Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Correlation Analysis of TSUNAMI Phenomena and Failure Rate Fluctuation in Manufacturing System

Youichi Nonaka * **Attila Lengyel** ** **Makoto Ono** ***
Koichi Sugimoto ****

* *Manufacturing System 2nd Dept., Production Engineering Research Laboratory, Hitachi Ltd., Japan (e-mail: youichi.nonaka.ym@hitachi.com)*
** *Manufacturing System 2nd Dept., Production Engineering Research Laboratory, Hitachi Ltd., Japan (e-mail: attila.lengyel.fj@hitachi.com)*
*** *Manufacturing System 2nd Dept., Production Engineering Research Laboratory, Hitachi Ltd., Japan (e-mail: makoto.ono.fq@hitachi.com)*
**** *Department of Mechanical Science and Engineering, Tokyo Institute of Technology, Japan (e-mail: sugimoto@mech.titech.ac.jp)*

Abstract: Tremendous growth of the home information appliances requests semiconductor manufacturing to respond *High Product Mix and Low Production Volume* condition. Such condition in manufacturing operations challenges production management to have rapid improvement activities in an environment with uncertain productivity and demand. In this research *Visualized Coefficient of Variation Analysis (VCVA)* was applied to measure fluctuations in the flow of production material on a time-line basis. Based on this approach a monitoring tool was developed and implemented in a wafer manufacturing system and an assembling system to support production management in root cause analysis and productivity improvement. Results show the effectiveness of the method by visualizing *TSUNAMI* phenomena, as a typical case of *Butterfly Effect* in the material flow fluctuation, by identifying the root cause equipment as the source of productivity detractor, and by revealing significant relationship between material flow fluctuation and failure rate fluctuation.

1. INTRODUCTION

1.1 Motivation

The world wide market of home information appliances was announced 492 Billion US$ in 2004 and will grow to 869 Billion US$ by 2010 [Murakami(2004)]. In this market, semiconductor manufacturing is the key industry since *ASIC* (Application Specific Integrated Circuits) demand has been radical extending for the appliances. To fabricate *ASIC* in the latest semiconductor process technology, *High Product Mix and Low Production Volume* condition is required [Osada(2006)].

In the viewpoint of operations management, semiconductor manufacturing has a unique character as being a large size production system with dozens of exposure process. Systems are job-shop type production systems where equipments handle many process, and in which one process is distributed to several equipments. Additionally, production yield rate in mass production starts from under 50%, and improves with a violent fluctuation to the process maturity. To establish *High Product Mix and Low Production Volume* condition with these characters, rapid and continuous improvement activities with identifying manufacturing productivity decreasing factors are desired. This paper contributes to such improvement activities.

1.2 Approach

The approach describes a production system as a network having nested loops for re-entrant processes, and scrap operations. The system has unreliable equipments having imperfect random yield rate and uncertainty of process time and time to failure. In this condition, the focus is set on manufacturing variability analysis in order to identify productivity detractors.

For identifying productivity detractors, this research applies quantification analysis of variability using standard measures in statistics called *Coefficient of Variation (CV)*. To implement it in practice, a new method called *Visualized Coefficient of Variation Analysis (VCVA)* was developed that uses an effective visualization technique for material flow analysis on a time-line basis.

1.3 Related Literature

Manufacturing variability is studied in the field of quality control. DeVor, Chang, and Sutherland propose a process capability assessment from the viewpoint of statistical quality analysis [DeVor(1992)]. Hopp and Spearman describe measures and classes of manufacturing variability [Hopp(1995)].

There are also approaches that evaluate manufacturing performance in the viewpoint of flexibility. Vakharia, Askin, and Selim classify flexibility into specific levels to identify significant improvement points at the system design [Vakharia(1999)]. Parker and Wirth study key parameters for flexibility with use cases [Parker(1999)].

2. METHODOLOGY OF VCVA

2.1 Target

To identify productivity detractors, the most conventional techniques are the mutual comparison of each process throughput fluctuation and/or WIP (Work In Process) level fluctuation [Hopp(1995)]. However, using these techniques it cannot be concluded that the root cause of the productivity decreasing is in the most fluctuated process, since the effect of a detractor in another process might be transferred and intensified through several processes causing chained process performance fluctuations along with the production material flow. Applying CV without considering cause and effect, only each process capability to fluctuation can be understood. Hence, the target of this research is to establish an effective identification technique of manufacturing productivity detractors for large size production systems. The requested specifications for this research are to develop a technique that can be applied to more than 500 processes in a system, and identify detractors to support daily manufacturing productivity improvement activities.

2.2 Methodology

The procedure of $VCVA$ consists of the following steps.

(1) Coefficient of $VCVA$ (c_{ia}) calculation at any time domain and any process
(2) Visualization Matrix of $VCVA$ creation with c_{ia}
(3) Visualization Matrix of $VCVA$ coloring according to c_{ia} value
(4) Productivity detractors identification by Colored Visualization Matrix analysis

The following describes for each items.

In the definition of Hopp and Spreaman [Hopp(1995)], coefficient c of CV is defined as following equation.

$$c = \frac{s}{r} \tag{1}$$

In equation (1), s denotes standard deviation of manufacturing performance like tool throughput and WIP level at a tool. And r denotes mean value of the manufacturing performance. That is, coefficient c quantifies manufacturing fluctuation at one tool in a manufacturing system.

In the first of $VCVA$ (c_{ia}) calculation, the scope of CV is extended to analyze production material flow fluctuation on a time-line basis for identifying manufacturing productivity detractors, First, a time element as a CV parameter is added as follows:

$$r_{ia} = \frac{1}{k} \sum_{j=a-k}^{a} p_{ij} \tag{2}$$

In Equation (2), suffix j is the time element that refers to the examined time period and p_{ij} is the productivity indicator of process i at time period j. Throughput, equipment utilization and process failure rate can be productivity indicators as p_{ij}. The indicator p_{ij} is accumulated in the time period from $a - k$ to k. To indicate time related dependency, the moving average of productivity indicator p_{ij} of process i at time a within period k expressed with r_{ia}. The variance of p_{ij} is declared as follows:

$$s_{ia} = \sqrt{\frac{1}{k} \sum_{j=a-k}^{a} (p_{ij} - r_{ia})^2} \tag{3}$$

In Equation (3), s_{ia} denotes the variance of the productivity indicator p_{ij} of process i at time a within period k. Finally, the extended coefficient of variation is defined as follows:

$$c_{ia} = \frac{s_{ia}}{r_{ia}} \tag{4}$$

In Equation (4), c_{ia} is the extended coefficient of variation of process i at time a.

Process Flow

Time

	P_1	P_2	. . .	P_{i-1}	P_i	P_{i+1}	. . .	P_n
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
T_{x-1}	c_{1x-1}	c_{2x-1}	. . .	c_{i-1x-1}	c_{ix-1}	c_{i+1x-1}	. . .	c_{nx-1}
T_x	c_{1x}	c_{2x}	. . .	c_{i-1x}	c_{ix}	c_{i+1x}	. . .	c_{nx}
T_{x+1}	c_{1x+1}	c_{2x+1}	. . .	c_{i-1x+1}	c_{ix+1}	c_{i+1x+1}	. . .	c_{nx+1}
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

Fig. 1. Visualization Matrix of VCVA

Figure 1 shows the approach of visualizing process fluctuation on a time-line basis. In Figure 1, P_1, ..., P_{i-1}, P_i, P_{i+1}, ..., P_n denotes the set of manufacturing process in order of the manufacturing routing groups, and T_{a-1}, T_a, T_{a+1} are the series of the manufacturing performances within the time period.

And in the case of c_{i-1x} calculation with Equation (4), c_{i-1x} calculation window in Figure 1 locates P_{i-1} column and time period between T_{x-1} and T_x, if c_{ia} has two time domain moving average ($k = 2$ in Equation (2) and Equation (3)).

Next, the background color of each cell is set according to the value of c_{ia}.

Type	Class	Color	Fluctuation
A	$c_{ia} < LB$		Ignorable
B	$LB \leqq c_{ia} < UB$		Middle
C	$UB \leqq c_{ia}$		Heavy

LB; Lower Boundary, UB; Upper Boundary

Fig. 2. Color definition in Visualization Matrix of VCVA

Figure 2 shows the c_{ia} color classification to visualize material flow fluctuation on a time-line basis. To use Type A, B, and C classifications in Figure 2, cells in Figure 1 can compose some patterns that reflect fluctuations of material flow showed in Figure 3.

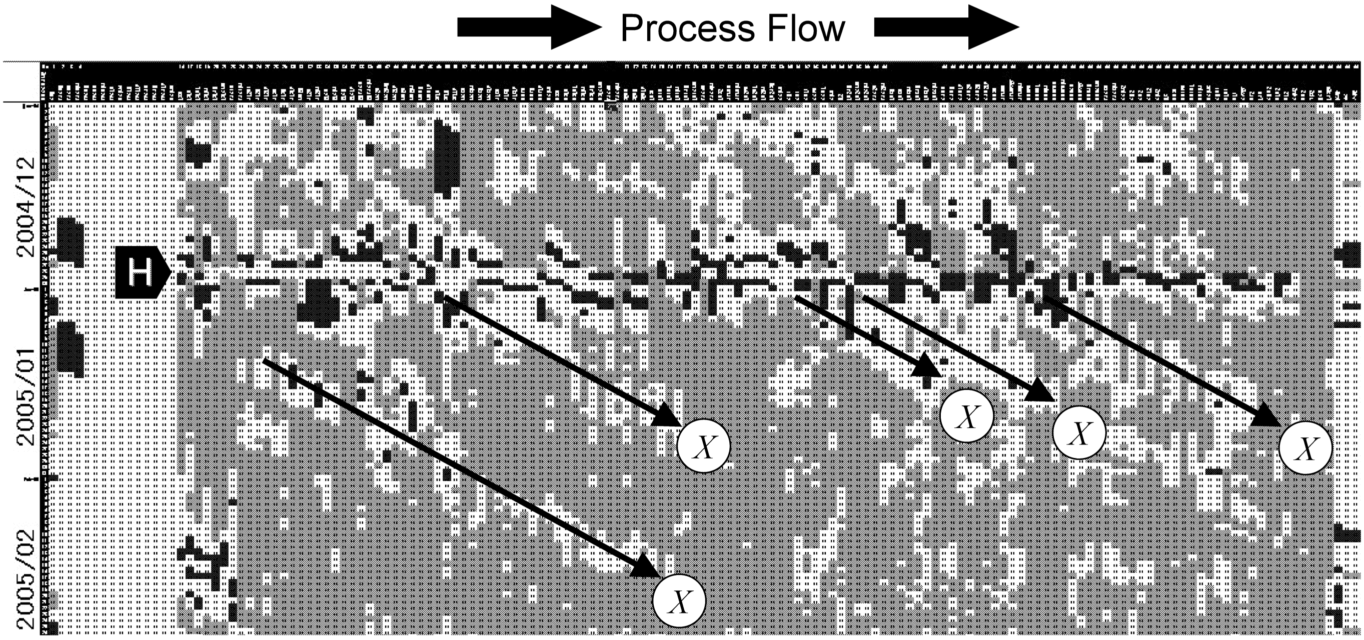

Fig. 4. TSUNAMI Phenomena on VCVA Visualization Matrix

Process Flow →

Time ↓	P_1	P_2	...	P_{i-1}	P_i	P_{i+1}	...	P_n
...	...	...	...	...	...	...	...	...
T_{x-1}	c_{1x-1}	c_{2x-1}	...	c_{i-1x-1}	c_{ix-1}	c_{i+1x-1}	...	c_{nx-1}
T_x	c_{1x}	c_{2x}	...	c_{i-1x}	c_{ix}	c_{i+1x}	...	c_{nx}
T_{x+1}	c_{1x+1}	c_{2x+1}	...	c_{i-1x+1}	c_{ix+1}	c_{i+1x+1}	...	c_{nx+1}
...	...	...	...	...	...	...	...	...

Fig. 3. Colored Visualization Matrix of VCVA

In this study, the distributions of the manufacturing system behaviors are assumed to follow Normal Distribution, so LB is set as 0.75 and UB as 1.33 to refer manufacturing operation variability classes[Hopp(1995)]. This assumption remains to be solved since what phenomena follow Normal Distribution would be in a minority when the distribution of social phenomena or animate beings population phenomena is considered. But in the real application phase, this criterion can be changed systematically in order to improve that resolution for continuous improvement of each manufacturing system performance. At last, by those patterns in Figure 3, mutual process fluctuation influences on a time-line basis is visualized rapidly even in a large size production system.

3. APPLICATION RESULTS

3.1 TSUNAMI Phenomena

The VCVA methodology was applied to semiconductor manufacturing systems to verify the effectiveness of the approach. Figure 4 shows an application result to a complex job-shop manufacturing system that has about 500 processes.

In Figure 4, the set of manufacturing process in order of the manufacturing routing is indicated in a transverse direction. In the longitudinal direction, manufacturing operational days are indicated. The daily throughput is set as the productivity indicator in the *VCVA* matrix, and LB is set as 0.75 and UB as 1.33 in the color definition. In this examination, the examined period contains a shut down of the manufacturing system according to the factory calendar. In Figure 4, Symbol 'H' sign shows the shut down period.

In this matrix, several clusters can be seen composed by Type B and C colors indicating fluctuations occurred in the material flow of the system. Especially, some clusters named X in Figure 4 extend diagonally downward right at some length. Those special clusters was generated by equipment performance fluctuations at the system resumption and become manufacturing productivity detractors. These detractors are accounted for generating a large amount of WIP. As it can be seen in the matrix, the accumulated WIP is transferred into the downstream.

To express this phenomenon, in the research work this effect is called *TSUNAMI of WIP* and it is accounted as the root cause of large fluctuations in the downstream processes. It can be noted that the *TSUNAMI* phenomena is a special case of the *Butterfly Effect* in chaotic theory observed in a manufacturing system. *Butterfly Effect* describes a nonlinear phenomenon where small variations in a system may cause large variations in the long-term system behavior. In chaotic theory, *Butterfly Effect* is usually observed in meteorological variation of natural world and social phenomenon like population growth, but there are few cases observed in manufacturing system. *TSUNAMI* phenomena in this study can be a typical example of *Butterfly Effect.*

According to this result, the maintenance procedures of an etch equipment and a photolithography equipment were found as the root cause of the *TSUNAMI of WIP*. By those tool maintenance procedure improvement, productivity improvement of the system was achieved.

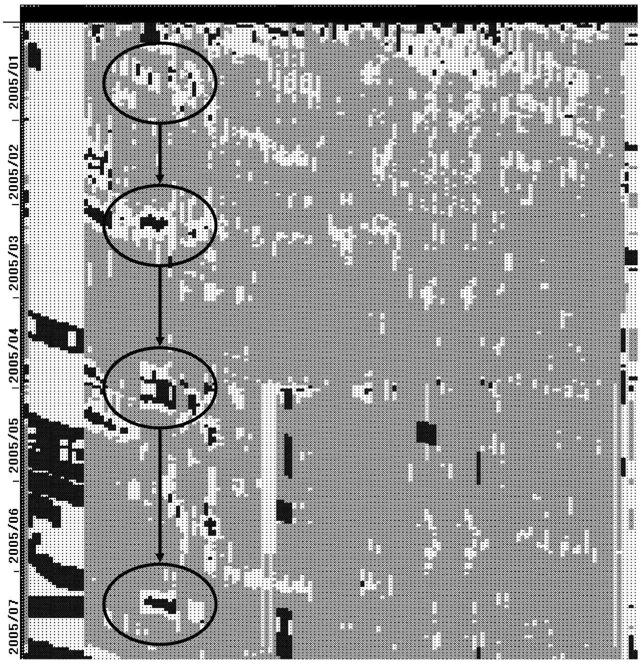

Fig. 5. Periodical Maintenance Effect on VCVA visualization matrix

3.2 Periodical Maintenance Effect

Figure 5 shows another result in the same system of Figure 5. In Figure 5, the set of manufacturing process in order of the manufacturing routing is indicated in a transverse direction. In the longitudinal direction, manufacturing operational days are indicated. The daily throughput is set as the productivity indicator in the *VCVA* matrix, and *LB* is set as 0.75 and *UB* as 1.33 in the color definition. In Figure 5, one group of clusters are observed as a periodical chain on a time-line. This cluster does not transfer to downstream, different from *TSUNAMI*. The repetition interval is about 1.5 month, and the interval was matched to periodical maintenance of an ion beam sputter tool. A detail investigation found periodical maintenance failure of the ion beam sputter tool was caused manufacturing fluctuation showed as clusters in Figure 5. By the maintenance improvement, productivity improvement of the system was achieved.

4. CORRELATION ANALYSIS TO FAILURE RATE FLUCTUATION

The previous section reveals *VCVA* is an effective tool to visualize material flow fluctuation and to identify root cause of productivity detractors. At this point, if the material flow fluctuation is caused by human operator's error, such as lack of human resources, operation skill, and so on, then the material flow fluctuation like *TSUNAMI of WIP* is supposed to correlate with fluctuation of human failure rate. That is, if material flow fluctuation is stabilized by *VCVA* results, then human failure rate must be decreased to improve manufacturing productivity, too. In this section, *VCVA* is applied to not only material flow fluctuation but also failure rate fluctuation for the analysis of this correlation.

First, failure rate y_{ia} is described as following equation.

$$y_{ia} = \frac{f_{ia}}{d_{ia}} \tag{5}$$

In Equation (5), f_{ia} is the amount of failures at process i time a, d_{ia} is the total amount of completion at process i time a. Using Equation (2), (3), and (4), *VCVA* (c_{ia}) calculation for failure rate is defined as following equations.

$$r_{ia} = \frac{1}{k} \sum_{j=a-k}^{a} y_{ij} \tag{6}$$

$$s_{ia} = \sqrt{\frac{1}{k} \sum_{j=a-k}^{a} (y_{ij} - r_{ia})^2} \tag{7}$$

Equation (6) indicates failure rate moving average at process i at time j with moving average period a, and Equation (7) is failure rate variance at process i at time j. Finally, Equation (4) for failure rate is calculated by Equation (6) and (7).

Failure rate correlation analysis was executed an assembling manufacturing system that has some dozens of assembling process with many operators work for each process. In each process, not only daily completion volume and WIP level but also failure rate are recorded since inspection is executed for each. The system has monthly target production volume, but no systematical progress control like Kanban, Scheduler, and Dispatcher.

Figure 6 shows a result of *VCVA* failure rate correlation analysis. The leftside figure shows daily completion volume, and the rightside figure shows failure rate. In both figures, the set of manufacturing process in order of the manufacturing routing is indicated in the transverse direction, and manufacturing operational days are indicated in the longitudinal direction. And *LB* is set as 0.75 and *UB* as 1.33 in the color definition. In the left side figure, production fluctuation is centered in the end of month since bright band in lateral direction is observed. With some detail investigation this phenomena reveals to be occurred by the production progress skew, since operators tend to be overworked to achieve monthly target production volume. That is, overload of operation caused production fluctuation.

In the right side figure, some failure rate fluctuations occur in several processes since black bands in vertical direction are observed. And failure rate fluctuation seems to be centered in the end month, but the convergence is not so obvious compared to the production fluctuation in the left side figure. If correlation between production fluctuation and failure rate fluctuation is clear, then the production progress skew is verified to affect not only production fluctuation but also production quality. So, to verify the correlation, a comparative statistical analysis is applied in the following. In this study, the daily trend of mean value was calculated for each *VCVA* result.

Figure 7 shows the daily trend of mean value in production fluctuation *VCVA* result. And Figure 8 shows the daily trend of mean value in failure rate fluctuation *VCVA* result. In both figures, the bar chart of daily mean value is ordered by date. And a convex trend is observed in the end

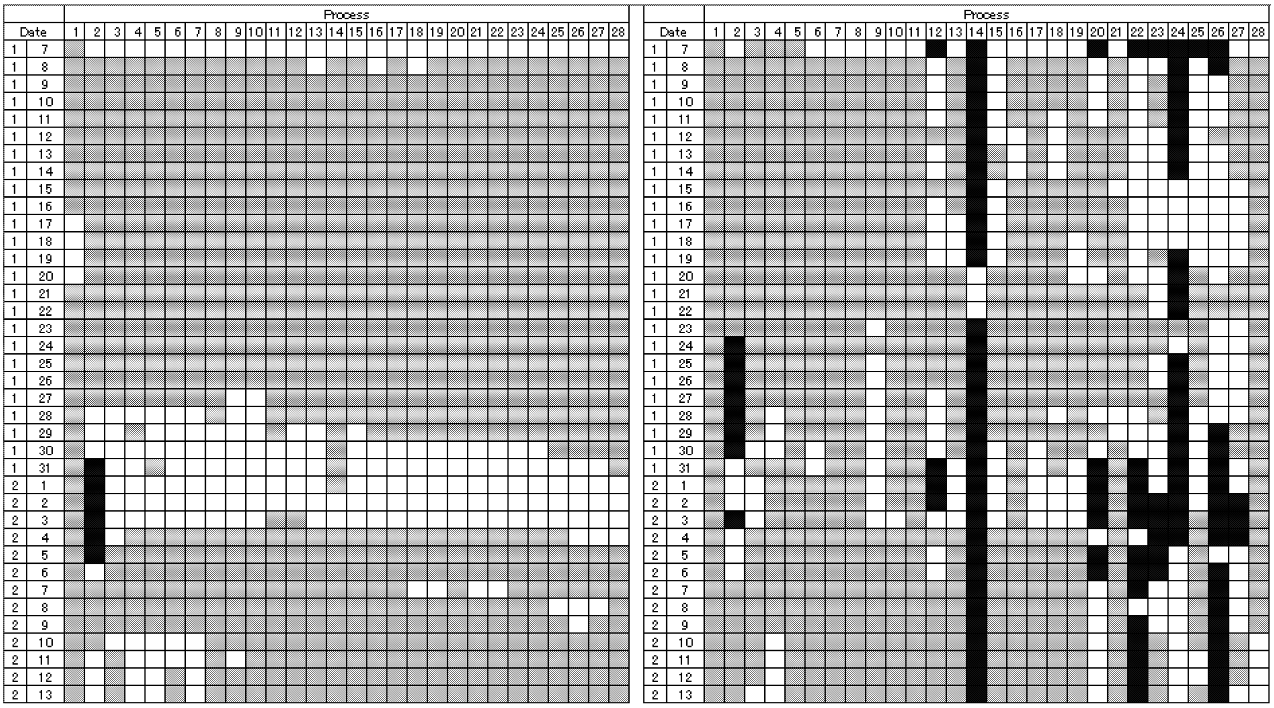

Fig. 6. CVA Result of Daily Completion and Failure Rate

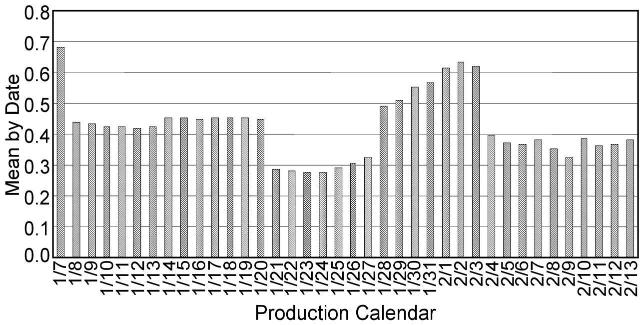

Fig. 7. Daily Meam Value of Daily Completion CVA Result

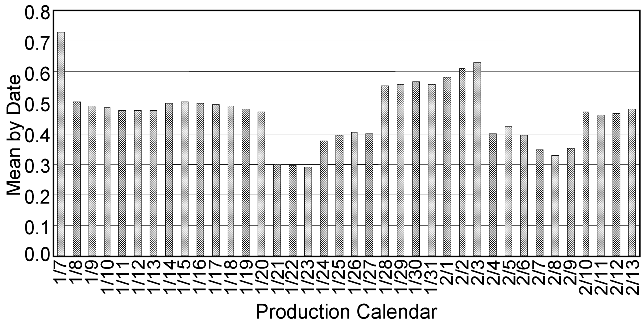

Fig. 8. Daily Meam Value of Failure Rate CVA Result

of the month for each figure. That is, this analysis reveals production fluctuation correlates directly with production quality. At last, since material flow fluctuation is supposed to correlate with fluctuation of human failure rate, when material flow fluctuation is stabilized by *VCVA* results, then human failure rate will be decreased to improve manufacturing productivity, too. According to this result, some manufacturing performance improvement plans are promoted to the sampled manufacturing system so as to avoid the production progress skew by a CONWIP[Hopp(1995)] type control system application. This system is now under evaluation.

5. BUSINESS CONTRIBUTION

VCVA check cycle has been established in a continuous manufacturing performance improvement activity in a real manufacturing condition. After the implementation of *VCVA* technology to a manufacturing execution system as a real-time manufacturing visualization tool, production management team come to monitor *VCVA* status daily. And when they find there is going to be a TSUNAMI in the manufacturing system, they find the detractors from *VCVA* monitor, analyze the root cause by checking process tool log of each detractor, and modify some to terminate the detractors. Also, they have reviewed past manufacturing status through *VCVA* monitor to find improvement potentials. If they find a TSUNAMI in the past manufacturing status, then they find the detractors, analyze the root cause by checking process tool logs of each detractor, and modify some to terminate the detractors.

Figure 9 shows an improvement result of a semiconductor manufacturing system with the system shut down influence to the manufacturing productivity. In the figure, symbol 'H' indicates annual system shutdown and resumption by the production calendar. The left side figure shows 2005 manufacturing condition in *VCVA* result before application of the *VCVA* check cycle, and right side figure shows 2006 manufacturing condition in *VCVA* result after application of the *VCVA* check cycle. In both figures, the set of manufacturing process in order of the manufacturing routing is indicated in the transverse direction, and manufacturing operational days are indicated in the longitudinal direction. And LB is set as 0.75 and UB as 1.33 in the color definition.

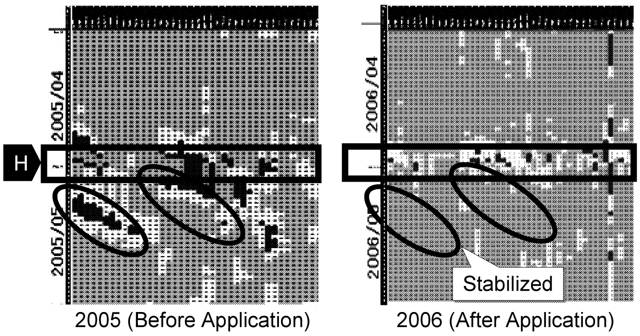

Fig. 9. A productivity improvement result

Since the system has an annual shut down at the end of April, some *TSUNAMI of WIP* were observed in the leftside figure due to some manufacturing tool resumption procedure errors affect manufacturing fluctuation. After application of the *VCVA* check cycle shown in the rightside figure, a stable resumption could be achieved in the same system. Actually, the workload of the resumption has reduced from 2 weeks to 5 days.

6. CONCLUSION

By identifying manufacturing productivity detractors using *VCVA* method, rapid and continuous improvement activities were established and supported in a large sized manufacturing system. *VCVA* was revealed to detect *Butterfly Effect*, *TSUNAMI of WIP*, leading to a significance productivity detractor. And *VCVA* was also revealed the correlation between material flow fluctuation and human failure rate fluctuation, so when material flow fluctuation is stabilized by *VCVA* results, then human failure rate will be decreased to improve manufacturing productivity, too. Following experimental verification in some factories, the technique has now been adopted as standard factory monitoring tool.

REFERENCES

[Murakami(2004)] K. Murakami, Ministry of Economy, Trade and Industry, 2004, Road Map for Increasing Profitability of Home Information Appliance Industry, NIKKEI Digital CORE. http://www.nikkei.co.jp/diglcore/report/041102/01.html.

[Osada(2006)] T. Osada, Economy of Semiconductor Productivity Improvement - 450mm & 300Prime -, SEMI Technology Symposium 2006 Proceedings, 1-6 - 1-9.

[DeVor(1992)] R.E. DeVor, T. Chang, and J.W. Sutherland, Process Capability Assessment, Statistical Quality Design and Control: Contemporary Concepts and Methods, 255-297.

[Hopp(1995)] W.J. Hopp and M.L. Spearman, 1995, Variability Basics, Factory Physics, 248-286.

[Vakharia(1999)] A.J. Vakharia, R.G. Askin, and Hassan M. Selim, 1999, Flexibility Considerations in Cell Design, Handbook of Cellular Manufacturing Systems, 249-274.

[Parker(1999)] R.P. Parker, A. Wirth, 1999, Theory and Methodology: Manufacturing Flexibility: Measures and Relationships, European Journal of Operational Research 118, 429-449.

[Hopp(1995)] W.J. Hopp and M.L. Spearman, 1995, Basic Factory Dynamics, Factory Physics, 213-247.