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FR-Based Scheduling Using the Independence Axiom for Shortening Lead-Time of Mold Manufacturing

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ABSTRACT

Mold manufacturing operators have to make a number of decisions for each product. For shortening lead-time of mold manufacturing, we applied axiomatic design, principally the Independence Axiom, to analysis and management of the decisions. At first, we set each human decision as a functional requirement (FR). Our proposed method, a rule of "one decision per one process" or a rule of "no feedback" in a "decision-based process design", re-scheduled the processes (=DPs) to satisfy the Independence Axiom. For example, among the 583 decisions made for one-mold production, we removed those that the computer could settle, and further reduced the number of selections with the standardization. These improvements dropped the number of human decisions (=FRs) down to the minimum set of 77 independent ones. The less human decisions can reduce the thinking/ negotiating/ waiting time, shortening the lead-time by 14 %.

Secondly, we applied the method to a real production factory that produces about 120 molds per month with randomly varying receiving orders and machining time. To optimize the scheduling of multi-mold production, we set each finish time of the mold as the FR and cut down the number of changes of priorities (=DPs). An operation manager tends to set the changes in an ad hoc manner. The rule of "no priority change" can set the finish times (=FRs) of each mold independently. These consistent priorities not only decreased the queue time to reduce the lead-time, but also increased the production by 50 % with the same amount of resources. Mold manufacturing is difficult to operate procedurally due to unexpected tool damage and flaws in NC programming. To prevent this trouble from spreading the other mold production, we prepared a re-fabrication line for the troubled mold. In the future, it will need a large-scale flexible system that can cope with the unexpected trouble in real time.

Keywords: scheduling, independence axiom, mold manufacturing

1 INTRODUCTION: DECISION-BASED PROCESS DESIGN TO SHORTEN THE PROCESS LEAD-TIME

Manufacturing has three functions that are effective in growing the business: quantitative increase of production, quality improvement, and shortening the process lead-time. This paper deals with shortening the process lead-time. To prove the effect in the actual production, we applied our proposal to a factory of metal molds for plastic injection molding. The special feature of the mold production is a "one product per one order". The product is totally individual, and the order is not received periodically. Even though the scheduling is too complicated, a computer could simulate and optimize it at some time or other; but before using the computer, we simplified and decoupled the factory processes using axiomatic design. In this paper, we will apply the Independence Axiom of axiomatic design [1] in re-scheduling for the shorter lead-time.

Mold manufacturing operators have to make many decisions for each elemental process. We proposes a method, called a "decision-based process design", to actively hide the decisions from the human by having the computer handle them instead [2]. This method promotes process standardization by narrowing the selections for decision-making, and speeds up the operator work by eliminating some steps of making selections or verifications. Consequently it smoothes out the operator work, that is subdivided into smaller tasks distributed by the computer, and shortens each thinking/ negotiating/ waiting time.

Moreover in our study, the cause of a longer lead-time in the actual multi-mold production factory were looked into, finding the large number of human decisions come into play to make ad hoc priority changes. The decision-based process design introduces another scheduling rule. For example, a rule of "no priority change" refuses human decisions, so the finish time of the product may be predicted upon receiving an order.

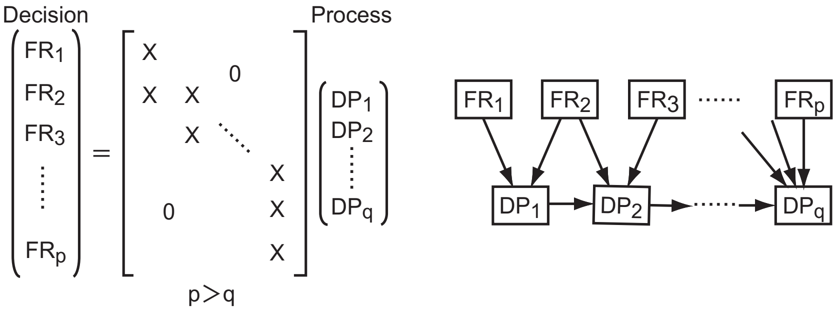
2 DECOUPLED PROCESS DESIGN OF ONE-MOLD PRODUCTION: FR = DECISION, DP = PROCESS

In this chapter, we focused the application on a one-mold production: the prototyping aluminum mold production for injecting a cellular phone shell.

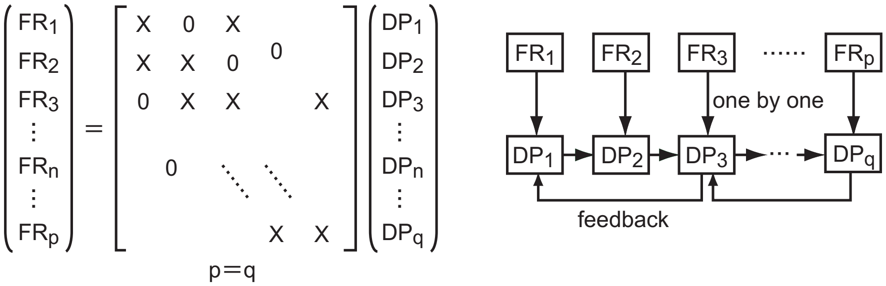
Figure 1 shows the design equation of the one-mold production, which employs "FR = decision" and "DP = process". We will explain the figure step by step.

2.1 Problem of conventional process definition

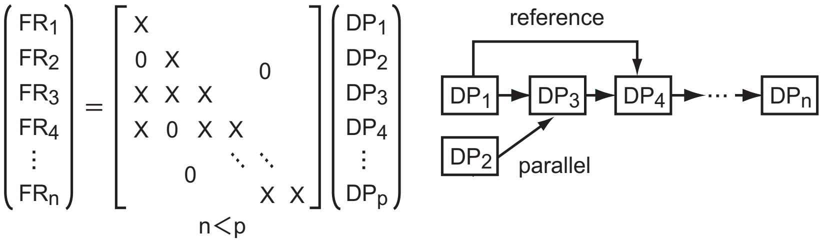
Figure 2 shows an example of conventional process definition. The machining process has a number of human decisions, e.g., "transfer" has "selecting the tool and work" and "setting the tool and work". So far the process was defined as an operator's action or a machine work, not as a human



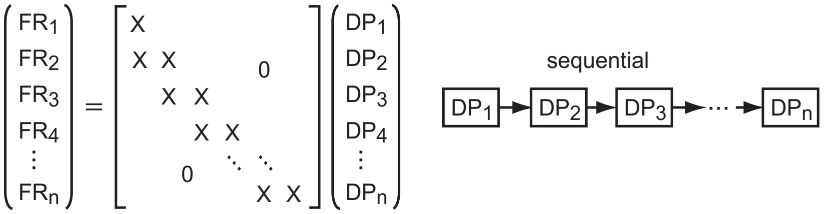
(a) Too many decisions but a few processes indicate a coupled design.



(b) Rules of "one decision per one process" makes a square matrix, but some feedbacked adjustments still keep a coupled design.



(c) Rules of "no feedback" successfully decoupled. Moreover, decision-based process design reduced the number of human decisions, namely, the number of FR and DP.



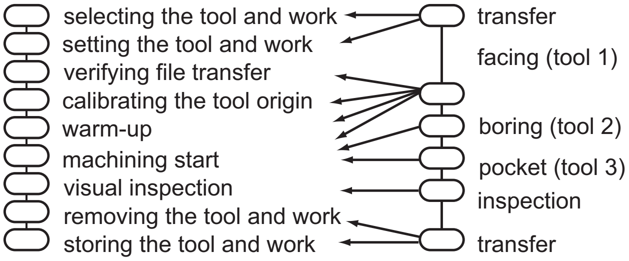
(d) Only sequential processes applied by decision-based process design produce an easy-managed decoupled design.

Figure 1: Decision-based process design, producing an easy-managed decoupled design.

decision. In the most case, the number of FR is more than that of DP as shown in Figure 1(a). The rectangular design matrix means that it is coupled.

2.2 Rule of "one decision per one process"

Next, we introduced a rule of "one decision per one process", namely, the number of FR = that of DP. The rule subdivided the conventional processes into elemental processes as shown in Figure 2(a); exceptionally, the "machining" is one process even though the machining time is too long, because the operator only verifies that the NC has started after pushing the button.



(a) Human decision = elemental process (b) Conventional process

Figure 2: Machining process with many human decisions.

Table 1: Decision category.

Category	Examples in designing and manufacturing injection molds
(a) Setting an unknown parameter from continuous values prepared in advance	Setting the locations of parting lines or moving parts in CAD.
(b) Setting an unknown parameter from discrete values prepared in advance	Selecting the machining pattern from a number of options in the decision table in CAM.
(c) Setting an unknown parameter from selections that cannot be prepared in advance	Taking measurements after the machining is complete and analyzing the cause of defects in fabrication.
(d) Checking with known parameters	Checking operations if the previous works went well or not in facrication.
(e) Completing with known parameters	Setting the cavity dimensions with consideration to shrinkage of plastics in CAD.

Figure 1(b) indicates the design matrix becomes square, but it is full because some processes needed feedback-controlled adjustments. For example, vent hole or pin gate was re-formed after trial injection with a finished mold, or tool origin was re-adjusted after dimension measurement of a previous product.

2.3 Reduction of the number of human decisions

To decouple the matrix, we took away the feedback using tacit knowledge heard from the fabrication site. We keep a rule of "no feedback". And process standardization narrows the selections for decision-making. The matrix reduces non-zero elements.

Moreover, we decreased the number of human decisions. Table 1 shows the category of the decision; (a)(b)(c) are some of high-level decisions that have to select the best from finite or unknown options like solving an unexpected trouble, but (d)(e) are that of low-level one that can reach a unique or known solution like solving a mathematical equation. Only high-level decisions are called human decisions; low-level decisions are made by machines, computers and sensors. Figure 3 indicates that the total number of decisions is 583, but the number of high-level ones is only 77. The designing and manufacturing mold factory drastically shortened the lead-time from 352 hours to 49.8 hours [2]. Then, of course, we applied four solutions with some contribution ratio of the total lead-time reduction.: decision-based process design (39 %), 3D-CAD/CAM (9 %), high-speed machining (39 %), and high-precision machining (13 %).

Figure 1(c) shows a smaller square, lower triangular matrix. The low-level decisions were fixed and omitted. Production is converted into a decoupled design. However, it still has some interference elements in referring the previous data or summing the two data in parallel.

2.4 Sequential processes producing an easy-managed decoupled design.

Finally, we made only sequential processes without any referring or summing. Figure 1(d) shows a diagonal-like matrix, meaning an easy-managed decoupled design. Each process is decided by the data of the previous process and the production rules of its own process. For example, Figure 4 shows the process diagram of sequential processes in CAD. The diagram marks the high-level decisions with diamond

	Category in Table 1					Total	process time (*lead time)		shortened time	total operation time	average element operation time
	(a)	(b)	(c)	(d)	(e)		before application	after			
CAD	6	0	1	0	15	22	8day (64hr)	6.5hr	58hr	6.5hr	18min
CAM	20	12	15	17	123	187	15 (120)	8.6	111	64.6	21
Fabrication	0	0	19	35	306	360	20 (160)	32.8	127	114.0	19
Polish, Assy.	0	0	4	0	10	14	5 (40)	10.1	30	15.2	65
Total	26	12	39	52	454	583	44* (352)	49.8*	302*	200.3	20

Figure 3: Human decisions of categorized only in (a)(b)(c) were made in designing and manufacturing injection molding molds for cellular phone shells. The remaining decisions of (d)(e) were made by the computer, drastically reducing the process time by 14%.

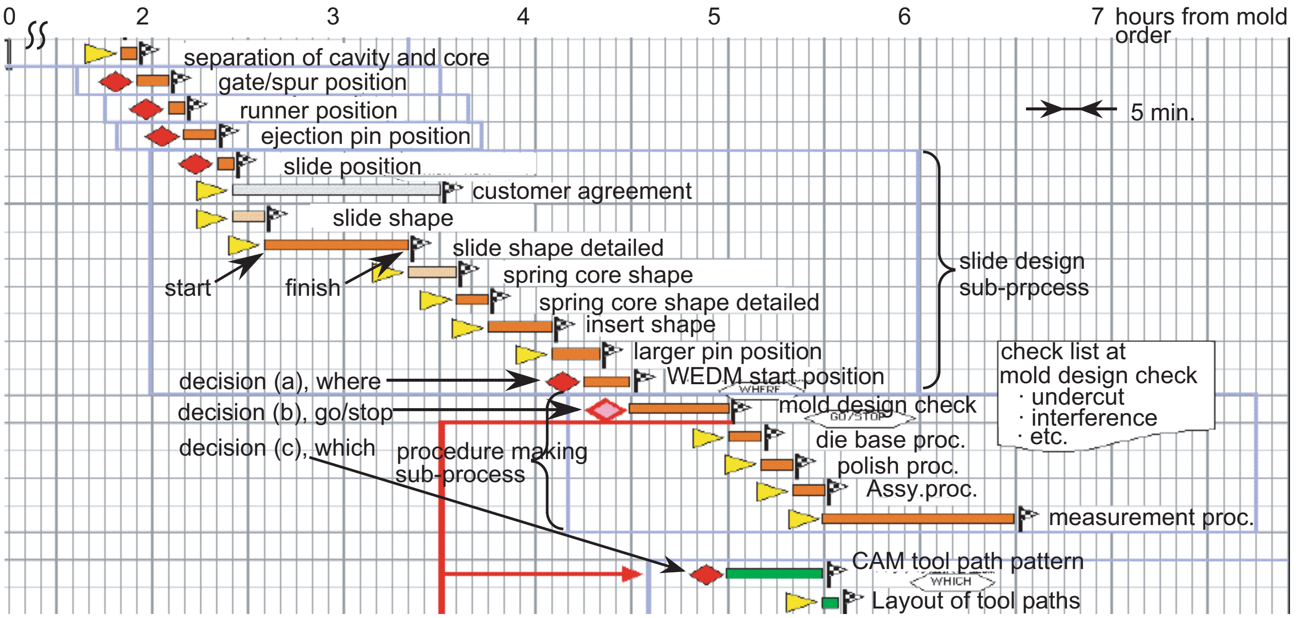


Figure 4: Example of sequential process diagram applied by decision-based process design in CAD.

symbols.

We noticed that the process design represented by the diagonal-like matrix is easy-managed; we can change, adjust, or add a process with a minimum influence against the other processes. Now, we are managing all processes of all molds with the computer in real time.

3 UNCOUPLED OPERATION DESIGN OF MULTI-MOLD PRODUCTION: FR = FINISH TIME, DP = PRIORITY

The work in last chapter concentrated on the "express" production of a single mold that had no queue time. The 49.8 hours, 2.1 days was the ideal shortest lead-time. In the actual factory, the average lead-time, however, was 15.8 days because the various about 60 molds, 480 parts were operated at the same time on the same floor.

Figure 5 shows the design equations of the multi-mold production. In this chapter, "FR = finish time" and "DP = priority" are addressed. We will decouple the design for shortening the queue time, i.e. the lead-time.

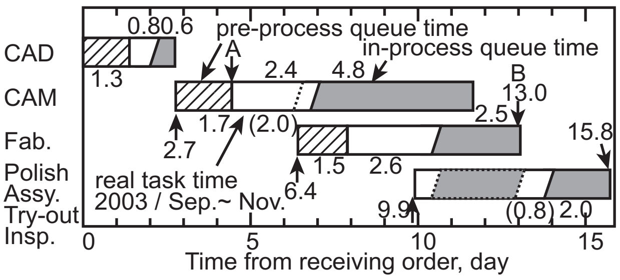


Figure 6: Process diagram of mold production.

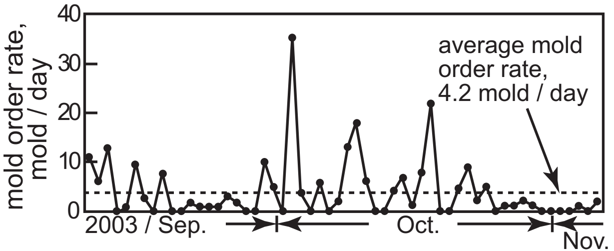


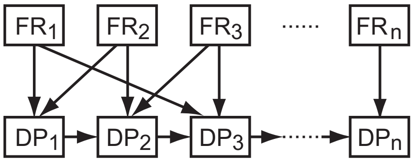
Figure 7: History of receiving orders for molds.

3.1 Problem of multi-mold production

Operation engineer can calculate delay time, that is, the queue time when the inter-arrival time of receiving orders and the service time per server are fluctuated [3]. The process proceeds in "first come, first served" like with store checkout counters. Take, for examples, a simple case like a later described CAD process that has Poisson distributions with its orders and services. When the arrival rate A = 4 molds/day, the service rate per server S = 1 mold/day, and the number of servers N = 5 are set, then absolute utilization U (= A/(S*N) = 0.8 < 1) can give the average wait time. Therefore, the

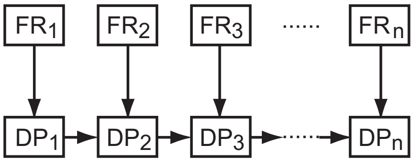
Finish Time Priority

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} X & 0 & X & \cdots & 0 \\ X & X & 0 & \cdots & 0 \\ 0 & X & X & \cdots & 0 \\ & \vdots & & \ddots & \\ 0 & 0 & 0 & & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_n \end{Bmatrix}$$



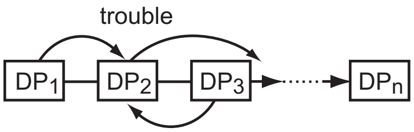
(a) Process manager changes priorities frequently, and makes a coupled design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} X & & & & \\ & X & & 0 & \\ & & X & & \\ & & & \ddots & \\ & 0 & & & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_n \end{Bmatrix}$$



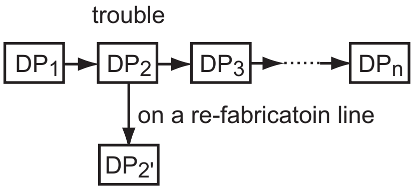
(b) Rules of "no priority change" converts the coupled design into an easy-managed uncoupled design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} X & X & & 0 & \\ X & X & X & & \\ & X & X & & \\ & & & \ddots & \\ & 0 & & & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_n \end{Bmatrix}$$



(c) A sudden fabrication trouble generates a traffic jam, and a coupled design happens again.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_n \\ FR_{2'} \end{Bmatrix} = \begin{bmatrix} X & & & & & \\ & X & & 0 & & \\ & & X & & & \\ & & & \ddots & & \\ & 0 & & & X & \\ & & & & & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_n \\ DP_{2'} \end{Bmatrix}$$



(d) An independent re-fabirication line was prepared, stably producing an uncoupled design against the trouble.

Figure 5: Rules of "no priority change", producing an easy-managed uncoupled design.

expected time in queue Q is calculated on Q = 1.0 day, which approximately matches the 1.3 days described in the left-upper pre-process queue time of Figure 6.

In reality, the sales person makes a trade-off between "take all orders possible" and "meet the dead-line" in setting the order. For example, as Figure 7 shows, there were as many as 35 orders of molds in one day, and this sets the expected time in queue for the last mold as long as 7 days. The fluctuation of the arrival rate induces the pre-process queue time, total 4.5 days as indicated in Figure 6.

In CAM (cutter path generating) and fabrication (NC machining) that follows CAD, one mold is separated in average into 8 parts like core, cavity, slide, plate, etc, and the amount of work on each part varies widely. It means the service time or the service rate varies. This variation will be also widened according to the deadline required by customers and unexpected reprocessing. Moreover, increase in orders raises the motivation for the workers. It means the number of servers increases. With their overtime, workforce shifting, outsourcing or effect from learning, the capacity naturally jumps up by 25 %. The fluctuation of the service rate and the number of servers induces the in-process queue time, total 9.9 days as indicated in Figure 6.

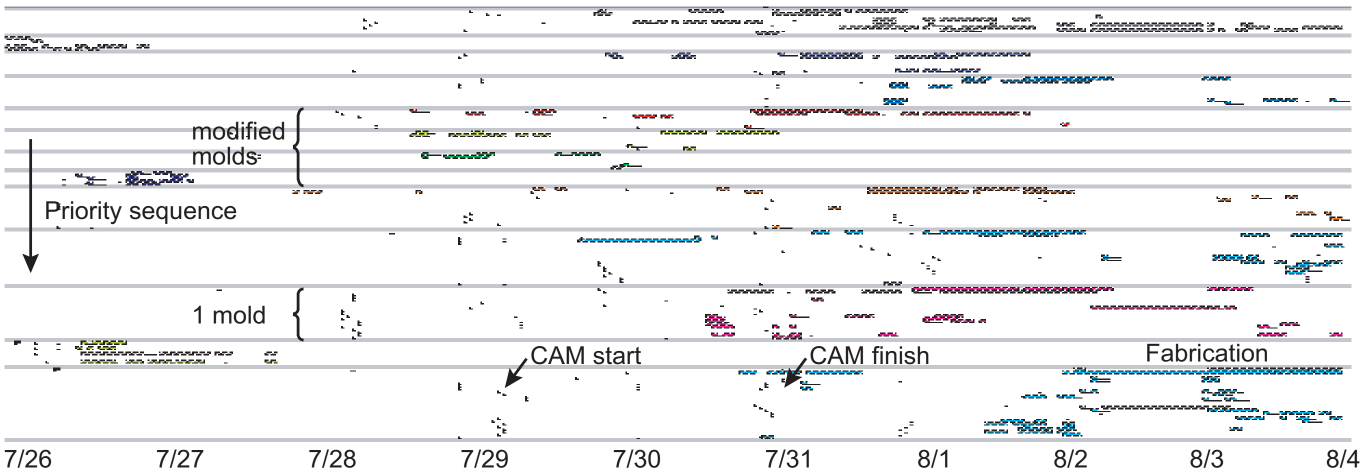


Figure 8: Process log of CAM and fabrication before applying the rule of no priority change.

Figure 8 is a process log of CAM and fabrication of the part groups for each mold. The horizontal axis spans 10 days; in the vertical position, the processes advanced from upper molds with higher priorities to lower ones Priorities of the parts and molds were changed for local optimization that a process manager changes priorities frequently, and then caused variation in finish time. The diagram looks unnecessarily scattered and elongated. As Figure 5(a) shows, the design matrix becomes a full matrix.

Furthermore, produced mold models are so widely various in our factory that the service time is fluctuated additionally. The prototyping mold production, which is concentrated in the previous chapter, had an only 47 % share of the whole production. The other mold models come into play: mass production type steel molds (10 % share) with longer machining time by 50 %, modified molds (16 % share) with less lead-time by 33 %, and different shaped molds for automobile electric parts design (26 % share) with longer design time using a non-customized CAD/CAM. The wider variation of the service time shows a longer real task time, total 6.6 days in Figure 6.

Eventually, being cancelled the overlapped time, the average lead-time is elongated to 15.8 days from 2.1 days in multi-mold production.

3.2 Rule of "no priority change"

We introduce a rule of "no priority change" as shown in Table 2. No engineer can change any priorities for all processes once the priority is set upon receiving an order, described in rule (a). However, he can prioritize two primary parts of "core and cavity" over other small parts of slides and plates during CAM and fabrication, in rule (e). The core and cavity have 1.9 times longer in machining than the slides and plates. Moreover, he can prioritize troubled molds during fabrication, assembly, or injection trial, in rule (g). The trouble that stops any task and is reported from the field revealed there were 550 cases a month and 4.6 a mold on the average.

Table 2: Rule of no priority change.

(a) Priority cannot change for all processes once the priority is set upon receiving an order.
(b) If a simultaneous order consists of a group of prototypes, the mold with more complex shape that seems to require more work has priority.
(c) Do not limit the work of each operator in CAD and CAM.
(d) Do not switch the operator during CAD and CAM.
(e) Prioritize core and cavity over other small parts during CAM and fabrication.
(f) Do not limit the machining tool for each part.
(g) Prioritize troubled molds during fabrication, assembly or try-out.

Table 3: Requests of emergent priority changes.

(i) Prioritize a modified mold over a new mold, because the modified one tends to promise a shorter turn-around to the customer (24% of all changes).
(ii) Re-placed prioritize on molds with minimum slacktime, because more accurate the machining time was estimated after completing the CAM process (21%).
(iii) Prioritize the mold firstly, because the customer reported a claim to keep the promised delivery date (14%).
(iv) Lowered the mold's priority, because the mold had a large slack to the delivery date (13%).
(v) Placed priority on incomplete jobs for molds whose preprocesses are almost all complete, keeping a steady workload for the following processes (12%).
(vi) Selected electric discharge machining (EDM) or etching vendors based on their holiday and weekend schedules (5%).

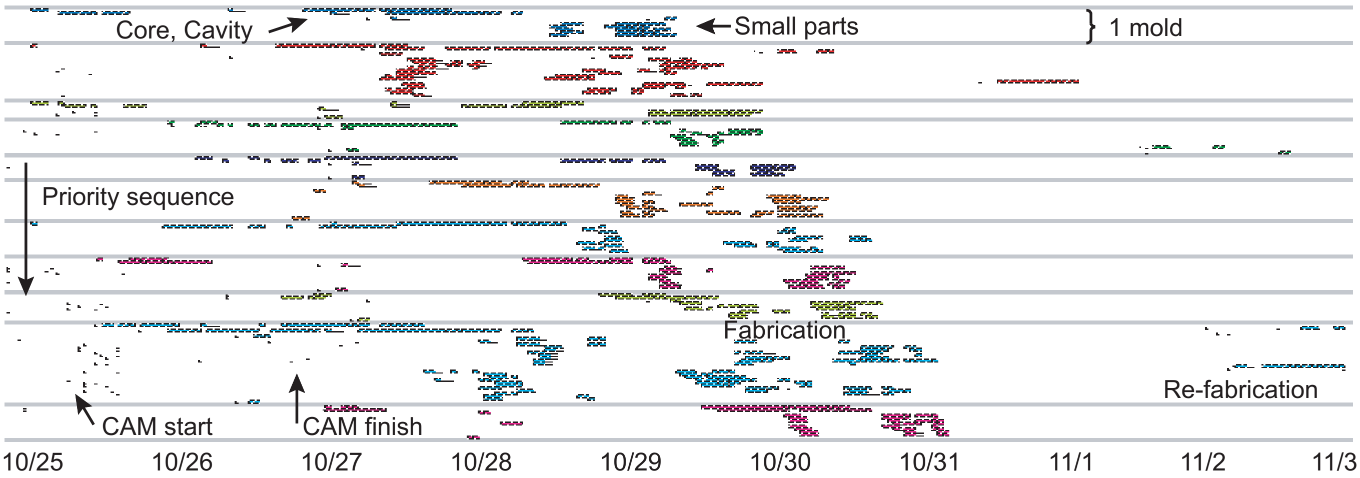


Figure 9: Process log of CAM and fabrication after applying the rule of no priority change.

Countering these troubles extends the lead-time by an average of 1.2 days, which are included in the in-process queue time. 77 % of the total troubles occurred in the machining process and 18 % of those machining troubles required rework.

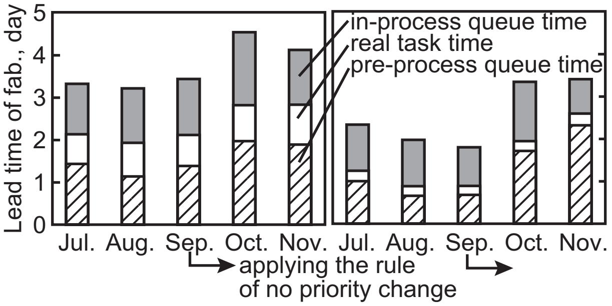
Figure 9 is a process log of CAM and fabrication after applying the rule. Compared with the scattered log in Figure 8, the log in Figure 9 shows orderly process advancement for each mold in a "plug and flow" manner. Figure 5(b) shows the full design matrix is converted into a diagonal matrix, meaning an easy-managed uncoupled design is generated.

3.3 Problem of a traffic jam caused by the troubles

The rule of "no priority change" prioritizes the troubled mold. But so many troubled molds required the reworks, disturbing priorities of the other molds. For example, the average fabrication rework takes 2.4 hours in queue and 8.2 hours in machining.

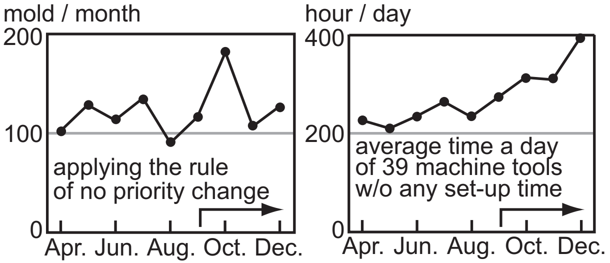
Moreover, an operation manager or a sales person requires a number of emergent, exceptional, mandatory priority changes even after applying the rule: 75 cases a month, 0.5 per mold. Table 3 shows the reasons for changes. He changed the priorities for "earliest due date, first served" in (i), "minimum slack time, first served" in (ii)(iv), "louder complaint, first served" in (iii) and so on. This frequent priority change induced a longer in-process queue time. Figure 5(c) comes back to a coupled matrix because one priority change of the mold influences some finish time changes of the other molds.

Figure 10 shows the history of the fabrication lead-time of the core in (a) and that of the small parts in (b). The rule of "no priority change" could have decreased the lead-time even though the rule had not been kept tightly. Unexpectedly, the lead-time increased by about 30 % after applying the rule, because the sales persons received more orders than the capacity as mentioned in section 3.1. The increase of the pre-process queue time in the figure implies the overwork. But even in this busy working, in-process queue time didn't change or decreased in the figure. It means the rule smoothes out the



(a) Core fabrication (b) Small parts fabrication

Figure 10: History of lead time of fabrication.



(a) Shipped molds (b) Total real cutting time

Figure 11: History of production capacity.

operation without any disturbance of useless decisions. Figure 11 shows that, after applying the rule, the number of shipped molds and total real cutting time increased by about 50 %. The employee might also have some motivation for increasing the capacity as mentioned in section 3.1. Anyway, the capacity increased by about 50 % without any increase of resources in the result.

3.4 Preparation of a re-fabrication line

To convert back to a diagonal matrix, we prepared a redundant re-fabrication line. The line should be independent; then the matrix becomes uncoupled in Figure 5(d). In the future, it will need a large-scale flexible system that can cope with the unexpected trouble in real time.

We found out that the operation design represented by the diagonal matrix is also easy-managed; we can change the priority without any influence against the other processes. Now, we are predicting the finish times of all molds and all parts with the computer.

4 CONCLUSION: THE UNCOUPLED, EASY-MANAGED SCHEDULING

FR-based scheduling for shortening the lead-time of mold manufacturing is introduced. We analyze the design equations of FR = human decision and DP = elemental process for one-mold production, and those of FR = finish time and DP = priority for multi-mold production. To obtain an uncoupled design, we proposed a method, i.e. "decision-based process design": especially, the rule of "one decision per one process", the rule of "no feedback", the rule of "no priority change" and so on.

With the method applied to the actual factory for injection molds, we could schedule all processes as uncouple, easy-managed design. Consequently, the lead-time of one-mold production became shorter from 44 days to 2.1 days by 14 %. The capacity of multi-mold production became larger by about 50 % without any increase of resources.

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