COUPLING HOIST SCHEDULING AND PRODUCTION LINE ARRANGEMENT FOR PRODUCTIVITY MAXIMIZATION

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Abstract

Hoist scheduling is an important element for productivity maximization in multi-stage material handling processes, especially in electroplating system. However, the productivity of a multi-stage process not only depends on the hoist schedule, but also substantially relies on the production line arrangement, i.e., the design for spatial allocations of various processing units. In this paper, an MILP model has been developed to couple cyclic hoist scheduling and production line arrangement for global maximum of productivity. The efficacy of the proposed methodology is demonstrated by a virtual case study. The in-depth analysis for hoist scheduling with and without consideration of production line arrangement has also been provided.

Keywords

Hoist scheduling, Production line arrangement, Optimization, MILP, Multi-stage material handling

Introduction

There are thousands of electroplating shops in the U.S. annually producing numerous work pieces for many pillar industries. Hoist scheduling obviously is the most relevant factor to improve the production efficiency of a processing recipe fixed production line. A hoist (or a crane) is a controlled robot mainly conducting job lifting, releasing, and moving along its production line for material handling by following a preset movement schedule based on the processing recipe. It is reported that as high as 20% reduction in mean job waiting time and 50% improvement in standard deviation of cycle time can be achieved by hoist scheduling (Kumar, 1994).

Cyclic hoist scheduling (CHS) involves one hoist for processing a single type of product in a cyclic way (Lei and Wang, 1989). Historically, hoist schedules were once developed based on experience. The first reported effort for computerized scheduling was made by Phillips and Unger (1976). Since then, a number of other new methods, especially mathematical programming based methods, have been introduced. Moreover, CHS is later on applied in many fields to offer other benefits besides productivity enhancement, such as environmental benefits. Xu and Huang (2004) pioneered in this area with a proposed graphic assisted scheduling methodology, which incorporated fresh water minimization as a part of objective functions. The application showed it not only improved the productivity, but also reduced the wastewater generation in an electroplating line. After that, Liu et al. (2011) considered integrating CHS and water reuse network design (WRND) problems into a multi-objective mixed-integer dynamic optimization (MIDO) model for the simultaneous consideration of the productivity and water use efficiency. Very recently, Liu et al. (2011) addressed simultaneous productivity maximization, energy saving, and freshwater/wastewater minimization for the optimal design and operation of

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electroplating processes, which provides multi perspective decision supports for the design and operation of electroplating processes.

In previous works, how to feasibly and timely organize cyclic hoist schedules has been broadly studied. However, the productivity of a multi-stage process not only depends on the hoist movement schedule, but also substantially relies on the production line arrangement, i.e., the design for spatial allocations of various processing units. This is because a hoist needs to travel among processing units to pick up or drop different jobs for different processing purposes, and such travelling time greatly depends on unit spatial allocation, which affects both job processing change-over time and cyclic hoist operation time or productivity. Thus, the production line arrangement and hoist scheduling are better to be considered simultaneously for the best performance of a hoist-employed multi-stage material handling process.

In this paper, an MILP model has been developed to couple cyclic hoist scheduling and production line arrangement for global maximum of productivity. The efficacy of the proposed methodology is demonstrated by a virtual case study. The comparison for hoist scheduling with and without the consideration of production line arrangement is also conducted.

Problem Statement

Electroplating is performed in a production line that consists of a number of chemical units with different processing purposes. The jobs to be treated are picked up from the unloading zone, then dragged into those chemical units following the preset sequence for manufacturing and finally be placed on the loading zone. For CHS, the hoist will repeat its movement schedule after a cycle, and the cycle time determines the productivity, i.e., the shorter of cycle time suggesting the higher productivity. To help understand the CHS problem with production line arrangement, the following terminologies are introduced in advance.

Job processing recipe. A job processing recipe gives processing requirements for a job, which includes the processing sequence and resident-time window for each processing step. In the CHS model, the units following the steps will be numbered, and the unloading zone will be labeled as the first unit; loading zone is the last unit. In reality, usually a deck will be utilized as both the loading and unloading zone.

Unit job capacity. In electroplating production, a unit usually permits only one job to occupy at a time. A multi-job capacity unit consists of multiple slots, which allows simultaneously processing multiple jobs.

Hoist movements and idle waiting. The hoist travels between units to pick up a job or to release a job by following the hoist schedule. The speed of the hoist travelling is steady, so the hoist movement time is proportionally depending on the distance between the hoist starting and ending units. When a hoist travels without a job, it is called a free move; otherwise, if a hoist travels with a job, it is called a loaded move. Meanwhile, when the hoist is ready to pick up the job in a certain unit, the hoist may be idle waiting for some time above this unit according to the resident-time window.

Production line arrangement. How the chemical units aligned spatially is the production line arrangement. Usually, the chemical units are constructed in a row, and the loading and unloading zone is designated at one side of the production line.

General Methodology

In this section, the CHS model with production line arrangement is introduced as an MILP model. Suppose this CHS schedule handles M chemical units and let $I=\{1,2,\cdots,M\}$. Unit 1 is the first processing unit in manufacturing (unloading zone), and unit M is the last one (loading zone). Those processing units need to be allocated based on the distance to the loading/unloading zone with $K=\{1,2,\cdots,N\}$. Location 1 is the closest, and N is the farthest. A binary variable $z_{i,j}$ is introduced to determine a free move ($z_{i,j}$ is 1 if the free move is from unit i to unit j; otherwise, $z_{i,j}$ is 0). Another binary variable $x_{i,k}$ is to determine the unit location ($x_{i,k}$ is 1 if the unit i is at the position k; otherwise, $x_{i,k}$ is 0). The CHS MILP model is summarized below:

$$J=\min T \tag{1}$$

s.t.

$$\sum_{i=1}^{M} z_{i,j}=1, \quad \forall j\in I \tag{2}$$

$$\sum_{j=1}^{M} z_{i,j}=1, \quad \forall i\in I \tag{3}$$

$$z_{i,i}=0, \quad \forall i\in I \tag{4}$$

$$\sum_{k=1}^{N} x_{i,k}=1, \quad \forall i\in I,\, i\neq 1 \text{ and } i\neq M \tag{5}$$

$$\sum_{i=2}^{M-1} x_{i,k}=1, \quad \forall k\in K \tag{6}$$

$$A\left(w_{i,j}-1\right)\leq \sum_{k=1}^{K} D_k x_{i,k}-\sum_{k'=1}^{K} D_{k'} x_{j,k'}\leq A w_{i,j}, \quad \forall i,j\in I,\, 2\leq i,j\leq M-1 \tag{7}$$

$$\sum_{k=1}^{K} D_k x_{i,k}-\sum_{k'=1}^{K} D_{k'} x_{j,k'}-\frac{1}{2}Q_{i,j}\leq A\left(1-w_{i,j}\right), \quad \forall i,j\in I,\, 2\leq i,j\leq M-1 \tag{8}$$

$$\sum_{k=1}^{K} D_k x_{i,k} - \sum_{k'=1}^{K} D_{k'} x_{j,k'} - \frac{1}{2} Q_{i,j} \geq A(w_{i,j} - 1), \quad \forall i, j \in I, 2 \leq i, j \leq M - 1 \tag{9}$$

$$-2Aw_{i,j} \leq Q_{i,j} \leq 2Aw_{i,j}, \quad \forall i, j \in I, 2 \leq i, j \leq M - 1 \tag{10}$$

$$mv_{i,j} = Q_{i,j} - \left(\sum_{k=1}^{K} D_k x_{i,k} - \sum_{k'=1}^{K} D_{k'} x_{j,k'} \right), \quad \forall i, j \in I, 2 \leq i, j \leq M - 1 \tag{11}$$

$$mv_{i,j} = mv_{j,i}, \quad \forall i, j \in I \tag{12}$$

$$mv_{1,i} = mv_{M,i}, \quad \forall i \in I \tag{13}$$

$$mv_{1,i} = \sum_{k=1}^{K} D_k x_{i,k}, \quad \forall i \in I, i \neq 1 \; and \; i \neq M \tag{14}$$

$$mv_{1,M} = 0 \tag{15}$$

$$S_1 = 0 \tag{16}$$

$$E_{i+1} = S_i + mv_{i,i+1}, \quad \forall i \in I, i < M \tag{17}$$

$$0 \leq E_i + mv_{i,j} - h_{i,j} \leq T^{up}(1 - z_{i,j}), \; \forall i, j \in I \tag{18}$$

$$h_{i,j} \leq T^{up} z_{i,j}, \quad \forall i, j \in I \tag{19}$$

$$S_j = \sum_{i=1}^{I} h_{i,j} + W_j, \quad \forall j \in I, \; j \neq 1 \tag{20}$$

$$\sum_{i=1}^{I} h_{i,1} \leq T \tag{21}$$

$$P_i = S_i - E_i + (C_i - 1)T + g_i, \quad \forall i \in I \tag{22}$$

$$T^{lo}(1 - y_i) \leq T - g_i \leq T^{up}(1 - y_i), \quad \forall i \in I \tag{23}$$

$$T^{lo} y_i \leq g_i \leq T^{up} y_i, \quad \forall i \in I \tag{24}$$

$$-T^{up} y_i \leq S_i - E_i \leq T^{up}(1 - y_i), \quad \forall i \in I \tag{25}$$

$$P_i^{\min} \leq P_i \leq P_i^{\max}, \quad \forall i \in I \tag{26}$$

In this model, the objective is to maximize the productivity, which is equivalent to minimize the cycle time, *T*. This optimization problem should satisfy the constraints (2) through (26). Within one cycle, every unit will be released and lifted a job only once, which makes each hoist free movement unique. Equation (2) suggests only one departure unit for the hoist free move to unit *j*, and Equation (3) ensures only one destination unit for the hoist free move from unit *i*. The free move cannot start and end at the same unit by Eq. (4).

For the production line arrangement, each unit *i* is allocated to a spatial position, as shown in Eqs. (5) and (6). The distance between the *k*-th position and the loading/unloading zone is represented as D_k, indicating the distance from unit *i* to the loading/unloading zone is $\sum_{k=1}^{K} D_k x_{i,k}$. Since the hoist travelling speed is steady, the hoist movement time is proportional to the distance, the hoist movement time from unit *i* to unit *j* can be formulated as $mv_{i,j} = \left| \sum_{k=1}^{K} D_k x_{i,k} - \sum_{k'=1}^{K} D_{k'} x_{j,k'} \right|$. To linearize this constraint, Eqs. (7) through (11) are employed. Here, another binary variable $w_{i,j}$ is defined in Eq. (7), where $w_{i,j}$ is 1 if $\sum_{k=1}^{K} D_k x_{i,k} \geq \sum_{k'=1}^{K} D_{k'} x_{j,k'}$; otherwise, $w_{i,j}$ is 0. Note that *A* is a sufficient large number. Then the hoist move time can be reformulated by discarding the absolute sign as: $mv_{i,j} = (2w_{i,j} - 1)\left(\sum_{k=1}^{K} D_k x_{i,k} - \sum_{k'=1}^{K} D_{k'} x_{j,k'} \right)$, which can be completely linearized by Eqs. (8) through (11). $Q_{i,j}$ is a variable defined in Eqs. (8) through (10) to replace the item of $2w_{i,j}\left(\sum_{k=1}^{K} D_k x_{i,k} - \sum_{k'=1}^{K} D_{k'} x_{j,k'} \right)$. The other constraints related to hoist movement time are given by Eqs. (12) through (15), which indicates that the loading/unloading zone is at the same location, so that the hoist movement time between them is 0.

The hoist scheduling is designed in a cyclic way and thus which unit the hoist scheduling starts from will not affect the schedule result. In this model, the unloading zone can be designated as the initial starting unit, thus the starting time is set to 0 in Eq. (16). The relation between the hoist lifting time point S_i and the releasing time point E_i are described by Eqs. (17) through (20). Following the recipe, the hoist is always carrying a job from unit *i* to unit *i*+1 (see Eq. (17)); however, the hoist free move is to be decided from the scheduling, and is controlled by the binary variable $z_{i,j}$. Variable $h_{i,j}$ is a variable to replace $(E_i + mv_{i,j})z_{i,j}$. Lifting time point S_j equals to the releasing time point E_i at unit *i*, plus the hoist movement time between units *i* and *j* and the idle waiting time if necessary. After the whole cycle, the hoist will be placed above the initial unit again, the time elapse equals the cycle time (see Eq. (21)).

The job processing time in unit *i* is represented as P_i. It is the time interval, during which a job stays in the unit. Equation (22) gives the general formula for calculating P_i. Suppose unit *i* can simultaneously process C_i jobs (unit job capacity is C_i). Then, when a job enters unit *i*, it should finish its processing in the next C_i or $C_i - 1$ cycles ($g_i = T$ or $g_i = 0$), which depends on the relation between the hoist lifting time point S_i and the releasing time point E_i. Consider the schedule in one cycle, the hoist first releases a job in unit *i* and then lifts it ($S_i \geq E_i$), the binary variable y_i is 0 (see Eq. (25)), resulting in $g_i = 0$ in Eqs. (23) and (24), and the job processing is finished in the next $C_i - 1$ cycles. If the hoist first lifts a job in unit *i* and then releases a job ($S_i \leq E_i$), the binary variable y_i is 1

(Eq. (25)), resulting in $g_i = T$ in Eqs. (23) and (24), and the job processing is completed in the next C_i cycles. The job processing time is also constrained by Eq. (26) with a required resident-time window.

Based on the above equations and explanations, the developed cyclic hoist scheduling model for a multi-stage material handling system is described by the objective function of Eq. (1), which is to minimize the cycle time; and the process constraints and specifications of (2) through (26). Note that the developed scheduling model is an MILP model and its global optimal solution can be guaranteed with the commercial solver of CPLEX.

Case Study

A virtual example is investigated with the developed methodology, where the production line consists of 8 units including the loading/unloading zone. According to the processing recipe, the processing unit is labeled as 1,2,...8. For each processing unit, its job capacity and resident time limit are shown in Table 1. Above the production line, it takes a hoist 2 seconds travelling between two adjacent processing units.

Table 1. Unit job capacity and unit resident time

Unit	1/8	2	3	4	5	6	7
C_i	1	1	1	2	1	1	1
$P_i^{\min}$	0	64	24	128	40	60	52

Based on the developed methodology, the MILP model is developed in GAMS version 23.3 and solved by CPLEX, which involves 634 equations, 156 integer variables, and 353 continuous variables. The average solving time with an 8-Core Xeon 3.2GHz Dell server for the case studies is within 2 seconds. Figure 1 shows the global optimal CHS result considering both hoist scheduling and production line arrangement. The total cycle time is 72 seconds including 32 seconds of loaded move and 40 seconds of free move (see Table 2). The unit alignment sequence is 1/8, 2, 3, 5, 6, 7, and 4. During the cyclic schedule, the hoist starts from lifting a job from unloading zone, after releases it to the unit 2, the hoist undergoes a free move to unit 4, then the hoist experiences a series of loaded moves and free moves according to the scheduling, and finally returns to the original starting unit and repeats the cycle (see Figure 1).

To compare with the optimal CHS based on the production line arrangement, a CHS case study without the consideration of the production line arrangement has also been conducted. In this case, the unit alignment sequence is randomly set as 1/8, 4, 2, 3, 5, 7, and 6. The optimal CHS based on this fixed production line has been solved and its global solution is shown in Figure 2. The detailed comparison is summarized in Table 2, where the difference between two cases comes from the total free move time. Based on the comparison, the total cycle time without production line arrangement is 76 seconds, which is 4 seconds longer than that of case 1, suggesting 5.3% productivity loss if the production line design is ignored. Therefore, the developed methodology does improve the productivity by reducing the total cycle time.

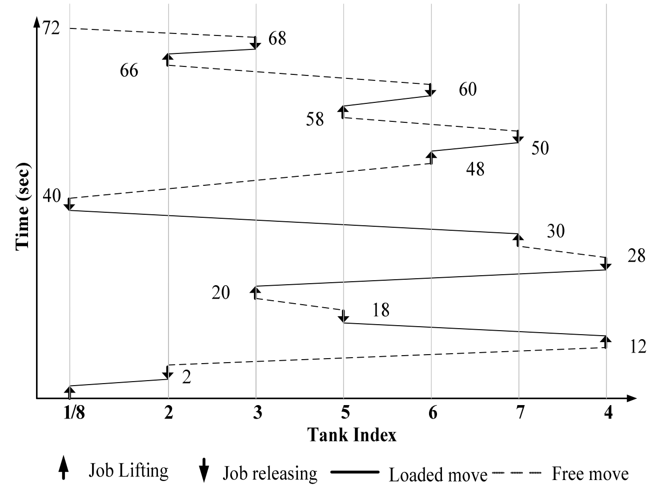

Figure 1. CHS with optimal production line

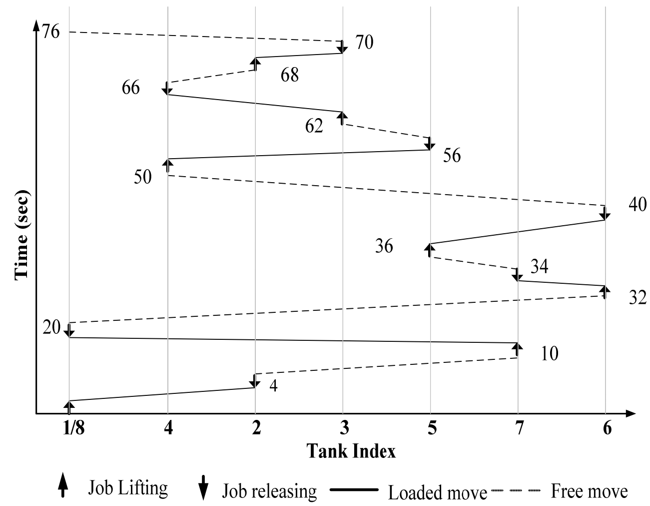

Figure 2. CHS with a fixed production line

Table 2. Case study results comparison

	Optimal production line	Random production line
Cycle time (sec.)	72	76
Loaded move (sec.)	32	32
Free move (sec.)	40	44

It should be noted that this developed methodology can also be applied to large scale processes, as long as the information of the production line and job recipe are given. Certainly, the solving time would increase with more variables and process constraints involved. Meanwhile, the methodology on coupling hoist scheduling and production line arrangement can also be widely used in electroplating industry, polymer coating industry, or any other multi-stage material handling systems that employ hoists or cranes for manufacturing. New improvements and more applications based on the development are expected in the near future.

Conclusions

The productivity of a hoist-employed multi-stage material handling system depends not only on the hoist movement schedule, but also the entire production line arrangement. In this paper, an MILP model was developed to couple cyclic hoist scheduling and the production line arrangement together for the productivity maximization. The efficacy of the proposed methodology is demonstrated by a virtual case study.

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