An Algorithm for the Hot Rolling Mill Scheduling Problem in a High-Grade Steel Production

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Abstract
A steel hot rolling mill subjects steel blocks to high temperatures and pressures in order to form steel billets or bar steel. The rolling of high-grade-steel is characterized as follows: (1) the production process includes multiple stages; (2) there exist linear, cyclic, converging and divergent material flows; (3) parts of the orders have to be pooled to rolling batches; (4) different setup times are required for different rolling batches to be processed; (5) product variety is frequently changed on the same equipment. The high-grade-steel scheduling problem can be viewed as a Job-Shop scheduling problem with sequence dependent set-up-times. The objective is to minimize the idle-time of the heating furnaces and the rolling units and to satisfy commercial objectives such as delivery on time. The algorithm presented in this
paper was designed for a European high-grade steel manufacturer and is based on the experience of the human planners.

Keywords: Production planning, Machine scheduling, Heuristics, Steel production

1. Introduction

The continuously growing cost pressure, individual production orders as well as decreasing innovation cycles are only a few characteristics of the vital structural change that the production industry has been confronted with during the past years. In order to stand out against the competitors and to gain an advantage in competition, an enterprise has to have the ability to adjust to the dynamic demands of the internal and external environment. A flexible scheduling system for the material flow is one possibility to meet these requirements.

Machine scheduling in steel production has been recognised as a difficult industrial scheduling problem (Cowling and Reizig\textsuperscript{1}, Cowling\textsuperscript{2}, Tang et al.\textsuperscript{3}). This is due to the fact that it involves a variety of complex technological processes, which implicate numerous production constraints. Furthermore, steel production is often affected by the occurrence of unpredictable real-time events (e.g. the breakdown of components or a whole unit) during processing time. This implies that in this environment it is highly recommended to use scheduling systems, which can react to unpredictable events in a very short time.

So far, much research concerning machine scheduling in steel production has concentrated on the steel-making scheduling\textsuperscript{4} and the hot strip steel scheduling\textsuperscript{5}, while little attention has been paid to the hot rolling mill scheduling, especially for high-grade-steel production. Early works of Jacobs, Wright, and Cobbs\textsuperscript{6}, Balas and Martin\textsuperscript{7} and Assaf, Chen, and Katzberg\textsuperscript{8} approach

\textsuperscript{1} Cowling/Reizig (2000).
\textsuperscript{2} Cowling (2003).
\textsuperscript{3} Tang et al. (2002).
\textsuperscript{4} Numao/Morishito (1991) and Tang et al. (2002).
\textsuperscript{5} Kosiba/Wright (1992) and Tang et al. (2000).
\textsuperscript{6} Jacobs/Wright/Cobbs (1988).
\textsuperscript{7} Balas/Martin (1991).
\textsuperscript{8} Assaf/Chen/Katzberg (1997).
simplified planning environments of the hot rolling mill scheduling problem by using optimization techniques to generate optimal or near optimal solutions. Although these models obtain optimal solutions it is hard to apply them in practice. This is due to the fact that these models show already with medium problem instances long computing times and can therefore not be used in a dynamic environment. Additionally, many constraints which can not be neglected in practice are hard or impossible to implement in these optimization models. Lopez, Carter and Gendreau\textsuperscript{9}, Cowling\textsuperscript{10} and Tang and Huang\textsuperscript{11} introduce more applicable models which are solved using heuristic optimization techniques. These techniques are characterized by the fact that they do not yield an optimal solution but try to find good solutions in tolerable computing times. They also allow the consideration of a large set of constraints which makes it easier to use those techniques with real-world-problems.

This paper is organised as follows: In section 2 a detailed description of the hot rolling mill scheduling problem of a European high-grade steel company is given. Section 3 presents an algorithm for this problem. Since the given problem is hard to be solved to optimality, a heuristic based algorithm was developed in order to generate good schedules which consider the numerous constraints. In section 4 conclusions are presented.

2. The planning environment

The planning problem for a hot rolling mill is a Job-Shop scheduling problem involving several groups of machines and personnel. Figure 1 gives an overview of the given production system.

In order to produce steel billets, bar steel and flat bar steel the unshaped steel blocks have to be subjected to high temperatures in special furnaces. In the given production system there exist one pusher furnace and 18 batch furnaces, four of them with three cells, six with two
cells and eight with one cell. The temperature in the different cells of one batch furnace can
not be varied, meaning that it is not possible for one cell of a two-cell batch furnace to be
heated up to e.g. 1.200 °C and for the other one to gain a temperature of e.g. 1.000 °C. The
heating treatment in those furnaces takes several hours. It is assumed that all steel blocks
which can be warmed up in a pusher furnace can also be treated in a batch furnace. However,
the reversal of this assumption does not apply\textsuperscript{12}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Operations in a hot rolling mill}
\end{figure}

After the heating treatment the steel blocks are subjected to high pressures of several rolls. In
the given case study there exist four roll stands (Figure 1). “Roll stand I” has to be passed by
all steel blocks for a rough shaping. Depending on the operating instructions and type of steel,
the steel blocks have to be subjected to one or more roll stands or have to be reheated in one
of the furnaces. Therefore, the following material flows, which are special to the hot rolling of
a high-grade steel production, can occur:

1. The steel block only needs the rough shaping.

2. After the rough shaping the steel block has to be reheated in a batch furnace and is
   afterwards subjected again to pressures of “Roll stand I”. Furthermore the block passes
   one of the next possibilities.

3. Additional to the shaping on “roll stand I” the steel block passes “roll stand II”, “roll
   stand III” and “roll stand IV”.

\textsuperscript{12} Schiefer (2009).
4. The steel block has to be subjected to the pressures of “roll stand II” and “roll stand III”.

5. There is only one additional shaping process on “roll stand II” necessary.

6. After the rough shaping the steel block has to pass “roll stand III”.

Depending on the dimension that is asked the roll stands have to be equipped with the right pair of rolls. There are several dimension-groups which are rolled. An example for a dimension group is “110 mm – 130 mm”, which is divided in the dimension-levels “110 mm – 120 mm”, “121 mm – 125 mm” and “126 mm – 130 mm”. The set-up times between two dimension-levels takes about 25 minutes, while the set-up times within one dimension-level takes 15 minutes. The set-up time between two dimension-groups can take more than an hour and should therefore be performed between two planning horizons. The rolls of “roll stand I” and “roll stand II” are always the same, meaning that they do not depend on the required dimension of the steel block. They have to be exchanged after each shift due to abrasion. The rolls of “roll stand III” and “roll stand IV” on the other hand have to be matched with the required dimension of the steel block and therefore have to be changed during the shifts.

Note that from now on all steel blocks which only have to be shaped on “roll stand I” or on “roll stand I” and “roll stand II” are called billets, while the other steel blocks are called bar steel.

After the rolling process the steel blocks are cooled down either on a cooling bed or in a special annealing furnace (Figure 1) which allows a controlled cooling of highly sensitive steel blocks.

The objective of the given machine scheduling problem is to minimize the idle-time of the heating furnaces and the rolling units. This means that on one hand as many steel blocks as possible have to be scheduled for one shift and on the other hand the set up times on the roll stands have to be minimized. Note that in order to minimize the idle-time of the roll stands during a shift there should be jobs scheduled for “roll stand I” and “roll stand II” while the
other roll stands are equipped with the right rolls. Therefore a right mixture of billets and bar steel has to be scheduled. Furthermore, the main commercial objective – delivery on time – has to be satisfied as well.

The planning horizon describes the time period for which the hot rolling mill scheduling problem has to be solved. In the given problem the planning horizon is 2 shifts, meaning one workday. In exceptional cases (see section 3) the planning horizon can be extended to 3 shifts, meaning one and a half workdays.

Table 1 gives an overview of the definitions and notations that are used in the next sections.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>total number of scheduled Jobs</td>
</tr>
<tr>
<td>$m_1$</td>
<td>total number of pusher furnaces</td>
</tr>
<tr>
<td>$m_2$</td>
<td>total number of batch furnaces</td>
</tr>
<tr>
<td>$m = m_1 + m_2$</td>
<td>total number of furnaces</td>
</tr>
<tr>
<td>$l$</td>
<td>total number of shifts of the planning horizon</td>
</tr>
<tr>
<td>$j, j = 1,...,n$</td>
<td>$j^{th}$ Job</td>
</tr>
<tr>
<td>$i, i = 1,...,m$</td>
<td>$i^{th}$ heating furnace</td>
</tr>
<tr>
<td>$k, k = 1,...,l$</td>
<td>$k^{th}$ shift of the planning horizon</td>
</tr>
<tr>
<td>$b_{\text{min}}$</td>
<td>minimum number of bar steel jobs that should be scheduled for one shift in order to guarantee a right mixture of bar steel blocks and billets</td>
</tr>
<tr>
<td>$b_{\text{max}}$</td>
<td>maximum number of bar steel jobs that should be scheduled for one shift in order to guarantee a right mixture of bar steel blocks and billets</td>
</tr>
<tr>
<td>$d_{j,\text{min}}$</td>
<td>minimum dwell time in the heating furnace for Job $j$</td>
</tr>
<tr>
<td>$d_{j,\text{max}}$</td>
<td>maximum dwell time in the heating furnace for Job $j$</td>
</tr>
<tr>
<td>$d_j$</td>
<td>due date of Job $j$</td>
</tr>
<tr>
<td>$t_{j,\text{min}}$</td>
<td>minimum temperature in the heating furnace for Job $j$</td>
</tr>
<tr>
<td>$t_{j,\text{max}}$</td>
<td>maximum temperature in the heating furnace for Job $j$</td>
</tr>
<tr>
<td>$c_i$</td>
<td>maximum capacity of furnace $i$</td>
</tr>
<tr>
<td>$s_{\text{min}}$</td>
<td>number of billets that should be scheduled during the set-up time within one dimension level</td>
</tr>
<tr>
<td>$s_{\text{max}}$</td>
<td>number of billets that should be scheduled during the set-up time between two dimension levels</td>
</tr>
<tr>
<td>$D$</td>
<td>dimension group that has to be rolled during the planning horizon</td>
</tr>
</tbody>
</table>
3. Heuristic solution method

Given the nature of the problem it is not realistic to search for an optimal solution (a complex constraint satisfaction problem with conflicting optimisation goals). In practice the human planner searches for an adequate schedule considering the difficulty of the planning instance and the available time. Furthermore, the human planner will not allow a black-box schedule. He has to be able to understand the generated solution. Due to these facts an algorithm, which is based on the experience of the human planners and priority rules, was developed.

The first four steps of the algorithm are preparatory ones and are described below.

**Step 1: Determination of the initial planning situation**

At the beginning of the algorithm the initial situation of the planning instance has to be determined. The following cases can be differentiated:

- **Planning situation 1**: There exist only bar steel blocks to be scheduled during the planning horizon. Continue with Step 9.
- **Planning situation 2**: There only exist billets to be scheduled during the planning horizon. Continue with Step 2.
- **Planning situation 3**: Billets as well as bar steel blocks have to be scheduled during the planning horizon. Continue with Step 2.

The named initial situations depend very strongly on the production program of the hot rolling mill. The most complex situation is “planning situation 3” because in this case one has to deal with a large product variety.

**Step 2: Determination of the dimension-group of the bar steel**

For each planning horizon it is defined which dimension-group has to be rolled. Therefore in this step, the dimension group \( D \) for the current planning horizon is determined. Continue with Step 3.
Step 3: Determination of the number of bar steel jobs for the planning horizon

At this point of the algorithm the number of bar steel jobs which belong to the dimension-group $D$ and which are already released from the steel mill is determined. These jobs are stored in an array $A$ and arranged considering their required dimension. This means that the sorting process starts with the jobs with the smallest dimension and ends with the jobs with the largest dimension.

Furthermore, this sorted array $A$ is split into two sub-arrays $A_k$, $k=1,...,l$ ($l=2$). Two constraints have to be considered, when dividing $A$:

1. The number of jobs in the arrays $A_k$ should be approximately the same.
2. The cut should not be performed within one dimension.

Continue with Step 4.

Step 4: Determination of the special planning situation

Depending on the number of blocks assigned to the arrays $A_k$, $k=1,...,l$, the following planning situations can occur:

- **Planning situation 3a**: The number in one of the arrays $A_k$, $k=1,...,l$, exceeds $b_{\text{max}}$. In this case the planning horizon has to be expanded to three shifts, meaning $l=3$.

  Like in Step 3 the array $A$ has to be split again in sub arrays $A_k$, $k=1,...,l$, but this time $l=3$.

- **Planning situation 3b**: The number in one of the arrays $A_k$, $k=1,...,l$, is smaller than $b_{\text{min}}$. In this case the shifts have to be “filled” with billets (see Step 12).

- **Planning situation 3c**: The number of bar steel jobs in the arrays $A_k$ are $\geq b_{\text{min}}$ and $\leq b_{\text{max}}$.

- **Planning situation 3d**: There do not exist enough billets in order to fill the shifts. In this case the second shift of the planning horizon has to be reduced.
Continue with Step 5.

The following steps describe the actual assignment of the jobs to the machines and have to be repeated for every single shift of the planning horizon.

**Step 5: Assignment of the steel bar jobs to the pusher furnace**

In Step 5 the bar steel jobs are assigned to the pusher furnace. The allocation of the jobs to the pusher furnace takes place first because this furnace type is not allowed to stand still since this will cause disturbances.

The following steel bar jobs \( j \) of \( A_k \), \( k = 1, \ldots, l \) are assigned to the pusher furnace:

- \( j \) is allowed to be treated in a pusher furnace.
- The temperature of the pusher furnace matches \( t_{j,\text{min}} \) and \( t_{j,\text{max}} \).
- If one block has a conical shape an even number of conical steel bar jobs of the same dimension have to be scheduled.

The selected jobs are sorted starting with the smallest dimension.

Continue with Step 6.

**Step 6: Quality Sort**

So far the pusher furnace was filled with steel bar blocks. The accrued schedule is now elaborated concerning the quality of the jobs. Within one dimension the blocks are sorted starting with the softest quality. This is necessary because new rolls have to warm up first and therefore jobs with a soft quality should be scheduled first.

Continue with Step 7.

**Step 7: Assignment of the steel bar jobs to the batch furnaces**

At this point of the algorithm all steel bar jobs which could not be assigned to the pusher furnace have to be scheduled for a batch furnace. The policy of this assignment is that on one hand the smallest possible number of furnaces should be used and on the other hand big units (more than one cell) should – if possible – not be scheduled at this point. They are needed for
the billets which have to be assigned later on. Furthermore one batch furnace has to be left free for the billets that have to be reheated at the beginning of the shift.

The assignment of the steel bar jobs to the batch furnaces can be described as follows:

1. The remaining jobs in $A_k$, $k = 1,\ldots,l$ are pooled to groups with the same temperatures, taking into consideration $t_{j,\min}$ and $t_{j,\max}$.

2. These groups are again split up into sup-groups according to the dimension of the jobs. Thus there exist several groups which contain jobs with the same heating temperature and the same dimension.

3. Next the steel bar jobs are assigned to the batch furnaces. First the sub-group is selected which includes those jobs with the smallest dimension. The jobs are assigned to a free unit. In case the number of jobs is too big for a batch furnace with one cell, a bigger unit is chosen. This step is repeated until all jobs are scheduled or all units are occupied.

4. Now this first assignment is being adjusted to the dwell times of the jobs. For each job $j$ it has to be checked whether the job is pulled from the furnace at the right time, meaning that $d_{j,\min}$ and $d_{j,\max}$ are not violated. In case this necessary conformance is not given, the job $j$ is put back into $A_k$, $k = 1,\ldots,l$.

5. At this time of the scheduling algorithm $A_k$, $k = 1,\ldots,l$ includes all steel bar jobs that have not been assigned to a heating furnace yet. For each job $j \in A_k$, $k = 1,\ldots,l$ it is now checked whether the job can be assigned to a batch furnace with free capacities. Therefore $t_{j,\min}$, $t_{j,\max}$, $d_{j,\min}$ and $d_{j,\max}$ as well as the time when the dimension of the job is being rolled has to be considered.

In case the planning instance is based on “planning situation 2” the algorithm stops at this point. The steel bar jobs have been assigned to the furnaces according to their dimension, their heating temperature and their dwell times.
Step 8: Number of steel bar jobs in the pusher and batch furnaces

A very important issue that has to be considered is that it is not efficient to roll a block with a new dimension while a block with the preceding dimension is still in a heating unit. Therefore the following computation is performed during this step of the algorithm:

- $x_d$: number of steel bar jobs with dimension $d$ scheduled for a pusher furnace.
- $y_d$: number of steel bar jobs with dimension $d$ scheduled for a batch furnace.

Continue with Step 9.

Step 9: Assignment of the billets to the pusher furnace

For each dimension the values $x_d$ and $y_d$ are compared with each other:

- $x_d = y_d$: no billets are assigned to the pusher furnace.
- $x_d < y_d$: between dimension $d$ and $d + 1$ $y_d - x_d$ billets are assigned to the pusher furnace. The billets again have to fulfill the requirements for being scheduled for heating treatment in a pusher furnace.

In the case of “planning situation 1” only billets are assigned to the pusher furnace which means that the dimensions of the bar steel jobs can be neglected. In this case the assignment is performed using the earliest due date rule.

Continue with Step 10.

Step 10: Assignment of the billets to the batch furnaces

This step is very similar to the prior step. For each dimension with $y_d < x_d$ $x_d - y_d$ billets are assigned to a batch furnace with free capacities. Also at this stage the constraints dwell time and heating temperature have to be taken into consideration. In the case of too many billets the earliest due date rule decides.

In the case of “planning situation 1” only billets are assigned to the batch furnaces. Like in Step 10 this assignment is performed using the earliest due date rule.

Continue with Step 11.
**Step 11: Including the set-up times**

Now the set-up times for equipping “roll stand II” and “roll stand III” with the right rolls have to be considered. In order to minimize the idle times on “roll stand I” and “roll stand II” billets are scheduled while the other “roll-stands” are being prepared. $s_{\text{min}}$ billets are scheduled during the set-up times within dimension levels and $s_{\text{max}}$ billets are assigned for set-up times between two dimension levels. Depending on $c_i$, $i = 1,...,m$, the billets should either be all assigned to the pusher furnace or be split up between the pusher furnace and the batch furnace.

In case the planning instance is based on “planning situation 3b” continue with Step 12, otherwise continue with Step 13.

**Step 12: Fill up shifts**

In this case there do not exist enough steel bar jobs according to $s_{\text{min}}$. Therefore the free capacities of the units are used by scheduling more billets than necessary during the set-up times. Whether the billets are assigned to a batch furnace or to the pusher furnace depends on the free capacity of the furnaces, the dwell times and the required heating temperatures.

Continue with Step 13.

**Step 13: Fill up the batch furnaces**

At this point of the algorithm the free capacities of the batch furnaces are used by scheduling billets for the end of the shift. Again for each job $j$ that might be assigned during this step, $d_{j,\text{min}}$, $d_{j,\text{max}}$, $t_{j,\text{min}}$ and $t_{j,\text{max}}$ have to be taken into consideration.

Continue with Step 14.

**Step 14: Examine the capacities of the annealing furnace**

So far $c_i$ of the annealing furnace has not been considered. Therefore during each step of the algorithm it has to be made sure, that this constraint $c_i$ is not violated. In the case that a job should be scheduled for the annealing furnace the free capacities of this unit have to be
checked. If $c_i$ would be violated by scheduling the job, the job is not allowed to be rolled during the current shift.

Table 2 gives an overview of the prior described algorithm.

\begin{verbatim}
begin Algorithm
Step 1  Determination of the initial planning situation
        $A := planning\ situation$ ;
        if $A == 3$ then continue with Step 9 else continue with
        Step 2 end if;
Step 2  Determination of the dimension-group of the bar steel;
Step 3  Determination of the number of bar steel jobs for the
        planning horizon;
Step 4  Determination of the special planning situation;
        $h := number\ of\ shifts$;
        for $z = 1$ to $h$ do
        Step 5  Assignment of the steel bar jobs to the pusher
        furnace;
        Step 6  Quality Sort;
        Step 7  Assignment of the steel bar jobs to the batch
        furnaces;
        if $A == 2$ then continue with end Algorithm else
        continue with Step 8 end if;
Step 8  Number of steel bar jobs in the pusher and batch
        furnaces;
Step 9  Assignment of the billets to the pusher furnace;
Step 10 Assignment of the billets to the batch furnaces;
Step 11 Including the set-up times;
        if $A == 3b$ then continue with Step 12 else
        continue with Step 13 end if;
Step 12 Fill up shifts;
Step 13 Fill up the batch furnaces;
Step 14 Examine the capacities of the annealing furnace;
        $z = z + 1$;
        end for;
end Algorithm;
\end{verbatim}

Table 2: Overview of the algorithm

4. Conclusion

The problem description in this paper shows the complex structure of the machine scheduling problem in a hot rolling mill for high grade steel production. The complexity is based on cost-intensive and sequence-dependent set-up times, procedural constraints, several material flows, single-purpose units and no buffers between the units. The algorithm presented here takes into
consideration all these constraints and is based on the experience and knowledge of the human planner. The implementation of the algorithm in the PPS-system of the client showed that good schedules can be generated within a few minutes. These short computing times allow the reaction to unpredictable events which implies that the algorithm is very well suited for use in the daily planning procedures.

5. References


