Scheduling Method for Simultaneous Reduction of Makespan and Weak Points of Workers

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Abstract. Recent production environment promotes development of new products and production of various types of products in short periods by diversification of customer's needs. These phenomena cause that many factories treat high-mix low-volume production. Therefore, many factories introduce cell production system for assembly process based on small number of workers to which multi-works are assigned in order to flexibly produce different types of products in the production environment. However, the production system depends on workers' skill with regards to effectiveness of production. This study focuses on cell production system for assembly process based on workers to which multi-works are assigned. We propose scheduling method to assign jobs to workers who possess different skill levels. In addition, evaluation method of workers' skill to treat similar products and similar operations is proposed. The scheduling method is mainly constructed by mathematical model for simultaneous reduction of makespan and weak points of workers. The scheduling method uses data obtained by the evaluation methods of workers' skill. The evaluation of workers' skill is constructed of two types of analyses: analysis of the difficulties of operations based on parts structures of products and analysis of operation time of workers obtained from actual works of similar products. Numerical experiment is performed to evaluate the effectiveness of the proposed scheduling method by using simple products.

Keywords: Scheduling problem, Mathematical model, Workers' skill, Similarity of operations, Analysis of skill and similarity

1. INTRODUCTION

In many factories for high-mix low-volume production or single product manufacturing, a process line is constructed by assigning multiple handling works to single workers (Iwamoto 2002). Although different works and parts are allocated to this process line for processing different products, similar products and similar works are ordinarily included in the works and the parts (Kadota, et al. 1991).

Therefore, the processes easily cause mistakes of works in the line that consists of single workers assigning multiple handling works. In addition, productivity of the line is influenced by difference of workers' skill if works are inadequately assigned to workers.

If the production system to complete manufacturing a product by single workers is promoted, single workers have to operate individually and workers continuously process without waiting time to start the continuous operation. However, since operation is difficult to continuously maintain constant time in the production system to complete manufacturing a product by single workers, operation time is easily varied and prolonged and total productivity easily comes to be reduced in the factory.

If the level of workers' skill is evaluated and works are assigned to adequate workers, productivity of production process can be enhanced in the factory. In order to resolve the problem, it is valuable that the level of workers' skill is quantitatively evaluated depending on characteristics of works. Furthermore, scheduling method to assign works to workers can be developed to prevent from mistakes and troubles of operations by using the quantitative level of workers' skill.

In this study, we focus on multiple handling works for parts assembly process on high-mix low-volume production and propose multi-objects scheduling method to assign works to workers to minimize both makespan and possible level of trouble of operations of workers. Factors that cause difficulties of works are determined from relative structure of a part and a semi-finished product in order to quantitatively evaluate the level of workers' skill. In addition, a method to evaluate the level of workers skill is developed by using the measured operation times of resemble works and the difficulties level estimated from the relative structure. Parallel processing production system consisting of multiple workers is assumed as the scheduling problem for multiple handling works. Mathematical model is constructed to resolve the problem as scheduling method. The numerical experiment is performed to evaluate the proposed method to estimate the level of workers' skill and the proposed scheduling method.

2. EVALUATION OF WORKE'S SKILL AND SIMILARITY OF OPERATIONS

2.1 Evaluation of characteristics of workers' skill

The following two characteristics for evaluating difficulties of works require to be evaluated in order to generate a schedule considering workers' skill aiming at construction of efficient process line.

(1) Skill of workers depending on works in an assembly process

(2) Similarity of operations depending on structure of products

Characteristics (1) and (2) are related to personal characteristic of workers and physical structure of products, respectively. Characteristic (1) indicates that characteristics of strong and weak points for works are quantitatively evaluated for all workers. If the works could be assigned to workers who have strong points for the works, mistakes of operations and operation times could be reduced. Characteristic (2) indicates that similarity of operations is evaluated in different jobs. When a job was previously assigned to a worker who has strong points for the job and similar jobs to the job are assigned to the identical worker, it is expected that both operation time and mistakes of operations are reduced.

In this section, we focus on a method for evaluating difficulty of jobs related to Characteristics (1). When the level of workers' skill can be quantitatively evaluated, jobs including strong or weak point can be analyzed for individual workers, productivity would be promoted by assignment of jobs to workers who have strong points in the jobs. We propose a method to analyze characteristics of workers' skill from two types of operation times for individual workers: predetermined operation time calculated by MTM method (Sellie, 1991), measured operation time. Strong or weak point included in the jobs for manufacturing new products is evaluated for different workers from the analyzed characteristics. "Evaluation value of workers' skill level" is defined as Equation (1) in order to evaluate skill level of individual workers.

$$\text{Evaluation value of workers' skill level} = \frac{\text{measured operation time}}{\text{predetermined operation time}} \quad (1)$$

Here, "predetermined operation time" denotes operation time predetermined by using MTM method under the condition that the easiest operations are assumed to assemble a product. Figure 1 denotes schematic diagram to evaluate workers' skill level by the proposed analysis method. If jobs include high difficult works, measured operation times of the jobs would be larger than estimated operation time of the jobs that are constructed of the easiest and simplified operations. Therefore, "evaluation value of workers' skill level" can be used to evaluate influence of difficulties in jobs with regard to individual workers. The workers' skill denotes low level when the evaluation value is a large number.

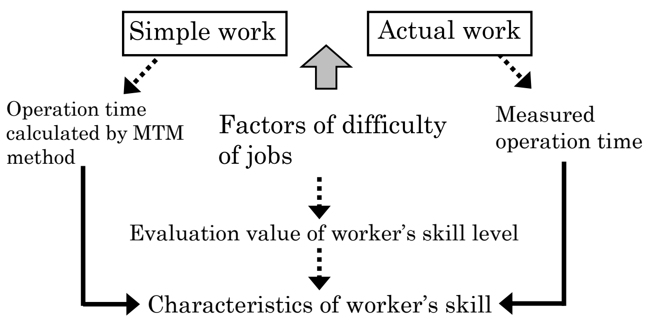


Figure1: Schematic diagram of evaluation method of workers' skill

2.2 Evaluation of difficulties of operations in assembly process

In this study, we focus on factors that cause difficulties of operations in assembly process in order to evaluate the difficulties. Here, it is assumed that multiple factors influence difficulty of every operation and levels of operation difficulties of the factors depend on physical structure of products. Workers individually influence operation difficulties of the factors and works to manufacture new products can be separated into triumphant works and un-triumphant works for every worker.

We consider that assembly process of products consisting of parts represents that a single part is continuously assembled to a semi-finished product to complete the finished product. The operation to assemble a single part to a semi-finished product regards as a single work element to complete the product. Figure 2 shows Factor Analysis Figure related to factors that cause operation difficulty in assembly process with parts. Figure 2 denotes factors can be separated into three categories: a part to assemble, a semi-finished, and support parts as screws, nuts, bolts, and so on. We evaluate eleven factors as shown in this figure. Table 1 shows sample of quantitative levels of factors of difficulties of operation evaluated from physical structure of a semi-finished product when a single part is assembled to the semi-finished product. This table is generated from Figure 2 and is published by Arakawa (Arakawa, 2009).

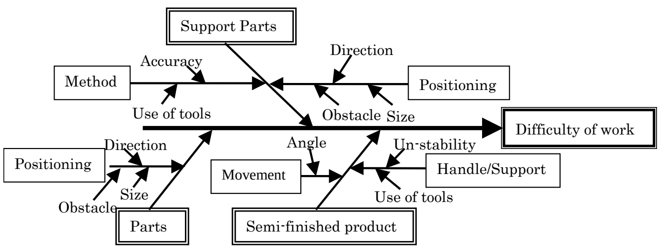


Figure 2: Cause and effect diagram related to difficulties of operations in assembly process

Table1: Sample of levels of factors of difficulties of operations

Objects	Categories	Factors
Parts	Positioning	(1) Direction or side from which a single part is assembled (5 levels)
		(2) Size (5 levels)
		(3) Obstacles near the parts (7 levels)
Support parts	Positioning	(4) Direction or side from which a single part is assembled (5 levels)
		(5) Size (5 levels)
		(6) Obstacles near the parts (7 levels)
	Method to assemble parts	(7) Usage of tools (3 levels)
		(8) Clearance (5 levels)
Semi-finished product	Supporting	(9) Unsteadiness (5 levels)
		(10) Unsteadiness of parts (5 levels)
	Movement	(11) Angle of rotation of semi-finished product (4 levels)

2.3 Evaluation of similarity of operations from physical structure of products

In this section, we focus on a method for evaluating similarity of operations depending on structure of products related to Characteristics (2). When jobs including strong points for the workers are assigned to the identical workers by using similarities of the operations included in the jobs of new product, the scheduling would be generated for high productivity by assignment of the jobs.

In this study, we evaluate the similarities of operations in jobs by comparison of physical structures of parts between different products for Characteristics (2). Because physical structures of parts influence assembly processes in which a single part is continuously assembled to a temporal semi-finished product. The levels of the factors of difficulties of operations are evaluated from physical structures of a semi-finished product and a single part to assemble by using Table 1. The levels of different factors of difficulties of operations are normalized by the maximum level values of the factors. The averages of the normalized levels of individual factors of all operations are calculated by using Equations (2). The average levels are adopted as characteristic difficulties of operations in assembly process for the product. Using these average levels, the characteristic difficulties of operations for the product are presented by radar chart as show in Figure 3.

$$e_{p,k} = \frac{1}{n_p} \sum_{w=1}^{n_p} e_{p,k,w} \qquad \forall p, \forall k \qquad (2)$$

Here, $e_{p,k}$ and $e_{p,k,w}$ indicate the non-dimensional levels of factor k of total operations and operation w respectively in assembly process for product p. n_p indicates the number of operations in assembly process for product p.

We evaluate the similarity of operations between different products, $simil_{p,p'}$, by calculating the ratio of the overlapped inner area to the maximum area combined from two radar charts obtained from the products. The ratio of the overlapped inner area to the maximum area is approximately calculated as a singles non-dimensional value by using Equations (3), (4), and (5). When the value is approximately 1.0, similarity of operations denotes high between the different products. On the other hand, when the value is smaller than 1.0, the similarity denotes low.

$$e_{\min\, p,p',k} = \min\{e_{p,k}, e_{p',k}\} \qquad \forall p, \forall p', \forall k \qquad (3)$$

$$e_{\max\, p,p',k} = \max\{e_{p,k}, e_{p',k}\} \qquad \forall p, \forall p', \forall k \qquad (4)$$

$$simil_{p,p'} = \frac{\sum_{k=1}^{K} e_{\min\, p,p',k}}{\sum_{k=1}^{K} e_{\max\, p,p',k}} \qquad \forall p, p' \qquad (4)$$

Here, $e_{min\, p,p',k}$ and $e_{max\, p,p',k}$ indicate the minimum and the maximum non-dimensional level of factor k of operations between products p and p'. K indicates the number of factors to evaluate difficulty of operations.

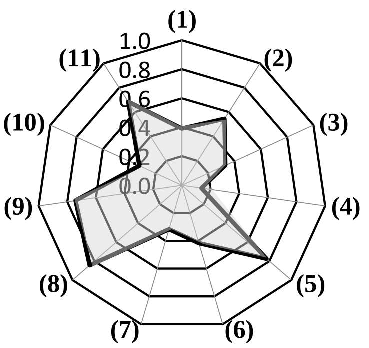


Figure 3: A sample of radar chart for the characteristic difficulties of operations (The numbers indicate factors between (1) and (11) in Table 1.)

3. CASE STUDY

3.1 Evaluation of difficulties of jobs and similarities of operations using actual products

In this section, the similarity of operations and the difficulty of jobs are evaluated by performing an assembly process using actual products. Figure 4 shows the products used in the evaluation. The products are two types of structures made of LEGO blocks (LEGO Co. Ltd.): Products 1 and 2. Subjects who perform the experiment are consists of three males between 22 and 23. They are called as Subject A, B, and C, hereafter. The skill levels of to the subjects are analyzed and the assignment of jobs to the adaptive subjects is performed according to the following process:

(1) All subjects perform assembly process of Product 1 and operation time is measured. The evaluation value of workers' skill level is calculated for all subjects by using Equation (1) for semi-finished products of Product 1.

(2) The difficulties of jobs for the semi-finished products of Products 1 and 2 are evaluated from physical structure of the products.

(3) The difficulties of jobs in assembly processes for the semi-finished products of Product 2 are evaluated by using the results obtained in (2). The similarity of operations is calculated in assembly processes for all semi-finished products of Products 1 and 2.

(4) The jobs are assigned to the adaptive subjects for assembling the semi-finished products of Product 2. The jobs are assigned to workers who have high skill level to assemble similar jobs.

Here, the following semi-finished products of Products 1 and 2 are evaluated in order to easily evaluate the difficulty of jobs and the similarity of the operations: head, body, legs, and tail.

(1) Product 1 (2) Product 2

Figure 4 Products used in case study

3.2 Evaluation of assignment of the jobs to the subjects

Figure 5 shows the operation times measured in the assembly process of the semi-finished products of Products 1 with regard to all subjects. P1-Head, Body, Leg, and Tail indicate the semi-finished products corresponding to the head, the body, the leg, and the tail of Product 1, respectively. The operation times measured at 6th trial are used for all subjects in Figure 5. Table 2 denotes the evaluation values of workers' skill level for assembling the semi-finished products of Product 1. The evaluation values are calculated by using the measured operation times in Figure 5 and the predetermined operation times calculated by MTM method. The subjects who have strong points are recognized for assembly process of different semi-finished products from Table 2. Subject A is most efficient to assemble P1-Head.

Table 3 denotes the similarities of operations for assembling between different semi-finished products. The values of the similarities are calculated by using Equation 4 with the radar charts for the semi-finished products. Here, since the table of the similarities between the products is a symmetric matrix, parts of elements where duplicating values are allocated are reduced in Table 3. We can recognize the semi-finished products of Product 1 which is most similar to different semi-finished products of Product 2, because the largest value denotes the most similar operations between the products. Table 4 denotes the most adaptive subjects to assemble the semi-finished products evaluated from the similarities of operations. The results are generated from Tables 2 and 3. The most adaptive subjects are selected to assemble the products from Table 2. Then, the semi-finished products of Product 1 which are most adoptive to the semi-finished products of Product 2 are selected from Table 3. Finally, the subjects which are most adoptive to the semi-finished products of Product 2 could be selected as shown in Figure 5. These tables denotes that the evaluation of difficulties of operations for different workers and similarities of jobs between different products is valuable.

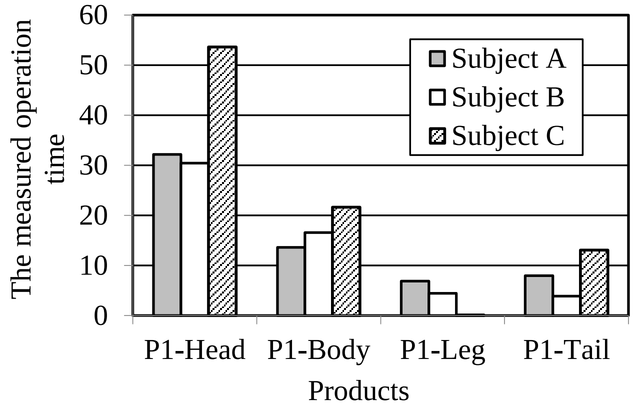


Figure 5: The measured operation time to assemble different semi-finished products of Product 1

Table 2: The evaluation values of workers' skill level for assembling different semi-finished products

	Subjects		
	A	B	C
P1-Head	1.16	1.10	1.93
P1-Body	0.71	0.86	1.13
P1-Leg	0.63	0.41	0.01
P1-Tail	1.99	0.97	3.26

Table 3: The similarities of operations for assembling between different semi-finished products

	P1-Head	P1-Body	P1-Leg	P1-Tail
P1-Head	1	0.673	0.656	0.696
P1-Body	0.673	1	0.813	0.67
P1-Leg	0.656	0.813	1	0.819
P1-Tail	0.696	0.67	0.819	1
P2-Head	0.774	**0.854**	0.847	0.724
P2-Body	0.656	**0.975**	0.830	0.679
P2-Leg	0.601	0.878	**0.917**	0.747
P2-Tail	0.765	0.773	0.857	**0.886**
	P2-Head	P2-Body	P2-Leg	P2-Tail
P2-Head	1	0.847	0.777	0.824
P2-Body	0.847	1	0.894	0.784
P2-Leg	0.777	0.894	1	0.786
P2-Tail	0.824	0.784	0.786	1

Table 4: The most adaptive subjects to assemble the semi-finished products evaluated from the similarities of operations

Subjects	The semi-finished products			
A	P1-Body		P2-Head	P2-Body
B	P1-Head	P1-Tail	P2-Tail	
C	P1-Leg		P2-Leg	

4. SCHEDULING METHOD CONSIDERING LEVEL OF WORKERS' SKILL

4.1 Scheduling model

In this chapter, the scheduling method is developed to promote productivity and to reduce mistakes of operations by using the analyzed data related to characteristics of workers. A process line is constructed by assigning multiple handling works to single workers. The similarities of operations between different products and the evaluation values of workers' skill level for the products are used to assembling different semi-finished products are considered in the scheduling problem.

The parallel process system consisting of multiple workers is constructed as the model to promote productivity. Multiple handling works are assigned to every worker. Figure 6 shows schematic diagram of this model. Multiple products are processed in the process line and semi-finished products are manufactured by each workers. If there are multiple same works or same semi-finished products, these same works or these same semi-finished works are prefer to be assigned to the same workers to enhance productivity. Figure 7 shows a sample of schedule obtained under the condition shown in Figure 6. 'Job' shown in Figure 6 denotes the jobs related to operations to complete semi-finished products in the problem. And 'WK' denotes the workers.

In this study, we suppose that operation times of jobs are not influenced by workers' skill and difficulties of operations depending on parts structure. Because the operation times are difficult to be estimated and the operation times including deviations are similar among skilled workers. However, we evaluate the difficulty of operations for jobs by considering workers' skill and difficulties of operations depending on parts structure when the jobs are assigned to workers.

Multi-objective functions are introduced in this scheduling problem: makespan and total of all workers' skill levels. The mathematical model is constructed to resolve the problem. Numerical experiment is performed to evaluate the performance of the model.

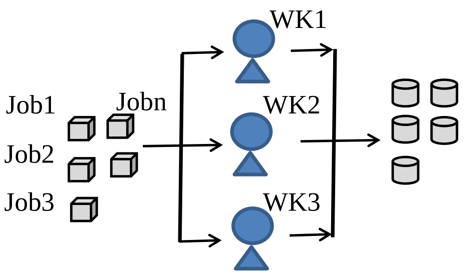


Figure 6: Schematic diagram of the scheduling model

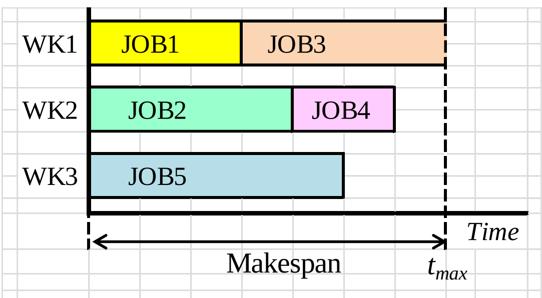


Figure 7: A sample of schedule obtained under the condition shown in Figure 6

4.2 Mathematical model

In this section, the mathematical model is constructed for the scheduling problem. The mathematical model is represented as follows:

Parameters:

j : Job $j \in \{1, 2, \dots J\}$

w : Worker $w \in \{1, 2, \dots W\}$

$t_{j,w}$: The operation time of job j when worker w is assigned to the work element,

$q_{j,w}$: The difficulty of operations for job j when worker w is assigned to the job,

$r_{j,j'}$: The similarity of operations between job i and job i' . When the operation of job i is no similar to that of job i' , the parameter is 0,

$k_{i,w}$: The coefficient to estimate operation time considering difficulty of job j when worker w is assigned to the job. The coefficient is corresponding to the evaluation value of workers' skill level,

L_{max}: The lower value of similarity of operations for jobs assigned to identical workers,

Q_{max}: The maximum number of the difficulties.

Variables:

$\delta_{j,w}$: When job j is assigned to worker w, the variable is 1. Otherwise, the variable is 0,

$z_{j,j',w}$: When job j and job j' are assigned to workers w, the variable is 1. Otherwise, the variable is 0.

Objective Function:

$$Min \quad t_{\max} \tag{5}$$

$$Min \quad \sum_j \delta_{j,w} q_{j,w} \tag{6}$$

s.t.

$$t_{\max} \geq \sum_j \delta_{j,w} k_{j,w} t_{j,w} \qquad \forall w \tag{7}$$

$$\sum_w \delta_{j,w} = 1 \qquad \forall j \tag{8}$$

$$1 + M(\delta_{j,m} + \delta_{j',w} - 2) \leq z_{j,j',w} \qquad \forall j, j', w \tag{9}$$

$$z_{j,j',w} \leq 1 + \frac{1}{M}\left(\delta_{j,w} + \delta_{j',w} - 2\right) \qquad \forall j, j', w \tag{10}$$

$$\sum_j \sum_{j'} r_{i,i'} z_{j,j',w} \geq L_{\max} \qquad \forall w \tag{11}$$

$$\sum_j \delta_{j,w} q_{j,w} \leq Q_{\max} \qquad \forall w \tag{12}$$

$$q_{j,w} = r_{j,j'} \, q_{j',w} \tag{13}$$

Here, $q_{j,w}$ is predetermined from the table related to workers' skill level for assembling semi-finished products shown as Table 2. $r_{i,i'}$ is predetermined from the table related to the similarities for assembling semi-finished products shown as Table 3.

Equations (5) and (6) are objective functions. Equations (5) and (6) denote minimization of makespan of the schedule and minimization of total difficulty of works assigned to all workers, respectively. Equation (7) denotes the condition of makespan which is larger than the total operation times of jobs assigned to workers in the parallel processing system. In this equation, the operation times of jobs assigned to workers are estimated by using coefficients depending on workers' skill level. Equation (8) denotes that every job is assigned to a single worker. Equations (9), (10), and (11) denote the equations to calculate the similarities of jobs assigned to identical workers. Here, Equation (11) denotes that the total similarities of jobs assigned to identical workers is equal to or larger than the lower number, L_{max}.

Although multi-objective functions are introduced in the mathematical model, Equation (12) is added after excluding Equation (6) and Equation (5) is adopted to resolve as the single objective problem of the model. The model is resolved by controlling of the value of Q_{max}. Equation (12) denotes that the total difficulties of operations for jobs assigned to workers is no greater than the maximum number of the difficulties, Q_{max}. Equation (13) denotes the equation to calculate the difficulty of operations for job j for worker w when $q_{i,w}$ requires to calculate from the difficulty of operations for job i'.

4.3 Numerical experiment

Numerical experiment is performed to evaluate the performance of the mathematical model. glpk (GNU Linear Programming Kit) is used to resolve the mathematical model. The difficulties of operations and the evaluation value of workers' skill level could be used in the mathematical model. Ordinarily, the measured data and the calculated data shown in Tables 2 and 3 should be used. However, we use the data which are randomly generated in order to clearly evaluate the effectiveness of the mathematical model in this section. Three workers and 12 jobs are predetermined for the scheduling problem.

Table 5 denotes the operation times of jobs. The operation times are generated by using a random function. It is assumed that the coefficient to estimate operation time, $k_{i,w}$, is 1.0 and the operation times of all jobs are constant for all workers. Table 6 denotes the difficulties of operations for jobs and workers, $q_{i,w}$. Table 7 denotes similarities of jobs, $r_{i,i'}$. In this table, U is 0.5, W is 0.2. We set 0 in the diagonal elements in this table to avoid calculating similarities caused by single jobs on purpose.

Table 5: The operation times of jobs for numerical experiment

JOB	Time	JOB	Time	JOB	Time
1	5	5	9	9	11
2	13	6	15	10	5
3	19	7	11	11	18
4	11	8	17	12	10

Table 6: The difficulties of operations for jobs and workers.

JOB	A	B	C	JOB	A	B	C
1	2.12	1.06	1.93	7	0.7	2.33	1.88
2	0.98	1.8	1.33	8	2.11	1.9	0.59
3	2.36	1.94	2.02	9	1.49	1.88	0.89
4	1.12	1.62	2.12	10	1.07	1.84	2.08
5	0.86	0.78	2.22	11	1.4	0.54	1.03
6	1.58	0.74	1.59	12	2.16	1.04	0.95

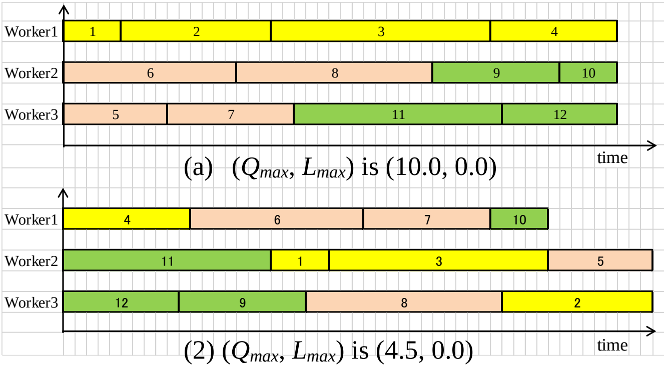
Table 7: The similarity of difficulties of operations for jobs and workers. U is 0.5, W is 0.2.

JOB	1	2	3	4	5	6	7	8	9	10	11	12
1	0	U	W	0	1	U	W	0	1	U	W	0
2	U	0	U	W	U	1	U	W	U	1	U	W
3	W	U	0	U	W	U	1	U	W	U	1	U
4	0	W	U	0	0	W	U	1	0	W	U	1
5	1	U	W	0	0	U	W	0	1	U	W	0
6	U	1	U	W	U	0	U	W	U	1	U	W
7	W	U	1	U	W	U	0	U	W	U	1	U
8	0	W	U	1	0	W	U	0	0	W	U	1
9	1	U	W	0	1	U	W	0	0	U	W	0
10	U	1	U	W	U	1	U	W	U	0	U	W
11	W	U	1	U	W	U	1	U	W	U	0	U
12	0	W	U	1	0	W	U	1	0	W	U	0

The numerical experiment is performed under the condition that Q_{max} is 10.0 , 5.0, and 4.5 and L_{max} is 0.0 and 4.0. Figure 8 shows Ganttcharts obtained under the condition that (Q_{max}, L_{max}) is (10.0, 0.0) and (4.5, 0.0). The makespan in the resultant schedule under the former condition is 48 and the makespan under the latter condition is 51.

By resolving the mathematical model under these conditions, the generated schedules give the following results of makespan, the maximum difficulty of jobs in all workers, and the minimum similarity of operations in jobs in all workers: (48, 6.58, 3.8). (49, 4.73, 1.4), and (51, 4.47, 3.8) with regard to (makespan, the maximum difficulty of jobs in workers, the minimum similarity of operations in workers). These results denote relationship of tradeoff between three measures to evaluate the schedule.

The results show that the developed mathematical model is effective to generate schedules to maximize productivity and to minimize difficulties of operations considering workers' skill level and similarities of operations. In addition, the result denotes that we require to develop the optimal algorithm for tri-objective problem for scheduling problems including workers' skill and difficulty of operations.



(a) (Q_{max}, L_{max}) is (10.0, 0.0)

(2) (Q_{max}, L_{max}) is (4.5, 0.0)

Figure 8: Ganttcharts of the generated schedules

5. CONCLUSION

In this study, the scheduling method and the analytical method to evaluate workers' skill level are developed aiming at promoting productivity and reducing mistake of workers on multiple handling works for parts assembly process for high-mix low-volume production. The analytical method to evaluate the similarity of different operations is developed and adopted to assign similar works to the same workers in the scheduling method. Mathematical model is constructed as the scheduling method. Three objective functions are evaluated in the scheduling problem: makespan, total difficulties of works assigned to workers, and total similarities of works assigned to workers. Numerical experiment is performed by assembly process using actual and simple structures in order to evaluate the performance of the scheduling method and the analysis method. The result shows the effectiveness of the analytical method of the difficulties and the similarity of operations. In addition, the result shows that the scheduling method could generate the significant schedules to minimize makespan and the total difficulties of the works, and to maximize the total similarity of operations, simultaneously.

Since the optimal solutions could be obtained in a short computational time by resolving the developed mathematical model, the solutions are not compared with the solutions calculated by the multi-objective optimization algorithms in this study. However, since a long computational time would be required to resolve large scale of schedule problems, the multi-objective optimization algorithms would be developed as Multi-objective Genetic algorithm or Particle Swarm Optimization algorithm in the future study. In addition, the scheduling method based on the mathematical model and the analytical methods of the difficulties and the similarity of operations would be adopted to actual factories including multiple handling works for parts assembly process for high-mix low-volume production.

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