\nolimits_{l=0}^{n_i} \int_0^{t_{i,l}} M_{i,l} dt \,/ \sum\nolimits_{l=0}^{n_i} t_{i,l} \tag{4}$$

In which, M_i – statistical average of material flow in i-th production state, t/h; $M_{i,l}$ – instantaneous material flow in the l-th occurrence of i-th state, t/h;

1) Total process energy consumption

The total process energy consumption is the sum of the energy consumption in each of the five production states within the statistical cycle:

$$\begin{aligned} E &= E_1T_1 + E_2T_2 + E_3T_3 + E_4T_4 + E_5T_5 \\ &= T(E_1\eta_1 + E_2\eta_2 + E_3\eta_3 + E_4\eta_4 + E_5\eta_5) \end{aligned} \tag{5}$$

In which, T_i – duration of i-th state, h; T – statistical cycle, h; η_i – operating rate of i-th state, %, it is defined as T_i/T.

2) Process production

The process production in the statistical cycle is the sum of the qualified product in each of the normal production, abnormal production, stop production, abnormal production transition, and stop production transition (volume of stop production is 0) state:

$$\begin{aligned} P &= M_1T_1\eta_{p1} + M_2T_2\eta_{p2} + M_4T_4\eta_{p4} + M_5T_5\eta_{p5} \\ &= T\left(M_1\eta_1\eta_{p1} + M_2\eta_2\eta_{p2} + M_4\eta_4\eta_{p4} + M_5\eta_5\eta_{p5}\right) \end{aligned} \tag{6}$$

In which, η_{pi} – qualification rate of i-th state, %.

3) The process energy intensity

The process energy intensity is:

$$e = E/P = (E_1\eta_1 + E_2\eta_2 + E_3\eta_3 + E_4\eta_4 + E_5\eta_5)/(M_1\eta_1\eta_{p1} + M_2\eta_2\eta_{p2} + M_4\eta_4\eta_{p4} + M_5\eta_5\eta_{p5}) \quad (7)$$

Let $\alpha_i = E_i/E_1$, $\beta_i = M_i/M_1$; then, the process energy intensity model is

$$e = K(\eta_1 + \alpha_2\eta_2 + \alpha_3\eta_3 + \alpha_4\eta_4 + \alpha_5\eta_5)/(\eta_1\eta_{p1} + \beta_2\eta_2\eta_{p2} + \beta_4\eta_4\eta_{p4} + \beta_5\eta_5\eta_{p5}) \quad (8)$$

In which, α_i – ratio of energy flow statistical average value in *i*-th production state and normal production state, simply as the *i*-th production state energy flow ratio; β_i – ratio of the material flow statistical average value in *i*-th production state and normal production state, simply as the *i*-th production state material flow ratio. And Eq. 8 is the process energy intensity model based on (E-P) method of cleaner production.

5. Case studies

The steel rolling mill of an iron and steel enterprise is analyzed quantitatively by using the process energy intensity. And the data for this study are excerpted from daily production report and energy report of this rolling process. The process energy intensity in normal production of this rolling process is 72.4 kgce/t (kgce: kilogram coal equivalent) through data analysis.

5.1 Model modification and base operating condition determination

1) Model modification

Within the statistical cycle, the durations of the two transitional states are short; the production in these two states can be approximated as 0; thus, the process energy intensity model can be simplified:

$$e = K(\eta_1 + \alpha_2\eta_2 + \alpha_3\eta_3 + \alpha_4\eta_4 + \alpha_5\eta_5)/(\eta_1\eta_{p1} + \beta_2\eta_2\eta_{p2}) \quad (9)$$

And then, the following constraint exists:

$$\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5 = 1 \quad (10)$$

Eq. 10 indicates that when one operating rate changes, other operating rates will be adjusted to satisfy the constraint relation. And then, the following provision is made for the constraint equation; when normal production increases, abnormal production decreases accordingly, and the operating rate of the other states remain unchanged, and vice versa.

2) Base operating condition determination

A certain statistical cycle of the rolling process is used as a reference point to discuss the influence of each parameter on the process energy intensity; this reference point is defined as the base operating condition. The related parameters are listed in Table 1. The process energy intensity under the base operating condition is 78.1 kgce/t by calculating. And then, the influence of each parameter in the model on the process energy intensity is analyzed through the discussion of the Eq. 9. Namely when the influence of change in one factor is discussed, other parameters remain constant. Meanwhile, it can be seen from Eq. 9: the main factors that affect the process energy intensity are operating rate and qualification rate. Therefore, these two parameters are discussed in the following sections.

Table 1 Values of the base operation conditions

Name	Values	Name	Values	Name	Values
α_2	1.1	η_1 (%)	92	η_{p1} (%)	96
α_3	0.3	η_2 (%)	6.25	η_{p2} (%)	90
α_4	1.2	η_3 (%)	0.2	K (kgce/t)	72.4
α_5	1.4	η_4 (%)	0.5		
β_2	0.8	η_5 (%)	5		

5.2 Influence of operating rate

Fig. 6 shows the variation of energy intensity in a rolling process under different operating rate. And evergy operating rate is changed from 0 % to 100 % in Fig. 6.

The process energy intensity exhibits an approximately linear relationship with the operating rates of normal production, abnormal production, abnormal production transition, and stop production transition, and it exhibits a nonlinear relationship with the stop production operating rate. it's proportional to the operating rates of abnormal production, stop production, abnormal production transition, and stop production transition and inversely proportional to the normal production operating rate (shown in Fig. 6).

The influence of change in the normal production operating rate on the process energy intensity is relatively small (for every 1 % increase, it decreases approximately 0.4 kgce/t), which is primarily because any change in normal production is converted into an abnormal production state; this is why Fig. 6(a) and Fig. 6(b) are symmetric to each other.

The influence of the abnormal production transition operating rate (for every 1 % increase, the process energy intensity increases 0.96 kgce/t) and stop production transition operating rate (for every 1 % increase, the process energy intensity increases 1.16 kgce/t) on the process energy intensity is relatively large, which is primarily caused by a higher energy consumption when the production is in a transition process in which the production equipment is at the start-up stage. Moreover, compared with the abnormal production transition, the stop production transition state has a lower starting point and longer duration and thus, has a larger influence on the process energy intensity.

Relative to the other operating rates, the influence of the stop production operating rate on the process energy intensity is extremely prominent, and this influence will gradually increase with the increase of the stop production operating rate. When the stop production operating rate is lower than 50 %, its influence on the process energy intensity is relatively small; when it is at 50-75 %, the influence increases significantly, and when it is at 75-100 %, the increase in the influence is extremely prominent. The primary reason for this changing influence is that as the stop production operating rate increases, the production volume continuously decreases. It is known from Eq. 2 that the production volume has an inversely proportional functional relation with the process energy intensity such that when the stop production operating rate reaches 75 %, abrupt changes in the process energy intensity will occur. Overall, for every 1 % increase in the stop production operating rate, the process energy intensity will increase 4.1 kgce/t in average.

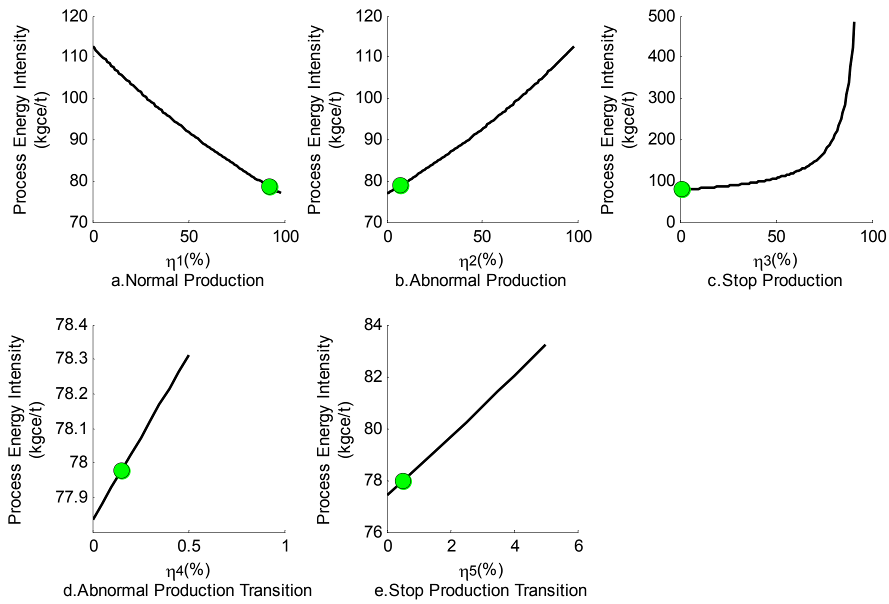

Fig. 6 Variation of energy intensity in a rolling process under different operating rate

5.3 Influence of qualification rate

Fig. 7 shows the variation of energy intensity in a rolling process under different qualification rate. And evergy qualification rate is changed from 0 % to 100 % in Fig. 7.

The process energy intensity is inversely proportion to the normal production qualification rate, and the relation is nonlinear; it's also inversely proportional to the abnormal production qualification rate, where the relation is essentially linear (shown in Fig. 7).

The influence of the normal production qualification rate on the process energy intensity is much larger than that of the abnormal production qualification rate primarily because the products produced in an abnormal production state within a statistical cycle are limited, and thus, the influence of its qualification rate is also limited. Moreover, as the normal production qualification rate gradually increases, its influence will gradually decrease; when the qualification rate is between 0-25 %, the influence is extremely prominent. As the normal production qualification rate continues to increase, the influence is significantly reduced, although it remains large compared with that of the abnormal production qualification rate. Overall, for every 1 % increase in the normal production qualification rate, the process energy intensity will decrease 12.8 kgce/t in averaged.

In summary, the influence of the stop production operating rate and normal production qualification rate on the process energy intensity is extremely prominent. Thus, these two indexes should be strictly controlled in actual production.

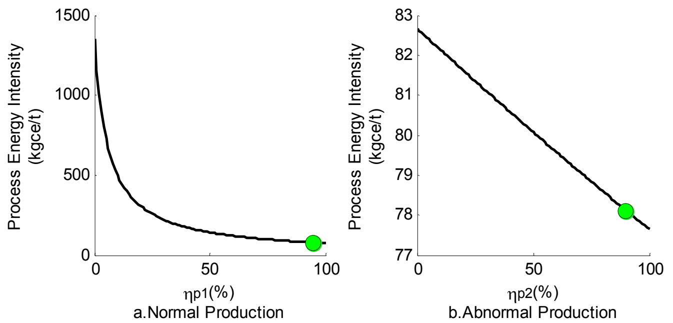

Fig. 7 Variation of energy intensity in a rolling process under different qualification rate

6. Discussion

Through above analysis, operating rate and qualification rate (especially the stop production operating rate and normal production qualification rate) are main parameters of production fluctuation. The prime factors, which bring about them change, are analyzed. And then, some management suggestions, which can improve these two parameters, are put forward.

6.1 Analysis of operating rate

The main impacts of operating rate are as follows in practical production.

1) Equipment failure or overhaul of research object

Equipment failure is the event or phenomenon that the equipment can't complete its regulation function, and it bears the characteristic of sudden. Meanwhile, it can be divided into slight fault and serious fault according to its consequences. Slight fault, which can result in decreasing of production, is generally partial functional deterioration of auxiliary equipment. This situation can be considered as abnormal production state because failure generally doesn't occur in the main production line, and equipment replacement or maintenance time is very short. Serious fault, which can bring about temporary stop production, generally occur in key equipment of the main production line. For instance, steel billets preserve heat by reducing the fuel supply in furnace when rolling mill function goes down. In any case, equipment needs to be urgent repaired, and production resumes as short as possible. In order to reduce the probability of equipment failure, what needs doing is specified as follows:

- The regulations of daily inspection tour and spot inspection should be formulated. That is, the entire production line needs to be regularly inspected, and the focal equipment should be checked carefully.
- Some parameters, which can represent equipment state, should be detected online, such as temperature, pressure, flow, voltage etc. And on-line diagnosis system should be established.
- Fault is strictly classified; fault maintenance project and strategy should be formulated. Once the failure occurs, maintenance personnel can operate in accordance with the regulations, and maintenance time can be further reduced.
- Maintenance personnel are regularly trained to enhance their professional skills.

Overhaul is the regular repair or replacement of equipment after the disintegration of all or most of the components. And then, the whole production process will be discontinued (planned shutdowns), it is characterized by a longer duration. For instance, the ironmaking process will be shut down in blast furnace overhaul. In order to shorten the overhaul time and resume production as soon as possible, some measures should be adopted, as shown in the following.

- Reasonable repair scheme, such as maintenance content determination and task allocation, is laid down before overhaul.
- Departments carry out their duties, and cooperate with each other in overhaul.

2) Equipment failure or overhaul of up-downstream production process

With the equipment failure or overhaul in up-downstream production process, the supply/demand of research object will decrease. In this paper, the relationship between the upstream production process and the research object is descried, because the influence of the up-downstream processes on the research process is consistent. There are obvious characteristics of series between the upstream production process and the research object, as shown in Fig. 8.

There is only one upstream production process in Fig. 8(a) and Fig. 8(b), so supply decreased slightly when slight fault occurs. And the inventory is adjusted dynamically to ensure the stability of the research object. When the upstream production process has a serious fault or overhaul, research object production can be kept stable if $I \geq R_s \cdot T$ (I: inventory level, metric ton; R_s: normal supply of upstream production process, metric ton/hour; T:shutdown time, hour). The demand for raw materials of the research object, that is R_s, is actively reduced in order to keep the production stability if $I \leq R_s \cdot T$, and research object is in abnormal production state at this moment. From the foregoing analysis, abnormal production is far superior to the stop production in the energy intensity. Where, it can only be discontinued if production decrease still una-

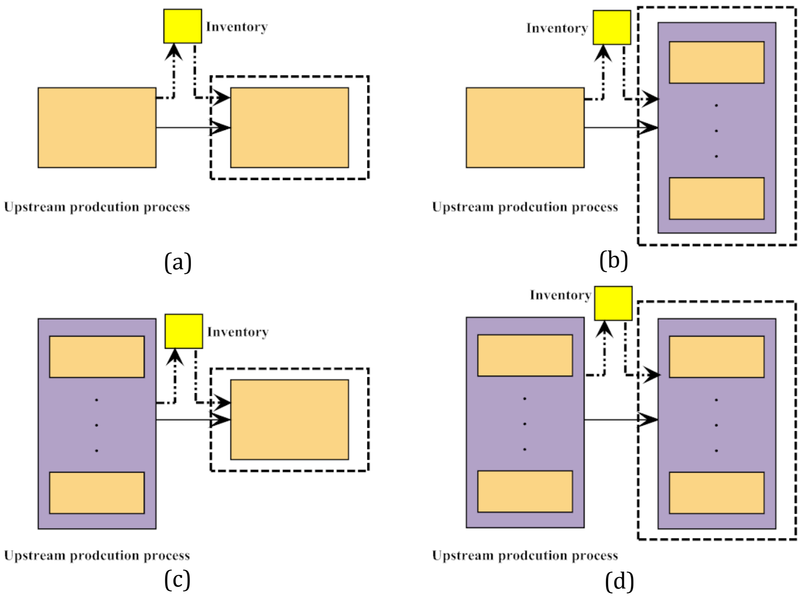

Fig. 8 The structure between production processes

ble to ensure continuous production. There are many production units in the upstream production process in Fig. 8(c) and Fig. 8(d), and there are characteristics of parallel between units. The research object will not stop production if one or a few units are discontinued (Not all). So the upstream production process also needs to formulate strict equipment maintenance regulations and reasonable repair schedules to minimize the probability of the occurrence and time of stop production. In addition, the establishment of the buffer unit (that is inventory) is beneficial to reduce the fluctuation of production.

3) The lack of market demand

Iron and steel enterprise need to reduce production because the shortage in market need. And the production capacity of iron and steel enterprise can't be fully released. So some measures should be done in order to make the production can be operated smoothly, such as readjusting product structure and remaking production schedule, according to changes in market demand.

6.2 Analysis of qualification rate

The main impacts of qualification rate are as follows in practical production.

1) The quality of raw material and fuel

The quality of raw materials is critical to the qualification rate of product. The impurity content of iron ore, which is the main raw material for iron and steel enterprise, will directly affect the quality of molten iron; even affect product quality of the subsequent process. For example, Sulfur and phosphorus are typical harmful elements in iron ores. High content of sulfur will cause the steel hot brittleness; reduce the ductility and toughness of the steel, and cracks are formed in forging and rolling. Meanwhile, sulfur is also detrimental to the welding performance and reduces corrosion resistance. In addition, High content of phosphorus will increase the cold brittleness of steel, deteriorate the welding performance and cold-bending property, and reduce the plasticity. The influence of fuel quality can't be ignored. For instance, the poor permeability of blast furnace and the furnace condition stability are affected when ash and sulfur content increase. Moreover, COG (Coke oven gas) is the major source of energy for heating furnace, some performance of steel will be poor, such as hot brittleness, if it contains high sulfur content.

2) Operating parameters of production process

Operating rules and regulations must be set up to strictly control the parameters in order to guarantee the quality of product. Otherwise, scrap rate will increase, and even cause stop production. For example, the blast kinetic energy determines the size and shape of the combustion zone in the furnace. If the blast kinetic energy is small, the gas distributes in the edge area. And conversely the center of the gas flow is disturbed. These two kinds of conditions can lead to poor quality of molten iron. Meanwhile, the billet is easy to produce surface crack and columnar crystal if the pouring temperature of the continuous casting machine is too high. Conversely inclusion can't float. Moreover, the billet is over heated and oxide scale of steel will increase if the heating furnace gas flow is too large. Conversely the billet can't be fully heated and can't be rolled.

3) Aging of equipment or backward production techniques

Inferior efficiency will happen due to aging of equipment or backward production techniques. Furthermore, qualification rate will reduce. So aging equipment and backward production techniques should be replaced or eliminated promptly.

7. Conclusions and suggestions

According to above-mentioned analysis, the following achievement can be obtained:

- This paper divides the process production state into five conditions: normal production, abnormal production, stop production, abnormal production transition, and stop production transition through analysing (E-P) method of cleaner production; and then, the process energy intensity model is constructed.

- Operating rate and qualification rate (especially the stop production operating rate and normal production qualification rate) are important index of production fluctuation on process energy intensity through case study.

Meanwhile, operating rate and qualification rate are analysed in order to reduce the impact of production volatility on process energy intensity. And some suggestions are proposed.

- Rules and regulations is a prerequisite to ensure the normal operation of equipment, and consummate rules should be formulated, such as daily inspection tour, spot inspection and fault treatment plans and so on. In addition, on-line fault diagnosis system also helps to reduce the probability of failure of equipment.
- Operation and maintenance personnel are the executive of the rules and regulations, so they need to be trained and assessed regularly to improve vocational skills.
- Buffer unit, which is conducive to reducing the volatility of production, should be adopted between production processes in iron and steel enterprise.
- The high-grade of raw/fuel and advanced production techniques favors to improve qualification rate of the product.
- Readjusting product structure and remaking production schedule can avoid production halt or abnormal production according to changes in market demand.

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Automatic high resolution measurement set-up for calibrating precise line scales

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A B S T R A C T

This paper presents a high resolution measurement set-up developed for calibrating precise line scales with measurement uncertainty of less than 0.1 µm over a total length of 500 mm. The system integrates a numerically controlled multi-axis stage, a laser interferometer, and a vision system for detecting line position. The measurement and the analysis processes are completely automated in order to minimize manual labour during the calibration process, but also increase the calibration accuracy. Increasing calibration accuracy leads up to better quality of industrial measurements which is required by modern precision industry. When designing this set-up, special attention was paid to the alignment of the measurement object in the measurement direction, considering the focus of the camera. The aim of this alignment was to reduce Abbe errors in 2 axes to negligible level. In addition, all uncertainty contributions have been determined and evaluated by performing extended experiments in specific measurement conditions. These contributions are presented in the uncertainty budget. The metrological capabilities of the presented measurement set-up were verified by some practical test measurements. Selected results of these measurements are presented in the article. This set-up will primarily improve a standard base for calibration of optical measuring devices. The use of the optical standards in the industry is constantly growing. Indirect users of the results of this research will be all manufacturers of precise products such as automotive and other industries.

A R T I C L E   I N F O

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1. Introduction

Line scales and grid plates are most common measurement standards for assuring traceability of optical measuring equipment, such as microscopes, profile projectors and digital "vision" systems. They are widely used in industry and research laboratories as calibration standards [8]. Line scales are important material standards of length, used for accurate positioning or measurement in one, two or three dimensions [1].

Industry is demanding more and more rapid and accurate dimensional measurements on diverse mechanical parts. In recent years, optical coordinate measuring machines (CMMs) having made substantial progress and are now often used for such applications. Especially CMMs equipped with imaging capabilities are frequently used for fast, non-contact measurements. Strong competition among manufacturers of such instruments and the demand for sub-micron accuracy has led to standardised tests, which are aimed for comparing and validating instrument performance [2]. Calibration, verification and also error correction of optical CMMs are mainly based on measurements using reference line scales or two-dimensional grid plates [3].

There are very many commercially available line scales made of different materials (steel, brass, invar, glass, quartz, zerodur). They can vary in length from below 1 mm to more than 1 m, and have resolutions (pitch) from below 10 nm to 1 cm. They can be calibrated by using different measurement set-ups, depending on their length and precision. Set-ups for calibrating high-precision line scales normally involve a microscope with an optical sensor for capturing and analysing the image of a line marker and a laser interferometer as a traceable measurement standard [4-6].

This paper introduces a measuring system developed for calibrating line scales with measurement uncertainty of less than 10 nm over a total length of 500 mm. The system integrates a numerically controlled multi-axis stage, a laser interferometer, and a vision system for detecting line position. With this measurement set-up, Abbe errors can be reduced to negligible levels. Abbe error occurs when the measurement point of interest is spatially separated laterally from the actual measuring scale location (reference line or axis of measurement), and when angular error motions exist in the positioning system. Abbe error causes measured displacement to appear longer or shorter than the true displacement, depending on the direction of angular motion. Spatial separation between the measured point and reference line is known as an Abbe offset [7].

Since it is possible to put optical components very close to each other, the air dead path error of the laser interferometer is also negligible. Software for detecting the middle of the lines is based on earlier design from 2009 [9]. In order to improve performance and to achieve better uncertainty, the software was improved and automatized, mechanics and optics have been redesigned and several uncertainty components better characterized. This facility will replace the old measurement facility that is manually operated. A model for evaluating uncertainty and the uncertainty budget for the demonstrated measuring system is presented in the paper.

2. Measurement system

2.1 Numerically controlled multi-axis stage

Numerically controlled multi-axis stage was designed and manufactured by Newport-micro controle [10] for the Laboratory for Production Measurement (LTM), University of Maribor, Slovenia. It is shown in Fig. 1, while its schematic diagram is shown in Fig. 2. The measuring system designed by the LTM is intended to perform 2D measurements on various objects, which will be fixed on a measuring table. This research is focused in 1D measurements. Newport's solution is based on a HybrYX-G5 stage featuring a ceramic carriage which freely slides in X and Y axes on a precision lapped granite reference plate, using proprietary pressure-vacuum air bearing design. The carriage is guided along Y axis by a rigid ceramic beam. The beam is supported and guided at each end with the ball bearing carriages of X axis. Both X and Y axes are motorized with linear actuators and include linear glass encoders. Both linear scale glass encoders are LIDA403 made by Heidenhain, length 440 mm for X axis and length 1250 mm for Y axis. This positioning system is equipped with the optional Z-Tip-Tilt and Theta stage. It is motorized by precision actuators equipped with miniature DC servo motors. The position system is built on a heavy granite table, which features a precision reference plane for the air bearing carriage. In addition, the granite structure includes a granite gantry allowing the fixation of a vertical motorized translation stage, which accommodates the measuring sensor, depending on an application. Two rails mounted on the gantry equipped with sliding carriages provide manual rough positioning capability. The granite structure is set on a heavy welded frame equipped with ND40 passive isolators. The position system has one XPS motion controller including dedicated drivers for the five DC motors and the three linear motors.

The X axis is dual axis composed of X1 and X2 actuators mounted on the flanks at both ends of the granite table. X1 and X2 carriages move the ceramic beam of the Y axes. The X axis travel range is +/- 175 mm. It has a linear encoder with 5 nm resolution. The maximal speed is 300 mm/s., while the repeatability is 500 nm.

The Y axis is a horizontal translation stage using air bearing technology and linear motor. The guiding beam of Y axes sub-assembly is attached to the carriages of the X1 and X2 short travel translation actuators. The guideways involve two parts: a large ceramic carriage and a Y-axis guide ceramic L-shape beam. The ceramic carriage freely slides in X and Y axes using pressure-vacuum air bearing design. The reference planes for the air bearing carriage are the precision lapped surface of the granite table and the vertical slide of the Y rigid ceramic beam. The Y axis travel range is +/- 500 mm. It contains a linear encoder with 5 nm resolution. Maximum speed is 600 mm/s., while the repeatability is 100 nm.

The ZTT Theta stage is mounted on the air bearing carriage; it is equipped at the top with the measuring platform, which allows installing measured objects. All axes are driven by the high precision motorized linear actuators. Three actuators are set in upright position with a travel range of 10 mm. One actuator is set horizontally to achieve the theta Z movement with a travel range of +/- 1°. All four actuators are equipped with a miniature DC motor made by Fulhaber.

Z axis is a vertical motorized translation stage on the middle carrier. It is a Newport catalogue stage reference M-IMS100V. The Z axis travel range is 100 mm, the minimum incremental motion is 0.3 μm, the encoder resolution is 0.1 μm, the maximum speed is 20 mm/s, while the repeatability is ± 0.5 μm.

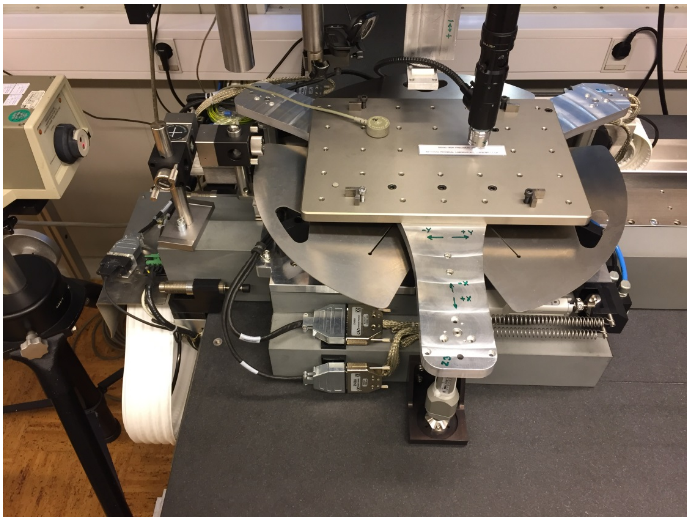

Fig. 1 Measurement set-up for calibrating line scales

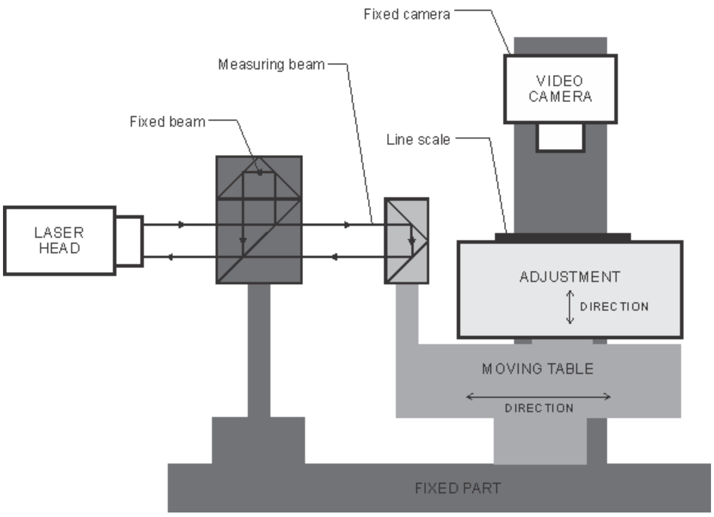

Fig. 2 Schematic diagram of measurement set-up for calibrating line scales

2.2 Laser interferometer

Laser interferometer position measurement systems provide very precise position or distance information. Our system consists of a laser head HP 5528A, Agilent module 55292A, and a variety of optical components and accessories such as material sensors and air sensor. The basic system measures linear displacement. The system uses the wavelength of light from a low-power helium-neon laser as a length standard. We normally set the resolution of the laser interferometer to 10 nm. Special mounting elements were constructed for the optics used for calibration. A schematic diagram of the laser interferometer and the position of the optics are shown in Fig. 2. The position of the optical elements and the moving parts are set in such way, that the measured object axis is set in the line with the centre of the laser linear retroreflector. It allows the Abbe errors to be reduced to negligible levels even for the most demanding dimensional metrology tasks [11]. The linear interferometer is fixed on the fixed part of the stage, while the retroreflector is placed on the moving table in the horizontal direction. Only the measured object is placed on the moving table that can move in the vertical direction.

2.3 Vision system for detecting line position

The vision system for detecting line position consists of a zoom microscope and a CMOS digital camera. The camera is connected to the computer via USB 3.0 port. The CMOS camera gets the images of the line scale and sends them to the computer software. The software analyses the images and determinates the middle of the line in the measured window as shown in Fig. 3, which is defended by the operator. The software calculates the distance in pixels from the reference position, which is marked with the blue line, to the middle of the measured line that, is marked with the red line. The image positioning screen with the measurement window, reference and measured line is presented in Fig. 3. The CMOS digital camera takes 15 monochrome images per second in resolution 2592 × 1944 pixels. The software analyses the images in real time. The distance calculated in pixels is transformed into micrometers [12]. The software for calculation the distance between lines is more detailed presented by the authors in paper [9].

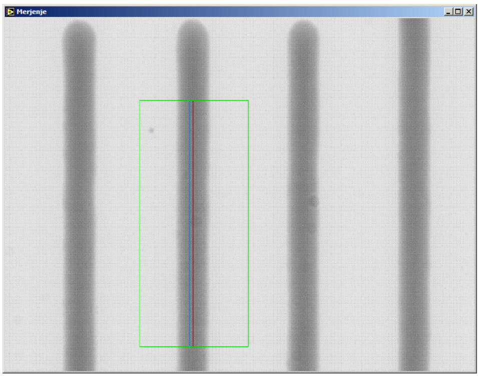

Fig. 3 Screen image of the vision system for detecting line position

2.4 Measurement procedure

Line scales are material measures made of glass, steel or other material, on which dimensions are marked with line marks. Since the materials have quite different temperature expansion coefficients, which are in many cases notexactly known, they are stabilized before calibration in the climatic room at 20 °C for 24 hours. The measurement system must be adjusted and initialized before the measurement. The line scale should be positioned under the camera by moving the measurement table. The measuring system, laser interferometer, vision system for detecting line position and line scale should be adjusted according to the measuring direction, which is defended by the movement of the horizontal direction of the table. The line scale should be fixed on the adjustment table under the camera. The camera is fixed. It is adjusted in such a way, that the focus of the camera intersects the centre of the laser linear retroreflector. The camera is focused on the lines of the line scale by moving the adjustment table (ZTT Theta stage) in the vertical direction. With this procedure, the line scale axis, the images of the lines and the centre of the laser linear retroreflector with the laser beam are positioned in the measuring direction. The image processing software should be initialized [9]. With the improved software, connection to the numerically controlled multi-axis stage and connection to the laser head, automatic measurements of distances are possible. The measurement goal is to measure distances between the reference line and the chosen measuring lines on the line scale automatically. Measured data are saved into the file where they are ready for further processing.

2.5 Principle for minimising Abbe error

In respect to the movement parts of the measuring system, the system can be divided into three different parts. The first part is the fixed part ant it includes the laser head, the linear interferometer and the USB 3.0 camera. The second part is the moving part in the horizontal direction and it includes the linear retroreflector, the moving table and the measured object. The third part is the moving part in the vertical direction and it includes the moving table and the measured object. The third part is used only for adjusting the line scale in respect to the measuring object direction. The camera is in the fixed distance, so that the focus of the camera is on the top of the moving table. This means that the theoretical measured lines that could be on the top of the table, are in the focus of the camera and simultaneously with the laser optics. Only the moving table with the line scale could be moved in the vertical direction. This procedure allows us moving the lines of the line scale into the focus of the camera and in the same time into the centre of the laser optics. With this procedure, the minimum Abbe error can be achieved.

One of the most important sources of error in dimensional measurement is Abbe error. Abbe error consists of an Abbe offset and a small angular variation due to pitch and yaw of the stage that moves the measuring table with the measured object and the linear retroreflector. This component is caused by the measuring table inclination along the measurement path (Y axis). The best available tool for analysing angular error is a laser interferometer. Pitch and yaw measurements were made by making angular measurements at multiple points along the linear travel path in the Y axis as shown in Fig. 4. The angles of the measuring table were measured by using angular interferometer optics. The greatest Abbe errors were evaluated by analysing extreme angular deviations.

For pitch (Fig. 4), the greatest angle differences along the measurement path of 500 mm was 7 µm/m. The maximum offset of the laser reflector of 3 mm in the Z direction was estimated. Therefore the expected error interval for pitch is:

$$I = 7\ \text{nm/mm} \cdot 3\ \text{mm} = 21\ \text{nm} \tag{1}$$

Standard uncertainty at supposed rectangular distribution for the Abbe error for pitch is:

$$u_{\text{zy}}(e_{\text{a}}) = \frac{21\ \text{nm}}{\sqrt{3}} = 12\ \text{nm} \tag{2}$$

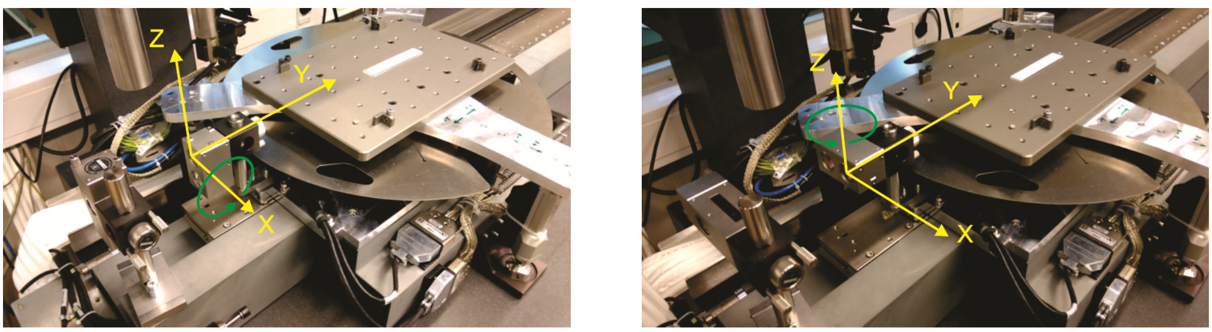

Fig. 4 Pitch and yaw measurements of the stage in Y direction

For yaw (Fig. 4), the greatest angle differences along the measurement path of 500 mm was 10 μm/m. The maximum offset of the laser reflector of 1 mm in the X direction was estimated. Therefore the expected error interval for the yaw is:

$$I = 10\ \text{nm/mm} \cdot 1\ \text{mm} = 10\ \text{nm} \tag{3}$$

Standard uncertainty at supposed rectangular distribution for the Abbe error for the yaw is:

$$u_{\text{xy}}(e_{\text{a}}) = \frac{10\ \text{nm}}{\sqrt{3}} = 5.8\ \text{nm} \tag{4}$$

Total standard uncertainty due to Abbe error $u(e_{\text{a}})$ is:

$$u(e_{\text{a}}) = \sqrt{u_{zy}^2(e_{\text{a}}) + u_{xy}^2(e_{\text{a}})} = 13\ \text{nm} \tag{5}$$

3. Uncertainty of measurement

3.1 Mathematical model of measurement

The measured value in the calibration of a line scale is a deviation from a nominal distance between two line centres. The distance between two lines is calculated as a sum of laser interferometer indication and vision system for detecting line position indication. The vision system for detecting line position measures the distance between the measurement point (scale mark) and the reference line. Deviation e (measurement result) is given by the expression:

$$e = (L_{\text{LI}} + L_{\text{V}} - L_{\text{LIref}}) \cdot (1 + \alpha_{\text{m}} \cdot \theta_{\text{m}}) - N + e_{\text{cos}} + e_{\text{mp}} + e_{\text{ms}} + e_{\text{a}} \tag{6}$$

where:

- e deviation (measurement result) at 20 °C
- L_{LI} corrected length shown by laser interferometer
- L_{V} distance between the measurement point (scale mark) and reference line in the image window
- L_{LIref} indication on the laser in the reference (origin) point
- α_{m} linear temperature expansion coefficient of the scale
- θ_{m} temperature deviation of the scale from 20 °C
- N nominal value (without uncertainty)
- e_{cos} cosine error of measurement (supposed to be 0)
- e_{mp} dead path error
- e_{ms} random error caused by uncontrolled mechanical changes
- e_{a} error caused by the measuring table inclination

3.2 Standard uncertainty

For uncorrelated input quantities the square of the standard uncertainty associated with the output estimate y is given by equation (7) [12]:

$$u^2(y) = \sum_{\text{i}=1}^{\text{N}} u_{\text{i}}^2(y) \tag{7}$$

The quantity $u_{\text{i}}(y)$ $(i = 1,2,\dots,N)$ is the contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with input estimate x_{i} [12]:

$$u_i(y) = c_i \cdot u(x_i) \tag{8}$$

where c_i is the sensitivity coefficient associated with the input estimate x_i, i.e. the partial derivative of the model function f with respect to X_i, evaluated at the input estimates x_i [12].

$$c_i = \frac{\partial f}{\partial x_i} = \frac{\partial f}{\partial X_i}\bigg|_{X_1 = x_1, \dots, X_N = x_N} \tag{9}$$

Table 1 Uncertainty budget for calibration of line scales

Value X_i	Estimated value	Standard Uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution
L_{LI}	0 mm	13 nm + $0{,}2{\cdot}10^{-6}{\cdot}L$	normal	1	13 nm + $2{,}5{\cdot}10^{-7}{\cdot}L$
L_{V}	<5 µm	25 nm	normal	1	25 nm
L_{LIref}	0 mm	9 nm	normal	-1	9 nm
α_{m}	10^{-5} °C^{-1}	$1{,}15{\cdot}10^{-6}$ °C^{-1}	rectangular	0,05 °C$\cdot L$	$0{,}06{\cdot}10^{-6}{\cdot}L$
θ_{m}	0°C	0.05 °C	normal	10^{-5} °C$^{-1}{\cdot}L$	$0{,}05{\cdot}10^{-5}{\cdot}L$
e_{cos}	0	0 nm	normal	1	0 nm
e_{mp}	0	9 nm	rectangular	1	9 nm
e_{ms}	0	30 nm	normal	1	30 nm
e_{a}	0	13 nm	rectangular	1	13 nm
				Total:	$\sqrt{(45\ \mathrm{nm})^2 + (5{,}6 \cdot 10^{-7} \cdot L)^2}$

3.3 Expanded uncertainty

Combined standard uncertainty, calculated from the uncertainty budget, is:

$$u = \sqrt{(45\ \mathrm{nm})^2 + (5{,}6 \cdot 10^{-7} \cdot L)^2} \tag{10}$$

The expanded uncertainty for the coverage factor k = 2 is then:

$$U = \sqrt{(90\ \mathrm{nm})^2 + (1{,}1 \cdot 10^{-6} \cdot L)^2} \tag{11}$$

3.4 Experimental results

The measurement accuracy of the numerically controlled multi-axis stage was verified with the laser interferometer [9] in Y direction over the distance (0 to 500) mm by twenty repeated measurements in eleven positions. The absolute difference between the reference value shown by the laser interferometer and the encoder value in the Y axis of the measuring system is shown in Fig. 5.

Experimental standard deviation that reflects random influences is shown in the diagram in Fig. 6. Random influences are caused by the multi-axis stage instability, vibrations and random changes of environmental conditions. Presented standard deviations were used in uncertainty budged of the calibration procedure.

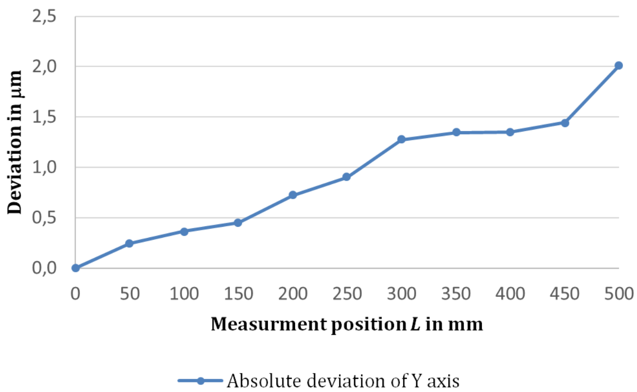

Fig. 5 Absolute deviation between laser values and encoder value

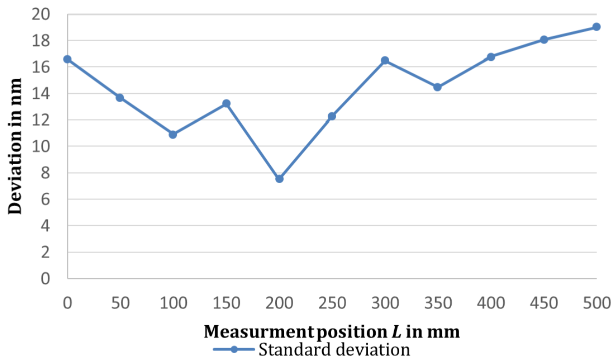

Fig. 6 Standard deviation on measurement positions

Measurement accuracy of the measuring system was verified on a calibrated line scale over the distance 0-100 mm. Experimental standard deviation s(L) (12):

$$s(L) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(L_j - \overline{L}\right)^2} \tag{12}$$

that reflects random influences is shown in the diagram in Fig. 7. The diagram also represents the deviation of measured values from the reference and estimated standard uncertainty. These results characterize the measuring system which will allow calibrations of length measurements without laser interferometer. Measuring results presented in Fig. 7 represent a linear characteristic. It is possible to compensate the error with the appropriate error mapping. From the results we can see that it is possible to improve the measurement uncertainty.

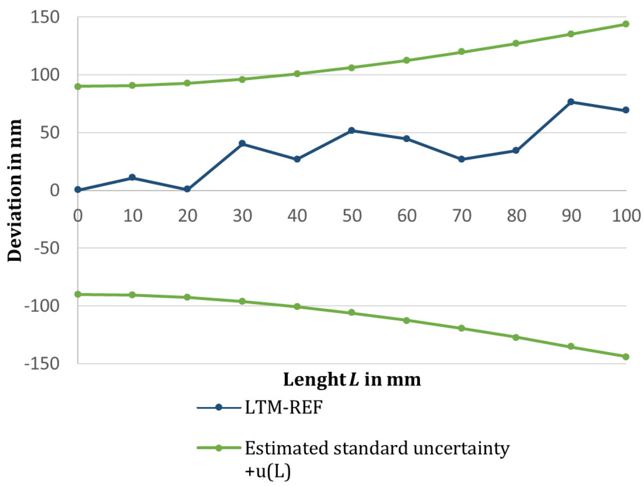

Fig. 7 Deviation of measured values from reference and estimated standard uncertainty

4. Conclusion

The main result of the presented research is a verified measuring set-up for calibrating line scales consisting of the numerical controlled multi-axis stage, the laser interferometer and the vision system for detecting line position.

The presented procedure for calibrating line-scales with lengths up to 500 mm, with the measuring uncertainty expressed by equation (11) has already been accredited by the national accreditation body. In respect to the previous measurement set-up, we have improved the measuring system with new automatic numerical controlled multi-axis stage, better CMOS camera and better environmental conditions. Better calibration and measurement capability (CMC) was achieved and approved. Improved measuring set-up and system alignment [12] procedure lead to better Abbe error characterization. The calibration, verification and also error correction of optical CMMs is mainly based on measurements using reference line scales or two-dimensional grid plates [2]. Our further work will focus on calibrating 2D optical grids and evaluating uncertainty of this calibration. The validation process and verification procedure for measuring precise 2D grids is in preparation. One of the final goals of this validation phase was to determine uncertainty of measurement in calibration and verification of new automatic high resolution measuring set-up for calibrating precise line scales [13, 14].

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Calendar of events

- 19th International Conference on Production Engineering and Management, Boston, USA, April 24-25, 2017.
- 10th International Conference on Industrial Tools and Advances Processing Technologies, Ljubljana, Slovenia, April 24-26, 2017.
- 8th International Conference on Material and Manufacturing Technology, Singapore, May 4-6, 2017.
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- 21st Conference of the International Federation of Operational Research Societies, Quebec City, Canada, July 17-21, 2017.
- 7th International Conference on Simulation and Modeling Methodologies, Technologies and Applications, Madrid, Spain, July 29-31, 2017.
- 2nd International Conference on Design and Production Engineering, Birmingham, UK, August 21-22, 2017.
- 11th International Conference on Advanced Materials & Processing, Edinburgh, Scotland, September 7-8, 2017
- 3rd International Conference and Exhibition on Automobile Engineering, Berlin, Germany, September 28-29, 2017.
- 4th World Congress on Robotics and Artificial Intelligence, Osaka, Japan, October 23-24, 2017.
- International Conference on Mechatronics, Automation and Intelligent Materials, Paris, France, October 30-31, 2017.
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