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ORIGINAL ARTICLE

Maximizing average efficiency of process time for pressure die casting in real foundries

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Abstract Scheduling of casting processes is the problem of determining the number of products that will be manufactured in each casting shift so as to optimize a predetermined objective function. In this paper, we propose a linear programming (LP) model that maximizes the average efficiency of process time for casting in real foundries. The considered casting process is pressure die casting, the most prevalent permanent mold casting process, equipped with an automated die exchange device. In permanent mold casting, the use of a mold or die installed on a casting machine requires a significant process time for casting. The objective function of the proposed LP model is defined as the average ratio of the actual process time to the pre-assigned operating time in a shift. A solution that minimizes the objective function will provide the maximum surplus time, hence optimizing the efficiency of casting operations in terms of process time. Numerical examples are presented to illustrate the applicability and reliability of the proposed model. The results demonstrate that this model is an effective and conveniently implemented tool for solving real casting sequences in a simple and practical framework.

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Notation

N	Number of product types in an order
M	Number of shifts (production run)
P	Number of furnaces ($P \leq N$)
Q	Number of casting machines ($Q \leq N$)
T_{qm}	Pre-assigned operation time of machine q in the mth shift
W_{pm}	Amount of molten alloy from furnace p in the mth shift
x_{nm}	Number of product type n manufactured in the mth shift
d_n	Total number of product type n that must be manufactured in M shifts
w_n	Unit weight of product type n
t_n	Cycle time for a cast product of type n to be manufactured
$s(q)$	Number of product types manufactured by machine q
$q(i)$	Indices of product types manufactured by machine q, $i=1,\ldots, s(q)$
$r(p)$	Number of product types manufactured from furnace p
$p(j)$	Indices of product types manufactured from furnace p, $j=1,\ldots, r(p)$
u_n	The setup time needed to remove a previous die and to install the die of product type n
R_{qm}	Ratio of the actual running time of machine q to the pre-assigned operation time in the mth shift
$S(q,m)$	Index set of product types having non-zero cast products by machine q in the mth shift
$\sigma(q,m)$	Product type made by machine q at the first stage of the mth shift

1 Introduction

Among several methods to shape materials into useful products, an obvious choice is making parts by casting molten alloy into a mold or die and letting it solidify. Casting is one of the oldest methods of net-shape or near-net-shape manufacturing. It is extremely effective for producing a very complicated part in a single piece, including shapes with internal cavities. With minimal limitation on size and shape, cast products can be efficiently and economically manufactured [1]. Cylinder blocks, cylinder heads, transmission housings, pistons, and wheels for automotives and a variety of aircrafts and vessel parts consist of only a small portion of modern castings. Castings occupy one of the highest volume, mass-produced parts made by the metalworking industry [2].

A foundry is a physical facility where various casting operations are actually performed. A foundryman must schedule casting processes in advance because a production plan deciding the quantity of each casting type, product sequences, and the duration of operations plays a vital role in realizing efficient and economical production. Erroneous production plans usually lead to an increase in process time and cost, and decrease in productivity. An accurate production plan requires a rigorous process of optimal scheduling.

There have been extensive research achievements on scheduling of casting; however, most of the previous research works have focused on the scheduling of continuous casting or secondary processing in massive-scale steel plants [3–10]. Only a handful of studies targeting direct scheduling of small to medium size foundries are found—e.g., Lewis [11]; Law and Green [12]; Deb, Reddy, and Singh [13]; and Deb and Reddy [14]; however, their concerns are limited to partial aspects of casting processes. Lewis [11] applied linear programming (LP) for a large-floor flaskless molding operation, and Law and Green [12] provided a description of heuristic scheduling rules to routine activities in a foundry such as melting, core-making, molding, heat treatment, and finishing operations.

Only Deb and his coworkers [13, 14] specifically aimed to schedule foundry production and optimize it using genetic algorithm (GA) in a somewhat simplified hypothetical environment. Adopting molten metal utilization percentage as an objective function, they attempted to evaluate feasible solutions for casting sequences. Though theoretically interesting, GA is hardly applicable because it inevitably involves enormous computational complexity and difficulty in actual implementation in a foundry. In addition, the works of Deb et al. [13, 14] fail to describe many real parameters in casting processes, including the time constraint present in real foundries.

Recently, Park and Yang [15] presented a scheduling scheme maximizing the same objective function as Deb et al. [13, 14], i.e., molten alloy utilization percentage. Instead of GA, however, they employed LP, a much simpler and straightforward optimization tool, and succeeded in obtaining a practical solution that can be readily implemented in real-world casting plants. Application of LP to scheduling problems in various industrial fields can be found in the literature [16–19].

The objective of this paper is to propose an LP model that solves the scheduling problem of casting sequences when cast products are made by pressure die casting machines with quick die change capability. Note that in the previous research [15], the consequence of optimizing the efficiency of melting furnaces is to save ingots by determining proper quantities of raw alloy prior to actual casting operations. On the other hand, the present study focuses the main concern on optimizing the efficiency of casting operations in terms of *process time*.

In the considered casting environment where all the cast products are made by automated die casting machines with flexible die exchange, casting procedures are executed recursively throughout shifts. A significant feature of this shift-based manufacturing is that a die casting machine is provided with a fixed operation time in each shift. Thus, the efficiency of process time is directly related with the ratio of the actual casting time spent in the machine to the pre-assigned operation time. Since the value of the main parameter is time, the efficiency is inversely proportional to this ratio. By reducing the actual casting time, we not only save power consumption of the foundry, but also impart an extra time to a foundryman, which will help to elevate productivity.

Another contribution of this research is to propose a post-optimization adjustment procedure for obtaining a further increase in the efficiency of process time. Since automated die casting machines manufacture multiple types of cast products in a shift, they have to go through die exchanges, costing the setup time for each die exchange. In this paper, we propose a scheme to reduce a portion of the total setup time by adjusting product sequences in the boundary stages of adjacent shifts.

The rest of this paper is organized as follows. In Section 2, we introduce the notion of scheduling in a die casting process, and address the motivation for maximizing the efficiency of process time. In Section 3, a mathematical formulation of casting processes is presented, and the objective function and constraints of the proposed LP model are derived. A detailed explanation on the adjustment of product sequences to reduce the setup time follows in Section 4. In Section 5, numerical experiments are conducted using real data from a foundry. Analyses of scheduling results and the adjustment of cast product sequences demonstrate the applicability of the proposed LP model. Finally, Section 6 concludes this paper.

2 Scheduling for automated die casting

2.1 Automated die casting

Die casting is the most important and widespread permanent mold casting process that requires a sophisticated and costly machine upon which a set of dies is installed. Traditionally, die casting was a single line-type production operation with no die changes in a shift. It signifies that a die casting machine was dedicated to only a specific type of cast products. Recently, however, die changes within a shift and shorter runs become a popular practice in die casting shops for flexible manufacturing [20]. This trend is especially favored in a high-mix, low-volume production environment (flexible manufacturing) or under just-in-time manufacturing. Different dies can run on a single die casting machine with the help of an automated device, i.e., automatic tie bar pulling with quick die exchange capability.

Under this situation, two or more types of cast products can be produced by a single die casting machine in a shift, which will be referred to as “automated die casting” in later discussion. Note that only one item can be made at a time in the machine because multiple sets of dies cannot be clamped on the machine simultaneously. Figure 1 illustrates an automated die casting. Incorporating fast die change features such as automatic tie bar pulling, automatic die clamping, and precision die carriers; a foundryman can accomplish a single-minute die exchange and versatility in die casting.

In automated die casting plants, a variety of cast products in assorted sizes are produced by solidifying molten alloy in a set of dies. Many ingots in solid state are charged and melted in a furnace for several hours prior to each shift of casting operation. Since two different kinds of alloys cannot be mixed in a furnace, a die caster needs multiple furnaces when he simultaneously casts products made of different alloys. In each shift, molten alloy is ladled from a furnace until either it is exhausted or the pre-planned amount of cast products is fully manufactured.

2.2 Average efficiency of process time

Suppose a die caster is given mixed orders, casting a number of different types of cast products that are made of multiple kinds of alloys. With limited numbers of melting furnaces and die casting machines, he must decide the production quantity of each type of cast products for each shift to complete the total order quantity within a due date. It is proven in [15] that LP can serve as a pertinent tool of scheduling for this complicated manufacturing problem. LP can manage many variables and constraints of a die casting process that produces various types of castings concurrently with different alloys and masses. Moreover, objective functions and constraints of casting scheduling can be expressed in the form of linear equalities and inequalities.

Fig. 1 Automated die casting process. **a** Automatic die casting machine and **b** automated die change device

Since die casting uses a die that accepts and contains molten alloy until solidification, it requires a considerable process time for each cast product. One cycle of die casting consists of ladling and injection of molten alloy, solidification, die opening and ejection of a solidified casting, and spraying and die closing. It is the solidification time that usually occupies most of the cycle time.

Process time, i.e., the sum of total cycle time, is certainly a very critical parameter that determines productivity of die casting processes [21, 22]. By reducing process time, a die caster can save power consumption of a foundry. He or she can also acquire extra time for other secondary operations which, as a whole, will elevate labor productivity measured as a ratio of total volume of cast products (output) per labor hour (input). In addition, he can reduce total costs and thus increase profits. This is because the unit price of a cast product is typically predetermined based on the total expected process time that is mutually acknowledged between a die caster and a customer when an order is offered by the customer. Lastly, a decrease in the operation time of a die casting machine reduces maintenance time and cost as well.

In a shift-based manufacturing, as mentioned earlier, time resource is allotted for each machine in each shift. Therefore, the objective function in our study is defined as the *average* ratio of process time spent by die casting machines to the pre-assigned operating time in a shift. The solution of casting schedule minimizes this ratio, which is equal to maximizing the average efficiency of process time.

3 Linear programming model

3.1 Preliminaries

We consider a foundry that has Q die casting machines and P melting furnaces, their types being different from each other. A casting process in the foundry lasts for M shifts in total. By customer orders, N product types should be produced. Here, we label each entity by enumeration, i.e., "machine q" ($q=1,\ldots,Q$), "furnace p" ($p=1,\ldots,P$), and "product type n" ($n=1,\ldots,N$). Since each furnace melts a unique type of alloy, P types of alloys are available in the foundry, namely "alloy p" for furnace p.

Let s_q (≥ 1) be the number of cast product types that machine q makes and let $q(i)$ ($i=1,\ldots,s_q$) be the indices of the corresponding types. Since each machine casts only the cast product types that are exclusively assigned to the machine, the following relation holds for s_q and $q(i)$.

$$\sum_{q=1}^{Q} s_q = N \tag{1}$$

$$\{q(1),\ldots,q(s_q)\} \cap \{q'(1),\ldots,q'(s_{q'})\} = \emptyset,\ q \neq q'$$

By analogy with s_q and $q(i)$, we define r_p as the number of cast product types that are made of the alloy from furnace p and $p(j)$ ($j=1,\ldots,r_p$) as the indices of the corresponding types. In a similar way to Eq. 1, r_p and $p(j)$ satisfy the following:

$$\sum_{p=1}^{P} r_p = N \tag{2}$$

$$\{p(1),\ldots,p(r_p)\} \cap \{p'(1),\ldots,p'(r_{p'})\} = \emptyset,\ p \neq p'$$

Every shift comprises the same cycle of the basic casting procedure—initial ingot melting, pouring and injection of molten alloy, solidification, die opening and ejection of a solidified casting, and spraying and die closing. Among these, injection of molten alloy is determined by fast shot velocity, slow shot velocity, and hold time, which are set in advance; however, due to the feature of consecutive operation and little intermittence between shifts, it is a realistic assumption that other parameters of machines and furnaces have different values with respect to shifts.

For instance, assume that a foundry operates on a two-shift basis a day with the condition that the duration of night shifts is half that of day shifts. Though a machine works the same job in any shift, the pre-assigned operation time of the machine should be arranged differently, e.g., setting the time for night shifts as half as the time for day shifts in this case. Generalizing this notion, we denote by T_{qm} ($q=1,\ldots,Q$, $m=1,\ldots,M$) the fixed pre-assigned operation time of machine q in the mth shift. All the manufacturing by machine q in the mth shift must be completed within time T_{qm}.

Another parameter affected by the characteristic of a shift-based foundry is the amount of molten alloy from a furnace. Owing to consecutive operation of shifts, a furnace providing its alloy in the current shift must suspend an operation during at least one shift for cleaning, and recharging and melting a new batch of ingots. These activities require a considerable amount of time, which implies that in fact, more than one furnace must exist for alloy p for continuous operations of a foundry and each one is used exclusively on alternate shifts. Hence, the capacity of a furnace, i.e., the amount of molten alloy provided by the furnace, may vary with respect to shifts.

In reality, different capacities of furnaces are very common in many foundries due to economic reasons. For instance, a die caster usually purchases a minimal number of furnaces one after another when necessary. As a result, furnaces with various capacities often exist in a foundry, and their numbers tend to grow as a foundry expands in size. We define W_{pm} ($p=1,\ldots,P$, $m=1,\ldots,M$) as the capacity of furnace p in the mth shift. For convenience, we still call furnace p for any furnace that melts alloy p.

3.2 Objective function

Since there are N cast product types and M shifts, we define $N\times M$ primary variables x_{nm} ($n=1,\ldots,N$, $m=1,\ldots,M$) as the number of type n manufactured in the mth shift. We also assume that the unit weight of product type n is w_n (kilograms), and d_n units of type n must be manufactured from the orders. In this paper, a production planner's objective is to determine the values of all x_{nm} so as to minimize the average ratio of the actual casting time to the pre-assigned operation time of casting machines. As a low average ratio implies a high efficiency of process time, minimizing the average ratio signifies maximizing the efficiency of process time.

With the considered die casting machines conducting in-process die exchanges for flexible manufacturing, the casting time of a machine in a shift increases linearly with respect to x_{nm}, the quantity of cast products [15]. Let t_n be the total cycle time for a cast product of type n to be manufactured. Then, Ψ_{qm}, namely the total time machine q spends in the mth shift to make products of the corresponding types $q(1),\ldots,q(s_q)$, is expressed as

$$\Psi_{qm} = \sum_{i=1}^{s_q} \left(t_{q(i)}x_{q(i)m} + u_{q(i)}\right) \tag{3}$$

where $u_{q(i)}$ is the setup time needed to remove a previous die and to install the die of type $q(i)$.

Define R_{qm} as the ratio of the actual running time, which includes the setup time of machine q in the mth shift, to the pre-assigned operation time. Using Eq. 3 and the definition of T_{qm}, we derive R_{qm} as

$$R_{qm} = \frac{\Psi_{qm}}{T_{qm}} = \sum_{i=1}^{s_q} \frac{t_{q(i)}x_{q(i)m} + u_{q(i)}}{T_{qm}} \tag{4}$$

R_m, the average of R_{qm} for all the Q machines used in the mth shift, is

$$R_m = \frac{1}{Q}\sum_{q=1}^{Q} R_{qm} = \frac{1}{Q}\sum_{q=1}^{Q}\sum_{i=1}^{s_q} \frac{t_{q(i)}x_{q(i)m} + u_{q(i)}}{T_{qm}} \tag{5}$$

Lastly, R, the average of R_m for the entire M shifts, is derived as

$$\begin{aligned} R &= \tfrac{1}{M}\sum_{m=1}^{M} R_m \\ &= \tfrac{1}{MQ}\sum_{m=1}^{M}\sum_{q=1}^{Q}\sum_{i=1}^{s_q} \tfrac{t_{q(i)}x_{q(i)m}+u_{q(i)}}{T_{qm}} \end{aligned} \tag{6}$$

We separate R into $R(x)$, the terms of primary variables, and a constant value R_0:

$$\begin{aligned} R &= R(x) + R_0 \\ R(x) &= \tfrac{1}{MQ}\sum_{m=1}^{M}\sum_{q=1}^{Q}\sum_{i=1}^{s_q} \tfrac{t_{q(i)}x_{q(i)m}}{T_{qm}} \\ R_0 &= \tfrac{1}{MQ}\sum_{m=1}^{M}\sum_{q=1}^{Q}\sum_{i=1}^{s_q} \tfrac{u_{q(i)}}{T_{qm}} \end{aligned} \tag{7}$$

$R(x)$ serves as the objective function of our LP model. R represents the average ratio of the actual process time of the casting process to the pre-assigned operating time in a shift, where $x{:=}\{x_{nm}|1\le n\le N,\ 1\le m\le M\}$ is the set of the number of product types manufactured in each shift. As stated earlier, minimizing R leads to maximizing the average efficiency of process time.

3.3 Constraints

We now turn to the constraints inherently imposed by a die casting process. The most indisputable constraint is that the primary variable x_{nm} must be a non-negative integer because x_{nm} represents the number of cast products.

$$x_{nm} \ge 0,\ x_{nm} \in I \tag{8}$$

Since d_n products of type n must be made throughout the entire shifts, x_{nm} is governed by the following equality:

$$\sum_{m-1}^{M} x_{nm} = d_n,\ n = 1,\ldots,N \tag{9}$$

The real casting time spent by a machine cannot exceed the pre-assigned operating time of the machine. Thus, Ψ_{qm} defined in Eq. 3 should be always less than or equal to T_{qm}, which induces the following inequality constraint:

$$\begin{aligned} &\sum_{i=1}^{s_q} \left(t_{q(i)}x_{q(i)m} + u_{q(i)}\right) \le T_{qm}, \\ &q = 1,\ldots,Q,\ m = 1,\ldots,M \end{aligned} \tag{10}$$

The final constraint imposed on x_{nm} is associated with the amount of molten alloy. In a similar manner to die casting machines, a cast product type is made of a unique molten alloy, which is provided exclusively by a corresponding furnace. In each shift, the total weight of cast products made of the alloy from a furnace cannot exceed the capacity of the furnace. Hence, we can derive the following inequality:

$$\begin{aligned} &\sum_{j=1}^{r_p} w_{p(j)}x_{p(j)m} \le W_{pm}, \\ &p = 1,\ldots,P,\ m = 1,\ldots,M \end{aligned} \tag{11}$$

Combining Eqs. 7–11, we formulate the LP model of Table 1 calculating the numbers of cast product types for all

Table 1 LP model for casting processes

Minimize : $R = \frac{1}{MQ}\sum_{m=1}^{M}\sum_{q=1}^{Q}\sum_{i=1}^{s_q} \frac{t_{q(i)}x_{q(i)m}}{T_{qm}}$
Subject to $x_{nm} \ge 0, x_{nm} \in I$ $\sum_{m=1}^{M} x_{nm} = d_n$ $\sum_{i=1}^{s_q} \left(t_{q(i)}x_{q(i)m} + u_{q(i)}\right) \le T_{qm}$ $\sum_{j=1}^{r_p} w_{p(j)}x_{p(j)m} \le W_{pm}$ for $n = 1,\ldots,N,\ m = 1,\ldots,M,\ q = 1,\ldots,Q,$ $p = 1,\ldots,P$

the shifts (x_{nm}) which minimize R or maximize the average efficiency of process time for the casting process.

As was mentioned, the proposed LP model has $N \times M$ primary variables. Tracing Table 1, we see that it has N equality constraints and $(N+Q+P)M$ inequality constraints. Moreover, the fact that primary variables x_{nm} are non-negative integers classifies the LP model as an integer programming.

4 Adjusting product sequence

Recall that $u_{q(i)}$ denotes the setup time spent by machine q to replace a previous die with the one for cast product type $q(i)$. When calculating an actual casting time, this value is added only once as shown in Eq. 3. This implies that when a specific die is installed in a machine, all the scheduled cast products of the corresponding type are manufactured in a row, which will minimize the frequency of die exchanges.

We can reduce the total casting time further by adjusting product sequences between adjacent shifts. Assume that the type of a cast product a machine makes at the final stage of a particular shift is identical to that of a cast product which will be made at the first stage of the next shift. Then, the machine does not have to change the previous die with a new one when starting casting in the next shift.

To present this adjustment method in formal terms, assume that all x_{nm} are obtained from the LP model of Table 1. Machine q will make $x_{q(1)(m-1)},\ldots,x_{q(s_q)(m-1)}$ cast products of types $q(1),\ldots,q(s_q)$ in the $(m-1)$th shift, and $x_{q(1)m},\ldots,x_{q(s_q)m}$ cast products in the mth shift. Let $S(q,m) \subseteq \{q(1),\ldots,q(s_q)\}$ be the index set of types that have non-zero cast product numbers by machine q in the mth shift, i.e.,

$$S(q,\ m) = \left\{ q(i) \middle| x_{q(i)m} \neq 0 \right\} \tag{12}$$

By the above definition, $S(q,m-1) \cap S(q,m)$ includes the cast product types that are manufactured by machine q both in the $(m-1)$th and mth shift. Then, we choose among $S(q,m-1) \cap S(q,m)$ the type with the longest setup time and post it at the last stage of the $(m-1)$th shift and also at the first stage of the mth shift. By this adjustment procedure, we can spare the setup time for the cast type in the mth shift. Note that once the type is determined with respect to the $(m-1)$th and mth shifts, it cannot be used in the next adjustment between the mth and $(m+1)$th shifts.

Denote by $\sigma(q,m)$ the result of the adjustment method, i.e., the cast product type that is made by machine q at the first stage of the mth shift [or at the last stage of the $(m-1)$th shift]. Then, for $m=1,2,\ldots,M$, $\sigma(q,m)$ is derived as ("\" denotes the difference set)

$$\begin{aligned} &\sigma(q,1) = \emptyset \\ &\sigma(q,m) = \arg\max_k u_{km}\ 2 \leq m \leq M, \\ &\text{where}\ k \in (S(q,m-1) \cap S(q,m)) \backslash \{\sigma(q,m-1)\}. \end{aligned} \tag{13}$$

To reflect the proposed adjustment of product sequences on the efficiency, let us define a partial function $\kappa: I \times I \times I \to \{0,\ 1\}$ as

$$\kappa(n,\ q,\ m) = \left\{ \begin{matrix} 0 & n = \sigma(q,m) \\ 1 & \text{otherwise} \end{matrix} \right\} \tag{14}$$

Then R'_{qm}, the ratio of the adjusted running time of machine q in the mth shift to the pre-assigned operation time, is defined as

$$R'_{qm} = \sum_{i=1}^{s_q} \frac{t_{q(i)} x_{q(i)m} + \kappa(q(i),q,m) u_{q(i)}}{T_{qm}}$$

Consequently, R', the modified average ratio of the actual casting time to the pre-assigned operation time with the adjusted product sequences, is

$$\begin{aligned} R' &= \frac{1}{MQ} \sum_{m=1}^{M} \sum_{q=1}^{Q} R'_{qm} \\ &= \frac{1}{MQ} \sum_{m=1}^{M} \sum_{q=1}^{Q} \sum_{i=1}^{s_q} \frac{t_{q(i)} x_{q(i)m} + \kappa(q(i),q,m) u_{q(i)}}{T_{qm}} \end{aligned}$$

Clearly, R' is less than the original value R in Eq. 6, which signifies a better performance by the adjustment. Note that although these combinatorial terms raise the average efficiency further, our model in this study is still a numerical optimization scheme; the amount of all x_{nm} remains constant after the adjustment. The main motivation for setting the scheduling of a casting process as a numerical optimization scheme is that in many cases, the setup time u_n for cast product type n is, if not insignificant, greatly less than its casting time t_n; however, in automated casting environments where very frequent die exchanges occur as well as the setup time is compatible with the casting time, a combinatorial optimization scheme is preferred and applied to obtain an efficient scheduling solution.

5 Experimental verification

5.1 Example problem

We investigate a real problem in a die casting foundry to evaluate the computational characteristics of the proposed LP model. We also explain the detailed procedure of reducing the total casting time further by adjusting product sequences between adjacent shifts. The LP model is implemented with the Risk Solver Platform® v9.5 [23], a standard LP software based on MS Excel. It can perform linear/quadratic programming, in which the branch and bound, cut generation, and other methods are applied to solve integer linear programming.

We consider a die casting shop using two types of furnaces (P=2), one melting ADC10Z Al alloy and the other ADC14 Al alloy. Two furnaces are assigned to each type of alloy respectively. One of them works in every odd shift while the other is idle for cleaning and re-melting of a new batch of ingots and vice versa in every even shift. As a result, four furnaces are employed in total in M=12 shifts. The capacities of the first type furnaces are W_{11}=620 and W_{12}=550(kg), and those of the second type furnaces are W_{21}=700 and W_{22}=600(kg) respectively. Table 2 summarizes the aforementioned data for alloys and furnaces.

As for the products, two customers order five types of cast products (N=5), namely A,...,E: A is a transmission (T/M) housing (n=1), B is a cylinder block (n=2), C is a cylinder head (n=3), D is an engine component of a small-sized vessel (n=4), and finally E is a turbo impeller (n=5). One customer asks production of types A, D, and E, and the other customer orders types B and C.

Types A and C are made of ADC10Z alloy from the first furnace (r_1=2), and B, D, and E are made of ADC14 alloy from the other furnace (r_2=3). We denote by D1 for a die that casts product type A, D2 for type B and so on.

The casting procedure involves two die casting machines (Q=2): a 2,500-ton machine (q=1) that casts product types A and B (s_1=2) and a 2,200-ton machine (q=2) that casts product types C, D, and E (s_2=3). Both machines have a sufficient die-locking force required to make their corresponding product types. Since a machine can install only one die at a time, each product type must be cast alternately. Accordingly, machine 1 has to exchange D1 and D2, and machine 2 D3, D4, and D5. Figure 2 illustrates the complete casting process in the foundry.

According to the order of the customers, the die caster should complete the entire casting operations in 12 shifts. The foundry is operated by day and night shifts consecutively, which last 420 and 300(min), respectively. A cycle time t_n for

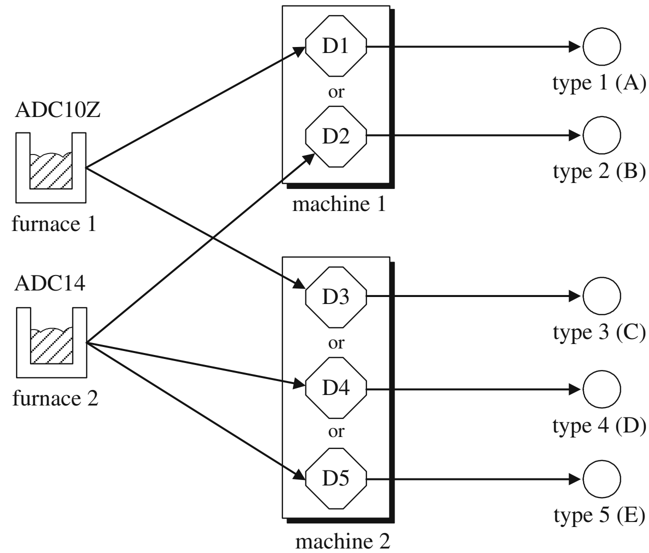

Fig. 2 Illustration of casting operation: N=5, P=2, and Q=2

a cast product actually includes multiple phases—ladling, injection, intensification, solidification and cooling, die opening with a retrieval of cores and slides, ejection, spraying of cooling and parting agent, and die closing time. The setup time u_n is additionally required whenever dies are exchanged. By virtue of the high speed of an automatic die exchange apparatus, the setup time is maintained as short as possible. The cycle time and setup time for each cast product along with the order quantity and unit mass of products are presented in Table 3.

5.2 Optimization result

Table 4 is the optimization result of the problem. The minimum value of the average efficiency of casting time is R=95.3(%). This means that for each shift, 4.7% of the pre-assigned operation time in average is saved and thus accessible to secondary jobs, such as additional operations of cast parts and maintenance of the production lines, etc. It enhances the productivity of the foundry as well as saves power consumption on account of the reduced on-time for machines.

Since all the values of R_{qm} are less than or equal to 100(%), the result of Table 4 satisfies the time constraint described by Eq. 10. We ensure that the amount constraint Eq. 11 is satisfied too. For instance, consider the result of shift 1, where x_{11}=20 and x_{31}=15. Recalling that product types A and C are made of the alloy from furnace 1 (see Table 3), it follows that the total weight of cast products from furnace 1 is $w_1x_{11}+w_3x_{31} = 620$(kg). As this value is equal to W_{11}=620 (see Table 2), the amount constraint in Eq. 11 is satisfied. We can further prove the validity for the entire shifts and furnace 2 in the same way.

Table 2 Specification of alloys and melting furnaces

Molten alloy	ADC10Z		ADC14	
Furnace index (P=2)	p=1		p=2	
Amount of alloy W_{pm} (kg)	620	550	700	600
Assigned shift m (M=12)	Odd	Even	Odd	Even

Table 3 Specification of products and machines

Product	A	B	C	D	E
Type n	n=1	n=2	n=3	n=4	n=5
Quantity d_n	210	150	150	160	145
Unit mass					
w_n (kg)	20.2	17.1	14.4	16.3	16.8
Furnace p	1	2	1	2	2
Machine q	1	1	2	2	2
Cycle time t_n (min)	11.4	10.1	7.9	9.4	9.4
Setup time u_n (min)	5.0	4.0	2.0	3.0	3.5
Operation time T_{qm} (min)	420 (m=odd), 300 (m=even)				

5.3 Adjustment of product sequences

We now apply the scheme of adjusting product sequences. As an example instance, we investigate the case of machine 1. Recall that $\sigma(1,m)$ is the product type that is made by machine 1 both at the last stage of the $(m-1)$th shift and at the first stage of the mth shift, that is, the setup time for product type $\sigma(1,m)$ is spared whenever $\sigma(1,m)\neq\emptyset$.

First, according to Eq. 13, $\sigma(1,1)=\emptyset$, that is, no adjustment can be made at the first stage of the first shift. Next, for obtaining $\sigma(1,2)$, we should derive $S(1,1)$ and $S(1,2)$ defined in Eq. 12. From Table 4, we recognize that $S(1,1)=S(1,2)=\{1, 2\}$, i.e., all the corresponding product types (A and B) are made in both shifts 1 and 2. Since the setup time of type A is greater than that of type B (Table 3), we determine $\sigma(1,2)=1$ by Eq. 13. Since machine 1 casts only two types of products (A and B), once $\sigma(1,2)$ is found we can determine the product order in the rest shifts sequentially, i.e., type A, type B, type A, and so on. Obviously, the prerequisite for this assignment is that at least one unit of both product types be made in all the shifts. As this is the case of the result of Table 4, we obtain the adjustment of product sequences for machine 1 as shown in the second column of Table 5. With $\sigma(1,m)$ and $\sigma(2,m)$, we derive $\kappa(n,q,m)$ defined in Eq. 14 and finally the modified average ratio R'=94.2(%). Comparing R and R', we can confirm that the proposed scheme raises the time efficiency further by 1.1(%) from 95.3(%).

Let us calculate the product rate of the adjusted sequences as another performance index. From Table 3, the total quantity of the manufactured products is Σd_n=815 and the total pre-assigned operation time is ΣT_{qm}=8,640 (min). Since R'=94.2%, the actual process time of the adjusted sequences of Table 5 is 0.942×8,640=8,138.9 (min). Dividing this value by the total quantity of the manufactured products, we obtain the average product rate 8,138.9/815=9.99 (minutes per unit), i.e., it takes an average 9.99 min to manufacture a cast product. On the other hand, if the LP model and the adjustment scheme were not applied, the product rate would be 8,640/815=10.60 (minutes per unit). Hence, the proposed optimization strategy raises the product rate by 0.61 (minutes per unit).

Table 4 Optimization result

Shift (m)	x_{1m}	x_{2m}	x_{3m}	x_{4m}	x_{5m}	R_{1m} (%)	R_{2m} (%)
1	20	11	15	31	0	82.9	99.6
2	21	5	3	0	28	99.6	98.5
3	15	17	22	23	2	83.7	99.4
4	21	5	1	0	30	99.6	99.5
5	11	22	27	19	0	84.9	95.3
6	21	5	0	14	17	99.6	99.9
7	20	17	15	25	0	97.3	86.2
8	21	5	1	2	28	99.6	99.5
9	20	18	15	23	1	99.7	84.0
10	5	23	25	2	8	99.4	100
11	12	20	26	21	0	82.8	97.9
12	23	2	0	0	31	97.1	99.9
Average R (%)						95.3	

Table 5 Adjustment of product sequences

Shift (m)	$\sigma(1,m)$	$\sigma(2,m)$	R'_{1m} (%)	R'_{2m} (%)
1	–	–	82.9	99.6
2	1	5	98.0	97.3
3	2	4	82.8	98.6
4	1	5	98.0	98.3
5	2	4	84.0	94.6
6	1	5	98.0	98.8
7	2	4	96.4	85.5
8	1	5	98.0	98.3
9	2	4	98.8	83.2
10	1	5	97.8	98.8
11	2	4	81.9	97.2
12	1	5	95.5	98.8
Average R' (%)			94.2	

The results of Tables 4 and 5 demonstrate that our LP model and adjustment scheme can solve the complex scheduling problem of automated die casting and raise the time efficiency further without compromising the optimality of the scheduling result.

6 Conclusions

Casting in foundries has been a typical field of hard computing for the past decades. The production planning for casting processes, on the other hand, is a novel approach that interprets the casting procedure as a kind of optimization problems. In this paper, we have proposed an LP model solving the number of products to be cast for automated die casting processes. The solution guarantees the minimum usage of the casting time, i.e., the average time efficiency is optimized. In association with the LP model, we have proposed a post-optimization adjustment procedure for obtaining a further increase in the efficiency of process time. A simulation study on a complex automated die casting problem validates the applicability of the proposed scheme.

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