AN EFFECTIVE APPROACH FOR REAL-WORLD PRODUCTION PLANNING

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Abstract: This paper shows an application of constraint logic-based approach to the realistic scheduling problem. Operations scheduling, often influenced by diverse and conflicting constraints, is strongly NP-hard problem of combinatorial optimisation. The problem is complicated further by real scheduling environments, where a variety of constraints in response are critical aspects for the application of a solution. Constraint logic programming technique well armed with the major function of constraint handling and solving mechanisms can be effectively applied to solve real-world scheduling problems. In this study, the scheduling problem addressed, based on a dye house involving jobs associated with the colouring of different fibres, is characterized by various constraints like colour precedence, dye machine allocation and time constraints. The solution procedure used takes into account a number of dye house performance measures which include on-time delivery and resource utilisation. The results indicate that constraint-based scheduling is computationally efficient in schedule generation in that a solution can be found within a few seconds. Furthermore, solutions produced always minimise the mean tardiness and maximise the utilisation of dyeing facilities.

1 INTRODUCTION

Competitive manufacturing requires the efficient use of facilities to meet the cost and time requirements of customers. This is addressed by the scheduling of work orders within the manufacturing system. The generic operations scheduling problem may be defined as assigning various jobs or work orders to resources over time windows in order to complete a set of jobs or orders for a given period. Many real-world manufacturing situations are particularly subject to difficult scheduling problems because they must satisfy many constraints for a successful solution. Most of the realistic scheduling problems belong to the class of nondeterministic polynomial (NP)-complete (Garey and Johnson, 1979), which implies that an optimal solution is not solvable in polynomial time. As highly combinatorial search problems, real-world scheduling problems are computationally complex. Much of the complexity comes from the need to attend to a large and diverse set of objectives, requirements and preferences that originate from many different sources in the plant-wide situation (Smith et al., 1986). In the large-scale scheduling environments, reducing complexity is especially crucial to obtain feasible schedules within acceptable response time.

The prime concern of scheduling in reality relies totally on its applicability, subject to various scheduling constraints which must be satisfied for a solution to be valid. Also the quality of a completed schedule may be evaluated according to a variety of constraints, including the degree to which the due dates of the orders are met, the total amount of time required to complete the operation sequences, and the utilisation of the resources. The motivation of this study is to systematically address all constraints encountered in scheduling environments, and to demonstrate the use of constraint manipulation as a solving mechanism over a scheduling domain. The goal of this paper is to show an intelligent scheduling methodology that is capable of solving operations scheduling problems within realistic, broadly constrained environments. In the process, constraint logic based scheduling approach that combines a declarative representation of solution domain with a constraint handling and solving mechanism is proposed.

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2 THE TARGET PROBLEM

The target problem addressed by the constraint logic-based approach is scheduling an efficient operations sequence in the dye house of a socks manufacturing company. On the whole, the production process of socks making is divided into five divisions. The first process in sock manufacturing is knitting using machines to turn raw materials (called yarn), such as wool, nylon and cotton, into semi-finished goods. The types of socks produced range from fine gauge business socks, right down to heavy cushion foot sports socks. The next phase is seaming, or toe closing. Jobs are required to go through three separate operations in this area. They are: (i) turning the socks inside out for sewing, (ii) sewing of the toe line, and (iii) turning back to the right side and expanding the toe line - to avoid having a large chunky over-locking line at the toe of the sock. After the toe closing operation socks are sent to the dye house for colouring or finishing. The socks are dyed in machines most suited to the fibre type. Wool takes about 4 hours to dye, while cotton can take up to 8 hours. There are 4 different dyeing machine groups in a dye house. The next process area is pressing. This operation provides a permanent setting of the fibre and a clean, smooth texture for final presentation for sale. After pressing, socks are examined and packed.

In this paper, the focus is on the use of constraint logic programming in the dye house scheduling of a socks manufacturing factory. The significance of scheduling in the dyeing division is grounded on the fact that it determines the quality of final products for the reason of dependencies among the sequence of colours, fibre types, and dyeing capabilities of machines. It also affects the productivity of the whole manufacturing process due to a limited number of facilities equipped being in operation. At present, the production scheduling in each division is handled manually. However, the shop floor is a very dynamic environment and the scope and the pertinent variables in scheduling far exceed any human scheduler's capabilities. As for dye house scheduling, the types of job schedules to be produced range from a three-day scheduling to daily scheduling, in alignment with the aspect of shop floor such as a set of job orders released from the previous stages, jobs to be delivered to the next process within the deadline requested, urgent orders to be scheduled for a short period of time and the capacity (load limits) of dye house resources. The human scheduler is only able to produce a rough schedule; the actual shop floor operation still depends on constant monitoring by the human scheduler.

2.1 The Test Domain

The scheduling domain is derived from actual manufacturing data. It is based on a general operations scheduling but remains grounded in a real-world application. The scheduling data used is provided by the factory. The test domain is based on a dye house covering the operations associated with the colouring of four types of fibres. The key characteristics of the problem are as follows:

- An order may consist of a set of sequenced operations to be dyed on the specified machine.
- The dye house consists of four major dyeing machine groups, defined in terms of their processing capabilities.
- The socks are dyed in dye machines most suited to the fibre type.
- The operation duration (processing times) ranges from 4 hours to 8 hours.
- In view of its previous process, each job operation has a requested start time to perform the operation.
- The number of colours at a dye house can be broadly divided into nine major groupings.
- The job sequence within specific machines for dyeing is constrained by the colour of the dyes which are ordered from light to dark colours.
- Each job operation has a requested deadline to meet the delivery of job order.

The descriptions of job operations at a typical dye house are given in Table 1. A job is identified by a unique job order (style) number, which is recorded in the job order column. However on the shop floor, a job is often identified by its operation formula which is combined by its fibre and colour used. Each job is assigned a requested start time and due time. The remaining column shows a description of the operation to be dyed (e.g., blue 69 etc. represents fabric dyeing of different colours). The predominant fibres to be dyed are 100% wool (WL) and wool-blends (WB), and 100% cotton (CT) and cotton-blends (CB).

Table 1: A partial list of operation data at dye house for scheduling.

Job order	Operation formula	Processing time (hrs)	Start time	Due time	Operation description
LP100173	WLB	4	0	12	wool : blue 69
SP132517	WBT	4	4	24	wol/bl : brown 8
EP180602	CTP	8	0	16	cotton : grey 57
EP148264	WBW	4	0	12	wol/bl : white 14
SP100770	CBG	8	4	24	cot/bl : green 75
SP113831	CBY	8	0	16	cot/bl : yellow 30
LP195812	WLU	4	4	20	wool : black 9
LP199860	CTK	8	0	16	cotton : cream 26
SP107015	WBR	4	4	20	wol/bl : red 42

2.2 The Schedule Constraints

The dye house scheduling problem involves the following constraint types:

- Colour precedence between operations. In other words, the sequence of operations is constrained by the colour to be dyed.
- Restrictions on the allocation of dyeing machines.
- Laid start time to execute the job operation.
- Enforced operation duration on the machine specified.
- Resources with limited availabilities. That is, each machine cannot process more than one operation at the same time.
- Imposed deadline to meet the order delivery.

2.3 The Schedule Objectives

The objectives of the dye house scheduling problem can be summarized as being geared to meet customer's requirements, in particular, the on-time delivery of order and quality of products. Also, from the maker's standpoint, maximum use of high-valued dyeing machines is one of the considerable scheduling goals. The overall quality of products (socks), as already mentioned, rests heavily on the colouring of fibres. Thus, the objectives of the target problem are: (i) to meet due dates and (ii) to maximise resource utilisation.

3 THE SCHEDULING APPROACH

Constraint logic-based approach adopted by the proposed scheduling methodology involves: (i) identifying potentially threatened constraints (i.e., colour) associated with the schedule state and selecting one to address, (ii) taking the decision clauses to tackle the scheduling constraints and (iii) propagating the consequences of each decision. The approach relies on constraint manipulation and propagation to drive decision making. Each decision type relates to scheduling constraints. In the dye house data under consideration, the primary scheduling constraint types are: (i) the colour imposed operation sequence, and (ii) the resource capacity limits. Each of these constraints is continuously monitored across the full scheduling horizon.

3.1 The Representation of Constraints

The scheduling solution must respect a number of constraints, in particular temporal-capacity constraints which may be dynamically monitored throughout the scheduling process. Temporal capacity constraints refer to colour-dependent order enforcements that apply over the time available for processing using a resource. Temporal-capacity constraints can be monitored in terms of the degree of threat to their satisfaction, which is a function of estimated demand and available capacity over time. These temporal constraints on operations impose a demand for time at the resource time period. The proposed constraint logic-based approach takes into consideration every resource time period of various durations covering the entire scheduling horizon.

3.2 The Scheduling Method

Scheduling in the constraint logic-based approach occurs at two levels: constraint solving and schedule generation. Constraint solving involves two steps of constraint handling based on temporal relations and resource capacity constraints. Temporal constraints can be solved by the successive refinement of operation time windows. For the dye house problem under consideration, the colour precedence constraint *L* before *D*, i.e. "operation *D* with dark colour can only start after *L* with light colour has completed," is implemented by:

$$operation\ (L) + duration\ (L) \leq operation\ (D)$$

On a machine performing a single operation at a time, the capacity constraints enforce the mutual exclusion for each operation pair (*L*, *D*) assigned to the same resource: *L* before *D* or *D* before *A*. The implementation uses the constraint clauses as choices:

exclusive (L, D):-
operation (L) + duration (L) ≤ operation (D);
operation (D) + duration (D) ≤ operation (L).

Evidently, the constraint solving mechanism in the proposed approach provides a computational efficiency that can be expected from the capability of constraint manipulation to prune the search space during the computation of a schedule.

Following constraint solving, each operation has been allocated to a specified resource and its start to a single time period. No specific operation start time has been set and operations allocated to the same resource and time period remain to be sequenced. This output from the constraint solver serves as the input to the scheduler. Two approaches have been developed for schedule generating. One involves a full search, and other uses a global scheduling approach. The feasibility of undertaking a full search depends on the number of allocation alternatives remaining after constraint solving. This is primarily determined by the extent to which temporal refinement is made by the constraint solver. Local scheduling based on full search proceeds by finding all possible operation allocations and selecting one to be allocated to the resource at this time. Meanwhile, in the case of global scheduling, the selection of which operation to allocate is made on the basis of a global constraint, i.e. the operation with the earliest due date. An ordering of operations can be inferred where for a pair of operations only one allocation sequence would allow the due dates to be met.

4 EXECUTION OF THE PROPOSED APPROACH

Having described the scheduling approach and methods used in this dye house implementation, the computational processes that operate on these solution methods can be examined in detail.

4.1 Constraint Solving

As stated in the previous section, there are three major types of constraints in the dye house scheduling problem. The constraints can be solved by a linear arithmetic solver. The first type, the colour precedence constraints state the order within a set of job operations.

$$O_i + d_i \leq O_j \qquad (1)$$

Where O_i (O_j) denotes the potential start time of each operation and d_i indicates the processing time or duration of operation O_i. There is therefore colour precedence between every two adjacent operations in every job set.

The second type states the exclusively disjunctive order between each possible pair of operations within the dye machine. This is in fact the non-determinism associated with the solution search. In dye machine Milnor, for example, operation w (represented by O_W) can be performed either before or after operation r (represented by O_R). In the proposed scheduling approach, this can be stated as

$$O_W + d_W \leq O_R \vee O_R + d_R \leq O_W \qquad (2)$$

There are a total of three such constraints for dye machine Milnor. In general, for a machine of n operations, there are $(n^2 - n)/2$ such constraints.

The last type of constraints is the bound constraints which state the bound of the time domain (values). These variables are key search variables in the scheduling environment. Under CLP(FD) system, they can be stated using the constraint *X in lower bound .. upper bound*. A procedure to solve the constraints within the proposed approach is to code it in the template of Figure 1.

% declare bound
O_W *in StartTime..Deadline,*
O_R *in StartTime..Deadline,*
O_T *in StartTime..Deadline,*
.
.

% precedence constraints
$O_W + d_W \leq O_R$,
$O_W + d_W \leq O_T$,
$O_R + d_R \leq O_T$,
.
.

% disjunctive constraints
$(O_R + d_R \leq O_T \,;\, O_T + d_T \leq O_R)$,
$(O_W + d_W \leq O_R \,;\, O_R + d_R \leq O_W)$,
$(O_W + d_W \leq O_T \,;\, O_T + d_T \leq O_W)$,
.
.

% solution found
show_solution $([O_W, O_R, O_T, \ldots, O_U])$.

Figure 1: Constraint solving schema in dye house.

4.2 Schedule Generation

From a dye house scheduling perspective, each job has several different operations to be dyed according to a given colour sequence. In other words, the socks should be dyed from light to dark colours in dye vessels. The dye house has four different dye machine groups. Each machine required is subject to the type of fibres such as wool, cotton, and so forth. The target of dye house scheduling is to produce a schedule showing the loading of jobs onto machines and what job order is to be used over a given period of time. The main task at any particular point in time is to first determine which machine will be employed allowing for a particular fibre dyeing, then jobs that can utilize this equipment are loaded based on the colour demanded. On the basis of the algorithmatic scheduling procedure, the solution of the illustrative example above is given below:

Dye machines	Job Operations
Milnor	$O_{EP148264}$,$O_{SP107015}$, $O_{SP132517}$
Smith Drum	$O_{LP199860}$, $O_{EP180602}$
Paddle	$O_{LP100173}$, $O_{LP195812}$
Washex	$O_{SP113831}$, $O_{SP100770}$

The key to the success of the constraint logic-based approach in tackling dye house scheduling problem involving various constraints lies in the combination of propagation and search. By imposing the constraints involved in the problem before commencing search, the size of the domains can be reduced through the action of consistency check and propagation. Furthermore, as the search proceeds, the effects of assignments made to variables are propagated to the domains of the, as yet unlabelled, variables, pruning the possibilities that remain open. Thus, propagation acts to reduce the branching in the search tree by eliminating paths that do not lead to solutions in advance.

5 DISCUSSION

The main purpose of this paper has been to demonstrate that the performance of a scheduling methodology can be enhanced by preserving and utilizing the constraints available within the problem and considering a broad range of perspectives on the state of problem solving. In this section, the performance of the proposed scheduling technique according to both the quality of its schedules and the computational efficiency of its approach will be discussed, followed by a summary of the findings on applying constraint logic-based approach to the dye house scheduling problem. Three performance criterions were employed to evaluate the schedule produced by the proposed approach. These measures are closely related to the scheduling objectives described in Section 2.3.

5.1 On-Time Delivery

For the dye house situation, the major concern in scheduling is to meet the delivery of a customer order. On-time delivery, which can be measured by the mean tardiness, is thus considered critical. Table 2 provides the summary of due date related schedule statistics of the three cases.

Table 2: Due date-related schedule statistic.

Performance Index	3-Day	2-Day	1 -Day
Mean Earliness	2.12	2.54	2.15
Mean Tardiness	0	0	0
Mean Lateness	-2.12	-2.54	-2.15
Average WIP	17.67	11.58	7.67
Average Inventory	18.67	12.75	8.83

Table 2 contains the indices of due date related statistics in three dye house cases. It is worth noting from the schedule statistics that, as would be expected, the mean tardiness of each schedule in the dye house is zero. This confirms the results of three dye house scheduling cases. Indeed, by incorporating the time bound of each job order over a computation domain before schedule generation, the scheduling window can be reserved by the bound constraints imposed. As a consequence, the constraint based scheduler always produces an excellent solution as far as job tardiness is concerned.

5.2 Resource Utilisation

Another measure of the performance in the dye house is maximum use of highly expensive facilities. Table 3 summarizes the results of three cases of dye house scheduling. Each case presented here indicates the average utilisation of four different dye machines - Washex, Paddle, Milnor, and Smith Drum. It can be seen from the results of Table 3 that daily scheduling produces better performance on machine utilisation, compared with that of the other two cases. This might be, along with idle time, caused by the size of manufacturing orders to be scheduled. In general the machine utilisation has an immediate relationship to the amount of orders to be performed.

However, the job order in this case is subjected to the influence of the state of front and rear manufacturing processes. Accordingly, the utilisation of dye house affects the situation of other shop floors.

Table 3: Time-related schedule statistic.

Performance Index	3-Day	2-Day	1-Day
Total Flow Time	1272	556	184
Av. Flow Time	37.41	25.27	14.15
Av. Processing Time	5.88	5.82	5.23
Av. Idle Time	2.58	2.91	2.15
M/C Utilisation	17.67	11.58	7.67

5.3 Computational Efficiency

The proposed scheduling scheme was programmed in CLP(FD) and CLP(R) and run on an IBM Pentium system. One issue to be dealt with, however, is the management of the additional data structures used to control constraints which are permutated and propagated in the process of scheduling. Indeed, these data structures may be more costly to maintain in terms of memory consumption and in terms of computation.

Table 4: Computer process time of dye house scheduling.

Dye house Scheduling	Manual Method	Proposed Approach* Local	Global
1-Day	45 min	50 ms	30 ms
2-Day	100 min	70 ms	60 ms
3-Day	240 min	160 ms	140 ms

Table 4 exhibits the results of the computation times for the three dye house scheduling cases. Based on the scheduling method and procedure, three different computation times are compared. The first one records the average scheduling time taken by the human scheduler under existing conditions. Obviously, the time required depends on the size of job orders to be scheduled. The second uses the local constraints only for the dye house scheduling without satisfying the global constraints, and in the third one the scheduling objective as a global constraint is given to the scheduler to optimize the solution. The results of constraint logic-based scheduling reflects that the more constraints, the faster schedule generation. Finally, it is worth noting from Table 4 that, unlike manual scheduling, the number of job orders has less influence on CPU time as far as the dye house scheduling is concerned.

6 CONCLUSIONS

With some notable exceptions (e.g., ISIS - Fox & Smith, 1984), most of the scheduling research discussed so far have concentrated on oversimplified and abstract target applications. Such abstract applications provide a means of focusing on key aspects of the scheduling problem and establish a good platform for controlled experimentation, but their practical viability and adaptability are limited. This paper addresses the specific scheduling context to which constraint logic-based approach has been applied, and attempts to achieve some level of validity by focusing on the modelling and solving of realistic scheduling problems. In this paper the main characteristics of the dye house problem were tested using the constraint logic-based approach. This paper has also presented a view of constraint manipulation as a solution procedure, and has attempted to place the constraint behaviours to solving mechanisms of the proposed scheduler.

From the point of view of a practical application, this case study has demonstrated the potential capability of applying the constraint logic-based scheduling technique in practice. The objective of constraint-based approach is to provide reliable, realistic, and computationally efficient schedules. In consequence, the application of constraint logic-based approach to the dye house scheduling problem has demonstrated that a schedule can be obtained within seconds.

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