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ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2020
Issue 1/2020

43 – 48

10.24425/afe.2020.131281

8/1

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Production Scheduling for the Two Furnaces – One Casting Line System

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Received 16.06.2019; accepted in revised form 02.10.2019

Abstract

The paper presents a production scheduling problem in a foundry equipped with two furnaces and one casting line, where the line is a bottleneck and furnaces, of the same capacity, work in parallel. The amount of produced castings may not exceed the capacity of the line and the furnaces, and their loads determine metal type from which the products are manufactured on the casting line. The purpose of planning is to create the processing order of metal production to prevent delays in the delivery of the ordered products to the customers. The problem is a mix of a lot-sizing and scheduling problems on two machines (the furnaces) run in parallel. The article gives a mathematical model that defines the optimization problem, and its relaxed version based on the concept of a rolling-horizon planning. The proposed approaches, i.e. commercial solver and Iterated Local Search (ILS) heuristic, were tested on a sample data and different problem sizes. The tests have shown that rolling horizon approach gives the best results for most problems, however, developed ILS algorithm gives better results for the largest problem instances with tight furnace capacity.

Keywords: Heuristics, Application of information technology to the foundry industry, Scheduling, Production planning

1. Introduction

In this article we examine the problem of production planning in a foundry working in the mode of make-to-order (MTO), which supplies its customers with many types of iron castings. The problem of production planning is to determine the lot size of castings produced from required alloys in each period of the finite planning horizon, which is divided into smaller subperiods (e.g. shifts). The decision maker must take into account two main criteria: on-time deliveries and costs minimization of tardiness or/and earliness. In order to solve this problem, commercial solvers are usually used to find solution for mixed-integer programming (MIP) models.

In our previous papers we investigated the production systems consisting of one furnace-one moulding line [1] and one furnace-two moulding lines [2], where the furnace was a bottleneck. This time we study a planning process in the foundry equipped with two furnaces and one moulding line, which is a bottleneck. This situation is confirmed by industrial observations: many enterprises try to eliminate bottlenecks by expanding their production capacities, which in turn causes other devices to become bottlenecks. To the best of our knowledge the considered here combined lot-sizing and scheduling problem has not been studied so far. Prior works have not addressed the problem where all the considered assumptions are fulfilled [3, 4, 5, and 6].

Of course, different variants of the operation of two furnaces system are possible; in this case, the simplest option, consisting of two furnaces with the same nominal capacity working in parallel, was tested. It is possible, therefore, to produce castings made from two different alloys in a single subperiod, and furnaces do not have to be equally loaded.

The aim of the article is to present effective methods of production planning in the system of two furnaces and a single casting line. Section 2 introduces the MIP model for the problem under consideration. Section 3 gives details of the proposed methods. The computational experiments are described in Section 4 and the conclusions are presented in Section 5.

2. MIP lot-sizing and scheduling model

The MIP model presented in this section is an extension of Araujo et al. lot sizing and scheduling model for automated foundry [3]. The model presented herein takes into account the assumption that the metal can be produced in two furnaces working in parallel, i.e. castings from two different alloy types may be produced in the same period. Additional constraint ensures that load of each furnace must not be less than a specified quantity. We use the following notation:

Indices

$i = 1,\dots, I$ – produced castings; $k = 1,\dots, K$ – produced alloy types,

$t = 1,\dots, T$ – planning horizon (days); $n = 1,\dots, N*T$ – casting lots, where N is the number of casts during the day,

$f = 1, 2$ – furnaces' index.

Parameters

d_{it} – ordered number of casting i in a day t; w_i - weight of casting i,

$a^k_i = 1$, if a casting i is produced from alloy k, otherwise 0,

C_f – loading capacity of furnace f,

L^f_{min} – minimum utilization of furnace f,

h_i^-, h_i^+ - tardiness (–) and earliness (+) cost of casting i,

s - setup cost resulting from a single change of alloy type.

Variables

I_{it}^-, I_{it}^+ – number of casting i that must be stored (+) or its deficiency (–) at the end of each day t,

$z^k_{fn} = 1$, if there is a setup resulting from a change to alloy k in furnace f, otherwise 0,

$y^k_{fn} = 1$, if cast of alloy k is planned to be melted in furnace f in lot n, otherwise 0,

x_{in} – number of castings i planned for manufacturing in lot n.

Using such notation the problem of planning and scheduling of alloy casts and production of castings can be defined as follows:

$$\text{Minimize} \quad \sum_{i=1}^{I}\sum_{t=1}^{T}(h_i^- I_{it}^- + h_i^+ I_{it}^+) + s\cdot\sum_{f=1}^{2}\sum_{k=1}^{K}\sum_{n=1}^{N\cdot T} z_{fn}^k \tag{1}$$

subject to:

$$I_{i,t-1}^+ - I_{i,t-1}^- + \sum_{n=(t-1)N+1}^{N\cdot T} x_{in} - I_{it}^+ + I_{it}^- = d_{it} \qquad i = 1,\dots,I,\ \ t = 1,\dots,T \tag{2}$$

$$L^f{}_{min} C_f y_{fn}^k \le \sum_{i=1}^{I} w_i x_{in} a_i^k \le C_f y_{fn}^k \qquad f = 1,2,\ k = 1,\dots,K,,\ n = 1,\dots,NT \tag{3}$$

$$\sum_{i=1}^{I} w_i x_{in} \le lC, i = 1,\dots,I,\ n = 1,\dots,NT \tag{4}$$

$$z_{fn}^k \ge y_{fn}^k - y_{f,n-1}^k,\ f = 1,2,\ k = 1,\dots,K,\ n = 1,\dots,NT \tag{5}$$

$$\sum_{k=1}^{K} y_{fn}^k = 1,\ f = 1,2,\ n = 1,\dots,NT \tag{6}$$

$$I_{it}^-, I_{it}^+, x_{it} \ge 0,\ I_{it}^-, I_{it}^+, x_{it} \in \mathfrak{I}, \quad y_{fn}^k = 0,1,\ z_{fn}^k = 0,1,\ f = 1,2, n = 1,\dots,NT,\ k = 1,\dots,K \tag{7}$$

The objective function (1) minimizes inventory costs of the castings produced before the due date (earliness), tardiness costs of the production delivered after deadline and setup costs resulting from alloy change. Constraint (2) balances the inventory and deficiency of the castings with a daily demand for them. Constraint (3) limits the total weight of the planned castings to the capacity of the furnaces. Simultaneously it keeps the minimum utilizations of the furnaces above a predefined value. Constraint (4) limits the production of castings to the capacity of a moulding line. Constraint (5) assigns 1 to z^k_{fn}, if an alloy type for a cast planned for furnace f differs from the previous one melted in the same furnace. Finally, constraint (6) allows for production of only one alloy cast in a single lot and a single furnace.

The presented model can thus be considered as a variant of a generalised lot-sizing and scheduling problem (GLSP) that is well recognised in literature. For such a standard problem, typical methods used by MIP solvers like branch and bound methods with additional constraints or relaxations usually provide satisfactory results. Since the model proposed by the authors combines both planning lot-sizing of castings and sequencing of casts, it requires a non-standard approach.

Since our initial experiments showed that for larger instances of the problem, the solution provided by CPLEX solver deviated from the theoretical lower bound by over 60% a heuristic method able to achieve more satisfactory results has been developed. Another method considered by the authors to increase the efficiency of the CPLEX was the adaptation of the method proposed by Araujo et al. in [3]. In this method a rolling horizon planning [7, 8] is used in which only the plan for a current day is calculated keeping all restrictions, while for the remaining days a relaxed version of the model is computed. Values of variables representing the plan for previous days are fixed. Such approach is called fix-and-relax. In the fix and relax method all variables x_{in} and y^k_{fn} for the lots that do not belong to the fixed day are relaxed. Variable x_{in}, representing the number of castings i produced in lot n for relaxed periods, contains continuous values instead of integer ones, and variable y^k_{ft} for the relaxed periods contains integer values representing the aggregated number of lots in which a given alloy is produced.

Thus constraint (3) is used only for the day that is currently planned (t_f) and for the remaining days it must be changed as follows:

$$L^f{}_{min} C y_{ft}^k \le \sum_{i=1}^{I} w_i x_{in} a_i^k \le C y_{ft}^k \qquad f = 1,2, k = 1,\dots,K,\ t = 1,\dots,T, t \ne t_f \tag{8}$$

Similarly, constraint (5) for the days following the currently planned day can be redefined as follows:

$$\sum_{k=1}^{K} y_{ft}^k = N, \qquad f = 1,2, t = 1,\dots,T, t \ne t_f \tag{9}$$

In order to obtain the final solution, the calculation of the rolling-horizon model is repeated T times. Each time the values of variables x_{in} and y^k_{fn} computed for the days preceding the currently computed day are fixed in the model.

3. Solution methods

In this research we used the same approaches that has been described in [2]. Our goal was to find whether a simple heuristic can be efficient, when compared to the results achieved by CPLEX Solver. Additional goal was to assess the benefits from using rolling horizon (RH) method with CPLEX solver as the relaxation technique.

We launched presented two variants of model in the latest version of IBM CPLEX Optimization Studio (12.9). As a heuristic approach we use ILS (Iterated Local Search) introduced by Stützle in his PhD dissertation [9]. ILS is a simply procedure allowing for a perturbation move to escape from a local extremum [10].

The ILS algorithm is similar to the one proposed in [2]; in particular, we used the same evolutionary based algorithm as a local search and the same move in the perturbation phase. The modified representation (Table 1) consists of two parts (segments): table **y** representing alloy types that are produced in furnaces no. 1 and 2, and table **x** representing the quantity of castings that are produced in the following batches. The decoding mechanism is simple: as the types of produced alloy are known, the quantities of castings, related to alloy type, are multiplied by casting weights giving total load of each furnace. If the same type of alloy is produced in both furnaces, then the total load is divided in half taking into account that the castings' quantities are integer numbers.

Table 1.
Representation of the solution used in proposed ILS heuristic

Variables/lot	1		n		NT
alloy type, f=1	k_{11}	…	k_{1n}	…	k_{1NT}
alloy type, f=2	k_{21}	…	k_{2n}	…	k_{2NT}
number of castings, i=1	x_{11}	…	x_{1n}	…	x_{1NT}
	…	…	…	…	…
	x_{i1}	…	x_{in}	…	x_{iNT}
	…	…	…	…	…
number of castings, i=I	x_{I1}	…	x_{In}	…	x_{INT}

In order to satisfy constraints (3) and (4) we used a penalty function: the value 100,000 was added to the goal function (1) for any batch where these constraints were not respected.

4. Computational experiments

4.1. Test problems

Three sizes of lot sizing and scheduling problems were created: 10 castings made from 2 different alloys, 50 castings made from 10 alloys, and finally 100 castings and 20 alloys. The properties of these problems are presented in Table 2. The values for demand, weight and delaying cost were determined using uniform distribution within a given range.

Ten instances of the problem for each size were generated. The line capacity lC was obtained using the formula representing the total sum of the weights of ordered castings:

$$lC = \frac{\sum_{i=1}^{I}\sum_{t=1}^{T} d_{it} w_i}{T * N} \tag{10}$$

Table 2.
Test problems characteristics.

Parameter	Value
number of castings (I), number of alloys (K)	(10,2); (50,10); (100,20)
number of days (T)	5
number of subperiods (N)	10
demand (d_{it})	[10, 60]
weight of casting (w_i)	[2, 50]
line capacity (lC)	[5000, 5500]
furnaces capacity C_{max} [% of nominal C]	[100, 110, 120, 130, 140]
setup penalty (s)	(1000); (200); (100)
delaying cost (h_i^-)	[3.00, 9.00]
holding cost (h_i^+)	w_i * 0.02 + 0.05

Base furnaces capacity C was set to lC/2. In order to examine the influence of the bottleneck level on system performance, each instance was computed for five variants of the furnace capacity tightness C_{max} – from very tight 1.0*C to very loose 1.4*C (this parameter simultaneously determines an increasing level of line bottleneck). To ensure comparability of the results for problems of different sizes, three values of setup penalty for alloy type change between two subperiods were set to (1000, 200, 100), inversely proportional to the numbers of alloys in examined instances (2, 10, 20). Also, the minimal utilization of furnaces capacity during alloy melting process was set to 60% in each subperiod.

4.2. Results of the experiments

ILS algorithm was run for 5 times for each instance of the problem and the best result was chosen as the solution of the problem. The computational experiments had two purposes: first, to analyze the effect of the furnace capacity on the cost function and the utilization of the line was investigated, and second, to compare the effectiveness of the proposed heuristic was compared with the CPLEX solver (working alone and with RH fix-and-relax approach).

A single run of all approaches took 3, 5 and 10 minutes for problems (10,2), (50,10) and (100,20), respectively. The runs were executed using an Intel Core i7, 16 GB RAM, four cores working at 3.2 GHz, and Windows 10. The results are collected in Tables 3, 4, and 5. The tables show the mean solutions disparity of ILS heuristic and CPLEX solver compared to the best results (*Best*) among the three considered approaches. The disparity is calculated as:

$$Disparity = \frac{(Method\ solution - Best)}{Method\ solution} \tag{11}$$

Table 3.
Solution % disparity from *Best* for CPLEX solver

#/C_{max}	100	110	120	130	140
(10,2)					
Avg.	6.27	0.00	0.00	31.91	1.44
St. dev.	19.84	0.00	0.00	36.04	4.56
(50,10)					
Avg.	44.25	49.88	49.29	58.95	68.96
St. dev.	10.36	11.46	16.27	11.43	21.14
(100,20)					
Avg.	32.22	34.45	38.90	61.21	51.19
St. dev.	8.80	7.51	11.07	9.75	17.61
Avg.	27.58	28.11	29.40	50.69	40.53
St. dev.	20.96	22.54	24.20	25.62	32.96

Table 4.
Solution % disparity from *Best* for ILS heuristic

#/C_{max}	100	110	120	130	140
(10,2)					
Avg.	20.11	28.49	42.45	16.10	33.13
St. dev.	8.25	18.85	18.79	20.48	15.02
(50,10)					
Avg.	16.90	23.82	24.28	34.73	37.27
St. dev.	7.95	6.38	9.42	7.27	6.85
(100,20)					
Avg.	2.87	0.60	13.86	28.02	30.79
St. dev.	5.77	1.88	6.86	10.37	4.00
Avg.	13.29	17.64	26.86	26.28	33.73
St. dev.	10.44	16.67	17.21	15.54	9.85

Table 5.
Solution % disparity from *Best* for CPLEX+RH approach

#/C_{max}	100	110	120	130	140
(10,2)					
Avg.	10.16	31.45	46.25	34.58	46.13
St. dev.	13.23	25.58	30.15	26.65	18.14
(50,10)					
Avg.	0.28	0.00	0.00	0.00	0.00
St. dev.	0.87	0.00	0.00	0.00	0.00
(100,20)					
Avg.	5.37	11.63	0.00	0.00	0.00
St. dev.	5.49	9.86	0.00	0.00	0.00
Avg.	5.27	14.36	15.42	11.53	15.38
St. dev.	8.98	20.19	27.82	22.26	24.32

The disparity for heuristics is calculated individually for each problem instance, and since for some problem classes one heuristic is the best only for some instances, while for the other ones another heuristic gives better results, so the average value of disparity presented in the tables may be greater than zero.

We also collected the furnaces and line utilizations as the ratio of sum of castings' weights scheduled to the overall furnaces/line capacity in $N*T$ subperiods. The results are presented in Tables 6-8.

Table 6.
Furnaces and line utilizations for CPLEX solver

#/C_{max}	100	110	120	130	140
(10,2)					
F no. 1	0.9917	0.8885	0.8544	0.7601	0.7104
F no. 2	0.9923	0.9181	0.8053	0.7773	0.7175
Line	0.9920	0.9936	0.9958	0.9993	0.9995
(50,10)					
F no. 1	0.9568	0.8797	0.8014	0.7475	0.7055
F no. 2	0.9639	0.8886	0.8414	0.7504	0.6886
Line	0.9603	0.9726	0.9857	0.9736	0.9758
(100,20)					
F no. 1	0.9458	0.8800	0.8089	0.7415	0.6960
F no. 2	0.9452	0.8684	0.7996	0.7460	0.7023
Line	0.9455	0.9616	0.9651	0.9669	0.9788
Average					
F no. 1	0.9648	0.8827	0.8216	0.7497	0.7040
F no. 2	0.9671	0.8917	0.8154	0.7579	0.7028
Line	0.9659	0.9759	0.9822	0.9799	0.9847

Table 7.
Furnaces and line utilizations for ILS heuristic

#/C_{max}	100	110	120	130	140
(10,2)					
F no. 1	0.9682	0.8899	0.8258	0.7554	0.7158
F no. 2	0.9638	0.8902	0.8191	0.7650	0.6977
Line	0.9660	0.9791	0.9869	0.9883	0.9895
(50,10)					
F no. 1	0.9757	0.8876	0.8156	0.7612	0.7082
F no. 2	0.9747	0.8917	0.8246	0.7633	0.7077
Line	0.9752	0.9868	0.9896	0.9910	0.9911
(100,20)					
F no. 1	0.9717	0.8966	0.8304	0.7606	0.7049
F no. 2	0.9715	0.9058	0.8270	0.7640	0.7149
Line	0.9716	0.9816	0.9881	0.9910	0.9914
Average					
F no. 1	0.9719	0.8913	0.8239	0.7591	0.7097
F no. 2	0.9700	0.8959	0.8236	0.7641	0.7068
Line	0.9709	0.9825	0.9882	0.9901	0.9907

Rolling horizon approach performed unquestionably the best. In case of C_{max}=1.0*C, the difference between average RH and ILS solution is 8.0 pp and between average RH and CPLEX is 22.3 pp. Moreover, if the bottleneck level increases, the differences also increase: it's because RH is not very sensitive to the bottleneck level. However, it is worth noticing that the difference varied depending on the problem size and for (10,2) problem the CPLEX alone is the best approach. The gap between the solutions achieved by CPLEX and the solutions provided by the two other proposed approaches increases with the number of castings, the number of alloys and the bottleneck level. Not counting the smallest instances with 10 castings and 2 alloys, for the remaining cases with 50 and 100 castings the results achieved by CPLEX are worse on average by few dozen percent. For the larger instances of the problem CPLEX solver was apparently unable to sufficiently reduce the solution space of the problem and then efficiently use built in tools to improve the solution. Running the solver for up to 30 minutes brought only slight improvement of the solutions (from 1 to 3%).

Table 8.
Furnaces and line utilizations for CPLEX+RH approach

#/C_{max}	100	110	120	130	140
(10,2)					
F no. 1	0.9950	0.9085	0.8379	0.7286	0.6901
F no. 2	0.9874	0.8452	0.7552	0.7390	0.6795
Line	0.9912	0.9645	0.9559	0.9540	0.9588
(50,10)					
F no. 1	0.9819	0.8992	0.8118	0.7527	0.7119
F no. 2	0.9840	0.8852	0.8285	0.7656	0.6985
Line	0.9830	0.9814	0.9842	0.9869	0.9873
(100,20)					
F no. 1	0.9627	0.8838	0.8194	0.7655	0.7028
F no. 2	0.9621	0.8898	0.8269	0.7608	0.7126
Line	0.9624	0.9755	0.9878	0.9921	0.9908
Average					
F no. 1	0.9799	0.8972	0.8231	0.7489	0.7016
F no. 2	0.9778	0.8734	0.8035	0.7551	0.6969
Line	0.9789	0.9738	0.9759	0.9776	0.9789

The analysis of the results demonstrated that the increase in the maximum furnaces capacity C_{max} increases the level of the line utilization and process economy (goal value decreases). Obviously, the furnaces utilization decreases proportionally to this factor. The average utilization of the line is very high: 96% for $C_{max}=C$, and 99% for $C_{max}=1.4*C$. This is the effect of increasing flexibility in the operation of furnaces. Moreover, almost even utilization of two furnaces can be observed, which proves the correct operation of the proposed approaches.

It is interesting to compare the tested production system with one furnace-one line system. We used the same instances to examine the differences. Table 9 shows the best solutions disparity of ILS heuristic and CPLEX solver compared to the best solutions obtained for two furnaces system (*Best*). The disparity is calculated according to equation (11). Table 10 presents also the furnace and line utilizations.

If one furnace system is considered, all approaches give similar results, but for larger levels of line bottleneck ILS gives slightly better results than competitors. The disparity from best results is worse by few dozen percentage points and the utilization of the line is significantly smaller (1–2 pp) than in the case of the two-furnace system, which is due to the lower flexibility of the whole system. In this case, increasing the capacity of the furnace does not have the effect of increasing the use of the line.

It is also obvious that using two furnaces is safer than only one - in the case of a failure, the production can be continued (with limited utilization of moulding line).

Table 9.
Solution % disparity from *Best* for one furnace system

#/C_{max}	100	110	120	130	140
(10,2)					
CPLEX	42.34	49.82	63.85	54.01	54.69
RH	44.48	58.35	73.17	68.06	68.08
ILS	50.84	53.89	66.78	57.61	58.04
(50,10)					
CPLEX	25.50	40.33	45.12	46.31	44.70
RH	19.00	36.80	45.70	49.58	45.56
ILS	22.28	34.52	39.43	41.31	38.22
(100,20)					
CPLEX	39.19	50.02	61.99	62.48	62.38
RH	31.64	36.18	47.84	52.44	50.92
ILS	32.36	35.21	45.97	49.67	47.60
Average					
CPLEX	34.56	52.13	59.01	56.71	55.92
RH	31.71	53.06	62.18	62.38	60.67
ILS	35.16	50.63	57.57	55.53	54.12

Table 10.
Average furnace and line utilizations for one furnace system

#/C_{max}	100	110	120	130	140
Furnace					
CPLEX	0.9653	0.8764	0.8022	0.7455	0.6942
RH	0.9694	0.8722	0.7938	0.7317	0.6829
ILS	0.9593	0.8750	0.8047	0.7459	0.7011
Line					
CPLEX	0.9653	0.9640	0.9627	0.9691	0.9719
RH	0.9694	0.9595	0.9525	0.9512	0.9561
ILS	0.9593	0.9626	0.9657	0.9697	0.9741

5. Conclusions

This article presents a mathematical programming model for the complex problem of production planning in a foundry with two furnaces and one casting line. The model is a variant of the generalized lot sizing problem, extended by the bottleneck line and presence of two furnaces. It has been shown that such a model is very difficult to solve because it contains a large number of decision variables (several thousand for the problem of average size). The number of variables can be reduced by applying the concept of rolling horizon. In this approach, variables are calculated accurately for one period (day) only, and for the following days variables are calculated only roughly to meet constraints. However, as it has been shown, such a relaxed problem usually does not allow an optimal solution to be reached. Nevertheless, such an approach can provide a good approximation of the optimal solution in a short calculation time, giving better results than CPLEX itself or simple ILS metaheuristics.

The considered problem can be a good benchmark for the development of various types of algorithms, including computational intelligence heuristics. We plan to extend our approach to the case of three furnaces-two lines system in which planning is a much more difficult problem than the one considered here, and at the same time encountered in Polish casting practice. It would be also valuable to develop a better (specialized) local search algorithm, as the current one does not give repeatable results.

Acknowledgement

This work is financed by grants for the maintenance and development of research capacities.

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