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Abstract Title: An optimal production scheduling model of hybrid flow shop - a case of solar cell industry.

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Abstract

This paper studies a solar cell industry scheduling problem, which is similar to traditional hybrid flowshop scheduling (HFS). In past, a typical HFS with parallel machines problem, the allocation of machine resources for each order should be

scheduled in advance. Then, the optimal multiprocessor task scheduling in each stage could be determined. However, the challenge in solar cell manufacturing is the number of machines that can be adjusted dynamically to complete the job. This characteristic is different from the previous studies. As a result, an optimal production scheduling model is developed in this paper to explore these issues, considering the practical characteristics, such as hybrid flow shop, parallel machine system, dedicated machines, sequence-independent setup time, and sequence-dependent setup time. The objective of this model is to minimize the makespan and to decide the processing sequence of the orders/lots in each stage, lot-splitting decisions for the orders, and the number of machines used to satisfy the demands in each stage.

Key words: Hybrid Flow Shop, Mathematical Model, Scheduling, Solar Cell Industry

1. Introduction

Hybrid flowshop scheduling (HFS) was first proposed by Salvador (1973). HFS is defined as n number of jobs processed in m number of processing stages. The HFS scheduling problem comprises two general scheduling issues, namely parallel machines and process-type production scheduling. The parallel machine scheduling (PMS) problem relates to the allocation of a job to multiple machines; while the flow shop scheduling (FSS) problem relates to how the job production sequence is determined. Based on the machine characteristics, machines may usually be divided into three categories (Allahverdi and Mittenthal, 1994): (1) Identical parallel machines; (2) Uniform parallel machines; (3) Unrelated parallel machines.

The standard HFS production system is depicted in Figure 1, which includes the

following common features(Ruiz and Vazquez-Rodriguez, 2010):

1. Production stage m contains at least two stages (i.e., $m \geqq 2$).

2. For all processes in stage k, the number L of parallel machines for at least one process must be greater than or equal to two (i.e., $L \geqq 2$).

3. All the jobs are processed in the same sequence, such as stage 1, stage 2, ..., stage m.

4. All the jobs and processing machines can start the program with the time set at zero.

5. Each machine can process a maximum of only one job within the same time period.

6. Each job can only be processed on one machine within the same time period.

7. The setting time can be ignored and the buffer between the process stations can be unlimited.
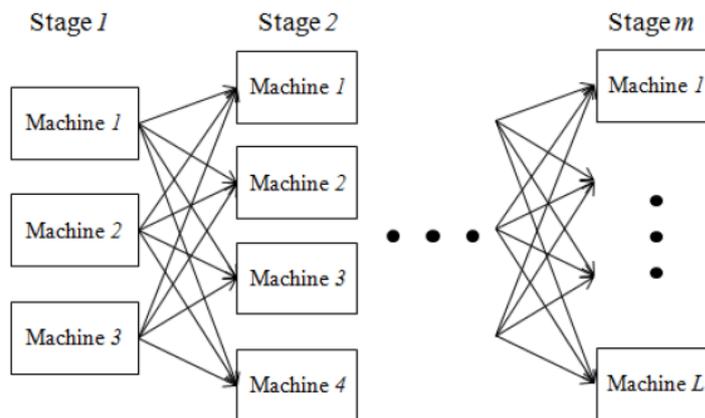

Figure 1 HFS standard structure

Under this type of production environment, not only the process sequence of a job (also called work order) needs to be considered, dispatching problems, such as job

allocations to machines, which increase corresponding complexity, must also be considered (Salvador, 1973; Ribas et al., 2010). Under the HFS production environment, the number of machine resources for each job had to be established or known (see Figure 2), and then, optimal multiprocessor task scheduling in each stage could be determined (Engin et al., 2011). HFS problems have evolved from the earliest use of one-job-on-one-machine to subsequent production environments with one-job-on-multiple-machines. However, the premise remains the same, namely, that the machine resource allocation (or machine configuration) of each job must be established in advance before a planning approach can be implemented. Currently, a realistic problem in the solar cell industry arises from unknown decisions of job production sequence, machine resource configuration, and resource allocation, which increase the difficulty and the complexity of production scheduling.
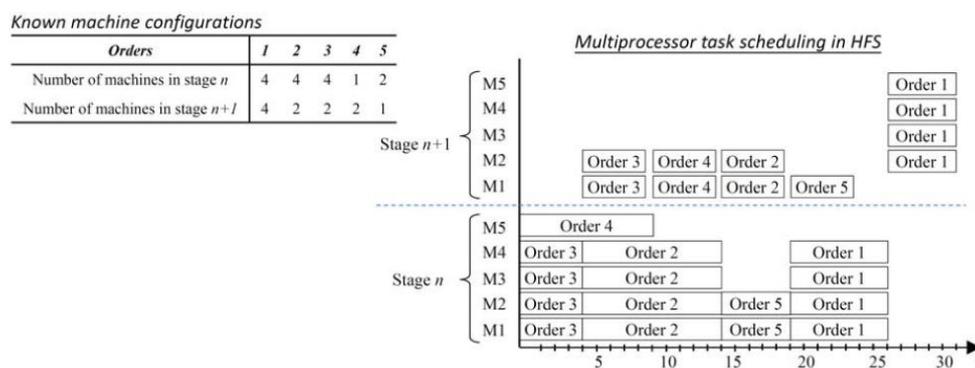

Figure 2 Schematic diagram of allocating a single job to multiple machines when the

machine configuration is known in advance

In the previous studies, Riane et al. (1998) solved the three-stage HFS scheduling

issues using a structure including one machine at the first station and another machine at the third station, with the second station having two dedicated machines. The objective of their study was to reduce the maximum makespan. They applied the characteristics of problems and the objectives of this paper to construct a mixed-integer linear programming model, and relaxed the conditions in searching for the lower bound. They used the branch and bound method and heuristic algorithm to solve the problem. Chen et al. (2007) used a container terminal as the research subject for finding a scheduling problem solution. The problem was regarded as an HFS scheduling problem that considers a non-equivalent parallel machine, job priority, sequence-dependent setup time, and blocking. The problem objective was to minimize the maximum makespan. They proposed a mixed integer programming mathematical model to determine its lower bound, and used tabu search (TS) to obtain the solution. Defersha (2010) proposed a generic mathematical model to solve the flexible HFS scheduling problem associated with lot streaming, with the minimization of the maximum completion time as the objective. According to the experimental results, HFS can generate an even lower maximum completion time than process-based production can, and the results of having considered lot splitting are better than those of not having considered lot splitting.

In recent years, the solar cell industry usually employed a production structure

similar to HFS environments which possesses a multiprocessor task scheduling architecture. The production planners in the solar cell industry not only determine the multiprocessor task scheduling, but also address the optimal machine configuration by dynamically allocating all jobs to multiple machines. Each job can be arranged with the largest number of machines during the production process. Additionally, the number of machines can be dynamically allocated to complete the job within the shortest possible time. The job production sequence only employs the traditional dispatching rules for job arrangement. Therefore, when the machine resource allocation and the job production sequence are unknown, the complexity of the entire production scheduling is increased considerably, as examined in the previous studies.

Therefore, this study conducts a case study on a company to explore the scheduling characteristics of crystalline silicon solar cell production. The characteristics include parallel processing, dedicated machines, sequence-independent setup time, and sequence-dependent setup time. A mixed integer linear programming (MILP) model, which considers these practical characteristics, is proposed to simultaneously generate optimal job production sequence, machine configurations, and parallel-machine scheduling in each stage to achieve the minimization of the maximum makespan.

This paper is organized as follows. In Section 2, the multi-stage and

parallel-machine scheduling problem in solar cell industry is defined and a mixed

integer linear programming model is developed. Then numerical examples are

discussed in Section 3, followed by the conclusion in Section 4.

2. Hybrid flow shop scheduling for solar cell manufacturing

2.1Manufacturing process and characteristics of crystalline silicon solar cells

Figure 3 illustrates the manufacturing process of crystalline silicon solar cells.

The manufacturing of crystal silicon solar cells comprises six processes, and each

process has its practical characteristics that influence the production schedule.

Therefore, these production characteristics should be included in the production

scheduling. The characteristics are detailed below:

(a) Dedicated machines: Crystalline silicon solar cells are basically of two types:

single-crystal silicon solar cells and polysilicon solar cells. Manufacturing

machines of both types of solar cells are the same. However, the difference lies

in the texturing stage. The dedicated polysilicon machines use an acid texturing

method for the polysilicon solar cells, whereas the single silicon dedicated

machines use an alkaline texturing method for the single silicon solar cells.

Therefore, the need for different numbers of dedicated machines for each of

these processes is obvious due to the variance in capacity. This difference

impacts the subsequent scheduling method in the job production process.

(b) Parallel machine processing: Identical parallel machines are used in the manufacturing process of crystalline silicon solar cells. When the job demand is high, a job must be allocated to more than one machine, increasing the capacity and reducing the makespan required to complete the job.

(c) Sequence independent setup time: In the printing stage, the electrodes are printed on both sides of the silicon that is used to collect and conduct the current flow. Depending on customers' requirements, different densities of printing designs are available. Because a few order can have the similarity design, the print setup are almost necessary for all kinds of orders, which is referred to as sequence independent setup time.

(d) Sequence dependent setup time: Due to the number of electrodes on the surface, the crystalline silicon solar cell can be categorized as: 2 busbars and 3 busbars. In the testing stage, the measurement probe must be adjusted according to the number of electrodes in both busbar types. For example, the 2-busbars form requires the installation of two probes for the measurement. If the next job is also 2-busbar form, the testing machines do not need setup. On the contrary, if the measuring machines operate on a 3-busbars product form, testing machines probe must be adjusted. Therefore, the probe adjustment time will be affected by the job sequence, which influences the setup time. This is referred to as sequence

dependent setup time. Setting the optimal production sequence to reduce the number of setups and shorten the overall completion time is the key focus of this restriction.
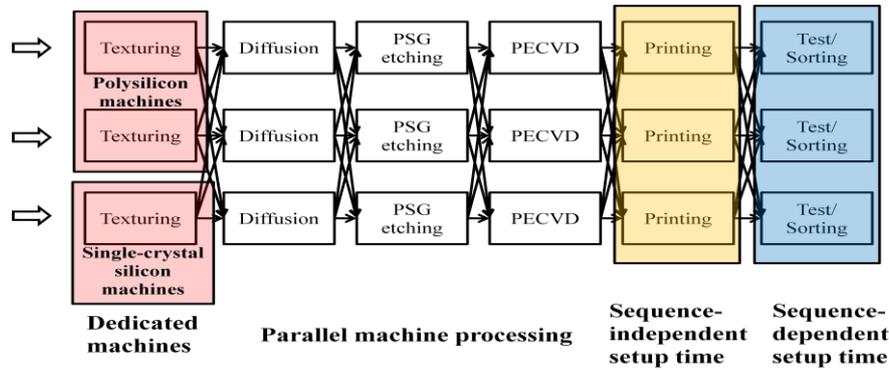

Figure 3 Manufacturing process of crystalline silicon solar cells

2.2 Problem description

The production of silicon solar cells belongs to an HFS environment. In addition to the process characteristics mentioned previously, the number of products of the job is very high. Production cannot be completed in a short time. A lot-splitting approach must be considered to split the order evenly into several sublots. Then, similar jobs can be processed simultaneously on a number of machines within the same process, thereby reducing production time. Therefore, in addition to considering the production sequence of a job as to how many sublots an order should be split into, and as to which machines the sublots should be assigned to, are the problems examined in this study, which are described as follows.

1. Determine the production sequence of all work orders.

2. Split each order into various sublots.

3. Configure the machines after lot splitting.

2.3 The Mathematical model

In this section, we formulate the mixed integer programming model for the addressed HFS scheduling problem in the solar cell manufacturing, which is based on the standard form of the HFS problem. The assumptions and notations are defined as follows.

2.3.1 Assumptions

1. All jobs and machines are available at time zero.

2. Machines at a given stage are identical.

3. Any machine can process only one operation at a time.

4. Preemption is not allowed.

5. The capacity of buffers between stages is unlimited.

6. The demand of each work order is a multiple of the number of machines at each stage.

7. The problem data is deterministic and known in advance.

2.3.2 Input data

1. Demand

The demand of each work order.

2. Product

The product attribute of each work order (single-crystalline silicon or poly-crystalline silicon). The required number of the busbars for each work order (two or three).

3. Time

The sequence independent setup time in the "Printing" stage for each work order. The sequence dependent setup time in the "Testing/Sorting" stage between two work orders

2.3.3 Notation definition

The detailed information of Notation definition is demonstrated in Table 1, 2 and 3.

Table 1 Indexes

Indexes
i, u = work order index, i, u=1,2,…, I.
j = processing stage index, j=1,2,.., J.
k = machine index, k=1,2,…, M_j, M_j is the number of machines at stage j.
l = the index of the lot splitting, l=1,2,…, L_j, L_j is the number of ways of lot splitting at stage j.

Table 2 Parameters

Parameters
d_i = the processing quantity demanded for work order i.
$p_{i,j}$ = the unit processing time for work order i at stage j.
$r_{j,l}$ = the production ratio factor at stage j when applying the lot-splitting way l.
s_i^{SI} = the sequence independent setup time for work order i.
b_i = the required number of the busbar for work order i (this value equals two or three).
s_{b_i,b_u}^{SD} = the sequence dependent setup time when work order i is a direct predecessor of

work order u.

$e_{i,k}$ = the specialized machine constraints. If the work order i can be processed in machine k, $e_{i,k}$=1; and otherwise, $e_{i,k}$=0.

M = a large enough number.

Table 3 Decision variables

Decision variables
C_{max} = the makespan.
$C_{i,j,k}$ = the completion time of work order i in machine k at stage j.
$X_{i,j,k}$ = the production ratio of work order i in machine k at stage j.
$Y_{i,j,k}$ = binary variable, $Y_{i,j,k}$=1, if work order i is processed in machine k at stage j; $Y_{i,j,k}$=0, otherwise.
$W_{i,j,k,l}$ = binary variable, $W_{i,j,k,l}$=1, if work order i is processed in machine k at stage j with applying the lot-splitting way l; $W_{i,j,k,l}$=0, otherwise.
$S_{i,u,j,k}$ = binary variable, $S_{i,u,j,k}$=1, if work order i is processed in machine k at stage j before work order u; $S_{i,u,j,k}$=0, otherwise.

2.3.4 Mixed integer linear programming model

A mixed integer linear programming model is formulated for the addressed HFS scheduling problem in the solar cell manufacturing. The objective function in Eq.(1) is to minimize the makespan of the schedule which is equal to the completion time of the last sublot processed in the system.

Objective function:

$$\text{Minimize } Z = C_{max} \tag{1}$$

Constraints:

$$C_{max} \geq C_{i,J,k} \quad \forall i,k \tag{2}$$

$$C_{i,j-1,k} + d_i \times X_{i,j,k} \times p_{i,j} \leq C_{i,j,k} \quad \forall i, j, k \tag{3}$$

$$X_{i,j,k} = \sum_{l=1}^{L_j} r_{j,l} \times e_{i,k} \times W_{i,j,k,l} \qquad \forall i, j, k; \ j = 1 \tag{4}$$

$$X_{i,j,k} = \sum_{l=1}^{L_j} r_{j,l} \times W_{i,j,k,l} \qquad \forall i, j, k; \ j > 1 \tag{5}$$

$$\sum_{l=1}^{L_j} W_{i,j,k,l} \leq 1 \qquad \forall i, j, k \tag{6}$$

$$\sum_{k=1}^{M_j} e_{i,k} \times X_{i,j,k} = 1 \qquad \forall i, j; \ j = 1 \tag{7}$$

$$\sum_{k=1}^{M_j} X_{i,j,k} = 1 \qquad \forall i, j; \ j > 1 \tag{8}$$

$$C_{u,j,k} \geq C_{i,j,k} + d_u \times X_{u,j,k} \times p_{u,j} - M(2 - Y_{i,j,k} - Y_{u,j,k}) - M(1 - S_{i,u,j,k})$$
$$\forall i, u, j, k; \ i < u; \ j = 1, \ldots, 4 \tag{9}$$

$$C_{i,j,k} \geq C_{u,j,k} + d_i \times X_{i,j,k} \times p_{i,j} - M \times (2 - Y_{i,j,k} - Y_{u,j,k}) - M \times S_{i,u,j,k}$$
$$\forall i, u, j, k; \ i < u; \ j = 1, \ldots, 4 \tag{10}$$

$$C_{u,j,k} \geq C_{i,j,k} + d_u \times X_{u,j,k} \times p_{u,j} + s_u^{SI} \times Y_{u,j,k} - M(2 - Y_{i,j,k} - Y_{u,j,k}) - M(1 - S_{i,u,j,k})$$
$$\forall i, u, j, k; \ i < u; \ j = 5 \tag{11}$$

$$C_{i,j,k} \geq C_{u,j,k} + d_i \times X_{i,j,k} \times p_{i,j} + s_i^{SI} \times Y_{i,j,k} - M(2 - Y_{i,j,k} - Y_{u,j,k}) - M \times S_{i,u,j,k}$$
$$\forall i, u, j, k; \ i < u; \ j = \tag{12}$$

$$C_{i,j,k} \geq d_i \times X_{i,j,k} \times p_{i,j} + s_i^{SI} \times Y_{i,j,k} \qquad \forall i, j, k; \ j = 5 \tag{13}$$

$$C_{u,j,k} \geq C_{i,j,k} + d_u \times X_{u,j,k} \times p_{u,j} + s_{b_i,b_u}^{SD} - M(2 - Y_{i,j,k} - Y_{u,j,k}) - M(1 - S_{i,u,j,k})$$
$$\forall i, u, j, k; \ i \neq u; \ j = 6 \tag{14}$$

$$C_{i,j,k} \geq C_{u,j,k} + d_i \times X_{i,j,k} \times p_{i,j} + s_{b_u,b_i}^{SD} - M(2 - Y_{i,j,k} - Y_{u,j,k}) - M \times S_{i,u,j,k}$$
$$\forall i, u, j, k; \ i < u; \ j = \tag{15}$$

$$X_{i,j,k} \leq M \times Y_{i,j,k} \qquad \forall i, j, k \tag{16}$$

$$Y_{i,j,k} \in \{0,1\} \qquad \forall i, j, k \tag{17}$$

$$W_{i,j,k,l} \in \{0,1\} \qquad \forall i, j, k, l \tag{18}$$

$$S_{i,u,j,k} \in \{0,1\} \qquad \forall i, u, j, k \tag{19}$$

$$X_{i,j,k} \geq 0 \qquad \forall i, j, k \tag{20}$$

$$C_{i,j,k} \geq 0 \text{ (integers)} \qquad \forall i, j, k \tag{21}$$

Eq.(2) state that the makespan of the schedule. Eq.(3) state that the completion time for work order i in machine k at stage j is greater or equal to the completion time on the preceding stage j-1 plus the processing time on the current stage j. Eq.(4) and Eq.(5) determine the production ratio ($X_{i,j,k}$). Because the number of processing machines at every stage is given in advance, all possible ways of lot-splitting at any stage are also known. Eq.(4) and Eq.(5) are similar except for the specialized machine consideration for single-crystalline or poly-crystalline silicon at the first stage in Eq.(4). Eq.(6) ensures that the production ratio ($X_{i,j,k}$) only equals one of all possible production ratio factors at any stage or zero. Eq.(7) and Eq.(8) state that the sum of the production ratio ($X_{i,j,k}$) of the order i in each machine k at stage j equals 1. Eq.(9) is enforced to guarantee that work order u will begin after completing the work order i. It is worth mentioning a significant saving in sequencing variables is achieved by $i < u$ as follows from Eq.(9) and Eq.(10). Eq.(11) and Eq.(12) are similar to Eq.(9) and

Eq.(10) except for adding the sequencing independent setup time in the "*Printing*" stage. Eq.(13) ensures that the completion time for work order i in machine k at "*printing*" stage is greater or equal to the processing time plus the sequencing independent setup time. That is, it must be considered the sequencing independent setup time when any one of work orders is initially processed in machine k. Eq.(14) and Eq.(15) are similar to Eq.(9) and Eq.(10) except for adding the sequencing dependent setup time between two work orders in the "*Testing/Sorting*" stage. In Eq.(16) is shown whether the work order i is processed in machine k at stage j. $Y_{i,j,k}$ equals 1 if work order i is processed in machine k at stage j ($X_{i,j,k} > 0$); otherwise ($X_{i,j,k} = 0$), $Y_{i,j,k}$ equals 0. Eq.(17)–Eq.(21) are the basic restrictions on the decision variables.

3. A numerical case study

A solar cell industry case is illustrated to verify the applicability and feasibility of the production scheduling model proposed in this paper. The solar cell manufacturing process involves six production stages. They are respectively texturing, diffusion, PSG etching, PECVD, printing and testing/sorting. Therefore, the production environment is a hybrid flowshop system which includes six stages. In this case, except the fact that there are five machines on the fourth stage, all of other stages involve three machines. Besides, all the machines on each stage are identical

parallel machines. Five work orders are scheduled to be produced. The production items of order 1 and 4 are single-crystalline silicon while those of the rest orders are poly-crystalline. On the first stage, single crystalline and poly crystalline should be etched in different solution, that is, single crystalline can only be processed by the alkaline etching machine (machine 3) while poly crystalline can only be processed by the acid etching machine (machine 1 and 2).

The detailed information of this case is demonstrated in Table 4, 5 and 6. In Table 4, including the unit processing time of the order, dedicated machines, the demands, the number of busbars, and the sequence-independent setup time on the fifth stage. Table 5 shows the production rate of the order on different stages when various lot-splitting approaches are used. Table 6 is the sequence-dependent setup time for the order needed on the sixth stage.

Table 4 The input data for the solar energy industry case

Stage	Machine			Work order										
				i=1		i=2		i=3		i=4		i=5	
j	k	M_j	L_j	$p_{j,k}$	$E_{i,j}$	$p_{j,k}$	$E_{i,j}$	$p_{j,k}$	$E_{i,j}$	$p_{j,k}$	$E_{i,j}$	$p_{j,k}$	$E_{i,j}$
1		3	3	3		3		3		3		3	
	1				0		1		1		0		1
	2				0		1		1		0		1
	3				1		0		0		1		0
2		3	3	3	-	3	-	3	-	3	-	3	-
3		3	3	3	-	3	-	3	-	3	-	3	-
4		5	5	6	-	6	-	6	-	6	-	6	-
5		3	3	3	-	3	-	3	-	3	-	3	-
6		3	3	3	-	3	-	3	-	3	-	3	-
	D_i			9000		3000		5400		4200		6600	
	B_i			3		2		2		3		3	
	S_i^{SI}			3600		3600		3600		3600		3600	

Table 5 The production ratio factor ($r_{j,l}$)

Stage	Lot-splitting approach				
	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$
j	$r_{j,l}$	$r_{j,l}$	$r_{j,l}$	$r_{j,l}$	$r_{j,l}$
1	1	1/2	1/3	-	-
2	1	1/2	1/3	-	-
3	1	1/2	1/3	-	-
4	1	1/2	1/3	1/4	1/5
5	1	1/2	1/3	-	-
6	1	1/2	1/3	-	-

Table 6 The sequence dependent setup time ($s^{SD}_{b_i,b_u}$) (time unit: second)

B_i	To	
From	2	3
2	0	900
3	1200	0

The current heuristic practiced by the case company involves two steps: (1) Manufacturing order sequence is determined by the priority-based method (e.g. due date, customer priorities), (2) Machine allocation adopts equal-partition allocation rule to minimize total makespan. For example, when stage m has three machines, order 1 is divided into three equal amounts and allocated to three machines, respectively. The makespan of this case by the current heuristic method in practice is 79,020 seconds.

Through the production scheduling model proposed in this paper, Figure 4 shows the scheduling result of this case. The makespan is 78,000 seconds. Compared with the current heuristic method in practice, the improvement rate is 1.3%. From Figure 4, not all the orders are split to every machine on each stage because the setup times will increase by this way and consequently the makespan will be lengthened. Therefore,

the start and finish limitation and setup time should be considered to decide the lot-splitting approach and moreover, the characteristics should also be considered in order to obtain an optimal result when scheduling. However, the complicated constraints and industrial characteristics will make the scheduling task more difficult and thus the planning staff is not able to efficiently get a better result by manual calculation. Therefore, the production scheduling model proposed in this paper may be employed to obtain an optimal scheduling decision and decide the processing sequence of orders, the lot-splitting approaches for the orders, and the number of machines used to satisfy each order. Shown from the result of the Gantt chart, the production scheduling model proposed in this research is feasible in the practical industry case and improves the quality of production scheduling.
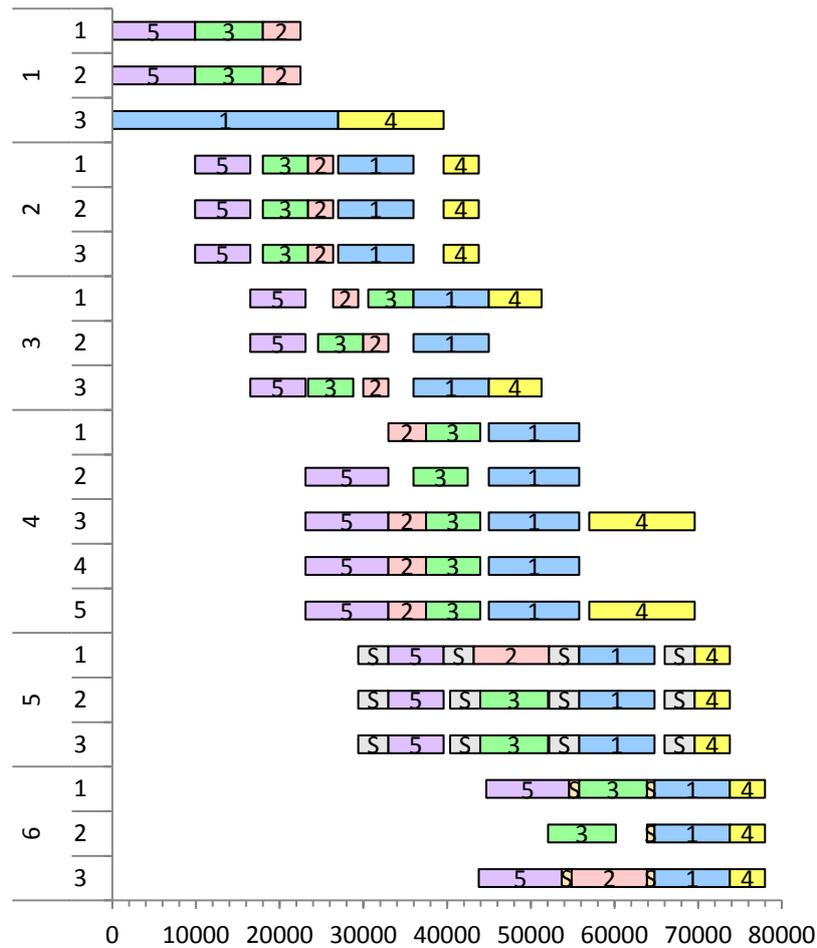
Figure 4 The Gantt chart for the solar energy industry case (C_{max} =78000)

4. Conclusions

By taking the solar cell industry for example, this research induces the practical characteristics of the production environment and manufacturing process. An optimal production scheduling model is then proposed. The characteristics of production scheduling in the solar cell industry include hybrid flowshop, parallel machine system, dedicated machines, sequence-independent setup time, and sequence-dependent setup time. The purpose of this research is to help the planning staffs to minimize makespan under the hybrid flowshop production environment and to decide the processing

sequence of the orders/sublots in each stage, lot-splitting approaches for the orders, and the number of machines used to satisfy the demands in each stage.

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