A heuristic model for production scheduling in the foundry industry with the employ of fuzzy logic

(004-0133)

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Abstract

This work describes the conception, development and application of a methodology for the production scheduling in foundries. It has two important and linked moments, which are the furnace scheduling and the molding machines scheduling. The challenge consists in determining an adequate sequencing of production orders in the molding lines, combining light weight with average and heavy pieces, in order to obtain a constant demand of molten metal in balance with the offer of furnace derived metal. The heuristic approach was chosen to search for a solution of the problem, and the fuzzy logic technique was selected for the representation and manipulation of experts knowledge, identified in a qualitative research. The application results demonstrated, besides the benefits of the knowledge systematization and the capacity of fast carrying out simulations to find the best alternatives of solution, a more efficient performance than the obtained by the foundries specialists.

Keywords: scheduling, fuzzy logic, foundry.

INTRODUCTION

Sacomano and Azzolini Júnior (2001) point out that already in the end of the sixties the importance of the manufacture in the organizational strategy, concerning its contribution to the survival, profitability and growth of the enterprise, from a pioneering work developed by Skinner (1969) was reported. In this context, the production administration systems play an important role so that the manufacture can reach its objectives. The great concern in the management of production systems is to improve the performance of the productive resources in any economic unit, adding value to the good or service produced, either through the improvement of the quality, increase of the productivity, reduction of the cost or reduction of the stated period of delivery, as Machline (1994), for whom the simultaneous persecution of these four objectives will assure the reason of the business, the profit on the investment, states.

The Production Planning and Control (PPC), according to Erdmann (1998), is a system of information that manages the production, since the attainment and conception of the planning data until its use in day-by-day, by means of the adoption of rules for its functioning, aiming at commanding the productive process. In the industrial companies, the PPC has, therefore, a basic participation for the competitiveness, with immediate and direct reflection in the cost and the attendance to the customer.

According to Terra and Pereira (2000), the decisions of the operational level directly deal with questions related to the shop-floor, as the assignment of the order of customers to the machines, the release, the processing and the expedition of this order, among others. These decisions are related to the activity of production scheduling, that is in the more detailed and complex level of a planning and control production system. Saisse (2003) comments that the programming of the production is one of the characteristic activities of the operational levels that has been little dealt to the strategic point of view, and that most of literature in manufacture strategy, when it comes to management systems of the production, summarizes it as a process of choice between classic tools like the MRP, JIT or OPT.

This article focuses the PPC in the foundry industry, more specifically the activity of the production scheduling. The segment of the foundries is very expressive in Brazil, in technological and economical terms. A survey carried out by the Brazilian Association of Foundry (ABIFA) in 1998, detected the existence of 1,015 foundry industries in the country. In 2003, there were 46,700 people employed in the existing foundries in Brazil, which produced 2,083,581 tons of castings (86% correspond to iron casting), having exported 16% of this volume. Fernandes and Leite (2002) stated that Brazil placed itself, in 1997, as 9th worldwide producer of casting, according to data of the magazine Modern Casting.
The production scheduling in a foundry has two important and linked moments: the scheduling of the furnace (definition of the alloy to be produced in each period) and the scheduling of the molding machines (definition of the molds to be produced). This aspect, pointed out by Southall and Law (1980), is corroborated by Vianna and Arenales (1995) and Araújo and Clark (2001). However, the inexistence of a technique, specifically directed toward the generation of a production program of very short term with a sequencing that promotes the balance of the capacity of metal generation in the furnace with the metal demand absorbed in the molding lines, was detected in the bibliographical revision as well as in the field research.

The heuristic approach for the search of a solution was chosen. The rules of decision of the foundry specialists have been identified through a qualitative research and, with the use of the fuzzy logic concepts, which is considered a metheuristic that integrates the area of artificial intelligence and, which has also found a fertile field of applications for the production planning and control, a model for the production scheduling for foundries was developed.

In this article the created heuristic model is presented, inserted in the PPC system, to sequence the production orders in the molding lines and generate a program of production integrated with the furnace, that recognizes the periods of greater and minor energy availability, in a very short term period, and gotten results with its application are discussed.

**PRODUCTION PLANNING AND CONTROL - A GENERAL VISION OF THE PPC SYSTEM**

The concept of the PPC as a system of information is not new. Zaccarelli (1973) already appraised the PPC as a point of convergence of certain information and its transformation for the command and control of operations. The PPC systems, according to Pedroso and Correa (1996, p. 61 and 62), must support the decisions of what, how much, when and where to produce and what, how much and when to purchase.

Erdmann (2000, p. 106) synthesizes the stages of programming and control in the following way: a) to define the amounts to be produced; b) to calculate the amounts and the dates when the materials will be necessary; c) to determine the dates when each stage will have to happen and the respective demanded capacities, adjusting load and capacity between themselves; d) to emission/release/sequence/destine the orders; e) to control the production.

Fandel, François and Gubitz (1994) present an iterative and interactive model where the PPC is constituted by a group of functions hierarchically structuralized, divided in two areas: the programming and the control. The programming comprehends some steps (functions, activities), that go from the planning of primary needs of the final items (also called master production schedule) to the detailed program of production, as observed in Figure I. The aggregate planning, the planning of the product and the process, and the demand forecast, according to this conception, are activities that precede the programming, that would be aimed to the daily activities, that is, focused on the short term. For Fandel, François and Gubitz (op. cit.), the programming of the production comprehends activities of short term, from the planning of the final items to the programming of the intermediate stages and the sequencing, while for Erdmann (1998, p.17) "the scheduling makes use of the planning as orientation for its action and as source of data".
Production scheduling
The scheduling of the production can be defined as "allocation of resources in the time for the accomplishment of tasks", according to Baker (1974, p. 2) and MacCarthy and Liu (1993). For Morton and Pentico (1993), the programming of the production involves the consideration of a series of elements that dispute many resources for a period of time, resources that have limited capacity. The elements to be processed are called production orders and are composites of elementary parts called activities or operations. One program can be understood, according to Pöltl (2001), as a grouping of similar orders that will have to be executed simultaneously, one after the other, considering determined limitations of resources (restrictions) in the process (machines, people, space, material, energy, packing, means of transport, tools).
Sequencing

Tubino (1997) observes that the sequencing, integrant stage of the scheduling, follows heuristic rules used to prioritize orders (decision 1) and to select resources (decision 2). Although there are optimizing mathematical solutions for the problem of the sequencing, like the linear programming, in practice the companies prefer to work with simplified solutions, therefore, frequently the dynamics of the environment makes the use of mathematical models difficult, due to their constant variation. The heuristic rules of sequencing, although not guaranteeing an excellent solution, try to arrive at a good and fast solution in relation to the intended objectives.

The sequencing rules can be classified according to various views. They can be divided in static rules and dynamic rules, local rules and global rules, of simple priorities and combination of rules of simple priorities, rules with weighed indicators and sophisticated heuristic rules. The more sophisticated heuristic rules determine the priorities incorporating information not associated to the specific work, like the possibility of anticipatedy load the resource, the employment of alternative routes, the existence of restrictions in the system etc (TUBINO, op. cit.).

The PPC in the foundry industry

Campos Filho and Davies (1978) state that the base of all the casting processes consists of pouring liquid metal in a mold with the required format, followed by a cooling, in order to produce a solid object resultant of the solidification. Laney (1982) points out some specific aspects of the foundry processes, that differentiate them of processes of other industries and that turn them unique:

a) the materials that are melted and poured in a mold are not requested for a specific order and, therefore, the order of purchase cannot be attributed to a determined customer;

b) when a mold is poured, the labor cost and the expenses for the melting and shake-out, equally there cannot be attributed to a specific order;

c) the metallurgic yield (relation of the net weight of pieces with the total weight of metal that is poured in the mold) is a determinative factor for the determination of the liquid metal demand, besides being a basic element for the calculation of cost;

d) the cooling times must be considered in the production lead-time;

e) if there is a thermal treatment present, there can be required specific procedures for the calculation of the machine-load and of the cost, when different orders are processed simultaneously.

The planning and the scheduling of the production play a fundamental role in the management of a foundry, as Southall and Law (1980), for whom the satisfaction of the customer depends on an efficient performance in this area, observe. The objective of the PPC in a foundry, in accordance with Law (1989), is to load the centers of key-work with the customers’ orders, with the maximum use of the available capacity, and at the same time looking for satisfying the dates of delivery commitments. As these objectives are conflicting, an ideal solution is rarely possible.

Scrimshire, Law and Dalmer (1984) designate that, to be effective, a system of production planning and control in a foundry must cover all the stages of its operation, like the processing and analysis of the customers orders, programming of the molds and components production, control of the products in process and supply of adequate managemental reports.

Araújo and Clark (2001) observe that two important and linked decisions for the lots sizing and production programming in a foundry exist: the scheduling of the furnace (operation of melting), when the type of alloy to be produced in each period of time, and the scheduling of the molding machines, that specify which and how many items will be produced in each period, must be decided.
Fernandes and Leite (2002) have detected, in research carried out with foundries located in the interior of the State of São Paulo-Brazil, that the importance of the production planning and the programming in a foundry continues revealing relevant. This is due to the factors as scrap reduction, better accomplishment of terms, prioritization of items for invoicing, maximization of the production volume by means of the best use of the equipment, and reduction of the energy consumption.

THE HEURISTIC APPROACH AND ARTIFICIAL INTELLIGENCE FOR THE SOLUTION OF PROBLEMS OF PRODUCTION SCHEDULING

The word “heuristic” originates from the Greek verb *heuriskein*, that means "to find" or "to discover". Pöltl (2001) verified that, historically, its understanding has been passing through several modifications. From 1970 on, when the systems based on the knowledge started to gain importance, the heuristic began to be considered as a set of rules, that the specialists used to arrive to "good" solutions. Currently, the heuristic is appraised as "techniques, in general, that they improve the performance of problem solution methods". For Gündra et al. (2002), heuristic methods are algorithms that do not necessarily provide an excellent solution, but allow arriving, through calculations, to an acceptable solution, within a reasonable period of time. According to Fiedler, Greistorfer and Voss (w.d), in general the heuristic can be understood as a method of problems solution that allows to find good solutions with acceptable costs.

Sauer (1997) claims that from the beginning of the 80th new techniques of modeling and problems solution, by means of artificial intelligence approach, to support the solution of practical problems of sequencing have been introduced. The employed techniques, as Tubino (1997, p. 156) states are. "complex heuristics, that try to simulate the decisions of the specialists composing techniques of artificial intelligence, genetic algorithms and simulation". Authors like Fiedler, Greistorfer and Voss (op. cit), relate to them as "methaheuristic", because they understand that they provide a superior strategy, that generally guides and modifies an simple heuristic applied to a specific problem, for the attainment of a better solution that this heuristic would find isolatedly. The fuzzy logic and the evolutive computation, where the genetic algorithms blunt, are some techniques that compose the artificial intelligence.

The fuzzy logic

The fuzzy logic is a heuristic method that uses the theory of fuzzy sets and integrates the area of artificial intelligence, discipline associated to the construction and the computer programming to simulate the human processes of reasoning, point out Heizer and Render (2001), which offers mechanisms for the representation and manipulation of the knowledge of specialists. Bonventi Jr (1998) comments that its application is appropriate in determined conditions, like the existence of continuous variables, a too complex system to be calculated in real time, and the existence of specialists that can indicate rules of behavior of the system and diffuse sets that represent the characteristic of each variable. The fuzzy logic, explain Heizer and Render (op.cit.), allows to work with approximate values, incomplete or ambiguous influences and data to take decisions. The capacity to classify the variable of a problem, in terms of qualitative instead of quantitative concepts, in an inaccurate way, conveys the idea of a linguistic variable, state Almeida and Evsukoff (2003). A linguistic variable is defined as an entity used to represent in an inaccurate way and, therefore, linguistic, a concept or a variable of a determined problem, admitting as values only linguistic expressions, like "cold", "very big", "approximately high" etc. The fuzzy representation process of knowledge depends basically on this concept. Nobre (2000) shows that the project and development of a system with the fuzzy logic can be summarized in three stages. The first step consists of describing the system for a set of linguistic rules or
phrases of declaration of the type *if - then* added of the logical connectives *and* and *or*. The variables of the system are defined as linguistic variables and assume linguistic values or words, not restricting to a numerical value. This type of declaration, according to Almeida and Evsukoff (2003) was considered in the decade of 70 by Mamdani, being known as model of Mamdani, also called of Max-Min inference, for using the operations of union and intersection among sets by means of minimum and maximum operators.

After using the knowledge of specialists to define the set of rules that will compose the base of the system, the second step, which consists of defining the pertinent functions that must quantitatively characterize the values of the linguistic variable, is started.

The third and last step consists of defining the mechanism of inference for the rules manipulation and the decision taking, also requiring the definition of the entrance interfaces and exit of the system that uses the fuzzy logic. The entrance interface has the function of mapping the numerical information of the environment for values characterized by pertinence functions, transforming quantitative information into qualitative (fuzzyfication). The exit interface executes the inverse mapping to the entrance (defuzzyfication), transforming qualitative into quantitative information, when converted into proportional scale value, or transforming qualitative into quantitative information to be used directly in qualitative diagnosis of decision taking.

**METHODOLOGICAL PROCEDURES**

The searched population in this study is constituted by four Brazilian iron foundries that present processes with the flow-shop characteristics. All of them have expressive participation in the demanding external market, and have advanced technology of manufacture, with their processes certified by international organisms of quality.

All have been visited personally, having been interviewed in each of the companies, professional of the PPC areas, logistic and operations, of the level of direction to the one of operation. As procedure for the data collection the method of structuralized and non-structuralized interviews was used, followed by a previously elaborated script, as well as the systematic and not participant observation. The collected data have been registered in the used scripts, systemized and analyzed with the adoption of the content analysis method, generating descriptive reports for each of the researched cases that after consolidated individually, allowed to generate the interpretative synthesis of all the cases, that in turn were compared with the researched theoretical base.

The model was created from the evidences of the carried out analyses, tested through simulation in electronic sheet, applied in one of the researched foundries, and the results were interpreted and evaluated.

The stages of the model construction, adapted of Erdmann (1998) and the instruments used, since the initial phase of data collection until the tests and simulations with the proposed system have been the following ones:

1 - The diagnosis of the situation:

The most important variables that were tried to identify in the visits to the foundries have been: management system, organization of the production system, organization of the system of PPC, horizon of planning, treatment given to the restrictions, used heuristic rules, use of the production capacity and items parameters (set-ups, lead-times, weights, politics of lot).

2 - Comparison of the interpretative synthesis of the existing situation with the searched theoretical base: this stage consisted of the search of solutions found in literature provided by the professionals of the searched companies with respect to the problem identified in the foundry, having detected the viability of using the fuzzy set theory to shape a heuristic capable to promote the sequencing of production orders to a balanced scheduling of the melting and the molding.
3 - Conception of the proposed model and creation of the tools: In this stage, the structure of the model was constructed, with representation of the flows, the interfaces of entrance and exit, of the linguistic rules base of the inference mechanism, culminating with its implantation in an electronic sheet.

4 - Simulations, application and analysis of results of the proposed model: Programs of production of many days of molding (items and amounts) of one of the studied foundry were tested, having described the results of the application, with its performance being evaluated towards determined indicators. The generated production programs also had been compared with the empirically established programming by the production programmer, having verified its adherence to the criteria used by him. The general work project is delineated in figure II.

The results of the research
All the units that have participated of the searched sample are market foundries, that is, they produce, under order, products of castings specified by third parts, and belong to brazilian enterprise groups. The greatest parcel of market is concentrated in the automotive industry in the country and the overseas as well. It does not have alternative routes and in all the studied cases, the companies have an ERP/MRP system, where the production orders are generated, and they are converted into programs production by means of processing in specific systems, in electronic sheets and even manually. The elaboration of the short-term production program is made in two stages. The first one, with monthly regularity and a horizon of 30 days. It objectives to identify the capacity necessities, plan the use of the resources and to determine the regimen of the furnaces operation with each alloy, and the second, with daily regularity, is to generate the daily production program for a four or five
day-horizon.

The short term procedures of the PPC, the heuristic rules and the used parameters also present a great similarity. The first priority, common to all the studied cases, is to take care of the committed amounts with the customers in the convened dates, with maximum exploitation of the productive capacity, requiring an efficient use of the restrictions. When a restriction is underutilized, the rule is to anticipate orders up to the limit of its capacity. For the joint programming of the furnace with the molding it is tried to balance the offer of liquid metal (melting) with the demand (consumption of the molding), through an adequate combination of light, average and heavy weight pieces. This problem is more critical when there are restrictions of electric energy in certain periods of the day, like it occurs in some cases. In the foundries where more than one alloy is produced there is also an additional complicator, requiring the use of set-up matrixes to sequence the exchange of alloy in the furnaces. A great problem pointed by the people in the foundry is in the reprogramming that is necessary during the period considered “steady” (less than five days), for requiring many changes that need to be adjusted fastly, however manually.

In short, the PPC system in all studied cases, presents as basic logic the calculation of resources, the assistance to the customers as main priority, the administration of multiple restrictions (efficient use of the restrictions, with anticipation of orders) and the use of heuristic procedures for the short term programming, that can be synthesized as follows:

Step 1: to sequence the items in the molding prioritizing the observance of the delivery dates in the expedition;
Step 2: to program the alloy exchanges observing the set-ups matrix;
Step 3: to reprogram the molding with anticipation of orders to allow the use of the maximum critical resources, guaranteeing the supplying of casting for the restrictions in the processes after-melting/molding, however respecting the limitations of core room (pre-molding) and of the molding itself;
Step 4: to program light pieces in the period of electrical energy restriction in the molding lines served by the melting;
Step 5: to program an adequate combination of light pieces, average pieces and heavy pieces in the molding lines out of the electric energy restriction, in order to obtain a more constant liquid metal demand.

The visited foundries, as well as the available systems in the market of production planning with finite capacity (APS), have developed solutions for several of these heuristic procedures. However, to carry through the joint programming of the melting and the molding (steps 4 and 5), it could be observed that the programmers adopt solely empirical heuristic rules of their practical knowledge. The absence of a systematic that could be used for this purpose was evidenced. It is a badly solved problem by the specialists in programming in the visited foundries, aggravated by the necessity of constant short-term reprogramming, resulted from the dynamics of the environment.

DEVELOPMENT OF THE MODEL AND GOTTEN RESULTS

The construction of the heuristic model for the sequencing of production orders for the joint programming of the melting and the molding, had its origin in the diagnosis elaborated from the cases studied, supported by the literature revision.

This procedure, based on the fuzzy logic, is inserted in the basic structure of the PPC system, and to develop the model, that comprehends the description of the set of linguistic rules, the definition of the pertinence functions (values of the linguistic variables), and the establishment of the mechanism of inference for rules manipulation and the decision taking, with definition of the entrance and exit interfaces of the system, a script presented by Nobre (2000), was followed.

The function of this model, implanted in an Excel electronic sheet with use of macro
Visual Basic (VBA) language, is to systemize the heuristic procedures used by the foundries for the very short term production programming, for the melting and the molding, and that refer to:

- programming light pieces in the period of electrical energy restriction in the molding lines;
- programming an adequate combination of light pieces, pieces of average weight and heavy pieces in the molding lines out of the period of electrical energy restriction, in order to obtain a more constant demand of liquid metal possible along the working hours.

In this paper, the following conventions have been adopted to characterize the weight of the pieces (in the jargon of the foundrymen, the weight of the piece refers to the weight of the set casted pieces + gates + risers, known in Brazil as "tree"): L = light (light pieces); A = average (pieces of average weight); H = heavy (heavy pieces).

**Construction of the model**

The construction of the heuristic model according to the fuzzy logic, using the data of one of the visited foundries, that has a melting unit and three lines of molding, comprehended the following stages:

a) the identification and description of the linguistic rules base for pieces simultaneously in production in the three lines of molding, determined by the alternatives of combination used by the production programmer (human specialist):

- if there is a light piece and an average then the third can be heavy;
- or
- if there is a light piece and an average one, then the third can also be average;
- or
- if there is a light piece and plus a light one, then the third can be heavy;
- or
- if there is a light piece and a heavy one, then the third can also be heavy;
- or
- if there is an average piece and plus an average, then the third can also be average;
- or
- if there is an average and a heavy piece, then the third can also be average.

The combinations that are not compatible with these rules configure rejection conditions. Picture I presents the allowed combinations.

**Picture I - Recommendable combinations of parts simultaneously in production in the molding lines**

<table>
<thead>
<tr>
<th>LINE 1</th>
<th>LINE 2</th>
<th>LINE 3</th>
<th>COMBINATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>A</td>
<td>H</td>
<td>One light, one average and one heavy</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>A</td>
<td>One light and two heavy</td>
</tr>
<tr>
<td>A</td>
<td>L</td>
<td>H</td>
<td>Two average and one heavy</td>
</tr>
<tr>
<td>A</td>
<td>H</td>
<td>A</td>
<td>One light and two average</td>
</tr>
<tr>
<td>H</td>
<td>A</td>
<td>A</td>
<td>Two light and one heavy</td>
</tr>
<tr>
<td>L</td>
<td>A</td>
<td>A</td>
<td>Three average</td>
</tr>
<tr>
<td>A</td>
<td>L</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>H</td>
<td></td>
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<tr>
<td>L</td>
<td>H</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

Source: Primary data (2005)
Another rule incorporated to the model refers to the aspect of electric energy offers reduction. If the furnace uses this kind of energy, there is a reduction in the melting capacity, and thus the lightest pieces should be programmed in the molding. This way, linguistic rules to contemplate this situation have been generated:
- if the schedule is of energy restriction, then the pieces in production must be light;
- if the schedule is of energy restriction, and there are no light pieces, then the pieces in production must be average;
- if the schedule is of energy restriction, and there are no light neither average pieces, then the pieces in production must be heavy.

b) definition of the maximum and minimum limits (Max-Min) of the fuzzy sets for each of the three molding lines: the items of each line have been divided in three classes, in a way that each set was with the same amount of items. The items have been ordered in accordance with the weight of the tree (from the smallest to the biggest and classified in light (L), that correspond therefore to the 1/3 of items, average (A), that also correspond to 1/3 of items, and heavy (H), that equally correspond the 1/3 of items of each line. Each set of items is specific for determined line. Thus, each line has its own items of light parts, average and heavy parts. The Max-Min limits for each set of each line were defined, like demonstrated in Figure III for the Line I.

Figure III - Functions of fuzzy inference of the Line I

Source: Primary data (2005)

To make a higher number of simulations possible in the use of the model, two more options of criteria to apply the limits have been introduced:
- ordinance by weight of all items codified in the diverse archives of the molding lines, applying the fuzzy indicators in function of the defined limits, together since the item of lowest weight of all the lines up to the item of highest weight of all the lines.
- it carries through fuzzy indicators application in function of the limits defined by the weight of items in each archive of the molding lines separately.

c) definition of the entrance and exit interfaces and creation of the inference mechanism: the numerical information of the environment has been mapped to be inserted in the fuzzy system of the heuristic model (entrance interface), constituted by values characterized by the pertinence functions, that is, inside of the Max-Min limits of each fuzzy set L (light); A (average), H (heavy). With this, the transformation of quantitative
information in qualitative occurred (fuzzycation).

Beyond these information, through the entrance interface the production program is supplied for a 24-hour day (items and amounts of programmed molds, ordered by molding line in the order of item code) and other data, like code of each item; weight of each item and production rates in melting and molding.

The inference mechanism was established through factibilization heuristic, which is a procedure defined to manipulate the rules and to take decisions (SILVEIRA and MORABITO, 2002).

Two heuristics of factibilization have been defined randomly:
· Type 1: it determines the sequencing of the program, carrying through an increasing ordinance of the lines that have more light pieces (of the L to the A and of the A to the H) and a decreasing ordinance of the lines that have more heavy pieces H (of the H to the A, and of the A to the L). If there is a pair number of molding lines, in half of the lines the increasing ordinance of the items for the weight of the pieces (light to heavy) is carried through and in the other half of the lines the ordinance is made in decreasing form (heavy to light). If the amount of lines of molding is uneven, the increasing ordinance is carried through in the half of lines minus 1, and the other half of the lines is ordered decreasingly.
· Type 2: it simultaneously verifies the occurrence of not recommended combinations (rejection conditions) of items in simultaneous production. Once identified the rejection condition, the item that provoked it is rescheduled for the end of the day, and the other items are anticipated. New comparisons based on rules are made, repeating the operation until eliminating the rejection conditions, or the rescheduling alternatives finish. In the hypothesis of the rejection condition is revealed in the first moment, the choice of the item to reschedule is random, through random number generated automatically by the electronic sheet.

Figure IV represents this heuristic.

Figure IV - Factibilization heuristic of type 2
Source: Primary data (2005)
The exit interface makes the inverse mapping to the entrance (defuzzycation), and presents the qualitative information transformed into qualitative (resultant combination of light pieces (L), averages (A), and heavy (H), as well as quantitative information (demanded weight of metal by the molding lines). The result is presented in an electronic sheet, which data are transferred to a table in the form as they are visualized by the users of the foundry.

In function of the subjectivity of the PPC specialist’s work in the foundry to sequence the orders of the molding program production, there have not been identified in the research performance indicators to evaluate the sequencing generated for the joint program of the melting with the molding. This way, there have been created indicators to evaluate the different alternatives of simulation generated by the model and to compare the results, also with the sequencing determined by the professional of the foundry: standard deviation in relation to the medium of the total weight demanded; amount of set-ups during one 24-hour day; time in which a rejection condition, not solved during the work day (in minutes), prevailed and capacity of lost production in the restriction resource along one day.

With all these implementations, the heuristic model for the joint programming of the melting and the molding, based on the fuzzy logic, presents the structure shown in figure V.

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**Figure V - Structure of the heuristic model based on the fuzzy logic for the joint programming of the furnace and the molding lines**

*Source: Primary data (2005)*

**Practical Application and Results of the Proposed Model**

The practical application of the model consisted of the accomplishment of the sequencing of items during several days of programming of one of the foundries searched. Thus, the necessities have been processed in the electronic sheet with the proposed model, using the three options of fuzzy limits for each one of the factibilization heuristics (type 1 and type 2), having been generated a production scheduling for each one of these alternatives. Each alternative had its performance measured by the indicators that have been defined to evaluate the model. Also the program generated empirically by the production programmer (specialist of the foundry) was evaluated by the same indicators. The results of four days of the model application are discussed, and for one of the days the program sequenced by the specialist of the foundry is presented and the same program generated by the best alternative of the proposed model.

On the first day the results were very similar in all the analyzed alternatives. The
simulations carried through with the factibilization heuristic of type 1, with general and isolated application per line of the fuzzy limits are apparently better for presenting a lesser standard deviation. The loss of capacity was of 5%, for an admissible minimum loss of 1.23% (medium of 22,717 kg for a capacity of 23,000 kg per hour in the melting).

On the second day, once more, the performances were very similar, having the alternative of type 1, with application of the fuzzy limits separately applied per line, presenting the lowest standard deviation and the lowest loss of capacity (7% for an admissible loss of 5.85%). The program generated by the specialist also presented the lowest loss of capacity (7% for a permissible loss of 4.85%). The alternative with type 1 and application of the medium limits presented the lowest condition of rejection, but it had a higher standard deviation and a higher loss of capacity.

On the third day, the alternative of type 1 with application of the isolated limits per line presented the lowest standard deviation, the lowest rejection condition and the lowest loss of capacity (5% for an admissible loss of 0.7%). The program generated by the specialist had a loss of 6% capacity. This means that the heuristic model provided a gain of 1% in the use of the melting capacity.

To better illustrate the application of the heuristic model, referring to the fourth day, there will be presented in details, the program generated by the specialist (Table I), and the program generated by the best simulation of the heuristic model, that is the alternative of type 2 with application of the medium limits (Table II).

Table I - Program of the fourth day with sequencing elaborated by the specialist

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<tr>
<th>Program of the fourth day - foundry specialist</th>
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<td>Line 1</td>
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</tr>
<tr>
<td>Item code</td>
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<tr>
<td>126</td>
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<tr>
<td>128</td>
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<td>170</td>
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<td>186</td>
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</table>

Source: Case A (2005)

Table II - Program of the fourth day with sequencing elaborated by the heuristic model (best alternative)

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<th>Program of the fourth day – heuristic model (best alternative)</th>
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<td>Line 1</td>
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Source: Primary data (2005)

The results of the simulation of day 04 are shown in table III.
On this day, the best alternative in terms of capacity loss was generated by the alternative of type 2, with application of the medium limits. The loss was of 8% (for an admissible loss of 5.7%), against a loss of 10% of the program generated by the specialist. This gain of 2% represents 11,040 kg of metal per day, what corresponds to the 220,800 kg per month, equivalent to the 9.6 additional hours of production per month. The alternatives of type one presented a lower standard deviation and a lower condition of rejection, but a higher loss of capacity.

The results of the practical application of the model in these four days allow to affirm that the proposed heuristic model could apprehend the rules and the processes of the specialists reasoning well, because at no moment the program generated by the model presented inferior results to the ones of the program generated by the specialist, on the contrary, in two opportunities (days 03 and 04) the program generated by the heuristic model presented superior results, in terms of exploitation of the production capacity. The generation of a production program with such sequencing allows, besides attending the order in the foreseen terms, to take great advantage of the existing capacity, perfectly attends to the necessities of quality and productivity of a foundry. A foundry that operates with fewer interruptions minimizes the losses of energy, because the liquid metal in the furnace needs to be kept hot, what means to keep the furnace on, independently of being or not attending the molding lines. Moreover, the metal transport ladles also need to be heated, what is favored with the most continuous operation possible, what also contributes to reduce melting defects. What can also be perceived is that depending on the characteristics of the daily program, different alternatives can generate the most satisfactory results. This means that, for each day, it is convenient to simulate all the sequencing alternatives, and select that one which best adjusts to the momentaneous needs, producing the best results. The simulations in the electronic sheet are executed with great speed and their results can practically be analyzed in real time. This aspect provides an additional benefit to the model, in what refers to the analysis of reprogramming that occurs with frequency at any time of the day.

**FINAL CONSIDERATIONS**

Even though the key point of the PPC of a foundry lies in the joint and integrated programming of the melting and of the molding, it was evidenced, in the revision of literature, as well as in the field research, that this problem used to be solved empirically through the practical knowledge and the experience of the production programmers, inexisting a specific methodology for such purpose. An adequate melting and molding
scheduling allows taking better advantage of the production capacity, as well as reducing the waste of energy and the foundry defects.

Thus, the proposal of this work was to develop a heuristic model for the simultaneous and integrated melting and molding programming, inserting the PPC system in mechanized foundries. The model was developed based on the concepts of the fuzzy logic, utilizing the rules of decision used by the production programmers, identified in the research. It allows guiding the sequencing of the production orders in the molding in a way to propitiate the best exploitation of the productive capacity, without prejudice to the attendance of the order in the required dates, since its horizon of performance is limited to the daily programming.

The practical results of the scheduling carried through during some days with the developed heuristic model have demonstrated an equivalent performance, in some days, and superior in others, to the program generated by the specialist of the foundry. Moreover, the possibility of transference of the specialized knowledge to a management tool is a very important aspect to be pointed out with the development of the model, because it propitiates ways for the sharing of information and the learning organization.

Another advantage of the method is the capacity to allow the accomplishment of simulations in electronic sheet with extreme speed, allowing analyzing alternatives and selecting the ones of better performance, practically in real time. This characteristic is particularly important for the analysis of reprogramming that occur during the day.

There is potential to improve the performance of the model even more. Its evolution could include the fragmentation of lots in the schedules out of the electrical energy restriction period, with the intention to promote a higher constancy in the metal liquid demand. Thus, new versions of the model could also consider additional rules and a heuristic of factibilization for the fragmentation of lots. This would cause the inclusion of the control of lost times for set-up. Another study, that could be taken to effect, relates to the amplification of the fuzzy sets. The existence of only three (light pieces, average weight and heavy pieces) promotes a great amplitude in the universe of the linguistic variable weight, what causes sensitive variations in the metal demand even with the allowed combinations. Thus, there could be introduced additional fuzzy sets, of the type "very light", "little light", "very heavy", "little heavy" etc.

A highly promising field is being object of some recent studies on the evolutive computation, whose concepts could be incorporated to the model. In accordance with Back (1996), it also deals with systems called evolutive algorithms, for the resolution of problems that use computational models, based on the theory of the natural evolution. For Haupt and Haupt (1998), the genetic algorithm is a process to optimize complex functions highly based on the mechanisms of natural evolution and the genetics, while for Carvalho, Braga and Ludermir (2003), the category of the genetic algorithms consists of evolutive programs based on the theory of the natural evolution and in the hereditary succession. This field of study presents a significant potential that is worth to be analyzed, with the development of a hybrid model for the production scheduling with the use of the fuzzy logic associated to the genetic algorithm.

REFERENCES


1995.


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