Combining DES, Optimization and Heuristics to Improve Steel Plates Thermal Treatment Scheduling

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Abstract

This paper focuses on thermal treatments of steel plates through an innovative scheduler made of both an optimization and a heuristic algorithm. The aim of this approach is to extend the planning procedure to the virtual material to improve production scheduling by adding more visibility by using a DES approach.

Keywords: optimization algorithm, steel production.

Introduction

The production of metal sheets in steel industry involves a strong optimization in order to obtain the maximum performances of the process, above all in terms of time and utilization of the various plants.

It is in particular important, for a good performance of the process, to optimize the loading of the plant ovens, by either: i) saturating the ovens capacity; ii) respecting the delivery times and the required quality of the product; iii) exploiting the possibility to load hot material exiting from lamination, in order to reduce the need of thermal energy.

In this paper, the authors investigate the thematic of the thermal treatments of metal sheets, through an informatics system constituted by two parts: i) an optimization part and ii) an heuristic part, in which rules are given to produce an improvement in the process performance.

The main aim of this informatics system is to extend the planning procedure to the "virtual material", which means, in practice, to predict the behavior of the sheets planned for production in the future.

1 Description of sheets production process

The production process (Briano et al., 2009; Damiani et al., 2014) starts from the cutting of plates, which are then rolled to produce a "mother plate" which is cut into "semi-plates" from which the single sheets will be then derived, each one according to its operational schedule. The operations are constituted by: lamination, cutting, thermal treatments and finishing which are carried out before shipping. The production refers to two steel grades: one “internal”, which determines the chemistry of the steel, and one “client” which determines the features of the operation and other mechanical features depending on the kind of treatment received.

The production structure is based on three levels:

- cycles, identifying the product
- phases, which are the decompositions into macro-operations of the production process (e.g. rolling-milled, treated, shipped …)
- treatments, which are the operations related to each phase.

The objectives of loading optimization are the saturation of the available resources (ovens), the respect of delivery dates, the reduction of thermal energy requirement. The treatment time depends on various factors, as:

- the type of steel to be worked;
- the material thickness;
- the oven in which the material is heated.

Each thickness requires a different residence time in the oven, for the phases of thermal treatment (ramp, temperature maintenance, controlled cooling). In case of quenching, which envisages two heating phases interspersed by a rapid cooling, the oven is considered engaged for all the cycle.

The loading of the oven is limited by three typologies of factors:

- maximum loaded weight;
- 3D size of the sheets;
- size of the loading, keeping into account the spacers.

There is a constraint on thicknesses that can be introduced in the same oven: the difference between maximum and minimum thickness cannot exceed +/- 25 mm.

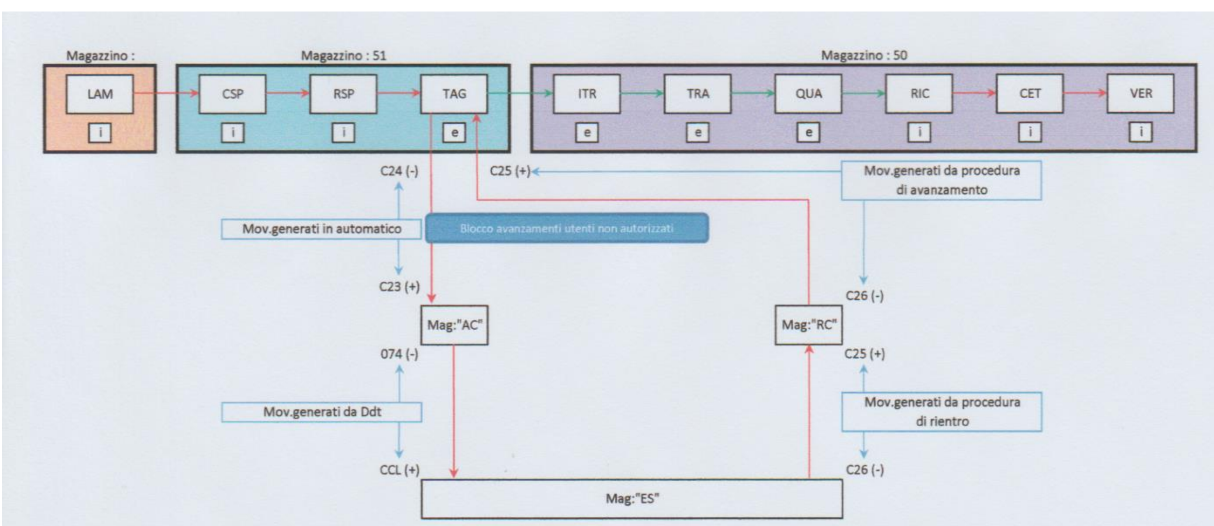

Figure 1: Phases of the production process.

In Figure 1 are represented the phases of the production process. Each phase refers to a "logical warehouse" in which the piece is placed in order to classify it.

Besides the logical warehouses, there are the warehouses for materials management provided by third parties:

- AC: waiting in the working centre;
- ES: third parties warehouses;
- RC: warehouse of return from a working centre.

The operational phases are the following:

- LAM: rolling;
- CSP: control. If negative, follows the fixing phase (RSP);
- RSP: fixing of the defects found in the phase CSP;
- TAG: cutting, one sheet is obtained for each record (can be effected also externally of the firm);
- ITR: waiting for the thermal treatment (can be effected also externally of the firm);
- TRA: thermal treatment, which may consist in various operations (can be effected also externally of the firm);
- QUA: quality control (can be effected also externally of the firm);
- RIC: possible fixing if quality control provides negative flag;
- CET: customer verification;
- VER: storing in warehouse waiting for shipping to the customer.

2 Available data

The available data for the planning process and for the production control are composed by two Excel spreadsheets, one for the sheets to be put into production (manual_launches.xls) and one for those already in production (advancement.xls).

The data from the first file are the following:

- Insertion date;
- Delivery date;
- type of calculation (manual or automatic);
- Customer;
- Edge of the sheet;
- Thermal treatment: natural (no treatment); quenched; normalized, re-cooked…;
- Thickness and tolerance;
- Width and tolerance;
- Length and tolerance ;

- Number of pieces to be produced;
- Synthetic description of the product;
- Customer steel: kind of steel

The orders which are launched into production introduce the concept of “job”, which is a liaison between raw material (slab or ingot) and orders.

To one job is connected a rolling plan, while the same rolling plan can be connected to different jobs. The plan identifies the section, the kind of steel, the type of rolling. The rolling mill has its sequence of rolling. From the rolling, is obtained a “mother plate”, which will be cut into several “semi-plates” which are sent to different thermal treatments according to the sequence:

- rolling (LAM)
- control (CSP)
- Cutting (TAG)
- Treatments

Treatments can be carried out internally or also externally from the firm; some types of treatments can be done only externally. The “natural” typology does not provide treatments, and is immediately stored in warehouse.

The data from the second file are the following:

- Code of the phase: it codifies the working phase related to the previous scheme (LAM, CSP, RSP …)
- Rolling plan: see previous description;
- Job number;
- Job record;
- Semi-plate: from the semi-plate, several products will be derived by cutting;
- Firing sequence in oven;
- Card: indicates the sheet which will be produced. There may be several cards for the same semi-plate, which are numbered progressively;
- UDC: unit of sampling;
- Warehouse: logical unit where the piece (card) is stored;
- Supplier;
- Launch date;
- Date of the last operation;
- Date of delivery;
- Priority;
- Matrix: indicates the provenance of the material: FOR (forged), LAM (rolled) …;
- Internal steel: chemistry of the internal steel;
- Customer steel;
- Type of cutting;
- Additional operations;

- Design thickness and tolerance;
- Design width and tolerance;
- Design length and tolerance;
- Thermal treatment code;
- Order number;
- Real thickness;
- Real width;
- Real length.

The described Excel spreadsheets give a picture of the orders situation; in addition, another spreadsheet summarizes the features of the thermal treatments. In particular, four sections are indicated: oven list; features of the treatments; thickness; employ of spacers.

Oven list:

The file identifies for each oven:

- the maximum size of the accepted pieces;
- the maximum exercise temperature;
- the type of thermal treatment;
- the average weight of the charge (tons);
- the treatment matrix, i.e. the types of products which can be treated.

Features of the thermal treatment:

The file identifies, for each typology of thermal treatment and for each thickness, the following information:

- ramp number: identifies the steps which need to be carried out;
- the starting temperature;
- the gradient, in °C/hour;
- the final temperature;
- the minutes of keeping in temperature, measured in minutes per mm of thickness;
- the minutes of keeping in temperature if independent from thickness;
- the time of waiting in air;
- the type of cooling;
- the positioning of cooling (in oven, in tank …);

Thickness:

It indicates the effect of the missing respect of the thickness difference constraint among the components of the oven load.

Employ of spacers:

The different treatments envisage the employ of spacers between the pieces; these are realized by steel blocks of opportune size. For sheets thicknesses lower than 60 mm, “packages” are built of a maximum thickness of 60 mm and spacers are applied to the latter.

3 Technological aspects

The application is developed in Java for AS/400 (i-Series) version 1.5+, employs DB2 as database, and is realized starting from a specific library (Library AS/400). The architecture is Web-Based with the possibility of employing Java applets as thick-client and JSP/Websphere server-side, to realize thin-clients on mobile devices (Android). For reporting exigencies, an AS/400 V5R3 installation has been employed for the development; the company has made available an AS/400 installation to be employed as a test-bed and pre-production. Since in a regular steel manufacturing plan the material to be rolled and/or thermal treated already in warehouse is quite often limited two one or two days of production the visibility over the planning period is limited. This is resulting in a poor performance since there is a great risk of adopting a sub-optimal plan simply because there is no enough visibility of the material to be treated and the possibility of product coupling (i.e. putting two batches in the same oven-cycle) is generally low. One possibility is a to use a Discrete Event Simulator (DES) in order to forecast immediate future production (2-3 weeks) and to look for better usage of oven-cycles (Briano et al. 2009). In the proposed application, a DES model was used to overlook future availability of materials to be treated. The material already in warehouse for the treatment was classified as “physical” the material availability that was estimated using simulation was classified as “virtual”. Both physical and virtual material was than considered as input for the algorithms. The oven-cycle process has been modeled using an innovative Hybrid approach based on System Dynamics formalism (Guizzi et al. 2013, Romano et al. 2009).

4 Algorithms for improving thermal treatment scheduling

The planning system employs two tables on DB2. The tables are related to:

- production orders (ORDERS table);
- Oven cycles (CYCLES table).

The model target is coupling the orders to the oven cycles in order to saturate as much as possible the oven capacity.

Each oven is characterized by 3+1 dimensions (height/total thickness, length, width and weights) which determine the kind of products which can be loaded; moreover, there is a limit to the total thickness of the charge, given by the sum of the thickness of products and spacers. Each product is loaded in the oven together with “blocks” which avoid the overlap, which might imply a non-uniform heating of the charge. The thinnest products are stacked together and the stacks are spaced by spacers.

Each order is characterized by different features:

- a type of treatment (TTREAT), integer;

- a release date (RDATE), integer; it indicates the number of hours between the current date and the instant in which the product will be available for cooking;
- a limit delivery date (DDATE), integer, indicating the number of hours within which the oven cycle must be finished including, if necessary, the cooling time which can be in air or in the oven itself. In both cases, the oven is considered engaged until the end of the operations;
- a limit date of loading in oven (HDATE), over which it is no more possible to consider a hot charge, having the material cooled down;
- 3 spatial dimensions, which need to be compatible with the oven size, in particular the thickness (THSIZE). The thickness includes the size of the spacers.
- the weight of a single loaded order (WSIZE); the sum of all the loaded pieces needs to be lower than the oven maximum capacity (ASIZE).
- a treatment time (PTIME), measured in hours, which includes both the oven process and the cooling process.

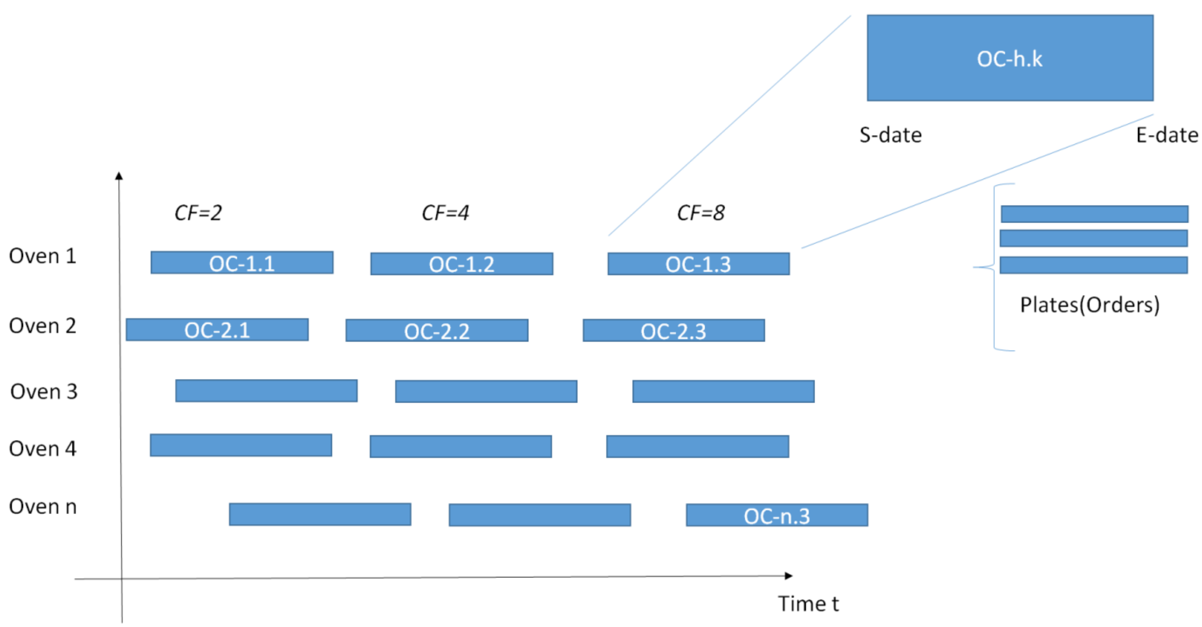

Figure 2: timeline of the production plan.

In Figure 2 is represented a diagram indicating the various working cycles in the ovens with time. To optimize the loading of ovens, it must be remarked that, for each oven, made equal the material to be worked, the cycles exceeding the first one should be avoided. In fact, they would be a cost, **as the oven would not work near its maximum load**. To avoid the exceeding cycles, the optimization algorithm associates a "cost" coefficient (CF in the figure) to each oven cycle; CF increases as the cycle number increases. In this way, the cycles exceeding the first one are discouraged. In term of Linear programming (LP) the optimization problem became:

Objective function:

- Minimize the unused capacity of oven{h} @ charge {k} preferring to saturate next charge

Subject to:

- Each plate should fit the perspective oven in each of 3 dimensions
- Total weight of plates in a charge should not exceed oven capacity
- Thickness of plates should be in a range +/- 25mm in a single charge
- R-Date should be respected
- D-Date should be respected if is committed
- H-Date should be respected if is committed

The optimization problem was implemented using OJAlgo (http://ojalgo.org/) is an Open Source Java code that has to do with mathematics, linear algebra and optimization and tested up to 40 orders on 3 ovens. Of course moving out from this small exercise to a real life application (approximatively 2000 orders to be optimized at once) the calculation time became impractical so a heuristics should be adopted (Gallo et al. 2012).

5 Heuristically based scheduling algorithm of the oven charge

The algorithm extracts all the records "ORDERS" which have not an assigned "CYCLES", and will group them by treatment type (TTREAT field) and by release date (RDATE), ordering these groups by increasing release date and increasing delivery date. Starting from the group with the highest quantity of orders, will be obtained an application of the class which implements the interface "OvenCyclesRequest"; will be first called the model_started (System.getCurrentTime()) method and then, through the getAvailableOvenCycles() method will be obtained an array of instances of the classes OvenFirstCycle, passing as parameters respectively: the treatment code, the soonest between the release dates of the orders considered in the group. At this point, the cycles will be filled one by one, verifying the maximum and minimum oven loading sizes, the weight of the charge and the maximum and minimum thickness of the charge. Each oven cycle is "closed" when one of the following conditions is verified:

- the weight of the loaded charge (WSIZE) is equal to the cycle capacity (ASPACE);
- the sum of the charge thickness (THSIZE) plus the spacers thickness is equal to the maximum acceptable thickness of the cycle (MAXTH);
- it is impossible to add another order to the cycle without violating the previous limits;
- no more available cycles are possible;
- no more available orders because incompatible with the oven size or with the dates of start and end of the oven cycle.

In this case, two conditions can be verified:

1) the cycle saturation coefficient (defined as the ratio between the sum of the weights of the loaded orders WSIZE and the cycle capacity ASIZE) is higher or equal to a threshold value; in this case the charge is confirmed and in the field of each order is indicated the ID of the selected cycle; moreover, in the field of the cycle loading coefficient is written the value obtained by the previous calculation.

2) the cycle saturation coefficient is not satisfying, and thus will be assumed the next release date forming a new group with order release dates lower or equal than the new date considered and the algorithm will be repeated starting from an ensemble of available cycles obtained by the new call of getAvailableOvenCycles().

In Figure 3 an example is provided, which is explained in the following.

orders

ID	TTREAT	RDATE	HDATE	DDATE	WSIZE	THSIZE	PTIME	ACYCLE
o1	1	0	50	56	45	18	22	ca
o2	1	0	12	70	53	25	23	ca
o3	1	0	58	48	49	31	24	cc
o4	1	8	16	65	25	17	22	cc
o5	1	8	24	170	38	19	23	cc

cycles

ID	ATREAT	ASPACE	SDATE	EDATE	MAXTH	SATUR
ca	1	100	0	23	60	0,98
cb	1	120	0	22	70	*0,40833*
cc	1	120	8	32	80	0,933333

Figure 3: Example.

The non-assigned orders *o1 – o5* are all related to the same thermal treatment with various durations of the treatment (PTIME), weight of the charge (WSIZE), thickness of the charge (THSIZE), date of release (RDATE), date of oven charging (HDATE) and date of delivery (DDATE).

Two ordered groups will be obtained: the first one is formed by the orders *o1*, *o2* and *o3* having the same treatment (TTREAT=1) and value of release date (RDATE=0); the second one is composed by the orders *o4* and *o5*, having the same thermal treatment but release date RDATE=8. From the call of the getAvailableOvenCycles() method an array of two instances of the classes OvenFirstCycle will be obtained, which will generate two cycles, respectively *ca* and *cb*. The first cycle will be filled in, which will include the orders *o1* and *o2*; the *o3* order inclusion would violate the cycle maximum capacity ASPACE and the maximum thickness MAXTH. At this point, the order *o3* should be assigned to *cb* cycle, but in this case there would not be a satisfying solution since the *cb* cycle would have a too low saturation (0.4083 < 0.85). In this case a new group would be formed having both the orders *o4* and *o5* and the not yet assigned order *o3*, since the latter might be processed in the cycle *cc*, thought initially for the second group, which would start after 8 hours (SDATE) since the presumed date of its completing (EDATE) and the oven charging date would be compatible (HDATE > SDATE and DDATE > EDATE).

In this way, two cycles over the three available would be saturated, respecting all the constraints and exploiting as well as possible the ovens, which would be utilized at respectively 98% and 93% of their capacity. It has to be reminded that the exercise cost of the ovens depends more on the number of cycles than on the size of the charge.

6 Conclusions

Proposed paper presents a scheduling problem that is likely to be encountered in real life steel manufacturing plants. Very often, the solution of this problem is left to operators that use semi-empirical rules. Authors present an application of both heuristics and simulation able to solve this issue in a proper and more efficient way.

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