Particle swarm based batch filling scheduling

Načrtovanje polnjenja šarž z uporabo rojev delcev

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Abstract: ŠTORE STEEL Ltd faces a problem of production of a huge amount (approximately 1 400) of different steel compositions in a relatively small quantities (approximately 15 t). This production is performed in batches of predetermined quantities (50–53 t). The purpose of this paper is to present the methodology for optimizing the production of predetermined steel grades in predetermined quantities before a customer's set deadline in such a way as to reduce the non-planned and ordered quantities with the date before the deadline and minimize the number of batches. The particle swarm method was used for the optimization. The results of the research have been used in practice since 2006 with reducing the non-planned and ordered quantities from 17.17 % up to 10.12 % since then.

Izvleček: ŠTORE STEEL, d. o. o., se spopada s problemom majhnih naročil (v povprečju 15 t) ter z izdelavo ogromne količine različnih kvalitet jekla (več kot 1 400). Jeklo se izdeluje v šaržah (50–53 t). V članku je predstavljena metodologija za optimiranje izdelave načrtovanih kvalitet in količin jekla v predvidenem roku z namenom, da se zmanjša odlita načrtovana količina jekla, kjer je dobavni rok daljši, kot je določen, ter nenačrtovana količina jekla. Optimizacija je bila izvedena z uporabo rojev delcev. Rezultati raziskave so uporabljeni v praksi od leta 2006, ko sta se v letu 2007 odlita načrtovana količina jekla, kjer je dobavni rok daljši, kot je bil določen, ter nenačrtovana količina jekla zmanjšali iz 17,17 % na 10,12 %.

Original scientific paper

Key words: steelmaking, continuous casting, steel grade, work orders, scheduling, optimization, particle swarm optimization
Ključne besede: jeklarstvo, kontinuirano odlivanje, kvaliteta jekla, delovni nalogi, načrtovanje, optimizacija, optimizacija z uporabo rojev delcev

INTRODUCTION

The steelmaking and casting represent basic steel production operations and play a primary role in the downstream steel production. The optimization of the casting batch planning according to the different requirements for chemical composition, ordering dates, casting quantities, etc., is an extremely challenging task. The complexity of batch planning increases with the number of different steel grades and customers' orders.

There is a lack of descriptions of batch filling scheduling in the open literature. Probably the most plausible reasons for this are the non-tendency of manufacturers to expose their well-understood heuristics in order to form production schedules, and the different technology and hardware equipment specifics.[1–3] On the other hand, there are plenty of publications on casting technology and physical modeling available[4–9] at the present.

One of the principal problems in steel production scheduling,[2] consists of determining the scheduling of operations to be performed on molten steel at the production stage from the steelmaking to the continuous casting. A theoretical basis of the time dependent batch scheduling is by the best of the authors' knowledge presented only in.[10, 11] Similarly,[12] explores the scheduling problem between the production and the transportation in a steelmaking shop, in order to minimize the completion time. Paper[13] deals with the schedules for casting of different casting moulds from a number of heats, and[14] deals with the scrap charge optimization problem according to its chemical composition in secondary steel production. The last reference is most probably most relevant with respect to the batch filling scheduling, discussed in the present paper.

To a great extent, at ŠTORE STEEL Ltd. work orders scheduling and related issues have been traditionally carried out by a highly skilled expert human scheduler. The particle swarm method was considered for generation of batch filling schedules in the present paper. During optimization the particles 'fly' intelligently in the solution space and search for optimal batch filling schedules according to the strategies of the particle swarm algorithm. Many different work order schedules were obtained during the optimization.

Work orders scheduling

ŠTORE STEEL Ltd. owns a small (200 000 t per year) flexible steel plant and is one of the best-known producers of flat spring steel in Europe. The company is producing more than 80 steel grades with more than 1 400 different customer-specific chemical compositions.

Customer can order hot rolled or cold finished bars. Purchasing department forwards the order to quality department where customers' delivery terms have been checked. After aproving the delivery conditions the order is processed by production planning department wher technology and delivery deadline is discused. After approving the technology and delivery deadline the purchasing department calculates the prices.

The production planning department assures the working orders for all steps in production chain which starts in the steel plant.

In the steel plant, scrap iron is melted in a 60 t capacity electric arc furnace. The liquid steel is then poured into the ladle (ca. 53 t), which a crane transports to a subsequent ladle furnace, where manganese, chromium, molybdenum, nickel, vanadium and other alloying elements are added to the steel in order to meet the chemical quality requirements. The molten steel is cast into square billets of dimensions 140 mm or 180 mm in a continuous caster. The billets are reheated afterwards and the steel bars of various shapes and dimensions are manufactured by means of hot rolling and finally according to customers' orders, heat treated, peeled, drawn or grinded.

The production of steel at ŠTORE STEEL Ltd. is usually deliberately cast for a pool of 384 customers. The mean cast quantity is 14.32 t (standard deviation 23.77 t). Due to the constraints posed by the production, some extra cast steel is produced on top of the ordered cast quantity. This is denoted as a non-planned cast quantity.

Structure of the work order

The work orders for batch processing are generated based on the customers' orders. A typical structure of work orders is presented in Table 1.

The work order number is a sequential number. The cover quality prescription and the work order chemical limitations define the chemical composition of the related batch.

Each quality prescription has also its own steelmaking technology (i.e. times, temperatures, sampling, purging, oxygen activities). There are, in general,

Table 1. Work order example

Work order number: 0001019			
Cover quality prescription code	Chemical limitations in mass fractions, *w*/%		
732.59.2	w(C)/% = 0.52–0.54; w(P)/% = 0.015(max.) w(Sn)/% = 0.02 (max.); w(As)/% = 0.04(max.)		
Quality prescription code	Customer order code	Ordered quantity t	Delivery date
732.54.2	0000855022	25	30. 1. 2009
732.01.0	0000937001	3.5	8. 11. 2009
732.59.2	0000855007	1.5	30. 1. 2009
732.59.2	Non-planned cast quantity	23	

two groups of steelmaking technologies: the first, for the extra-machinability steels[15], where the batch weight is 50 t, and the second, for the other steel qualities, where the batch weight is 53 t. In the extra-machinability steelmaking technology, the molten steel in the ladle is more reactive, so the molten steel quantity (batch weight) should be smaller.

Tables 2, 3 and 4 show three sample quality prescriptions (732.00.1, 732.59.2, 732.54.2) and their calculated chemical limits. Chemical limitations are calculated according to the quality prescriptions limits and simple rules presented in Figures 1 and 2. If the chemical aim value for the chemical element is prescribed in the quality prescription, it means that the ladle furnace operator has to obtain the exact chemical weight percentage of the element. The internal minimum and maximum are prescribed according to the technology procedure. The batch satisfies the customer's chemical requirements if the chemical weight percentage is within the customer's limits (minimum and maximum). The customers' set chemical limitations are because of the technology limitations and rules converted to internal composition limits in order to assure the customer set specifications. The briefly described rules dictate that the in plant chemical limitations are narrower than the set customers' chemical limitations.

In fact, all three of the quality prescriptions presented, fit into the chemical composition of 50CrV4 (W. NR. 1.8159) spring steel. For example, at the moment there are 53 quality prescriptions for 50CrV4 steel existing in the company, and it is not possible to chemically combine all of them.

Table 2. Quality prescription 732.01.0 and its calculated chemical limits (minimum and maximum)

Quality prescription 732.01.0						Calculated chemical limits	
Element	Customer minimum *w*/%	Internal minimum *w*/%	Aim *w*/%	Internal maximum *w*/%	Customer maximum *w*/%	Quality prescription limits – minimum *w*/%	Quality prescription limits – maximum *w*/%
C	0.47	0.50		0.53	0.55	0.47	0.55
Si	0.15	0.20		0.35	0.40	0.15	0.40
Mn	0.70	0.80		1.00	1.10	0.70	1.10
P				0.015	0.025	0	0.025
S				0.020	0.025	0	0.025
Cr	0.90	1.00		1.10	1.20	0.90	1.20
Mo				0.05	0.08	0	0.08
Ni				0.25	0.30	0	0.30
Al		0.010	0.011	0.015	0.100	0.010	0.015
Cu				0.25	0.40	0	0.40
V	0.10	0.14		0.17	0.20	0.10	0.20
Sn				0.030		0	0.030
As						0	100
N						0	100

Table 3. Quality prescription 732.54.2 and its calculated chemical limits (minimum and maximum)

Quality prescription 732.54.2						Calculated chemical limits	
Element	Customer minimum *w*/%	Internal minimum *w*/%	Aim *w*/%	Internal maximum *w*/%	Customer maximum *w*/%	Quality prescription limits – minimum *w*/%	Quality prescription limits – maximum *w*/%
C	0.49	0.50		0.52	0.54	0.49	0.54
Si	0.20	0.20	0.34	0.35	0.40	0.20	0.40
Mn	0.90	0.91		1.00	1.10	0.90	1.10
P				0.015	0.015	0	0.015
S				0.015	0.015	0	0.015
Cr	0.90	0.91		1.00	1.20	0.90	1.20
Mo				0.04	0.08	0	0.08
Ni				0.10	0.20	0	0.20
Al	0.010	0.010	0.011	0.015	0.025	0.010	0.025
Cu				0.25	0.25	0	0.25
V	0.10	0.11		0.14	0.20	0.10	0.20
Sn				0.015		0	0.015
As				0.035	0.040	0	0.040
N						0	100

Table 4. Quality prescription 732.59.2 and its calculated chemical limits (minimum and maximum)

Quality prescription 732.59.2						Calculated chemical limits	
Element	Customer minimum *w*/%	Internal minimum *w*/%	Aim *w*/%	Internal maximum *w*/%	Customer maximum *w*/%	Quality prescription limits – minimum *w*/%	Quality prescription limits – maximum *w*/%
C	0.51	0.52	0.52	0.55	0.55	0.52	0.55
Si	0.25	0.25	0.34	0.35	0.40	0.25	0.35
Mn	0.95	1.00	1.00	1.10	1.10	1.00	1.10
P				0.015	0.020	0	0.020
S				0.008	0.008	0	0.008
Cr	1.05	1.10	1.10	1.20	1.20	1.10	1.20
Mo				0.05	0.06	0	0.05
Ni				0.20	0.20	0	0.20
Al		0.010	0.011	0.015	0.040	0.010	0.015
Cu				0.25	0.25	0	0.25
V	0.10	0.15	0.16	0.18	0.25	0.15	0.18
Sn				0.025		0	0.025
As						0	100
N				0.016		0	0.016

Table 5. Batch chemical limitations

	Quality prescription 732.01.0 limits *w*/%		Quality prescription 732.54.2 limits *w*/%		Quality prescription 732.59.2 limits *w*/%		Batch chemical limitations *w*/%	
Element	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
C	0.47	0.55	0.49	0.54	0.52	0.55	0.52	0.54
Si	0.15	0.40	0.20	0.40	0.25	0.35	0.25	0.35
Mn	0.70	1.10	0.90	1.10	1.00	1.10	1.00	1.10
P	0	0.025	0	0.015	0	0.020	0	0.015
S	0	0.025	0	0.015	0	0.008	0	0.008
Cr	0.90	1.20	0.90	1.20	1.10	1.20	1.10	1,2
Mo	0	0.08	0	0.08	0	0.05	0	0.05
Ni	0	0.30	0	0.20	0	0.20	0	0.20
Al	0.010	0.015	0.010	0.025	0.010	0.015	0.010	0.015
Cu	0	0.40	0	0.25	0	0.25	0	0.25
V	0.10	0.20	0.10	0.20	0.15	0.18	0.15	0.18
Sn	0	0.030	0	0.015	0	0.025	0	0.015
As	0	100	0	0.040	0	100	0	0.040
N	0	100	0	100	0	0.016	0	0.016

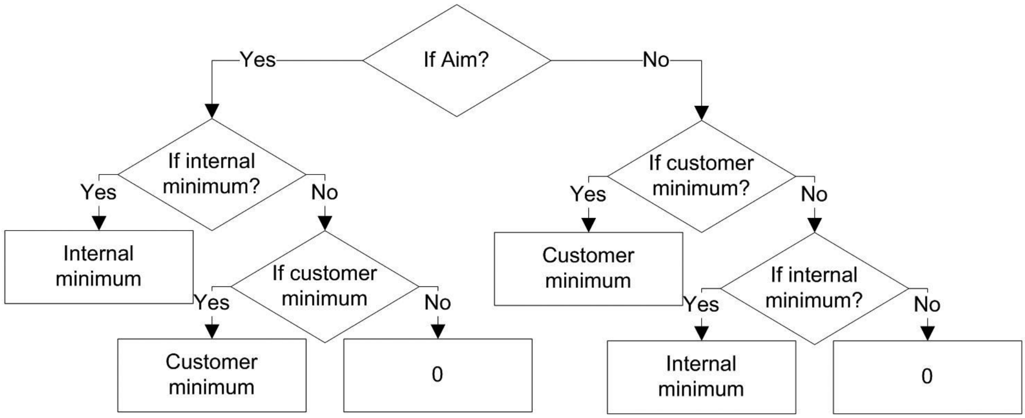

Figure 1. The rules for defining quality prescription minimum limit

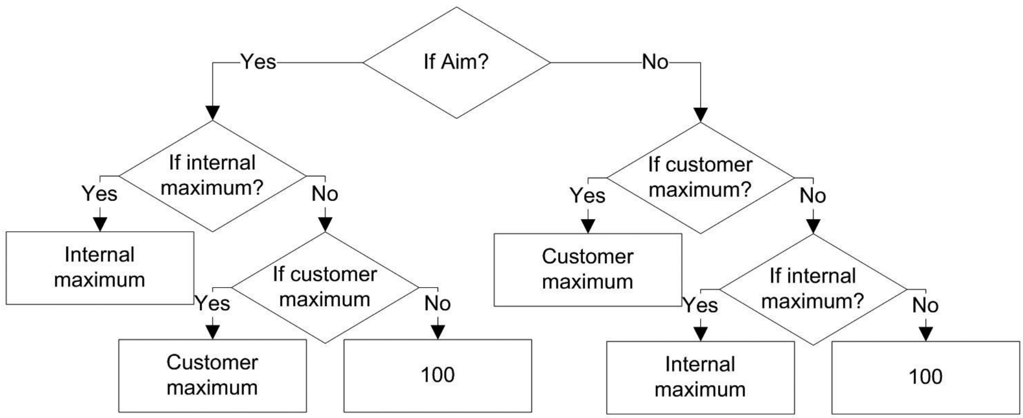

Figure 2. The rules for defining the quality prescription maximum limit

According to the selected customers' orders and their quality prescriptions (732.00.1, 732.59.2, 732.54.2), it is possible to easily calculate the batch chemical limitations (Table 5), based on the rules in Figure 1 and 2.

The logic for defining the cover quality prescription is as follows: The quality prescription with the highest number of chemical elements limitations among the selected work order quality prescriptions is defined as the cover quality prescription. In such case, the ladle operator uses the technology prescribed according to the cover quality prescription and adjusts the steelmaking technology according to the required chemical composition. In case of a customer order for the extra-machinability steels between the work order quality prescriptions, its quality prescription automatically becomes a cover quality prescription.

PARTICLE SWARM BATCH SCHEDULING

At the beginning of the batch scheduling, a grouping based on the ordered quantities is performed. The ordered quantities are divided into groups with similar chemical composition. The ordered quantity fits into the group if there are one or more ordered quantities with similar chemical composition (similar quality prescriptions) existing in the group.

After the grouping of the ordered quantities the particle swarm method was used for batch filling scheduling.[15]

The "particle" structure is conditioned by the problem's nature – consecutive events – the batch is cast consecutively. The biggest problem is in dealing with the batch filling schedule – organism evaluation.

BATCH FILLING SCHEDULES AS PARTICLES

The batch filling schedules are in fact the work order sequences and can be presented as sequence of batches with ordered quantities (Figure 3). Figure 3 shows the customer's ordered quantities cast within 4 batches. The ordered quantity 3 is cast within 3 batches, the ordered quantity 4 within 2 batches, and all other ordered quantities within one batch. The non-planned cast quantity can be observed in the last batch – batch 4.

Hence, the organism in Figure 3 can be written down as a sequence: Ordered quantity 1 - Ordered quantity 2 - Ordered quantity 3 - Ordered quantity 4.

The principal problem is to form the batch filling sequence according to the customers' ordered cast quantities, quality prescriptions, delivery dates, and possible additional rules.

FORMATION AND EVALUATION OF WORK ORDERS

The deadline must be defined in terms of the delivery date for ordered quantities. This means that all quantities

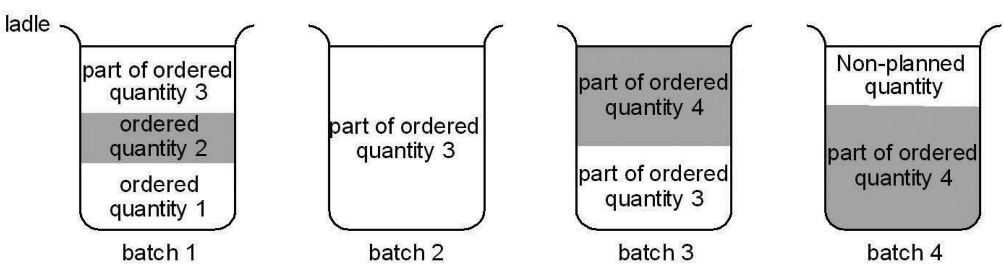

Figure 3. Work order schedule – the organism

should be cast in terms of that delivery date. The batch weight is defined according to the steelmaking technology – for extra-machinability steels, the batch weight is 50 t and for the other steel qualities the batch weight is 53 t.

From the ordered quantities pool the individual ordered quantities are added to the work order until the batch weight is reached. If the last added quantity exceeds the batch weight, which usually happens, the partial quantity is added to one or more consecutive work orders. The rule is that the partial quantities are added to the consecutive work order only when they exceed 5 %. Small orders of up to 5 t should not be split between the batches, i.e. to be cast within one batch.

For each ordered quantity, the chemical composition is compared to the quality prescriptions for the added quantity as well. In the event that the chemical composition does not fit the chemical prescriptions of the added quantities, the actual work order is filled with the non-planned quantity and the quantity is added to the consecutive work order (orders), which is filled according to the previously mentioned guidelines.

The work orders for quantities with a delivery date beyond the defined deadline are automatically abandoned.

The evaluation of the work order schedule consists of the following three parts:

O_1 The number of additional ordered quantities, where the ordered quantities are not cast within one batch (for instance, as seen in , we have to cast the ordered quantity 3 into 2 additional batches, and the ordered quantity 4 in one additional batch, so the total number of additional ordered quantities parts, where the ordered quantities are not cast within one batch is, in this case, 3)

O_2 Non-planned cast quantities in tons, and

O_3 All the customers' quantities in tons with the delivery date ahead of the deadline.

For the proper evaluation of optimum solution, weights were also used: w_1 = 4, w_2 = 1 and w_3 = 1 for each evaluation part (O_1 – number of additional ordered quantities parts, O_2 – non-planned cast quantities, and O_3 – all the customers' quantities in tons with the delivery date ahead of the deadline). The weights were selected according to the expert scheduler's advice and the preliminary test runs. The respective evaluation function can be simply written as:

$$f_e = w_1 \cdot O_2 + w_2 \cdot O_2 + w_3 \cdot O_3 \qquad (1)$$

The particle swarm optimization

The problem is set in a discrete space, so the most important issue in applying particle swarm optimization successfully is to develop an effective “problem mapping” and “solution generation” mechanism. If these two mechanisms are devised successfully, it is possible to find good solutions for a given optimization problem in acceptable time.

The particle swarm optimization used can be described in three following steps:[15]

1. Let initialization iterative generation be $k = 0$, initialization population size p_{size}, the termination iterative generation, *Maxgen*. Give birth to p_{size} initializing particles. Calculate each particle’s fitness value of initialization population, and let first generation p_i be initialization particles, and choose the particle with the best fitness value of all the particles as the p_g (g_{Best}).
2. Every $p_{i,k}$ and $p_{g,k}$ crossover can get two child particles, compare them and let smaller fitness value particle be final child of predecessors. Using equation (2) obtains “flying” velocity v_i particles, then utilizing equation (3) randomly permutating N particles of them. And using equations (4) and (5) with the same method gives birth to the next generation particles x_i. If the fitness value is better than the best fitness value p_i (p_{Best}) in history, let current value as the new p_i (p_{Best}). Choose the particle with the best fitness value of all the particles as the p_g (g_{Best}). If k = *Maxgen*, go to Step 3, or else let $k = k + 1$; go to Step 2.
3. Put out the p_g.

The changing of the particles’ velocities is presented by following equations:

$$v_{i,k+1} = p_{i,k} \otimes p_{g,k}, \quad (2)$$

$$(v_{r1}, v_{r2}, \ldots, v_{rN})_{k+1} = P(v_{r1}, v_{r2}, \ldots, v_{rN}), \quad (3)$$

$$x_{i,k+1} = x_{i,k} \otimes v_{i,k+1}, \quad (4)$$

$$(x_{r1}, x_{r2}, \ldots, x_{rN})_{k+1} = P(x_{r1}, x_{r2}, \ldots, x_{rN}), \quad (5)$$

where k represents the iterative generation number, and r ($1 \le r \le p_{\text{size}}$) is random integer which denotes permutating particle, and $\otimes$ is crossover denotation which denotes two particles making crossover operator. $P(v_r)$, $P(x_r)$ mean mutating particle v_r and x_r. The termination criterion for the iterations is determined according to whether the max generation (10 000).

For each final work orders schedule 100 independent runs were performed.

In the presented algorithm, each particle of the swarm shares mutual information globally and benefits from the discoveries and previous experiences of all other colleagues during the search process. The algorithm requires only primitive and simple mathematical operators, and is computationally inexpensive in terms of both memory requirements and time.

Results of the scheduling

In order to demonstrate the methodology, real data from production in October 2009 were used. There were 196 ordered quantities with an average quantity of 21.66 t (standard deviation 37.45 t). Table 6 enlists the quality prescription quantities (46 different quality prescriptions) and their calculated chemical limits within 196 orders. The deadline chosen was 31. 10. 2009.

From the quality prescription enlistment (Table 6), 29 ordered quantities groups can be established (Table 7) based on rules defined in section Formation and evaluation of work orders.

In order to make the presentation more clear, let us take a closer look at the batch filling scheduling of the largest group – group 23. Group 23 presents, in general, 50CrV4 (W. NR. 1.8159) spring steel. But we must state again that it is not possible to chemically combine all of them. For instance, we cannot cast within one batch orders with quality prescription 732.66.0 with 732.12.5 or 732.13.5, quality prescription 732.18.1 with 732.59.2 or 732.54.2 (Table 6). In group 23 there are 113 customer orders, with a total amount of 1699.239 t, with an average ordered quantity of 15.0375 t, and with 52 orders within the deadline.

The simulated swarm scheduled the group 23 with the following results:

- number of additional ordered quantities parts: 9
- non-planned cast quantities: 10.517 t
- customer quantities with the delivery date ahead of the deadline: 37.230 t
- number of work orders: 19.

The best batch filling schedule was obtained in the 6758-th generation (the generation 0 is a randomly generated generation). For clearer understanding, only the first five successive work orders of the best work order schedule are presented in the following tables (Tables 8–12).

It is possible to notice that the customer order 901000085507 is present at work order 0001020 (Table 8) and 0001021 (Table 9) – so the order is processed within two batches and thus has an additional part. The best solution is obtained, as mentioned before, when the ordered quantity is cast within one batch.

Table 6. Quality prescription quantities in October 2009 and their calculated chemical limits

Quality Prescription code	Steel quality	Ordered Quantity [t]	C *w*/%	Si *w*/%	Mn *w*/%	P *w*/%	S *w*/%	C *w*/%
108.15.0	44MnSiVS6	30.192	0.42-0.47	0.5-0.7	1.3-1.6	MAX 0.035	0.02-0.035	MAX 0.25
108.33.0	38MnVS5	121.5	0.35-0.4	0.5-0.7	1.2-1.5	MAX 0.035	0.045-0.06	0.15-0.25
108.70.1	38MnVS6 (extra machinability)	18.944	0.41-0.44	0.3-0.5	1.1-1.4	MAX 0.035	0.03-0.035	0.15-0.25
127.11.5	61SiCr7	83.841	0.57-0.65	1.6-1.8	0.7-1	MAX 0.02	MAX 0.015	0.25-0.4
140.11.1	CSN 15230.3[1]	18.038	0.24-0.34	0.17-0.37	0.4-0.8	MAX 0.035	MAX 0.035	2.2-2.5
193.31.0	27MnCrB5	18.352	0.25-0.3	0.15-0.35	1-1.4	MAX 0.035	MAX 0.035	0.3-0.6
193.52.0	30MnB5	26.374	0.27-0.3	0.1-0.3	1.05-1.2	MAX 0.035	MAX 0.035	MAX 0.3
193.54.0	28MnCrB7-2	53.872	0.26-0.28	0.15-0.25	1.68-1.78	MAX 0.03	0.02-0.04	0.48-0.53
503.14.0	St 37-2	4.019	0.14-0.17	0.15-0.5	0.4-1.4	MAX 0.035	MAX 0.035	MAX 0.3
503.31.1	RSt 37-2	97.65	0-0.08	0-0.08	0.28-0.45	MAX 0.02	MAX 0.02	
516.17.1	Cm45	13.616	0.43-0.48	0.15-0.35	0.6-0.7	MAX 0.035	0.02-0.035	0.17-0.23
523.00.0	C75	46.176	0.7-0.8	0.15-0.35	0.6-0.8	MAX 0.045	MAX 0.045	MAX 0.3
524.11.0	C70	0.918	0.65-0.75	0.25-0.35	0.8-0.9	MAX 0.02	MAX 0.02	0.2-0.3
615.12.0	C22E	30.251	0.16-0.19	MAX 0.1	0.3-0.4	MAX 0.015	MAX 0.015	MAX 0.2
623.32.0	70MnVS4	218.093	0.69-0.72	0.15-0.25	0.8-0.9	MAX 0.015	0.06-0.07	0.1-0.2
625.13.1	C50	105.08	0.5-0.53	0.2-0.35	0.8-0.9	MAX 0.03	0.015-0.02	0.23-0.3
635.36.5	C35R	23.088	0.36-0.39	0.2-0.4	0.65-0.8	MAX 0.03	0.02-0.035	0.2-0.3
636.11.1	C45	515.41	0.47-0.5	0.2-0.35	0.7-0.8	MAX 0.035	0.02-0.025	0.24-0.29
705.13.3	SAE 1141[2]	54.6	0.39-0.43	0.2-0.3	1.4-1.55	MAX 0.03	0.08-0.092	MAX 0.3
711.00.1	41Cr4	26.869	0.38-0.45	0.2-0.4	0.6-0.9	MAX 0.035	MAX 0.035	0.9-1.2
711.14.0	41Cr4	15.333	0.38-0.45	0.2-0.4	0.6-0.9	MAX 0.035	MAX 0.035	0.9-1.2
718.70.2	16MnCr5 (extra machinability)	55.388	0.14-0.19	0.2-0.4	1-1.3	MAX 0.035	0.02-0.035	0.8-1.1
724.24.0	42CrMo4	38.438	0.38-0.45	0.15-0.4	0.6-0.9	MAX 0.035	0.02-0.035	0.9-1.2
732.01.0	50CrV4	150.341	0.47-0.55	0.15-0.4	0.7-1.1	MAX 0.025	MAX 0.025	0.9-1.2
732.03.0	51CrV4	9.709	0.47-0.55	0.15-0.4	0.7-1.1	MAX 0.025	MAX 0.025	0.9-1.2
732.12.5	51CrV4	67.113	0.51-0.54	0.2-0.35	1-1.1	MAX 0.015	MAX 0.015	1.1-1.2
732.13.5	51CrV4	141.563	0.51-0.56	0.2-0.35	1-1.2	MAX 0.015	MAX 0.015	1.1-1.25
732.18.1	51CrV4	5.661	0.47-0.51	0.15-0.4	0.7-0.85	MAX 0.025	MAX 0.025	0.9-1
732.19.1	51CrV4	11.485	0.51-0.55	0.15-0.4	0.85-0.95	MAX 0.025	MAX 0.025	0.95-1.1
732.20.2	51CrV4	58.785	0.51-0.55	0.15-0.4	0.9-1.1	MAX 0.025	MAX 0.025	1.05-1.2
732.21.2	51CrV4	27.675	0.52-0.54	0.2-0.35	0.95-1.1	MAX 0.025	MAX 0.025	1.1-1.2
732.24.4	50CrV4	69.967	0.47-0.55	0.2-0.4	0.7-1.1	MAX 0.035	MAX 0.035	0.9-1.2
732.26.2	51CrV4	17.263	0.51-0.54	0.2-0.35	0.9-1.05	MAX 0.02	MAX 0.015	1-1.1
732.27.3	51CrV4	31.69	0.51-0.55	0.15-0.4	0.95-1.1	MAX 0.025	MAX 0.025	1.1-1.2
732.54.2	51CrV4	636.408	0.49-0.54	0.2-0.35	0.9-1.1	MAX 0.015	MAX 0.015	0.9-1.2
732.59.2	50CrV4	427.379	0.52-0.55	0.25-0.35	1-1.1	MAX 0.02	MAX 0.008	1.1-1.2
732.62.0	50CrV4	6.83	0.47-0.55	0.2-0.4	0.7-1.1	MAX 0.02	MAX 0.01	0.9-1.2
732.66.0	51CrV4	37.37	0.47-0.5	0.2-0.4	0.7-1.1	MAX 0.035	MAX 0.035	0.9-1.2
741.33.3	15CrNiS6	4.144	0.12-0.17	0.15-0.4	0.4-0.6	MAX 0.035	0.02-0.035	1.4-1.7
775.13.0	23MnNiMoCr5-4	25.693	0.21-0.24	0.15-0.25	1.25-1.4	MAX 0.02	MAX 0.012	0.5-0.6
779.27.1	16MnCrS5	414.9	0.14-0.17	0.2-0.35	1-1.1	MAX 0.035	0.02-0.03	0.8-0.9
779.71.4	16MnCrS5 (extra machinability)	40.848	0.17-0.19	0.15-0.3	1-1.1	MAX 0.025	0.03-0.035	0.9-1
780.10.0	20MnCrS5	52.8	0.2-0.23	0.15-0.25	1.3-1.4	MAX 0.025	0.02-0.03	1.2-1.3
780.13.2	20MnCr5	138.45	0.17-0.22	0.2-0.35	1.1-1.4	MAX 0.03	0.015-0.035	1-1.3
781.00.1	18CrNiMo7-6	17.997	0.15-0.21	0.2-0.4	0.5-0.6	MAX 0.035	MAX 0.035	1.5-1.8
781.18.1	19CrNiMo7-6	228.75	0.15-0.17	0.2-0.35	0.52-0.62	MAX 0.03	0.018-0.025	1.55-1.65

[1] Czech State Norm [2] Society of Automotive Engineers standard

M w/%	Ni w/%	Al w/%	Cu w/%	V w/%	Sn w/%	As w/%	N w/%
MAX 0.07	MAX 0.25	0.016-0.03	MAX 0.25	0.1-0.13	MAX 0.03		
MAX 0.08	MAX 0.3	0.02-0.038	MAX 0.25	0.08-0.13	MAX 0.03		0.015-0.018
MAX 0.08	0.15-0.25	0.01-0.03	MAX 0.3	0.13-0.15	MAX 0.03		0.011-0.02
MAX 0.08	MAX 0.3	0.015-0.025	MAX 0.25	MAX 0.1	MAX 0.02		
MAX 0.05	MAX 0.2	0.02-0.035	MAX 0.25	0.1-0.2	MAX 0.03		
MAX 0.05	MAX 0.2	0.02-0.035	MAX 0.25	MAX 0.05	MAX 0.03		
MAX 0.08	MAX 0.3	0.02-0.035	MAX 0.4	MAX 0.1	MAX 0.02		
MAX 0.1	MAX 0.3	0.02-0.05	MAX 0.25	MAX 0.1	MAX 0.02		MAX 0.012
MAX 0.08	MAX 0.3	0.02-0.035	MAX 0.4	MAX 0.1	MAX 0.03		MAX 0.009
		0.015-0.025				MAX 0.012	
MAX 0.07	MAX 0.25	0.01-0.05	MAX 0.25	MAX 0.05	MAX 0.03		
MAX 0.08	MAX 0.3	0.02-0.1	MAX 0.4	MAX 0.1	MAX 0.03		
MAX 0.05	MAX 0.2	0.015-0.05	0.05-0.25	MAX 0.1	MAX 0.03		
MAX 0.1	MAX 0.2	0.02-0.035	MAX 0.2	MAX 0.05	MAX 0.03		
MAX 0.06	MAX 0.2	MAX 0.03	MAX 0.25	0.14-0.15	MAX 0.03		0.013-0.016
MAX 0.08	0.15-0.24	0.02-0.035	MAX 0.25	MAX 0.1	MAX 0.03		0.008-0.013
MAX 0.08	MAX 0.3	0.02-0.03	MAX 0.25	MAX 0.1	MAX 0.03		
MAX 0.08	0.15-0.2	0.02-0.035	MAX 0.25	MAX 0.1	MAX 0.03		0.008-0.013
MAX 0.08	MAX 0.3	0.015-0.02	MAX 0.3				
MAX 0.08	MAX 0.3	0.02-0.1	MAX 0.4	MAX 0.1	MAX 0.03		
MAX 0.08	MAX 0.3	0.02-0.1	MAX 0.4	MAX 0.1	MAX 0.03		
MAX 0.08	MAX 0.3	0.02-0.1	MAX 0.4	MAX 0.1	MAX 0.03		MAX 0.015
0.15-0.3	MAX 0.25	0.02-0.045	MAX 0.25	MAX 0.1	MAX 0.03		
MAX 0.08	MAX 0.3	0.01-0.015	MAX 0.4	0.1-0.2	MAX 0.03		
MAX 0.08	MAX 0.3	0.01-0.015	MAX 0.4	0.1-0.2	MAX 0.03		
MAX 0.08	MAX 0.2	0.01-0.015	MAX 0.25	0.1-0.2	MAX 0.02	MAX 0.04	
MAX 0.08	MAX 0.2	0.01-0.015	MAX 0.25	0.1-0.2	MAX 0.02	MAX 0.04	
MAX 0.08	MAX 0.25	0.01-0.04	MAX 0.25	0.1-0.25	MAX 0.025		
MAX 0.08	MAX 0.25	0.01-0.04	MAX 0.25	0.1-0.25	MAX 0.025		
MAX 0.08	MAX 0.25	0.01-0.04	MAX 0.25	0.1-0.25	MAX 0.025		
MAX 0.07	MAX 0.2	0.01-0.015	MAX 0.25	0.12-0.2	MAX 0.025		
MAX 0.05	MAX 0.2	0.01-0.015	MAX 0.25	0.1-0.2	MAX 0.03		MAX 0.012
MAX 0.04	MAX 0.2	0.01-0.015	MAX 0.25	0.11-0.15	MAX 0.025		
MAX 0.08	MAX 0.25	0.01-0.04	MAX 0.25	0.1-0.25	MAX 0.025		
MAX 0.08	MAX 0.2	0.01-0.015	MAX 0.25	0.1-0.2	MAX 0.02	MAX 0.04	
MAX 0.06	MAX 0.2	0.01-0.015	MAX 0.25	0.15-0.18	MAX 0.025	MAX 0.016	
MAX 0.08	MAX 0.2	0.01-0.015	MAX 0.25	0.1-0.2	MAX 0.03		MAX 0.012
MAX 0.08	MAX 0.3	0.01-0.015	MAX 0.25	0.1-0.25	MAX 0.03		MAX 0.012
MAX 0.08	1.4-1.7	0.02-0.1	MAX 0.25	MAX 0.1	MAX 0.03		MAX 0.013
0.5-0.6	1-1.1	0.02-0.05	MAX 0.25	MAX 0.1	MAX 0.02		MAX 0.012
MAX 0.05	MAX 0.15	0.02-0.03	MAX 0.25	MAX 0.1	MAX 0.03		MAX 0.013
MAX 0.07	MAX 0.15	0.02-0.03	MAX 0.28	MAX 0.1	MAX 0.02		0.01-0.012
0.07-0.1	0.15-0.25	0.02-0.03	MAX 0.25	MAX 0.1	MAX 0.03		0.008-0.012
MAX 0.1	MAX 0.35	0.02-0.05	MAX 0.25	MAX 0.1	MAX 0.02		
0.25-0.35	1.4-1.7	0.02-0.1	MAX 0.4	MAX 0.1	MAX 0.03		
0.25-0.35	1.42-1.52	0.02-0.03	MAX 0.25	MAX 0.1	MAX 0.03		

Table 7. Ordered quantities groups

Ordered quantities groups #	Quality prescriptions within the group	Number of customer orders	Ordered quantities [t]
1	108.15.0	2	30.192
2	108.33.0	2	121.5
3	108.70.1	1	18.944
4	127.11.5	14	83.841
5	140.11.1	3	18.038
6	193.31.0	2	18.352
7	193.52.0	4	26.374
8	193.54.0	1	53.872
9	503.14.0	8	4.019
10	503.31.1	7	97.65
11	516.17.1	1	13.616
12	523.00.0	1	46.176
13	524.11.0	1	0.918
14	615.12.0	1	30.251
15	623.32.0	2	218.093
16	625.13.1	2	105.08
17	635.36.5	1	23.088
18	636.11.1	3	515.41
19	705.13.3	2	54.6
20	711.00.1, 711.14.0	3	42.202
21	718.70.2	3	55.388
22	724.24.0	2	38.438
23	732.01.0, 732.03.0, 732.12.5, 732.13.5, 732.18.1, 732.19.1, 732.20.2, 732.21.2, 732.24.4, 732.26.2, 732.27.3, 732.54.2, 732.59.2, 732.62.0, 732.66.0	113	1699.239
24	741.33.3	1	4.144
25	775.13.0	2	25.693
26	779.27.1	1	414.9
27	779.71.4	4	40.848
28	780.10.0, 780.13.2	3	191.25
29	781.00.1, 781.18.1	6	246.747

Table 8. The first work order (out of 19) from the best batch filling schedule

Work order number: 0001020			
Cover quality prescription code	Chemical limitations		
732.54.2	/		
Quality prescription code	Customer order code	Ordered quantity [t]	Delivery date
732.54.2	901000085507	53	30.10.2009

Table 9. The second work order (out of 19) from the best batch filling schedule

Work order number: 0001021			
Cover quality prescription code	Chemical limitations		
732.54.2	*w*(C)/% = 0.51–0.54; *w*(Cr)/% = 1.05–1.2; *w*(Al)/% = 0.015–0.025		
Quality prescription code	Customer order code	Ordered quantity [t]	Delivery date
732.20.2	901000086002	3.148	9.11.2009
732.01.0	901000087902	5.765	8.11.2009
732.54.2	901000085507	44.087	30.10.2009

Table 10. The third work order (out of 19) from the best batch filling schedule

Work order number: 0001022			
Cover quality prescription code	Chemical limitations		
732.59.2	*w*(Al)/% = 0.015–0.04; *w*(N)/% = 0.012 (max.)		
Quality prescription code	Customer order code	Ordered quantity [t]	Delivery date
732.01.0	901000093717	16.639 t	31.10.2009
732.20.2	901000087401	5.535 t	31.10.2009
732.01.0	901000093711	5.698 t	31.10.2009
732.01.0	901000093712	11.1 t	31.10.2009
732.20.2	901000086001	5.594 t	31.10.2009
732.62.0	901000094102	6.83 t	31.10.2009
732.59.2	901000084801	1.604 t	2.11.2009

Table 11. The fourth work order (out of 19) from the best work order schedule

Work order number: 0001023			
Cover quality prescription code	Chemical limitations		
732.59.2	*w*(C)/% = 0.51–0.54; *w*(P)/% = 0.015 (max.); *w*(Al)/% = 0.01–0.025; *w*(Sn)/% = 0.02 (max.); *w*(As)/% =0.04 (max.)		
Quality prescription code	Customer order code	Ordered quantity [t]	Delivery date
732.01.0	901000093718	5.683	31. 10. 2009
732.54.2	901000090501	31.909	30. 10. 2009
732.03.0	901000090401	9.709	31. 10. 2009
732.59.2	901000093101	5.594	31. 10. 2009
732.59.2	Non-planned cast quantity	0.105	

Table 12. The fifth work order (out of 19) from the best work order schedule

Work order number: 0001024			
Cover quality prescription code	Chemical limitations		
732.54.2	*w*(C)/% = 0.52–0.54!; *w*(P)/% = 0.015 (max.) *w*(Sn)/% = 0.02 (max.); *w*(As)/% = 0.04 (max.)		
Quality prescription code	Customer order code	Ordered quantity [t]	Delivery date
732.54.2	9010000873/1	45.028	30.10.2009
732.54.2	9010000855/21	3.337	30.10.2009
732.24.4	9010000883/10	4.635	30.10.2009

As a remark: in work order 0001023 (Table 12), we can notice that the optimal batch weight (53 t) is not achieved – non-planned cast quantity is 0.105 t, which is practically insignificant. Usually this quantity is added to one or more ordered quantities (within 5 % of ordered quantity).

Conclusions

The present paper deals with improving of the batch filling scheduling by using the particle swarm algorithm. The scheduling problem was divided into the following subsequent steps:

- grouping of ordered quantities according to the chemical composition,
- work order representation and evaluation, and finally,
- particle swarm based search for optimal batch filling schedule.

The batch filling scheduling strategy has been implemented in ŠTORE STEEL Ltd. as follows:

1. The period up to 2006: Only the expert knowledge of the batch scheduler was used. The non-planned and ordered quantities with the date ahead of the deadline presented 17.17 % of the total production in 2005.
2. The period after 2006: The particle swarm based search has been used to globally optimize the proper combination of the batches in order to reduce the non-planned and ordered cast quantities with the date ahead of the deadline, and to minimize the number of batches. The non-planned and the ordered quantities with the date ahead of the deadline, presented 10.12 % of the total production in 2006, and 10.12 % of the total production in 2007. This was enhanced to 16.22 % in 2008, and 32.70 % in 2009. The reasons for the increase lie in the off-standard ordered quantities due to the global economic crisis, and not in the deficiency of the represented algorithm.

These quantities would be of course much higher in case of using the expert knowledge only.

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