HOIST SCHEDULING PROBLEM: STATE-OF-THE-ART

Christelle Bloch[1], Astrid Bachelu[1], Christophe Varnier[1], Pierre Baptiste[2]

1: LAB / ENSMM / UFC-UMR CNRS 6596, 25 rue A. Savary, 25 000 Besançon (France)
2: KAIST, Dept Comp. Sc., 373-1 Koosung-Dong, Yusung-Gu, Taejon 305-701 (Korea)

Abstract: In automated plating processes, hoists ensure the transfer of products between workstations. Scheduling their movements is known as the Hoist Scheduling Problem (HSP). It belongs to the class of strongly NP-hard problems (Lei and Wang, 1989b). Many studies, dealing with different complexity levels of the problem have been published, and the following classification should give the reader quite a large overview of them.

Keywords: scheduling algorithms, industrial production systems, robotic manipulators control, optimisation problem, classification

1. INTRODUCTION

Electroplating facilities are made up of tanks, between which hoists transfer products according to a given route. The Hoist Scheduling Problem (HSP) consists in scheduling the hoist movements to maximise the throughput, while respecting the following specific constraints: processing times are strictly bounded, no wait and no storage between tanks is allowed, hoists share a single track and must not collide, transport time cannot be neglected. The following classification should give the reader a survey of the various studied cases found in literature. First, the problem will be briefly described. Then, four main approaches will be presented: a predictive one determines the optimal cyclic scheduling of a line producing a single type of pieces; the second and the third ones solve the problem either in advance or in real-time when parts are not identical; finally, layout is considered.

2. PROBLEM DESCRIPTION

The complexity of the problem depends on kind of line, processing specifications and production mode.

2. 1 Different types of facilities

Parts, held in "carriers", undergo given sequences of treatment through workstations, from a loading buffer to an unloading one. Hoists transport carriers, one at a time, from tank to tank.

In the simplest kind of line each tank processes one job at a time and a single hoist is used. But, more generally, some tanks may be duplicated and several hoists are used, while preventing them from colliding. At least, loading and unloading may be executed in the same station (called single I/O station), which further increases complexity .

2. 2 Processing requirements

Parts are processed in tanks according to strict specifications: the order in which stations must be visited and the bounded soak time in each of them. In the simplest case, tanks are sequentially visited. But, practically, the given route makes some tanks, called multi-function tanks, be visited several times. At least, in order to simplify the problem, some authors assume that processing times are fixed.

2. 3 Existing production modes

Single-product mode: In mass production , the line is dedicated to a single type of pieces. Then, the problem is called: "Cyclic Hoist Scheduling Problem" (CHSP) and consists in finding the sequence of moves that hoists must periodically repeat. The time to execute such a sequence is called the period. The optimal schedule can be computed off-line by minimising the cycle length (i.e., the average time to perform a job). The cycle is said to be n-periodic if n jobs are introduced into, and consequently n jobs are removed from, the line in each cycle. Thus the cycle length is obtained by dividing the period by the cyclic degree n.

Sometimes, the line is used to process large batches of identical parts. This kind of production seems like several successive CHSP and transitional periods must be studied; otherwise operators must empty the line before treating a new batch.

Multi-product mode: When jobs are different, two cases may arise :

If production forecasts are known (i.e. predictive approach), the schedule can be found beforehand. Usually, the entering sequence that minimises total completion time is determined, possibly by defining identical batches of non-identical parts that periodically enter the line. Thus, a cyclic schedule can be found off-line.

In the opposite case (i.e. reactive approach) the problem is called " Dynamic Hoist Scheduling Problem " (DHSP) as products randomly enter the line. Consequently, authors mainly use either expert scheduling systems or heuristic methods.

2. 4 Conclusion

Most of the published works deal with the single product case, fewer focus on DHSP and layout. So, the paragraphs below are organised as follows. Section 3 provides a review on CHSP. Section 4 makes a survey of approaches based on the multi-products assumption. At least, section 5 presents works studying either the layout of the stations or the optimal number of hoists to be used.

3. CYCLIC HOIST SCHEDULING PROBLEM

CHSP studies can be classified in two main categories, according to the chosen model :

- in the "carrier model", the products being simultaneously on the line are considered,
- in the "cycle model",the order of hoist movements in the resulting period is focused on.

Generally, authors solve the basic problem and later bring extensions to solve more complex ones. The basic problem is the search of the optimal 1-periodic schedule in a line composed of one hoist, no duplicated and no multi-function tank. Consequently, tanks are numbered according to the given route. In a general way, authors define an integer linear model and use a solving procedure based on branch and bound principle. The two following parts will first present variables and associated constraints. Then authors' solving proposals and, finally, extensions, will be examined.

3.1 Carrier model

The variables of the problem are the transfer starting dates and the period. (ÊThey are written in bold characters in the following formulation.)

nt	the number of treatments in the sequence
o_i	the real time the i-th soak operation of the resulting sequence takes ($1 \le i \le nt$)
m_i, M_i	the soak time boundaries of the i-th soak operation
Ri	the i-th transfer operation of the sequence of treatment (1 2 i 2 nt-1)
r_i	the time required to execute R_i
$d_{i,j}$	the constant time a free hoist needs to move from tank i to tank j
T	the period
$\mathbf{t_{i,k}}$	the date at which the i-th transfer operation (R_i) concerning the product k starts
k	the number of the considered products ($1 \le k \le K_{max}$, K_{max} is a constant which represents the maximum number of products on the line at the same time)

NB : K_{max} is fixed by authors in the basic case but can be a variable to be determined in other cases.

The cyclic structure imposes that a product k enters exactly k-1 periods later than the first one and that all the transfers are performed during the cycle:

$$\forall\, i,\ 1 \le i \le nt\text{-}1,\ k > 1, \quad \mathbf{t_{i,k}} = \mathbf{t_{i,1}} + (k-1)^*\mathbf{T} \tag{1}$$

So, solving the problem consists in determining **T** and the $\mathbf{t_{i,1}}$ variables (simply called $\mathbf{t_i}$). Such a model is composed of nt variables. The first strong constraint represents the bounded soak times :

$$\forall\, i,\ 1 \le i \le nt\text{-}1, \quad m_i \le \mathbf{t_{i+1,k}} - (\mathbf{t_{i,k}} + r_i) \le M_i \tag{2}$$

This constraint is independent of k. As all the products are identical, it only has to be set for the first one. Besides, limited capacity of tanks, associated with the cyclic assumption, implies that during a cycle, each tank has one product dropped in and another one removed from it (but not necessarily in this order). So, the period must be longer than all the soak operations :

$$\forall\, i,\ 1 \le i \le nt\text{-}1, \quad \mathbf{T} \ge \mathbf{t_{i+1,k}} - (\mathbf{t_{i,k}} + r_i) \tag{3}$$

The hoist holds one job at once and must have enough time to move from the tank it has just filled to the one it must empty. So, disjunctive precedence constraints are set between hoist operations :

$$\forall\, i,j,\ 1 \le j < i \le nt,\ 1 < k \le K_{max}, \quad \mathbf{t_{j,k}} - \mathbf{t_i} \le r_i + d_{i+1,j} \ \text{ or } \ \mathbf{t_i} - \mathbf{t_{j,k}} \le r_j + d_{j+1,i} \tag{4}$$

Many solving methods rest on that model:

Shapiro and Nuttle, (1988) solve a benchmark presented by Phillips and Unger, (1976) but consider separated loading and unloading tanks. The starting dates t_i are deduced from the vector $S = (s_1, ..., s_{nt})$ of the resulting soak times. At each node of the search tree, a product j is added and relative orders are defined between this product and in process jobs (from 1 to j-1). An order is represented by a vector $V_h = (v(1), ..., v(nt-2))$ with $1 \leq h \leq j-1$; $v(i)=k$ means that the i-th transfer of the product j follows the k-th transfer of the product j-h and precedes the k+1-th transfer of the product j-h. At this step a linear program checks the feasibility of relative order $[V_1, ... V_{j-1}]$ regarding the current constraints and S. When $\mathbf{Vp(1)}$ is equal to nt this means that a solution composed of p-1 products has been found.

Lei and Wang, (1994) define a schedule function $\phi(i,j)$ which assigns an order number to the i-th transfer operation of the product j. This number fixes the place of a transfer operation in the schedule. So, at each step of the search, they determine which move can take place at the next free row in the sequence. To select moves, they also use temporal windows which express the earliest and the latest starting date to perform a move.

Baptiste, *et al.*, (1994) have developed an original approach by using Constraint Logic Programming (CLP). They use a depth first search that consists in fixing a disjunction (i.e. to choose one of the mutually exclusive inequations (4) and checking the consistency of the current problem using a complete constraint solver). The solving method goes on until all disjunctive constraints are fixed. If the consistence test fails, the system backtracks.

3.2 Cycle model

This model considers the starting date of the transfer operations executed during a cycle and **T**. Besides, boolean variables are used to specify precedence relations between transfer operations.

τ_i the starting date of the i-th operation transfer (R_i) in the cycle

$x_{i,j}$ the boolean variable expressed as:

$$\mathbf{x_{i,j}} = 1 \text{ if } \tau_i > \tau_j, \text{ else } \mathbf{x_{i,j}} = 0 \quad \text{with } \mathbf{x_{i,j}} + \mathbf{x_{j,i}} = 1 \tag{5}$$

As a single cycle is considered, it is no use setting constraints (1). Besides, equation (2) and (3) become:

$$\forall\, i,\ 1 \leq i \leq nt\text{-}1,\quad m_i \leq \tau_{i+1} - (\tau_i + r_i + x_{i,i+1}{*}T) \leq M_i \tag{6}$$

$$\mathbf{T} \geq \tau_{i+1} - (\tau_{i,k} + r_i + x_{i,i+1}{*}\mathbf{T}) \tag{7}$$

Using $\mathbf{x_{i,j}}$ simplifies constraint (4) expression:

$$\forall\, i,j,\ 1 \leq i \leq nt,\ 1 \leq j \leq nt,\ i \neq j,\quad \tau_j - \tau_i \geq d_{i+1,j} + r_i - x_{i,j}{*}T \tag{8}$$

Phillips and Unger, (1976) were the first to be interested in the CHSP. They have used this model to represent a complete example, called the Phillips benchmark. The latter deals with a basic line supplied with a single I/O station and is considered as the reference problem. Phillips and Unger have developed a Mixed Integer Programming method based on a branch and bound procedure to solve it.

Armstrong, *et al.*, (1992) define a schedule (M,T) where $M = (m[1], ..., m[nt])$ is a sequence of transfer operations, m[i] being the i-th move in a cycle, where $T = (t[0], ..., t[nt])$ is the relative starting time of the moves. The authors progressively build the schedule and use a parameter called the Minimum Time Span (MTS) that gives a tight lower bound on the time required to complete any partial sequence of moves. This bound takes into account both the hoist moving time and the job minimal processing time.

It seems that Hanen and Munier, (1994a) mix the "cycle model" and the "carrier one". They have defined a relation between variables τ_i and $\mathbf{t_i}$:

$$\tau_i = \mathbf{t_i} + \mathbf{k_i} * \mathbf{T} \quad (1 \leq i \leq nt) \tag{9}$$

$\mathbf{k_i}$ is called occurence of the transfer operation R_i. Indeed, a transitional period is needed to make all the products enter the line and so $\mathbf{k_i}$ "pseudo periods" elapse until the hoist executes R_i for the first time. Hanen and Munier wanted to develop a CHSP specific algorithm instead of using classical linear programming. Thus, they have studied the structure of the problem solutions and have presented a solving method based on the graph theory. They have also used time windows to build the cycle (called ñthe motifî) progressively.

Chen, *et al.*, (1995) solve the problem with two branch and bound procedures. The first one finds an initial state of the line and the second one determines the corresponding sequence of movements. In the first step, they have defined a useful bound K_{max}. The program lists the feasible distribution and represents one distribution in a vector $Cn = (c(1), ..., c(n))$ where c(i) is equal to 1 when a product is in tank i at the initialisation stage and equal to 0 otherwise. The second program manages conflicts between two operations. A bi-valued graph is used to check the feasibility and estimate the period.

3.3 Extensions of the basic problem

Phillips and Unger, (1976) extend their model by considering multi-function tanks. Shapiro and Nuttle, (1988) have considered duplicated tanks. They have indicated that it might be difficult to include the n-periodic assumption. Although their solving method is efficient for simple cases, Chen, *et al.*, (1995) have proposed no extensions.

Other extensions developed in many papers are the n-periodic and the multi-hoist case. Armstrong, *et al.*, (1992) have proposed to extend their model to the multi-hoist problem (Lei, *et al.*, 1993) while precising this requires additional constraints to prevent the hoists from colliding. Both Manier, *et* *al.*, (1994) and Lei and Wang, (1989a) solve the n-periodic problem, but they restrict their search to low degrees (n<4) to limit the number of variables. They consider complex lines with duplicated tanks, multi-function tanks and several hoists. In this case, moves must be assigned to hoists. Manier, *et al.*, (1994) and Hanen and Munier, (1994b) solve this problem in a less restrictive way than Lei does: they allow hoists to move on the same part of the line (overlapping zone) whereas Lei and Wang, (1991) make consecutive hoists share only one common tank (non-overlapping zone).

Some papers consider fixed processing times, and develop polynomial algorithms to solve the problem (Hanen and Munier, 1994, Son, *et al.*, 1993, Levner, *et al.*, 1995). This can also be used to get a first solution for the complete CHSP.

At least, an other extension consists in determining a transitional period between two cyclic productions (Varnier and Baptiste, 1995a). Knowing two fixed cycles, an algorithm, based on the work of Manier, schedules the hoist moves to perform progressively moves of the second cycle instead of those of the first one. So simultaneously, the first type of product leaves the line when the second one comes in, while ensuring that soak times boundaries are respected.

4. MULTI-PRODUCT CASE

The following sections present a survey of reported works solving multi-product HSP either in advance or in a reactive way. Most of these papers rest on heuristic algorithms and consider a basic line.

4.1 Predictive approach

When products to be processed during the next several hours are supposed to be known, the problem can be solved off-line.

Fleury, *et al.*, (1996) assume that they know the next 24 hours production. Kangaroo algorithm and hill climbing are used to choose the best entering sequence. A Multi-Agents simulation evaluates the makespan and schedules all movements. A specific constraint is added: the number of carriers is fixed, which means that empty carriers can not leave the facility and must be considered in the schedule. Soak time constraints may be violated.

Ptuskin (1995) considers fuzzy processing times. An entering sequence of n non-identical parts, the order of which is supposed to be known, is periodically repeated. Each part entering date Vi in the sequence, a period R and exact soak times must be determined. All the tanks are sequentially visited by all the parts, according to various processing times. The algorithm uses n sub-CHSP solvings to find a set of common periods and a rule called "Fuzzy Prohibited Intervals Rule" representing the hoist disjunctive constraints, to determine variables Vi.

4.2 Reactive approach:

When products randomly arrive, the line must be dynamically controlled. Most of the methods proposed to solve this problem are either based on expert scheduling systems or on heuristics:

Expert scheduling systems: Thesen and Lei (1986, 1990) present a rule based expert system. Some decision rules permit to choose the heuristic to be applied according to the line current state. The used heuristics rest on priority levels associated with each in-process carrier (according to its current treatment and soaking time) and on hoist assignment rules. This kind of control system can quite easily drive several hoists.

Sun, *et al.*, (1994) develop a simulation system, based on Thesen and Lei's dispatching rules, in order to help schedulers by letting them "watch" the system's operations before they are implemented. When loading a job, they check fewer future assignments than Thesen and Lei do. Hence, they can not ensure that no defective job will be produced. Besides,they consider multifunction tanks, which is not examined by Thesen and Lei, but they assume that processing times are fixed.

The main drawback of such approaches is that they do not necessarily satisfy processing time constraints. That is why some authors have chosen to use heuristic algorithms to solve DHSP.

Heuristic approaches: All of them determine a new hoist movement schedule before letting the new entering product n be processed, which guarantees that no product will become defective. They are all based on a generalised "carrier model" that differs in the way constraint (3) is expressed. Indeed, the period T can not be considered anymore and r_i must be replaced by $r_{i,k}$, where k is the considered product. Besides, S[i,k] is the tank in which the i-th soak operation on job k is performed. So, constraint (3) becomes:

$$\forall\ i,j,k,l,\ 1 \le i < nt_k,\ 1 \le j \le nt_l,\ k \ne l,$$
$$\text{such as } S[i,k]=S[j,l]$$
$$\mathbf{t_{j,l}} - \mathbf{t_{i-1,k}} \le r_{i-1,k}$$
$$\text{or } \mathbf{t_{i,k}} - \mathbf{t_{j-1,l}} \le r_{j-1,l} \quad (9)$$

The published works either keep the partial schedule related to the already in-process products or not.

Yin and Yih (1992) make the moves related to job n fit in the existing schedule. First, the timing of the product n transfers is computed from an initial entry time and minimum soak times, without considering the in-process carriers. Then, tanks and hoist constraints satisfaction is checked by looking for overlaps in the Gantt Chart. When a treatment of product n is responsible for a constraint violation, either its processing time is extended, or the product entry time is updated.

Yih (1994) improved this algorithm by using all the processing time tolerances: the order of the previous schedule is kept, but move starting dates may be changed.

Cheng and Smith (1995) applied a constraint satisfaction problem solving model for deadline scheduling to the problem Yih had set out. They used a heuristic procedure, generically called "precedence constraint posting", that relies on a temporal constraint graph representation.

Ge and Yih (1995) do not hold the previous schedule. Their heuristic method is based on a depth first branch and bound search that terminates on discovery of a feasible schedule . At each node, the algorithm chooses the next move to be performed, by trying first to make the new product enter. If it is not possible, the search order is defined from the time each job can still remain in its current tank before becoming defective. The feasibility of each sub-branch is checked by solving a linear programming problem based on the "carrier model".

Lamothe (1996) uses a depth first branch and bound search that gives priority to tank constraints. The search order is also defined according to increasing operation ready dates. Each sub-branch is evaluated by finding the longest path between two nodes on a PERT graph. If a positive circuit is detected, this proves the constraint system's inconsistency. Moreover, a dynamic backtracking procedure is used. It stores information from previous DHSP solvings, named Nogoods to explain why the backtrack is necessary. Thus, when a new job n arrives, Nogoods can be used to modify the previous search-tree (dealing with n-1 products). Up to now, Lamothe (1996) is the only author who solves DHSP in complex lines (with duplicated tanks, multi-function tanks and n hoists).without producing defective jobs.

Bloch, *et al*, (1996) compare the solutions given by hill climbing, simulated annealing, taboo search, kangaroo method and genetic algorithm. The previous schedule is partially called into question, since two adjustable points are defined to specify which portions of the sequence can undergo changes. The criterion evaluation rests on the same longest path assessment as the one presented in Lamothe (1996) apart from the fact that no information is stored when an inconsistency is detected.

5. LAYOUT

The layout of the tanks and the number of hoists are generally considered as fixed data. Yet, few authors have studied the relationship between layout of the tanks and productivity. Other ones have determined the optimal number of transporters. All of them consider a single type of product.

5.1 Layout of the tanks

Grunder, *et al.*, (1997) underline the relationship between the physical layout of the stations and the productivity of a treatment line. They focus on saturated single-hoist production lines. (In such lines, there are n-1 products simultaneously processed in a line of n stations.) They first consider a particular class of layout that is commonly used by industrial users and show that this class does minimize the hoist moving time during a cycle time. Then, they demonstrate that this particular class of layout is, however, not dominant in all cases for maximizing the productivity of the line. Finally, they propose a branch and bound algorithm to determine the optimal layout for maximizing the productivity in such lines.

5.2 Optimal number of hoists

Armstrong, *et al.*, (1995) determine the minimum number of hoists so that all the transport operations can be executed while satisfying all the constraints and avoiding traffic collision. The set of operations is partitioned in groups, each of them being served by a single hoist. The optimal solution, that corresponds to maximum group sizes, is obtained by solving linear programming subproblems, the duals of which are structured as shortest path problems.

Kats and Levner (1995) find the optimal number of hoists needed to meet a given schedule for all possible periods. They determine the minimal number of hoists as a function of T. They consider the basic case with fixed processing times.

6. CONCLUSION

This survey shows that a lot of different cases have been solved. Yet, a wide research field has still not been explored, particularly concerning multi-products cases, layout, and the simultaneous assignment and scheduling problem. Moreover, papers dealing with similar problems could have been quoted, such as Su and Chen (1996) or Rochat (1995). To permit the reader to place these works among the other described approaches, they have been included in the synoptic classification graph that is provided in appendix.

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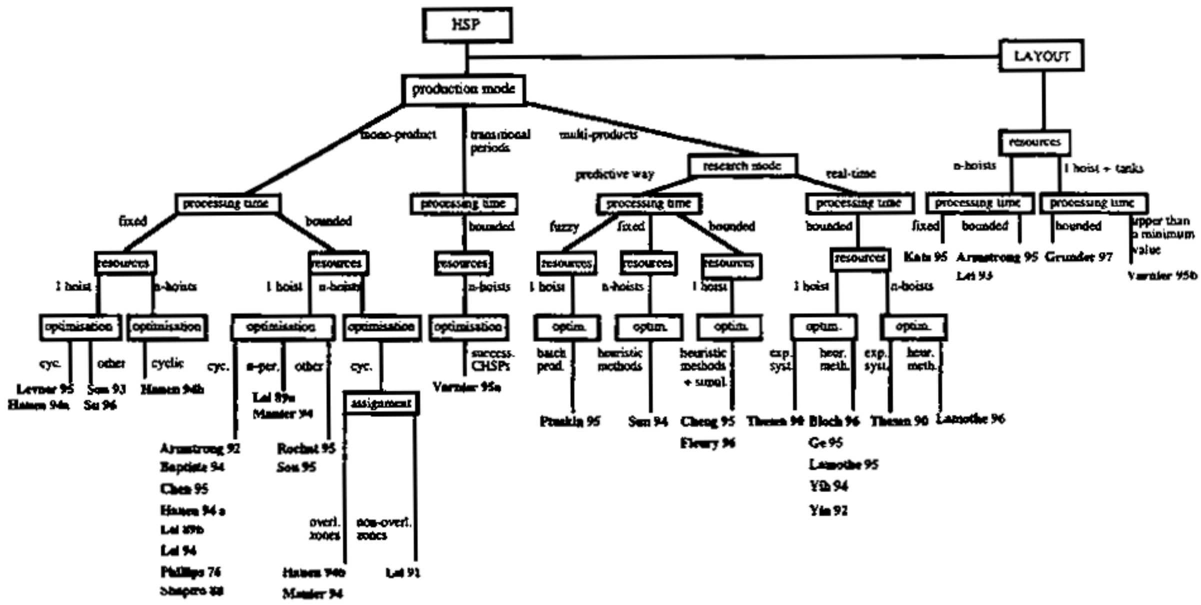
APPENDIX

The synoptic classification graph. To simplify, only the first author and date are mentioned.



Classification of different publications on HSP

Abbreviations:

batch prod.: batch production
cyc.: cyclic
exp. sys.: expert system
heur.meth.: heuristic methods
n-per.: n-periodic
non-overl. zones: non-overlapping zones
overl. zones: overlapping zones
simul.: simulation
success. CHSPs: successive CHSPs