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PROPAGATION OF WORKING-TIME DELAY IN PRODUCTION

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Abstract. *Manufacture of products proceeds in multiple stages from the beginning of production. Such volatility is encountered in every stage of manufacturing, and the delays in the production line propagate this volatility to the successive step. A delay in the production process is equivalent to a "fluctuation" in physical phenomena. For example, there is the deviation from the thermal equilibrium state to fluctuations in physics. The propagation of fluctuation (volatility) in each stage delays the entire process. In this study, we mathematically analyzed this phenomenon and assessed whether volatility is encountered during manufacturing. Finally, we examined the propagation of fluctuation-induced delays to successive stages in manufacturing.*
Keywords: Delay propagation, Throughput, Potential energy, Fluctuation

1. **Introduction.** Several studies have addressed the problem of increasing the productivity of production processes used in the manufacturing industry [1, 2]. Moreover, in the field of manufacturing, various theories have been applied to improve and reform manufacturing processes and increase productivity. In a previous study [3], we addressed the problem of reducing construction work and inventory in the steel industry. Specifically, we investigated the relationship between variations in the rate of construction and delivery rate. In this study, we perform analysis using the queuing model and apply log-normal distribution to model the system in the steel industry [3].

Moreover, several studies have reported approaches that lead to shorter lead times [4, 5]. From order products, lead time occurs on the work required preparation of the members for manufacturing.

Many aspects can potentially affect lead time. For example, from order products, the lead time from the start of development to the completion of a product is called the time-to-finish time, such as the work required preparation of the members for production equipments.

Moreover, several studies have focused on reducing customer lead times. In [6], the author addresses the problem of reducing the production lead time.

In [7], the authors propose a method that increases both production efficiency and production of a greater diversity of products for customer use. Their proposed approach results in shortened lead times and reduces the uncertainty in demand. Their method captures the stochastic demand of customers and produces solutions by solving a nonlinear stochastic programming problem.

In summary, several studies have considered uncertainty and proposed practical approaches to shorten the lead time. The demand is treated as a stochastic variable and applies mathematical programming. To our knowledge, previous studies have not treated lead time as a stochastic variable.

Because fluctuations in the supply chain and market demand and the changes in the production volume of suppliers are propagated to other suppliers, their effects are amplified. Therefore, because the amounts of stock are large, an increase or decrease of the suppliers' stock is modeled using differential equation. This differential equation is said as Billwhip model, which represents a stock congestion [8, 9].

The theory of constraints (TOC) describes the importance of avoiding bottlenecks in production processes [10]. When using manufacturing equipment, delays in one production step are propagated to the next. Hence, the use of manufacturing equipment may lead to delays. In this study, we apply a physical approach and regard each step as a continuous step. By applying this approach, we can mathematically analyze the delay of each step and obtain methods to address it. To the best of our knowledge, previous studies have not applied physical approaches to analyze delays.

In a previous study [11], we constructed a state in which the production density of each process corresponds to the physical propagation of heat [17]. Using this approach, we showed that a diffusion equation dominates the manufacturing process.

In other words, when minimizing the potential of the production field (stochastic field), the equation, which is defined by the production density function $S_i(x,t)$ and the boundary conditions, is described using the diffusion equation with advection to move in transportation speed ρ. The boundary conditions means a closed system in the production field. The adiabatic state in thermodynamics represents the same state [11].

To achieve the goal of a production system, we propose using a mathematical model that focuses on the selection process and adaptation mechanism of the production lead time. We model the throughput time of the production demand/manufacturing system in the manufacturing stage by using a stochastic differential equation of log-normal type, which is derived from its dynamic behavior. Using this model and the risk-neutral integral, we define and compute the evaluation equation for the compatibility condition of the production lead time. Furthermore, we apply the synchronization process and show that the throughput of the manufacturing process is reduced [12, 13].

This paper reports the difference between the synchronous and asynchronous manufacturing processes and shows that the throughput of a manufacturing process depends on volatility. In the synchronous process, the machining of parts and assembly lines produce the required product volumes in accordance with a predetermined schedule [14]. The synchronous process is the best approach available, but its application to real-world situations is difficult. Thus, we propose a more realistic method referred to as "synchronization-with-preprocessing". This method relaxes working-time volatility by reclassifying the working process. In general, the lead times of the processes need to be equal. However, in the synchronization-with-preprocessing method, before the beginning of the manufacturing process, we analyze a particular process and select different lead times. With this approach, the synchronization-with-preprocessing method can achieve a higher throughput. To the best of our knowledge, the synchronization-with-preprocessing method has not been proposed by any previous study.

To verify the effectiveness of the proposed method, we applied it to a flow production system. We show that the proposed method reduces volatility, which in turn minimizes risk; here risk refers to the working-time delay in each process [14].

This paper also reports the applicability of "edge of chaos", which is used in complex systems, to the manufacturing industry. In the manufacturing industry, "edge of chaos" is caused by a loss of synchronization between the production line and throughput.

This phase transition is observed in the process throughput during the manufacture of control equipment. In this study, we also examined the phase transition in the system by using a flow production system. This flow production system is a high-mix product line production system which is commonly used.

To maintain the synchronization between manufacturing and process throughput, it is necessary to determine the critical point of the phase transition. We have decided the critical point on the basis of years of experience. From an economic perspective, it is important to ensure that the critical point is not crossed [15].

In manufacturing, when a delay occurs in a stage, the delay propagates to the successive stage. This delays the entire production process, which is equivalent to fluctuations in physical phenomena. A delay in the entire process is attributed to the propagation of fluctuations (volatility). We mathematically analyzed this phenomenon, and to the best of our knowledge, this approach has not been considered by any previous study.

Furthermore, we simulated the process of production in order to verify the propagation of the fluctuation. The flow production system, which is a manufacturing method employed in the production of control equipment. The flow production system, which in this case has nine workers by processing six stages, is commercialized by the production of material in steps S1-S6 of the manufacturing process. The mathematical modeling of the stochastic throughput of the manufacturing process is shown in this paper.

2. **Production Systems in the Manufacturing Equipment Industry.** The production methods used in manufacturing equipment are briefly covered in this paper. More information is provided in our report [12].

This system is considered to be a "Make-to-order system with version control", which enables manufacturing after orders are received from clients, resulting in "volatility" according to its delivery date and lead time. In addition, there is volatility in the lead time, depending on the content of the make-to-order products (production equipment).

In Figure 1(A), the "Customer side" refers to an ordering company and "Supplier (D)" means the target company in this paper. The product manufacturer, which is the source of the ordered manufacturing equipment presents an order that takes into account the market price. In Figure 1(B), the market development department at the customer's factory receives the order through the sale contract based on the predetermined strategy.

3. **Stochastic Throughput Modeling.** Generally, a company predicts the demand of a particular product. We show that the distribution of the rate of return forms a lognormal probability distribution [13]. The predicted throughput is proportional to the rate of return. Therefore, it is assumed that the probability distribution of the throughput is also a lognormal distribution [12].

About "Supplier (D)" in Figure 1, we calculated the return of 10 years from Apr., 1999 to Mar., 2008 on a month-by-month basis to calculate rate-of-return deviation. The result is shown in Figure 2. Here, given that the return of nth month is S_n, a rate of return was defined by (1).

Regarding the reason that ζ^* can be converted as $\zeta^* = \ln \zeta$, we have found that, from observed monthly cash flow data (return deviation), a probability density function is

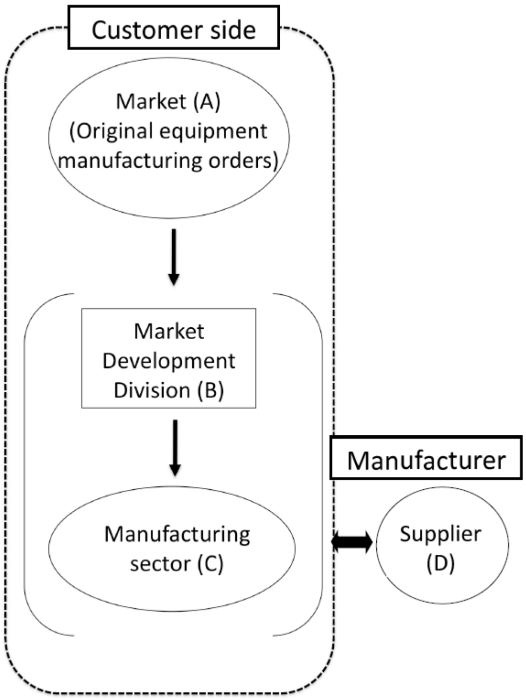

Figure 1. Business structure of company of research targe

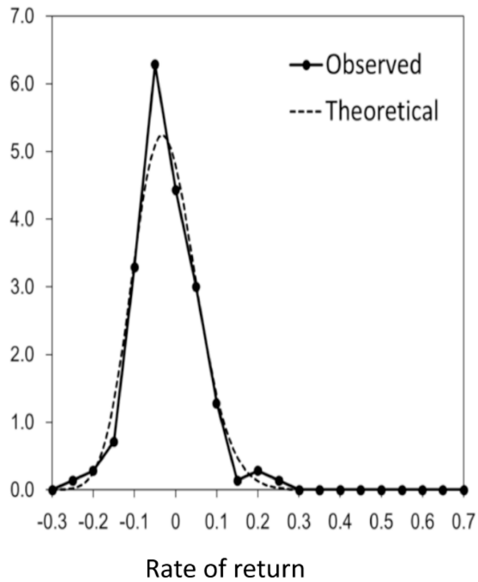

Figure 2. Probability density function of rate-of-return deviation: actual data (solid line) and data based on theoretical formula (dotted line)

log-normally distributed (Figure 2). A theoretical curve was calculated using EasyFit software (http: www.mathwave.com/), and, as a result of Kolmogorov and Smirnov test, the observed values conformed to a log-normal distribution (P = 0.588). Parameters of the theoretical curve were $\mu = -0.134$, $\sigma = 0.0873$, $\nu = -0.900$.

Next, a production density function that changes from the initial value of $S(0) = ET$ (flow level), declines while taking positive values. Therefore, as a dynamic model, the following equation is assumed. This model is a frequently used model as a reality-based model. Therefore, by performing conversion of $t = \ln t$, the following assumption is made.

Here, the rationale of definition of the sales model as (1) is that the probability distribution of the rate of return is represented by a probability distribution of a log-normal type. In general, the sales volume is proportional to the rate of return. $S(t,x)$ is

$$dS(t) = \alpha_s S(t,x)dt + \sigma_s S(t,x)dW(t) \tag{1}$$

Alternatively, it is developed as the throughput of the log-normal model.

$$dC(t,x) = \alpha_s C(t,x)dt + \sigma_s C(t,x)dW(t) \tag{2}$$

However, for this model throughput

$$dC(t,x) = C^* C(t,x)dt + \sigma C(t,x)dW(t) \tag{3}$$

From this, let (3) be the stochastic throughput model. If (3) is the sales model, we use (1). If a revenue model is also needed, we use (2).

Here, we propose the stochastic throughput model as follows [11]:

$$\frac{\partial C(t,x)}{\partial t} + v\frac{\partial C(t,x)}{\partial x} = D\frac{\partial^2 C(t,x)}{\partial x^2} + \sigma\frac{\partial B(t,x)}{\partial t} \tag{4}$$

Equation (4) is the stochastic advection diffusion equation. If $v = 0$ in (4), we are able to obtain as follows:

$$\frac{\partial C(t,x)}{\partial t} = D\frac{\partial^2 C(t,x)}{\partial x^2} + \sigma\frac{\partial B(t,x)}{\partial t} \tag{5}$$

4. **Ginzburg and Landau Free-Energy.**

The Ginzburg and Landau (G-L) free-energy theory for the rate of return in the production process describes the ability to earn during the production process [11].

Therefore, in the present study, we describe the G-L free-energy theory in terms of statistical mechanics, apply it to a production system, and describe the parameter constraining the G-L free-energy [11].

Definition 4.1. *Definition of transfer coefficient of production units*

$$\frac{\partial \mathcal{F}(S_i)}{\partial x} = -\kappa grad(S_i) \tag{6}$$

Equation (6) is described by

The gradient of potential energy
= − (Transfer coefficient of production units)
× (Gradient of a production density)

$$F(S_i) = \int_0^L dx \left[f(S_i) + \frac{D}{2}(\nabla f(S_i))^2 \right] \tag{7}$$

where L represents the production unit, $f(S_i)$ is the potential function of the variable S_i, and $(\nabla f(S_i))^2$ is the “fluctuation” of S_i [11, 20].

5. **Order Parameter in Production.**

$F(S_i)$ is the G-L free-energy that determines the rate of return in the production process, i.e., the ability for earning in a production process. In other words, $F(S_i)$ represents the time average value of the production density S_i in (6),

$$S_{im} = < \int_0^t h_i(S_i, \tau)d\tau > \tag{8}$$

where S_{im} is the time average value of the production density function and an order parameter in statistical mechanics [11]. $< \circ >$ represents the time average, and (7) is modified as follows:

$$F(S_{im}) = \int_0^L dx \left[f(S_{im}) + \frac{D}{2}(\nabla S_{im})^2 \right] \quad ^{\forall}0 \leq x \leq L \tag{9}$$

The G-L free-energy depends on the spatial variation in the order parameter S_{im} of the second term in (9). The first term of $f(S_{im})$ is a function of S_{im} for each production process.

Thus, to minimize the G-L free-energy in the entire production system with respect to the order parameter S_{im}, the variation in (9) as a function of the variation in S_{im} in the process (i) is expressed as follows:

$$\delta F(S_{im}) = \int_0^L dx[f'(S_{im})\delta S_{im} + D(\bigtriangledown S_{im}) \cdot (\bigtriangledown \delta S_{im})] \tag{10}$$

The second term of (10) is obtained by integrating the parts with constant D.

$$\int_0^L dx D(\bigtriangledown S_{im}) = -\int_0^L dx D(\bigtriangledown^2 S_{im})\delta S_{im} \tag{11}$$

Here the order parameter S_{im} is fixed at the boundary of the production system. When production stops, $\delta S_{im} = 0$, and the integrated parts at the boundary eventually become zero (corresponding to the reflecting wall) [11, 20]. Therefore, we obtain

$$\delta F(S_{im}) = \int_0^L dx[f'(S_{im}) - D(\bigtriangledown^2 S_{im})]\delta S_{im} \tag{12}$$

The condition for obtaining the minimum value of the G-L free-energy is $\delta F(S_{im}) = 0$ for any δS_{im}. Therefore, the following equation is derived for equipment production.

$$f'(S_{im}) - D(\bigtriangledown^2 S_{im}) = 0 \tag{13}$$

Therefore, by transforming (13), the condition for the minimum $F(S_{im})$ is

$$D\frac{d^2 S_{im}}{dx^2} = f^{'}(S_{im}) \tag{14}$$

Equation (14) corresponds to the law of conservation of mechanical energy. Then, it is obtained by

$$D\frac{d^2 S_{im}}{dx^2} - f^{'}(S_{im}) = const. \tag{15}$$

Furthermore, the width of the boundary region corresponding to the fluctuation is expressed as follows [11]:

$$x \equiv \sqrt{\frac{f''(S_{im}^1)}{D}} \tag{16}$$

Figure 3 shows the conditions for the coexistence of production and nonproduction. In this case, the G-L free-energy shows two local minima S_{im}^1 and S_{im}^2 and has a constant value. As for the potential energy with respect to (16), $S_{im}(-\infty) = S_{im}^1$ at $x = -\infty$, $S_{im}(+\infty) = S_{im}^2$ at $x = \infty$. Here, $f^{'}(S_{im})$ is considered as follows:

$$f^{'}(S_{im}) = -\frac{1}{2}S_{im} + \frac{1}{12}S_{im}^3 \tag{17}$$

In other words, the width of the boundary of the fluctuation is determined on the basis of the shape of the potential energy curve $f(S_{im})$.

Functions 1-4 in Figure 5 show the following.

- $1 : f(S_{im}) = -\frac{1}{2}S_{im}^2 + \frac{1}{2}S_{im}^4$
- $2 : f(S_{im}) = -\frac{1}{2}S_{im}^2 + \frac{1}{4}S_{im}^4$
- $3 : f(S_{im}) = -\frac{1}{2}S_{im}^2 + \frac{1}{8}S_{im}^4$
- $4 : f(S_{im}) = -\frac{1}{2}S_{im}^2 + \frac{1}{12}S_{im}^4$

That is, the phase transition in the production process is assumed to occur in the supply chain.

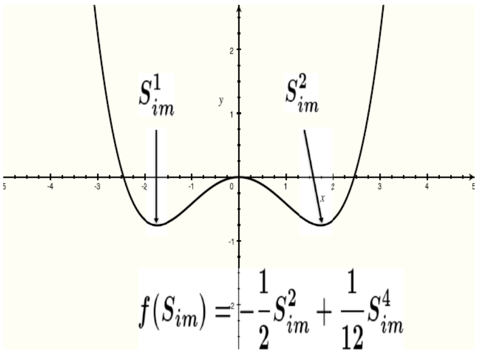

FIGURE 3. Phase 2 (non-production and production) is the coexistence

For example, this throughput results in a phase transition because of the uncertainty of the supply chain. The excess inventory and loss of opportunities imply that under-production and overproduction states occur in the stochastic field of the manufacturing process [16].

At this point, we define the risk of cost loss and perform computations using the appropriate parameters. We also have discussed the problem of deviation of the rate of return in phase transition [15].

6. **Application of Flow-Shop to the Supply Chain System.** A finite number of production systems in the manufacturing process constitute a flow shop. The model is shown in Figure 4. In Figure 4, $\{osc_i : 1, 2, 3, 4\}$ represents the flow shop throughput. $\{osc_0\}$ represents the throughput of the supply chain [18]. In addition, L denotes the

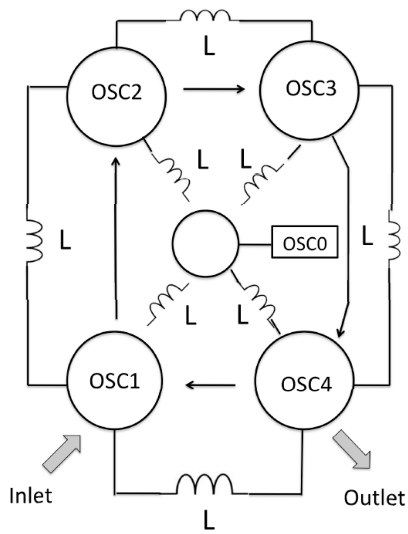

FIGURE 4. Trajectory change of potential function

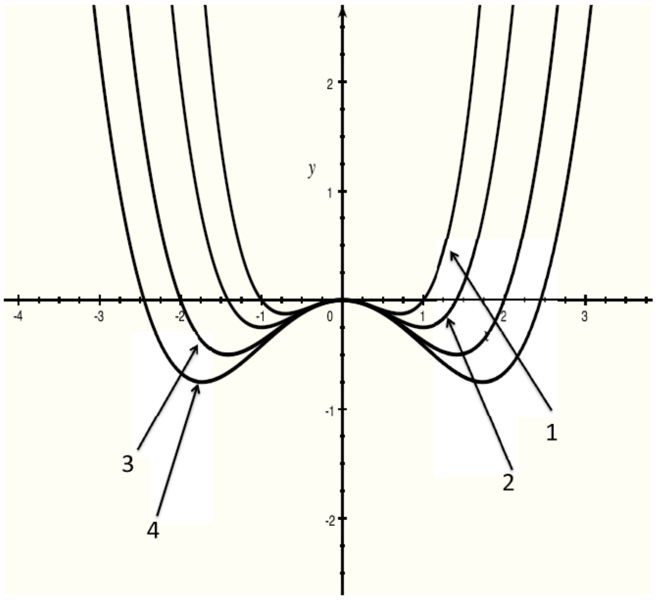

FIGURE 5. Graph to change the boundaries of the fluctuations

coupling coefficient that connects each flow shop to the other. The direction of the arrow represents the direction of the production flow.

Furthermore, production materials are supplied through the inlet, and the final product is shipped from the outlet.

In this system, the throughput of the supply chain, which is connected to each flow shop, fluctuates irregularly, and consequently, the throughput of each flow shop changes. As a result, if the throughput of each flow shop changes in the positive direction, this is overproduction. Conversely, a small throughput results in underproduction, this is under asynchronous production.

That is, the overall throughput undergoes a phase transition at $-\sqrt{kc}$ or $+\sqrt{kc}$. However, if the production materials are inputted form being shipped as final products (this is a production system supplied one), this phenomenon is a stagnation process and the throughput is typically too small. Throughput of each stage is propagated to the next stage.

In addition, when the production materials are supplied at distinct intervals, excess inventory occurs in every flow shop. Nevertheless, the throughput fluctuations in the supply chain significantly affect the functioning of the control system.

Such models are commonly studied in electrical engineering research. This is analyzed as a multiple vibration theory linked a lattice [21].

As described above, the data are obtained for the flow production system for six flow shops. The throughput at each flow shop is artificially changed rather than changing the throughput of the entire supply chain in Figure 2.

Consequently, it is inferred that phase transition takes place between Test-run1 and Test-run2 in Table 1 [15]. If the trend coefficient is constant, the system volatility fluctuates stochastically.

7. **Production Flow System.**

Figure 6 shows a manufacturing process that is termed as a production flow process. This manufacturing process is employed in the production of control equipment. In this example, the production flow process consists of six stages. In each step S1-S6 of the manufacturing process, materials are being produced.

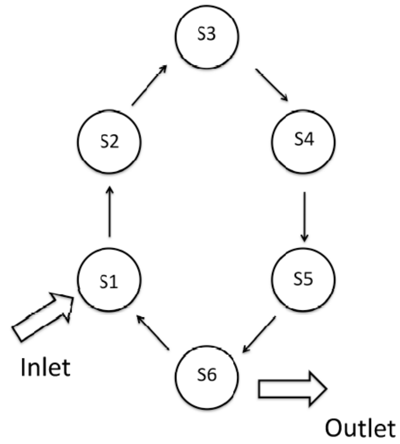

FIGURE 6. Production flow process

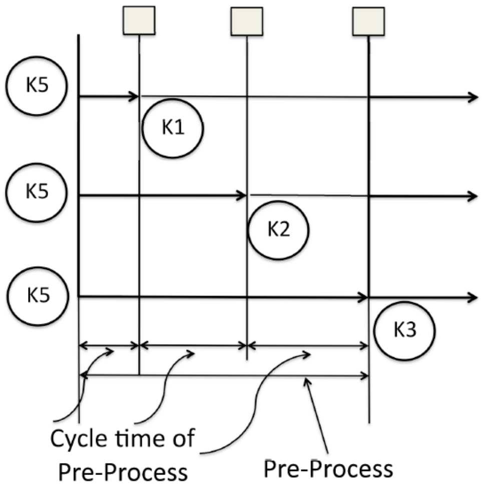

FIGURE 7. Previous process in manufacturing equipment

The direction of the arrows represents the direction of the production flow. In this process, production materials are supplied through the inlet and the end-product is shipped from the outlet. For this flow production system, we make the following two assumptions.

8. **Analysis of the Test-Run Results.** Table 1 shows a comparison table of the working time for the manufacturing method of the Test-runs1-3.

- (Test-run1): Each throughput in every process (S1-S6) is asynchronous, and its process throughput is asynchronous. Table 2 represents the manufacturing time (min) in each process. The volatilities of K3 and K8 increases due to the delay of K3 and K8 in Table 3. K3 and K8 of workers in Table 2 indicate the delay propagation of working time through S1-S6 stages. Table 3 represents the volatility in each process performed by workers. Table 2 represents the target time, and the theoretical throughput is given by $3 \times 199 + 2 \times 15 = 627$ (min).

  In addition, the total working time in stage S3 is 199 (min), which causes a bottleneck. Figure 9 is a graph illustrating the measurement data in Table 2, and it represents the total working time for each worker (K1-K9). The graph in Figure 10 represents the volatility data for each working time in Table 2.
- (Test-run2): Set to synchronously process the throughput.

Table 1. Correspondence between the table labels and the test run number

	Table Number	Production process	Working time	Volatility
Test-run1	Table 2	Asynchronous process	627 (min)	0.29
Test-run2	Table 4	Synchronous process	500 (min)	0.06
Test-run3	Table 6	"Hensoku" method	470 (min)	0.03

Table 2. Total manufacturing time at each stage for each worker

	WS	S1	S2	S3	S4	S5	S6
K1	15	20	20	25	20	20	20
K2	20	22	21	22	21	19	20
K3	10	20	26	25	22	22	26
K4	20	17	15	19	18	16	18
K5	15	15	20	18	16	15	15
K6	15	15	15	15	15	15	15
K7	15	20	20	30	20	21	20
K8	20	29	33	30	29	32	33
K9	15	14	14	15	14	14	14
Total	145	172	184	199	175	174	181

Table 3. Volatility of Table 2

K1	1.67	1.67	3.33	1.67	1.67	1.67
K2	2.33	2	2.33	2	1.33	1.67
K3	1.67	3.67	3.33	2.33	2.33	3.67
K4	0.67	0	1.33	1	0.33	1
K5	0	1.67	1	0.33	0	0
K6	0	0	0	0	0	0
K7	1.67	1.67	5	1.67	2	1.67
K8	4.67	6	5	4.67	5.67	6
K9	0.33	0.33	0	0.33	0.33	0.33

The target time in Table 4 is 500 (min), and the theoretical throughput (not including the synchronized idle time) is 400 (min). Table 5 represents the volatility data of each working process (S1-S6) for each worker (K1-K9).

- (Test-run3): Introducing a preprocess stage, the process throughput is performed synchronously with the reclassification of the process. The theoretical throughput (not including the synchronized idle time) is 400 (min) in Table 6. Table 7 represents the volatility data of each working process (S1-S6) for each worker (K1-K9).

From this result, the idle time must be set at 100 (min). Based on the above results, the target theoretical throughput (T_s') is obtained using the "synchronization-with-preprocess" method. This goal is

$$\begin{aligned} T_s &\sim 20 \times 6 \text{ (First cycle)} + 17 \times 6 \text{ (Second cycle)} \\ &\quad + 20 \times 6 \text{ (Third cycle)} + 20 \text{ (Previous process)} + 8 \text{ (Idle-time)} \\ &= 370 \text{ (min)} \end{aligned} \tag{18}$$

Table 4. Total manufacturing time at each stages for each worker

	WS	S1	S2	S3	S4	S5	S6
K1	20	20	24	20	20	20	20
K2	20	20	20	20	20	22	20
K3	20	20	20	20	20	20	20
K4	20	25	25	20	20	20	20
K5	20	20	20	20	20	20	20
K6	20	20	20	20	20	20	20
K7	20	20	20	20	20	20	20
K8	20	27	27	22	23	20	20
K9	20	20	20	20	20	20	20
Total	180	192	196	182	183	182	180

Table 5. Volatility of Table 4

K1	0	1.33	0	0	0	0
K2	0	0	0	0	0.67	0
K3	0	0	0	0	0	0
K4	1.67	1.67	0	0	0	0
K5	0	0	0	0	0	0
K6	0	0	0	0	0	0
K7	0	0	0	0	0	0
K8	2.33	2.33	0.67	1	0	0
K9	0	0	0	0	0	0

Table 6. Total manufacturing time at each stage for each worker, K5 (*): Previous process

	WS	S1	S2	S3	S4	S5	S6
K1	20	18	19	18	18	18	18
K2	20	18	18	18	18	18	18
K3	20	21	21	21	21	21	21
K4	16	13	11	11	13	13	13
K5	16	*	*	*	*	*	*
K6	16	18	18	18	18	18	18
K7	16	14	14	13	14	14	13
K8	20	22	22	22	22	22	22
K9	20	20	20	20	20	20	20
Total	148	144	143	141	144	144	143

The full synchronous throughput in one stage (20 min) is

$$T_s^{'} = 3 \times 120 + 40 = 400 \text{ (min)} \tag{19}$$

The throughput becomes about 10% reduction in result. Therefore, the “synchronization-with-preprocess” method is realistic in this paper, and it is recommended the “synchronization-with-preprocess” method in the flow production system [14].

In Table 6, the working times of the workers K4, K7 show shorter than others. However, the working time shows around target time.

Table 7. Volatility of Table 6, K5: Previous process

K1	0.67	0.33	0.67	0.67	0.67	0.67
K2	0.67	0.67	0.67	0.67	0.67	0.67
K3	0.33	0.33	0.33	0.33	0.33	0.33
K4	1	1.67	1.67	1	1	1
K5	*	*	*	*	*	*
K6	0.67	0.67	0.67	0.67	0.67	0.67
K7	0.67	0.67	1	0.67	0.67	1
K8	0.67	0.67	0.67	0.67	0.67	0.67
K9	0	0	0	0	0	0

Next, we manufactured one piece of equipment in three cycles. To maintain a throughput of six units/day, the production throughput must be as follows:

$$\frac{(60 \times 8 - 28)}{3} \times \frac{1}{6} \simeq 25 \text{ (min)} \tag{20}$$

where the throughput of the preprocess is set as 20 (min). In (20), "28" represents the throughput of the preprocess plus the idle time for synchronization. "8" is the number of processes and the total number of all processes is "8" plus the preprocess. "60" is given by 20 (min) × 3 (cycles).

Here, the preprocess represents the working until the process itself is entered. To eliminate the idle time after classification of the processes in advance, this preprocess was introduced. In Figure 7, for example, it represents the termination of the operation of step K5 during the preprocess. By making the corresponding step K5 to be the preprocess, there are eight remaining processes. When performing the 3 cycles in Figure 7, the first cycle is $\{K1, K2, K3\}$, the second cycle is $\{K4, K6, K7\}$, and the third cycle is $\{K8, K9\}$.

After completion of the third cycle, the workers start manufacturing the next product. That is, the first manufacturing process starts the first cycle. By adopting the preprocess cycle, the third cycle is adopted in a parallel process.

At this time, the theoretical throughput (T_s) is as follows.

Here, the preprocess is adopted in test-run 5 only.

The results are as follows. Here, the trend coefficient, which is the actual number of pieces of equipment/the target number of equipment, represents a factor that indicates the degree of the number of pieces of manufacturing equipment.
Test-run1: 4.4 (pieces of equipment)/6 (pieces of equipment) = 0.73,
Test-run2: 5.5 (pieces of equipment)/6 (pieces of equipment) = 0.92,
Test-run3: 5.7 (pieces of equipment)/6(pieces of equipment) = 0.95.
Volatility data represent the average value of each test-run.

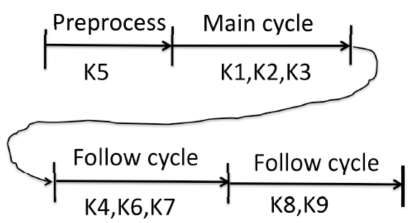

Figure 8. "Synchronization-with-preprocess" method in manufacturing equipment

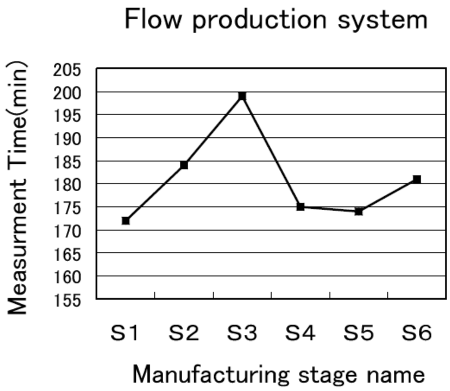

FIGURE 9. The total work time for each stage (S1-S6) in Table 2

FIGURE 10. Volatility data for each stage (S1-S6) in Table 2

9. **Conclusion.** The throughputs of Test-run1 and the entire process are asynchronous. It was proven that for workers K3 and K8 in Table 2, working-time delay is propagated through S1-S6.

Furthermore, the throughput fluctuations are due to volatility in the model. Indeed, actual data indicate that in a production process, fluctuations are propagated to the successive stages.

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REFERENCES

[1] M. E. Mundel, *Improving Productivity and Effectness*, Prentice-Hall, NZ, 1983.
[2] A. Neely, M. Gregorey and K. Platts, Performance measurement system design, *International Journal of Operations & Production Management*, vol.15, no.4, pp.5-16, 1995.
[3] K. Nishioka, Y. Mizutani, H. Ueno et al., Toward the integrated optimization of steel plate production process – A proposal for production control by multi-scale hierarchical modeling –, *Synthesiology*, vol.5, no.2, pp.98-112, 2012.
[4] S. Treville, R. D. Shapiro and A. Hameri, From supply chain to demand chain: The role of lead time reduction in improving demand chain performance, *Journal of Operations Management*, vol.21, no.6, pp.613-627, 1995.

[5] I. P. Tasiopoulos and B. G. Kingsman, Lead time management, *European Journal of Operational Research*, vol.14, no.4, pp.351-358, 1983.
[6] S. Hiiragi, The significance of shortening lead time from a business perspective, *MMRC*, University of Tokyo, no.392, 2012 (in Japanese).
[7] N. Ueno, M. Kawasaki, H. Okuhira and T. Kataoka, Mass customization production planning system for multi-process, *Journal of the Faculty of Management and Information Systems, Prefectural University of Hiroshima*, no.1, pp.183-192, 2009 (in Japanese).
[8] H. L. Lee, V. Padmanabhan and S. Whang, The bullwhip effect in supply chains, *Sloan Management Review*, pp.93-102, 1997.
[9] H. Kondo and K. Nisinari, Modeling stock congestion in production management, *Reports of RIAM Symposium, Mathematics and Physics in Nonlinear Waves*, no.20, pp.146-149, 2008 (in Japanese).
[10] S. J. Baderstone and V. J. Mabin, A review Goldratt's theory of constraints (TOC) – Lessons from the international literature, *Operations Research Society of New Zealand the 33rd Annual Conference*, University of Auckland, New Zealand, 1998.
[11] K. Shirai and Y. Amano, Production density diffusion equation propagation and production, *IEEJ Transactions on Electronics, Information and Systems*, vol.132-C, no.6, pp.983-990, 2012.
[12] K. Shirai and Y. Amano, A study on mathematical analysis of manufacturing lead time – Application for deadline scheduling in manufacturing system, *IEEJ Transactions on Electronics, Information and Systems*, vol.132-C, no.12, pp.1973-1981, 2012.
[13] K. Shirai, Y. Amano and S. Omatu, Process throughput analysis for manufacturing process under incomplete information based on physical approach, *International Journal of Innovative Computing, Information and Control*, vol.9, no.11, pp.4431-4445, 2013.
[14] K. Shirai, Y. Amano and S. Omatu, Improving throughput by considering the production process, *International Journal of Innovative Computing, Information and Control*, vol.9, no.12, pp.4917-4930, 2013.
[15] K. Shirai, Y. Amano and S. Omatu, Consideration of phase transition mechanisms during production in manufacturing processes, *International Journal of Innovative Computing, Information and Control*, vol.9, no.9, pp.3611-3626, 2013.
[16] K. Shirai, Y. Amano, S. Omatu and E. Chikayama, Power-law distribution of rate-of-return deviation and evaluation of cash flow in a control equipment manufacturing company, *International Journal of Innovative Computing, Information and Control*, vol.9, no.3, pp.1095-1112, 2013.
[17] H. Tasaki, *Thermodynamics – From a Modern Point of View (New Physics Series)*, Baifukan, Co., LTD., 2000.
[18] T. Kamibayashi and S. Matsuda, Analysis of a negative resistance oscillator-quasi-harmonic oscillation, *Shiga University Repository*, pp.56-66, 1973.
[19] P. Wilmott, *Derivatives*, John Wiley & Sons, 1998.
[20] K. Kitahara, *Nonequilibrium Statistical Physics*, Iwanami, Co., LTD, 1997.
[21] F. Takase, Multi-mode vibration in the group of transmitters coupled lattice, *KURENAI: Kyoto University Research Information Repository*, vol.413, pp.10-29, 1981.