



A Classification for Hoist Scheduling Problems

MARIE-ANGE MANIER AND CHRISTELLE BLOCH

University of Technology of Belfort-Montbéliard, 90 010 Belfort Cedex, France

Abstract. Electroplating lines are totally automated manufacturing systems that are used to cover parts with a coat of metal. They consist of a set of tanks between which the parts to be treated are transported by one or several hoists. Scheduling the movements of these hoists is commonly called a hoist scheduling problem (HSP) in the literature. But the assumptions and constraints that must be taken into account greatly depend on the production environment (physical system, manufacturing specifications, and management policies). Consequently, there exist several classes of HSPs. The systematic frameworks usually used to classify deterministic scheduling problems do not allow distinguishing between these various kinds of HSPs. Therefore, identifying the scope of each published work and comparing the various proposed scheduling methods turn out to be difficult. Thus, this article presents notation for scheduling problems in electroplating systems, to make the specification of problem types and the identification of studied problem instances easier. An associated typology gives a survey of the literature and demonstrates the usefulness of the proposed classification scheme.

Key Words: electroplating line, hoist scheduling problem, typology

1. Introduction

The hoist scheduling problem (HSP) deals with the scheduling of handling devices in electroplating facilities. Electroplating lines are totally automated manufacturing systems that are used to cover parts with a coat of metal. They are encountered in many industries: spectacle trade, mechanics, jewelry, household electrical appliances, and printed circuit boards. In particular, they allow the protection of parts from corrosion or give them some aesthetic properties. Such a process is important as it may constitute a bottleneck in the production cycle.

For some years numerous publications dealing with the HSP seem to consider it as a particular shop scheduling problem that is different from classical ones because of the number and the diversity of its constraints. The literature also shows a great variety in the production environment (for instance, in processing specifications), the characteristics of resources, and the various resolution approaches used. Consequently, the lack of a classification scheme makes it difficult to identify and to compare the different studies. So we found it useful to provide a typology associated with the hoist scheduling problem. To reach this goal, we needed to specify all of the features related to this problem, whatever the complexity of the encountered case could be. Then we gathered them in a dedicated notation allowing the classification of all possible instances.

In this article, we first present the physical system and the associated constraints. Then we compare the HSP to classical shop scheduling problems and show that existing notation is not adapted to represent all of the encountered cases. Therefore, we propose a HSP classification.

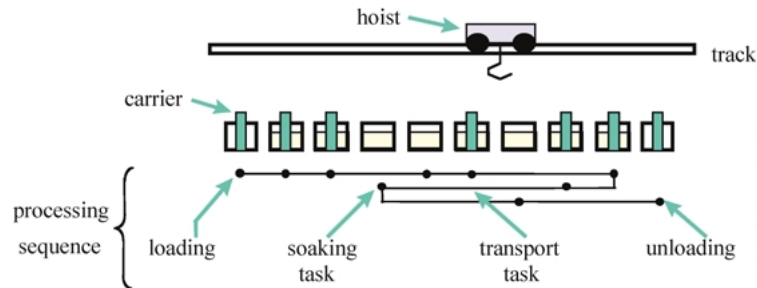


Figure 1. Example of electroplating line.

Applying this notation to the articles found in the literature provides a typology that allows identification of several classes of problems.

2. The hoist scheduling problem

The processing resources of an electroplating facility are tanks containing chemical baths in which parts must be soaked according to a given processing sequence (Figure 1). A processing sequence usually includes the three steps of the preparation (cleaning and rinsing of parts), the deposit of metal, and the finish (rinsing, passivation, and drying). Each step is decomposed into several soaking operations that cannot be preempted. The duration of each operation is bounded by minimal and maximal limits, because of chemical constraints: for example the thickness of the deposit depends on the surface to cover, the concentration of the chemical bath and the intensity in current rectifiers. When the duration is shorter than the minimal value, the deposit might be too thin. If the duration exceeds the maximal limit the parts might be damaged or the production cost might increase because too much metal is deposited.

Each operation is executed in a single tank. A tank may be used to perform several operations of a given sequence. Then it is a multifunction tank. Otherwise it is a monofunction tank.

Batches of parts are first loaded on carriers (frames for printed circuit boards, baskets, or barrels for screws). Then handling devices (hoist or crane) move carriers from tank to tank. All of the hoists are generally identical. They move along a single track above the line, which prevents them from crossing over.

A transport operation is made up of several steps. A hoist moves empty from its current location to the tank containing the carrier to be transferred. Then it grasps the carrier, raises it above the tank, and pauses to allow it to drip (to limit the pollution of the other tanks while moving). It transports the carrier to the next tank in the sequence of treatments. The hoist pauses again for stabilization and lowers the carrier to put it down in the new tank.

Then the hoist becomes free to perform another transfer operation. All of the moving times are fixed. A scheduling procedure must take them into account as they are as large as processing times. In fact, while moving a carrier, pauses of the hoist are not allowed except for dripping and stabilization steps whose durations are known. Other kinds of pauses may damage the parts (e.g., oxidation of parts remaining in the air too long).

In a basic line, all of the transport operations are performed by hoists. A complex line is composed of several basic lines and contains specific handling resources. The latter, called transfer systems, transfer carriers between two basic lines. Some constraints must be added to represent the synchronization between hoists and transfer systems.

Most of the time handling resources are disjunctive, whereas processing resources may be cumulative. When a processing time is much longer than the other processing times, the associated tank is duplicated (Shapiro and Nuttle, 1988) which means that it contains more than one available place.

Scheduling transport tasks in such lines is well known in the literature as the hoist scheduling problem (HSP). The searched schedule often aims at maximizing throughput. Other criteria may also be considered, such as maximizing the load of some resources. Whatever the goal may be, it must be reached while respecting all of the constraints of the system, namely the potential constraints involved by the processing sequence, the minimal and maximal limits on processing times, the capacity of resources (tanks, hoists, and carriers), and the time a hoist needs to move empty between two successive transport operations. This problem is a no-wait no preemption scheduling problem. Therefore, scheduling processing tasks is equivalent to scheduling transport tasks, hence scheduling hoist movements.

For a more precise description of the hoist scheduling problem, one can refer to Baptiste, Bloch, and Varnier (2001).

3. The HSP and the existing notation

The above presentation shows that a specific terminology, coming from electroplating industry, is used to characterize the HSP. Nevertheless the HSP is obviously a shop scheduling problem and a notation already exists to identify and classify such problems. But as is seen in the following, it fails to represent the whole set of parameters and constraints that characterizes the HSP.

One of the best-known notation, proposed by Rinnooy Kan (1976), Graham, Lawler, Lenstra, and Rinnooy Kan (1979), and described in Blazewicz, Ecker, Schmidt, and Weglarz (1993), includes different fields: $\alpha 1, \alpha 2 / \beta 1, \dots, \beta 8 / \gamma$. Parameters αi give some information on machine environment. Parameters βi characterize tasks and resources. γ specifies the criterion to be optimized. We assume that the reader is familiar with this notation. For more information, see Rinnooy Kan (1976), Graham et al. (1979), and Blazewicz et al. (1993).

This notation allows a clear and brief description of any classical shop scheduling problem. But it turns out to be quite restrictive for the characterization of complex real situations. For instance, only one type of resource can be considered: machines (processors) on which tasks are performed. Additional resources can also be mentioned but not really described. For the HSP, if machines can be assimilated to tanks (processing resources), the monoprodukt HSP can be identified as a flow shop ($\alpha = Fk$) and the multiprodukt HSP can be seen as a job shop ($\alpha = Jk$), where k is the number of tanks. Parameters βi indicate that the HSP is a no-wait, no-preemption scheduling problem, including precedence constraints and additional resources (hoists and carriers). γ gives the criterion to be optimized.

But many characteristics of the HSP do not appear, particularly: bounded soaking times, empty moves, the number of hoists, the capacity of tanks, the multifunction notion, the

circulation constraint, and the management of empty carriers. Now, a single hoist problem with no duplicated tank and no particular constraint related to carriers only involves disjunctive constraints, whereas cumulative constraints arise in the multihoist case and/or if there are some duplicated tanks. Therefore, such data and constraints constitute essential factors when choosing a solving approach. They cannot be ignored when one compares the efficiency of different resolution methods applied to the HSP.

Vignier, Billaut, and Proust (1999) extended the field α to characterize flexible flow shop problems: $\alpha 1 = FH$. Then in the monoproduit *HSP* each tank may be assimilated to a stage of a flexible flow shop. The number of machines in a stage corresponds to the number of places of the associated tank. Nevertheless such a comparison is not totally exact as hoist moves are not restricted between two tanks. Besides, the risk of collision is not a characteristic of such problems. Pinedo (1995) also proposed to add a parameter β_i related to recirculation, which could be used to represent multifunction tanks. Some other similar extensions could permit the specification of missing information in this notation, such as the generalization of β_5 to bounded processing times, ($mp_{ij} \leq p_{ij} \leq Mp_{ij}$). In the same way, the duplication of parameters $\alpha 1$ and $\alpha 2$ would allow the representation of both processing resources and transport resources. But these extensions make the notation quite different from the original one. Moreover, they are still not sufficient to totally represent the HSP, as no constraint related to carriers is indicated. It is the same for the risk of collision between hoists. Besides, no parameter specifies how the HSP may be addressed: statically, dynamically, repetitively, and so on.

Liu and MacCarthy (1996) proposed a notation adapted to flexible manufacturing systems in which five fundamental factors appear: system type, capacity constraints, part characteristics, production management environment, and performance measures. Then a single hoist line can be seen as a flexible cell, a multihoist line as a multimachine FMS, or a complex line as a multicell FMS. This notation also details resource constraints, part characteristics, and production environment. Nevertheless, a tank is not exactly a numerically controlled machine tool, and a cell does not strictly represent the real layout of electroplating lines. In particular, it does not indicate that hoists share a single track. Besides, some of the constraints are still not represented, particularly precedence constraints, the maximal number of operations per part, the number of part types, unloaded moves, bounded processing times, forbidden preemption, the risk of collision, and multifunction tanks.

Finally, Lee, Lei, and Pinedo (1997) suggested a modification of the notation described in Pinedo (1995) to characterize the HSP. They use $\alpha(K)$ instead of α to indicate the number K of handling devices and add some parameters β_i :

- J , the total number of part types,
- n , the total number of parts of different types to be processed,
- n_{mps} , the minimal part set, which equals 1 when all parts are identical and is equal to the number of different parts entering the system during a cycle if production ratios are used,
- tw , which represents bounded processing times, and
- nwt , which denotes the no-wait requirement.

The criterion to minimize is the cycle length Π_{\min} . The HSP is then described by $Fm(K)|J, nwt, tw|\Pi_{\min}$. But this notation is limited to unit capacity resources (both processing and transport ones). Moreover, some significant factors still do not appear: unloaded moves, the

risk of collision, multifunction tanks, and carrier constraints such as circulation. Finally, this notation only allows a classification of cyclic problems, whereas some of the various problems referred to as hoist scheduling problems in the literature are not periodic problems.

To sum up, the constraints identified for the HSP can be partly found in similar problems, such as FMS or robotic scheduling problems. But such scheduling problems rarely gather all of the characteristics encountered in the HSP: no-wait and no-preemption constraints, bounded processing times, transport times (as long as the latter), or risk of collision between hoists. So the existing classifications of scheduling problems only enable one to identify some subclasses of the HSP. Then it seems convenient to propose a specific notation and a typology for the HSP, to allow a concise and unambiguous identification of all the studied cases. We do not aim at characterizing all shop scheduling problems. First it would involve a notation (then a classification) that would obviously be less precise than wanted. It may allow us to point at the existing similarities between shop scheduling problems, but it would fail to categorize the numerous instances of HSP found in the literature.

4. Notation

In the notation we propose (which was first presented in Bloch and Manier (1999)), we consider some of the main physical and logical parameters we have found in the literature related to the HSP. This notation consists of four fields:

$$\alpha \mid \beta \mid \delta \mid \gamma.$$

- The first field α ($\alpha = XHSP$) describes the *type of HSP* to be studied. It implicitly denotes that processing times are limited within lower and upper bounds, no pause is allowed for parts when moving between two tanks, neither transport operations nor soaking ones may be preempted, and facilities include single capacity handling resources. Moreover, the moving times of such resources must be considered as they are rather similar to processing times. There also exist spatial constraints, such as risks of collision occur in multihoist facilities. The variable X in $XHSP$ denotes the type of HSP to be considered. We have identified four classes of HSP in the literature: $X \in \{C, P, D, R\}$. The first two classes correspond to static problems. The last ones are related to dynamic ones. The problems belonging to the first class are well known as *cyclic hoist scheduling problems (CHSP)* (Lei and Wang, 1989a) and consist in determining a repetitive sequence of hoist moves. We named the second class *predictive hoist scheduling problems (PHSP)* (Bloch and Manier, 1999). It includes other static problems: the first kind of problem aims at minimizing the duration of transient phases between two successive cyclic productions. The second kind of problem aims at scheduling parts that enter the line to minimize the C_{max} criterion. One solution just provides the date when each part enters the line such that there exists at least one feasible schedule of all of the soaking and moving operations. A feasible schedule satisfies all of the defined constraints. The *dynamic hoist scheduling problem (DHSP)* (Lamothe, Thierry, and Delmas, 1996) consists in computing a new schedule of all the operations each time a part enters the line, while respecting all of the constraints. The *reactive hoist scheduling problem (RHSP)* (Lamothe, 1996) is a real-time problem that deals with the dynamic assignment of hoists to transport tasks.

- The second field $\beta = \beta_1, \beta_2, \beta_3, \beta_4/\beta_5, \beta_6, \beta_7, \beta_8/\beta_9$ describes the *physical system*. β_1 and β_2 , respectively, denotes the *number of basic lines* to be considered ($\beta_1 = nl$) and the *number of transfer systems* connecting these lines ($\beta_2 = ntransfer$). If there is a single line, both of these parameters do not appear as they equal the default value empty set (\emptyset). The parameter $\beta_3 \in \{\emptyset, synchro\}$ expresses the need of *synchronization* between hoists and transfer systems. This occurs when a carrier needs to be transferred from a line to another one. If it cannot be stored in a buffer tank, the hoist moving this carrier and the transfer system must meet to perform the exchange operation. Then it involves an additional constraint for the handling devices. \emptyset represents independent moves of those transport systems. $\beta_4 = (\beta_{41}, \beta_{42}, \beta_{43})$ denotes, respectively, for each basic line of a facility, the *number of hoists*, the *number of tanks* ($\beta_{42} = mt$ except the load and unload stations), and the *maximal capacity of tanks*. $(\beta_{41}, \beta_{42}, \beta_{43}) = (mh, mt, ct)$ if at least one of the parameters mh or ct differs from one. β_{41} and β_{43} will not appear ($(\beta_{41}, \beta_{42}, \beta_{43}) = (\emptyset, mt, \emptyset)$) if the considered line is both a single hoist one and composed of single capacity tanks. Finally if the facility is composed of a single line, the parentheses are removed in the notation. β_5 to β_8 are related to carriers. $\beta_5 = nc$ is the *number of available carriers* (default value \emptyset if an infinite number is assumed). $\beta_6 \in \{\emptyset, circ\}$ indicates whether the carriers circulate (*circ*) or not (\emptyset). The *circulation* of carriers was introduced for the CHSP in Shapiro and Nuttle (1988). It means that the carrier unloaded during a cycle must be loaded again to enter the line in the following cycle. $\beta_7 \in \{\emptyset, ret\}$ is related to another handling system dedicated to the *return of empty carriers* from the unload station to the load one. \emptyset means either that a hoist ensures it or that the load and unload stations are associated (load and unload tasks are performed on the same station). $\beta_8 \in \{\emptyset, empty\}$ denotes the lack of storage for carriers, near the facility or at the load/unload stations ($\beta_8 = \emptyset$ if such storage places exist). Then empty carriers must remain on the line and be moved from tank to tank so as to prevent them from interfering with loaded carriers. $\beta_9 \in \{\emptyset, ass, diss\}$ describes the configuration of the load and unload stations. Those stations are often considered as fictitious tanks, and can be associated ($\beta_9 = ass$) or dissociated ($\beta_9 = diss$). If this configuration does not matter, the default value (\emptyset) is used. If some authors do not specify if their solving approach can be used for both these configurations, then use the generic value “load-unload”.
- The third field $\delta = \delta_1/\delta_2, \delta_3, \delta_4, \delta_5$ describes the *production environment* to be considered. The parameter $\delta_1 = nparts$ is the total number of parts to be treated on the line, or the number of batches (a batch corresponds to the capacity of the carrier associated with a part type). The default value \emptyset means that an infinite number is assumed. $\delta_2 = nps$ is related to the *number of part types*. Each part type is characterized by processing specifications that define both a totally ordered sequence of soak tasks in the tanks and bounds for soaking times in each tank. $\delta_2 = \emptyset$ means that all of the parts have identical processing specifications. $\delta_3 = nop$ is the number of operations of the longest processing sequence among the nps ones. $\delta_4 \in \{\emptyset, clean\}$ specifies whether carriers must be cleaned after being unloaded or not (\emptyset if unloading carriers is the last operation of all the sequences). $\delta_5 \in \{\emptyset, recrc\}$ introduces the notion and constraint of *recirculation*, as it was defined in Pinedo (1995). It is related to multifunction tanks. \emptyset means that all the tanks are monofunction ones.
- The last field $\gamma \in \{Cmax, \dots\}$ denotes the *criterion* to be optimized. The goal can be for the HSP: minimize the period ($Tmin$) or the number of hoists for a given period for the

CHSP, minimize the makespan (C_{max}), maximize the use of resources (hoists and tanks), or the number of good parts within a time window.

So the complete notation is

$$\begin{aligned} & \mathbf{XHSP} \mid \mathbf{nl}, \mathbf{ntransfer}, \mathbf{synchro}, (\mathbf{mh}, \mathbf{mt}, \mathbf{ct})_{i=1 \text{ to } \mathbf{nl}} / \mathbf{nc}, \mathbf{circ}, \mathbf{ret}, \mathbf{empty} / \\ & \mathbf{load-unload} \mid \mathbf{nparts/nps}, \mathbf{nop}, \mathbf{clean}, \mathbf{recrc} \mid \mathbf{criterion}. \end{aligned}$$

This notation was applied to most of the problems found in the literature. It turned out to be less complex than it seems, as default values were often used. The only parameters for which a numerical value must be given are β_{42} (number of tanks for each line) and δ_3 (number of operations of the longest processing sequence). They can never take a default value (\emptyset). For instance, the well known *CHSP* benchmark found in Phillips and Unger (1976) is simply described as follows: *CHSP* | 12 / / *ass* | /14 | *Tmin*. Even the most difficult cases of complex facilities can be rather concisely characterized as for the example studied by Caux, Fleury, Gourgand, and Kellert (1995):

$$\mathbf{PHSP} \mid 3, 4, \mathbf{synchro}, (15), (15), (15) / / \mathbf{dis} \mid 16/24, 17, \mathbf{recrc} \mid \mathbf{Cmax}.$$

Remark 1. Numerical parameters (mt , nps , ...) are related to the most complex example studied in the associated article. They are not always restrictive values. For instance, even if mt equals 10 in the notation, the algorithm given in the article may be successfully applied to lines containing more than 10 tanks. If no example is studied, generic terms can be used (mt or $nps > 1$, for instance).

Remark 2. The model developed in Phillips and Unger (1976) allows the consideration of multifunction constraints (see Figure 2 in the typology hereafter) but the problem solved as a numerical application only includes monofunction tanks.

5. Typology

Bloch, Bachelu, Varnier, and Baptiste (1997) proposed a typology for the HSP. We completed it by comparing and by matching it with the above notation. The resulting classification is represented using four trees (Figures 2–4). Each tree represents one of the four identified classes of problems (α). One leaf corresponds to a complete instantiation of the notation. Nevertheless, some of the parameters (such as nl or mt) do not explicitly appear. It makes those trees easier to read and it prevents one from obtaining one leaf per article. Besides, a classification of those articles may be hard as some parameters (such as *clean*) are not always clearly specified. This typology enables us to identify eight classes of problems, by grouping some leaves of a tree. These classes appear under each tree and correspond to more or less frequently studied cases in the literature. The bold parameters have the same value for all of the references of the corresponding class. When different values are possible, the generic value of the parameter is kept. This generic value does not necessarily equal the default value (\emptyset). For instance *nps* means that at least one of the articles does not deal with the monoproduct case. «*recrc*» (in bold) denotes that the problem is always studied

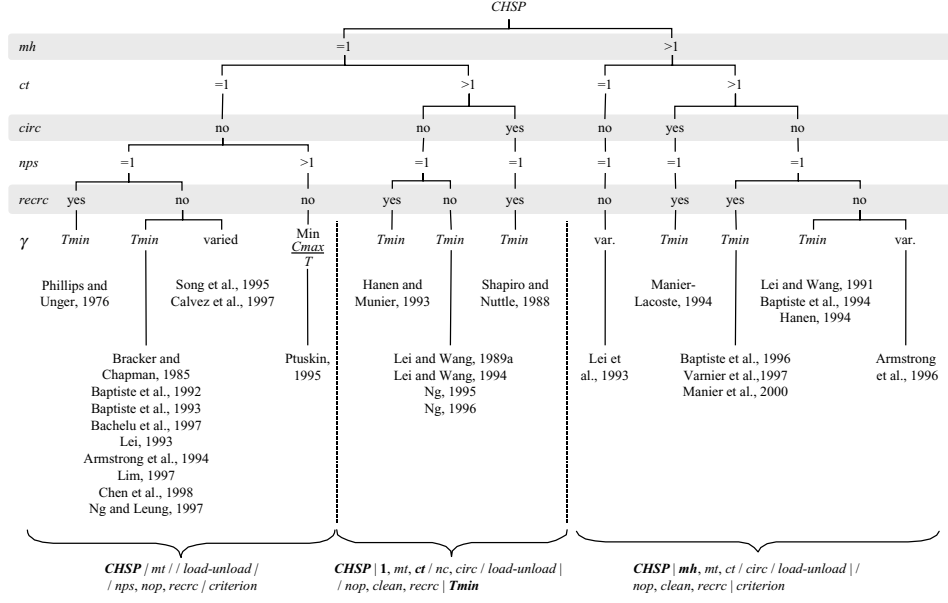


Figure 2. Cyclic hoist scheduling problems.

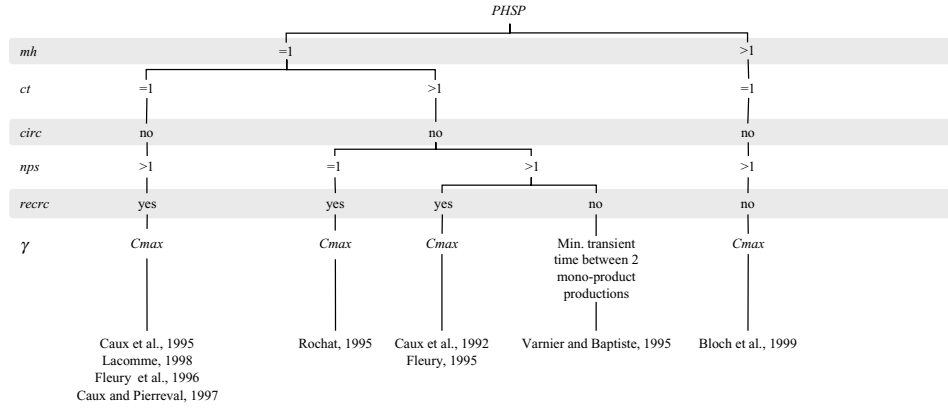


Figure 3. Predictive hoist scheduling problems.

with a recirculation constraint, whereas «*recrc*» indicates that some authors considered the recirculation constraint and others did not.

6. State of the art of the hoist scheduling problem

For each identified class, we provide a brief survey of the most significant papers among about 100 articles found in the literature related to the HSP. We deduce from the typology

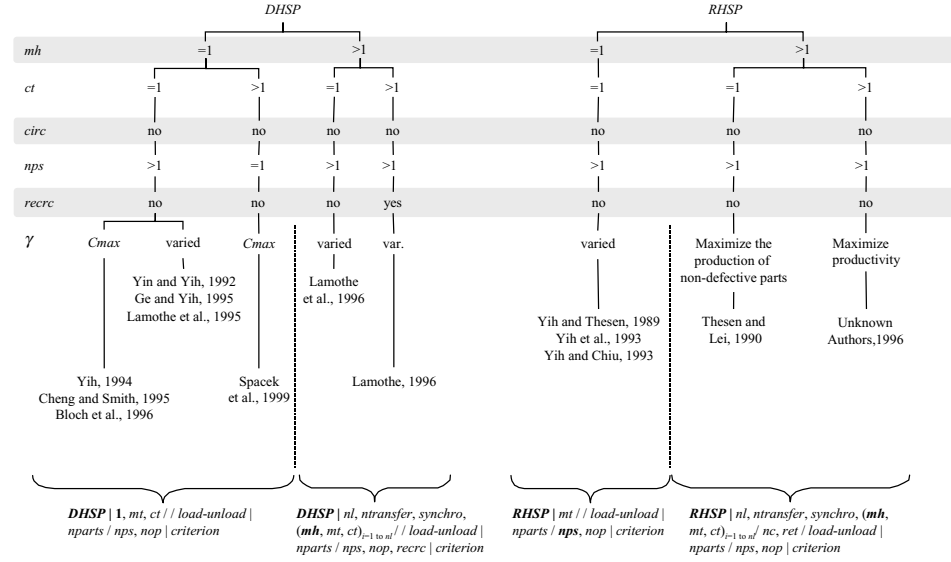


Figure 4. Dynamic and reactive hoist scheduling problems.

that static problems are obviously the most studied ones. Moreover very few articles deal with complex facilities (including more than one basic line). Many studies deal with a one-period schedule, for lines with monofunction tanks, no duplicated tanks, and with a single hoist. The problem related to such lines is called the basic problem and was proved to be NP-complete in Lei and Wang (1989b).

6.1. CHSP | *mt* // load-unload | /*nps*, *nop*, *recrc* | criterion

The cyclic HSP in the single hoist case and without duplicated tank is the more studied case in the literature. Phillips and Unger (1976) is the first study dealing with the CHSP. The authors use a mixed integer program and a branch and bound procedure to solve an industrial problem with 13 tanks (including the load/unload station). They a priori assign a value to the number of carriers being simultaneously used in the line during a cycle, which prevents them from providing the optimal solution. Bracker and Chapman (1985) give few details of the approach they employ. They seem to generate all possible schedules using linear programming, which can hardly be extended to real cases.

Baptiste, Legnard, and Varnier (1992) and Manier-Lacoste (1994) use a constraint logic programming approach implemented with Prolog III. The resolution procedure is similar to branch and bound. Each branching step consists in arbitrating a disjunctive constraint. A leaf of the search tree corresponds to a feasible sequence of movements. Baptiste et al. (1992) optimally solve a basic problem (defined at the beginning of Section 6) using a strategy of resolution based on a heuristic enumeration of disjunctive constraints. Manier-Lacoste (1994) extends this approach to *n*-periodic cases. Baptiste, Legnard, Manier, and Varnier (1993) improve the strategy of resolution presented in Baptiste et al. (1992) by

considering families of disjunctive constraints. This strategy aims at reducing the depth of the search tree. The implementation compares two constraint logic programming languages: Prolog III and CHIP. Bachelu, Varnier, and Baptiste (1997) analyze and modify the strategy of resolution found in Baptiste et al. (1993) and Baptiste, Legeard, Manier, and Varnier (1994). To reduce the computation time, the authors identify as soon as possible when the system of constraints becomes inconsistent. They use a matrix representation with interesting neighborhood properties. In particular this matrix allows the determination of a parameter k for each couple of operations. This parameter is used to identify some disjunctive constraints for which only one choice remains possible.

Lei (1993) and Armstrong, Lei, and Gu (1994) both use a minimal bound of the cycle time for a partial sequence of movements, called minimum time span (MTS). For a given sequence of movements, the MTS enables Lei (1993) to define minimal and maximal bounds of the period and then the optimal starting times of soak operations. In Armstrong et al. (1994), a branch and bound procedure uses the MTS parameter for the bounding steps. The procedure proposed in Lei (1993) is employed by Lim (1997) to evaluate the strength of chromosomes in a genetic algorithm. A chromosome represents a sequence of tanks unloaded by the hoist during a cycle.

Chen, Chu, and Proth (1998) propose two complementary branch and bound procedures. At each node, a bi-valued graph is first used to determine minimal and maximal bounds for a given initial state of the tanks (empty or occupied). Then the second procedure builds the optimal sequence of movements for this state. Ng and Leung (1997) allow pauses while moving parts, and computes the starting times of treatments for a given sequence of moves, using integer programming.

Song, Storch, and Zabinsky (1995) propose simple heuristic rules to determine minimal and maximal values of the period and evaluate the schedule associated with possible periods by simulation. Calvez, Aygalinc, and Khansa (1997) use a Petri net model to study the robustness of a given sequence of movements. Some properties of P-time Petri nets allow inferring some constraints. The latter characterizes the starting dates of moves and determines these dates for different values of the period. Ptuskin (1995) considers the multiproduct CHSP: parts are processed by the same tanks, according to the same route, but they have various processing times. A sequence of n different parts periodically enters the system. This sequence is assumed to be known, but the exact entering date of each part must be determined. This problem is decomposed in several monoprodukt subproblems and the solution corresponds to a common period.

6.2. *CHSP* | I , mt , ct/nc , $circ/load-unload$ | $/nop$, $clean$, $recrc$ | $Tmin$

The following articles deal with the cyclic HSP including a single hoist and at least one duplicated tank. They all consider the monoprodukt case. The problem tackled by Shapiro and Nuttle (1988) includes the greatest number of specific constraints: various configurations of load/unload stations, duplicated tanks, cleaning of empty carriers, and circulation are taken into account. A branch and bound procedure progressively builds the cycle. Each level of the search tree consists of adding a part and linear programs are solved at each node to check if the system of constraints is consistent.

The branch and bound procedure developed by Lei and Wang (1989a, 1994) also builds the sequence of movements progressively. At each node, a candidate move is chosen to be added in the cycle and the time windows of variables (move starting dates) are computed using an iterative program. The choice is based on a matrix that represents the current partial sequence, and the potential constraints to be satisfied. This algorithm finds n -periodic solutions. Hanen and Munier (1993) propose two linear models and two corresponding branch and bound procedures. The first one is combined with a bi-valued graph. The latter is used to compute a lower bound of the period, by adjusting the height and the length of each arc. The second one enumerates the permutations of moves in a cycle and uses a critical path evaluation to compute a lower bound.

Ng (1995) employs mixed integer programming and the branch and bound developed by Shapiro and Nuttle (1988), but assumes that some places of a duplicated tank may be never used. This allows Ng to determine the optimal number of places for each duplicated tank. Ng (1996) develops another branch and bound procedure to solve the problem when pauses of loaded hoists are allowed.

6.3. **CHSP** | *mh, mt, ct /circ /load-unload /nop, clean, reocr | criterion*

This class is the cyclic HSP in the multihoist case where a single part type is considered. Lei and Wang (1991) solve the CHSP with two hoists. In this approach, the line is partitioned into two sets of contiguous tanks and each hoist is assigned to a set. Each evaluated partition corresponds to two single-hoist subproblems. The authors determine the minimum common cycle that allows coupling single-hoist schedules. This work cannot be extended to consider multifunction tanks or associated load/unload stations because the flow is assumed to be unidirectional. It is extended to define more than two sets, while minimizing the number of hoists, in Lei, Armstrong, and Gu (1993) and Armstrong, Gu, and Lei (1996). These articles propose a specific way to compute the cyclic schedules associated with each set and find the minimum common cycle. The first one uses the algorithm developed by Armstrong et al. (1994), whereas the second one solves several linear programming subproblems, the duals of which are the shortest path problems.

Various extensions of the model or the strategy of resolution found in Baptiste et al. (1992) are proposed. Like Baptiste et al. (1993), Baptiste et al. (1994) discuss several procedures to improve the resolution time but also extend their model to the multihoist case. Results are provided for complex lines (26 tanks, the capacity of one tank equals to 10, and 3 hoists). Baptiste, Legeard, Manier, and Varnier (1996) extend the n -periodic model of Manier-Lacoste (1994) to consider duplicated and multifunction tanks and several hoists. Manier, Varnier, and Baptiste (2000) propose a static partition of the transfer operations performed by the hoists. The tanks belonging to a zone assigned to one hoist are not necessarily contiguous, and the zones of two adjacent hoists may overlap. As in Lei et al. (1993), single hoist schedules are determined with a common duration cycle. In addition, to avoid collisions, the remaining possible conflicts between two hoists are arbitrated with additional disjunctive constraints that enable priority to be given to one or the other hoist. Manier-Lacoste (1994) enriches those models by taking into account the constraint of circulation and the minimal required distance between hoists. Varnier, Bachelu, and Baptiste (1997)

deal with the conception of a decision support system. They use the multihoist model and the partitioning strategy found in Manier-Lacoste (1994). In addition, they establish a heuristic rule that defines the best partition to balance the charge time and the number of transfer operations for each hoist. Hanen (1994) extends the approach of Hanen and Munier (1993) using the same principle as Manier-Lacoste (1994) for the multihoist case. But they use a mixed integer programming formulation and a branch and bound resolution scheme in which the bounding techniques are based on the longest path computations.

6.4. PHSP

We can only instantiate the field α ($=PHSP$). No subclass of the predictive HSP appears. Nevertheless, we distinguish the articles of this class with the parameter “criterion”. Varnier and Baptiste (1995) optimize the transient period involved when a change of cyclic production occurs (from parts of type A to parts of type B). The method consists in combining the movements of two optimal cycles during the transient phase. The procedure is based on a linear model similar to Manier-Lacoste (1994) and uses constraint logic programming (Prolog III). A branch and bound procedure arbitrates the disjunctive constraints. The length of the transient phase is bounded and the sequence of movements of each subcycle (A and B) is not modified, which limits the number of disjunctions.

Other studies schedule the entry of different parts, to minimize the C_{max} criterion. One of the main approaches uses metaheuristics (simulated annealing, kangaroo algorithm, and taboo search) to find possible sequences. Then they are coupled with several kinds of simulation tools or dedicated heuristics, to evaluate these sequences: a discrete event system simulator for Caux et al. (1995), Caux, Fleury, Gourgand, and Kellert (1992), and Fleury (1995); a multiagents system for Lacomme (1998) and Fleury, Goujon, Gourgand, and Lacomme (1996); the earliest start heuristic for Caux and Pierreval (1997) (which delays the entry of some parts in the case of conflicts); and a modified shifting bottleneck heuristic for Bloch, Varnier, and Baptiste (1999).

6.5. DHSP | $I, mt, ct // load-unload$ | $nparts / nps, nop$ | $criterion$

The work dealing with the dynamic HSP are more recent and most of them are limited to the single hoist case. They propose heuristic solving methods. In Yih (1994) and Yin and Yih (1992), a heuristic delays some movements or delays the arrival of the entering part when conflicts between this part and the previous ones occur. Ge and Yih (1995) develop a branch and bound procedure to schedule movements progressively. At each node, the algorithm chooses the next movement to be added to the sequence and a linear problem is solved.

Cheng and Smith (1995) use a precedence constraints posting heuristic to sequence movements by selecting disjunctive arcs in a graph. Lamothe, Correge, and Delmas (1995) also employ disjunctive programming formulation but they improve the procedure by using a dynamic backtracking and storing data to describe why some constraints were not satisfied in previous iterations.

Bloch, Varnier, and Baptiste (1996) compare the efficiency of several metaheuristics (stochastic descent, taboo search, kangaroo algorithm, etc.) and use evolutionary computation to solve DHSP in a basic line. Spacek, Manier, and El Moudni (1999) use minimum–maximum P-time event graphs to model the HSP with duplicated tanks while considering a single part type. Then, a state equation in the $(\max, +)$ algebra is deduced. At each iteration, a heuristic rule enables to solve resource conflicts.

6.6. **DHSP** | *nl, ntransfer, synchro, (mh, mt, ct)_{i=1 to nl} / load-unload | nparts / nps, nop, recrc | criterion*

Few references were found for this class of problems. Only one of the approaches described in Section 6.5. Lamothe et al. (1995) has been extended to take into account several hoists (Lamothe et al., 1996), duplicated tanks, and more complex electroplating lines (Lamothe, 1996). The rules used to avoid collision between hoists are based on those defined in Manier-Lacoste (1994).

6.7. **RHSP** | *mt / load-unload | nparts / nps, nop | criterion*

Few articles were found for the reactive HSP in the single hoist case and without duplicated tank. Yih and Thesen (1989) compare several programming environments to implement a system named trace driven knowledge acquisition system (TDKA). This is dedicated to define the decision rules of an expert system. In a first stage, choices made by experts are interactively recorded. They constitute a knowledge base and are analyzed to deduce rules from expert behavior. In Yih, Liang, and Moskovitz (1993), a decision tree improves the analysis of the knowledge base in the TDKA system. In Yih and Chiu (1993), neural networks are used to generalize a semi-Markovian decision model describing the possible states of the system. A transient matrix provides the cost associated with each decision. The great number of possible states limits the resolution to small instances of the problem. To reduce the matrix size, only some states were first selected, associated with expert choices. Neural networks allow considering all of the possible states.

6.8. **RHSP** | *nl, ntransfer, synchro, (mh, mt, ct)_{i=1 to nl} / nc, ret / load-unload | nparts / nps, nop | criterion*

The articles we found about the reactive HSP in the multihoist case focus on the real-time control of electroplating lines by dynamically assigning tasks to hoists. Thesen and Lei (1990) propose an expert system that chooses the heuristic rule among four simple rules to be used according to the current state of the line. A paper (Anonymous, 1996) presents an industrial case. It describes in detail the layout of the line, production rates, and the different part types. As parts all belong to the same family of products, only one cycle is determined to treat all of them. Then, some rectifiers of current are controlled in real time to adjust processing times according to the part type.

6.9. Problems similar to the HSP

To finish this state of the art survey, we want to point out the existence of other problems similar to the HSP, including the robotic scheduling problem. Some of them correspond to a relaxation of the HSP as soon as one of the main characteristics defined in Section 4 (description of the first field XHSP) is not taken into account. Without being exhaustive, we give here some references of papers dealing with such similar problems:

- Problems where processing times are fixed: Levner, Kats, and Sriskandarajah (1996) and Kats and Levner (1997) develop a polynomial algorithm to find a cyclic schedule in a no-wait robotic flowshop. It can be seen as a relaxation of the CHSP. In the same way, Kats and Levner (1995) study a cyclic robotic flowshop problem and minimize the number of robots to be used when the period is known. They transform the basic problem into two assignment subproblems that can be solved with polynomial algorithms.
- Problems where the no-wait constraint is relaxed, such as those encountered in pathology laboratories (Rochat, 1995).
- Problems where processing times are fixed and without spatial constraints: Collart-Dutilleul and Denat (1997) study the robustness of a given periodic schedule when the time between two successive part entries and the moving times of hoists vary. This study considers several hoists but it does not take into account the fact that hoists move along a single track.
- Problems where processing times are fixed, the no-wait constraint is relaxed and hoists are cumulative resources: Su and Chen (1996) present heuristics, based on the enumeration of all possible cyclic schedules for two machines and extended to m machines. But they do not consider maximal values of processing times. In the same way, they schedule the moves of a double-gripper hoist, assuming that pauses are allowed while transporting parts.

We also refer to Sethi, Sriskandarajah, Sorger, Blazewicz, and Kubiak (1992). They optimally solve three sequencing problems in a robotic cell characterized by a single robot and fixed processing times. In single part type cases, the considered flowshop problem consists in finding a one-part cycle. It can be viewed as a simplified CHSP. When several part types are considered, the sequence of robot moves is given and the authors determine a schedule of parts at the entry station so as to maximize the long run average production rate. This case can also be considered as a relaxed PHSP. Note that in this article the review of the literature about scheduling of parts and robot moves in a robotic cell refers to some studied cases that remain rather far from the definition of the HSP: intermediate buffers and stochastic activity times. Moreover even in the multihoists case, none seems to consider spatial constraints.

Finally Crama, Kats, van de Klundert, and Levner (2000) define the robotic flowshop scheduling problem, in which they include the HSP. Indeed, as we have already discussed in the previous sections, the CHSP can be seen as a cyclic robotic flowshop scheduling problem, if there are only disjunctive resource constraints which forbid duplicated tanks, and if a single type of parts is considered (with the same processing sequence and the same processing windows). Consequently, Crama et al. (2000) focus on the cyclic and single part

type case, which we have identified as one of the aspects of the HSP, and which seems to be the more considered case in the literature.

We have already explained in the section dedicated to the analysis and comparison with the existing notation that some of the different instances of the HSP can be assimilated to various shop scheduling problems. Such papers also show that some significant similarities between the HSP and many problems studied in the literature effectively exist. Therefore, one could think that the notation and typology we propose could be extended to allow the description of these similar problems. However, the complexity of those problems seems to be significantly different (polynomial versus NP-hard) from the complexity of HSPs. For instance, Lei and Wang (1989b) proved that the basic problem (one of the simplest HSP) is NP-hard, whereas the cyclic robotic flowshop problem (similar problem with fixed processing times) can be solved in a polynomial way in Kats and Levner (1997).

Moreover, it seems illusory to describe any scheduling shop problem (robotic scheduling problems, FMS, and flexible flow shop) with a single notation. Too many similar problems might be identified to the HSP (or vice versa). This would require a simplification of the notation to make it be generic enough and it seems incompatible with our goal: enabling one to situate his/her hoist scheduling problem in one leaf of the typology trees even if the associated branch has not actually been explored yet. Then any searcher or industrialist may know which existing models he/she should refer to, or at least he/she will know the models corresponding to next leaves or branches likely to be used. To reach this objective, some specific characteristics of the problem (such as circulation for the HSP) and the less studied classes of HSP (transient phases between two cyclic sequences, several part types case) must appear. They are often more related to real applications than some simplified studies found in the literature. It was not possible to modify the notation to do so for each kind of similar scheduling problem. Otherwise it would become extremely complicated.

That is why we preferred not to extend the notation and the typology, although we are aware that it would be interesting to clarify the links between all of these scheduling problems. This question is still open. A research group (Bermudes) is studying the similarities and differences between the hoist scheduling problem, flexible manufacturing systems scheduling problems, and hybrid flow shop scheduling problems, to improve notation and typologies.

7. Conclusion

Once we realized a state of the art of the hoist scheduling problem (Bloch et al., 1997; Manier and Baptiste, 1994), we thought it was worth proposing a notation and the associated typology, in particular as it appeared difficult to place a given study among the research of the international community. Besides, we already found different descriptions of the same problem by several authors. Then a good evaluation and comparison of the various approaches can be more difficult to perform. We hope that the notation we propose can allow a reduction of such a drawback. At least it enabled us to characterize all of the publications we could find about the HSP. One possible use of this work is to automatically recognize the various instances of the hoist scheduling problem. Besides the associated typology helped us to identify the more studied cases (i.e., the single hoist CHSP) and the problems still

remaining to explore (i.e., multihoists DHSP and RHSP). This global evaluation shows that the hoist scheduling problem is far from being totally solved.

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