A DEVELOPMENT OF OPTIMAL BUFFER ALLOCATION DETERMINATION METHOD FOR μ-UNBALANCED UNPACED PRODUCTION LINE

by

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TABLE OF CONTENT

Page

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

μ	Mean process time of each work station
C_v	Coefficient of variation for each station's μ
X	Throughput rate (efficiency) of the production line
E	Number of extra buffer (buffers) after allocating the buffers equally among the buffer slots.
6 Steps OBA	Six mathematical steps developed by this research to get the OBA for the μ-unbalanced production line.
OBA Determination Flow	An easy (simple) flow developed for a management guidance on how to determine *OBA* for the production line.
pdf	Probability Density Function, a type of probability function for continuous random variables.
Unpaced	A production line where the material is not pulled by demand but in a push mode. No conveyor belt is used.
MODAPTS	*Modular Arrangement of Predetermined Time Standard,* a standard method used to determine time for doing a particular process using work study analysis.
SST	Standard Time, standard working time based on calculation from *MODAPTS* method
OBA	Optimal Buffer Allocation, the optimum number of buffers to be allocated in buffer slots for maximum throughput rate of the production line
Buffer	Work In Progress, inventory that is currently being processed in an operation or inventory that has been processed through one operation and is awaiting another operation.
Buffer slot	place to put buffer between stations.
Total buffer Size (*B*)	Total number of buffers allowed by management to be allocated in intermediate buffer slots between the workstations.
WIP	same meaning as buffer

FMEA	Failure Mode and Effect Analysis, a systematic technique which identifies and ranks the potential failure modes of a design or manufacturing process in order to prioritize improvement actions.
DOE	Design of Experiment, the complete sequence of steps taken ahead of time to ensure that the appropriate data will be obtained, which will permit an objective analysis and will lead to valid inferences regarding the stated problem.
SS	Six Sigma method, a set of techniques focused on business process improvement and quality.

PEMBANGUNAN KAEDAH PENENTUAN PERUNTUKAN PEMAMPAN OPTIMUM UNTUK TALIAN PENGELUARAN TIDAK MELANGKAH KETIDAKSEIMBANGAN-μ

ABSTRAK

Kajian ini membincangkan masalah peruntukan pemampan di dalam talian pengeluaran tidak melangkah dengan ketidakseimbangan-μ. Talian pengeluaran tidak melangkah adalah merujuk kepada satu talian pengeluaran dengan stesen kerja yang beroperasi secara bebas dan bahan tidak ditarik secara paksaan tetapi di dalam mod tolakan. Di dalam kajian ini, talian pengeluaran adalah tidak melangkah, ketidakseimbangan-μ tetapi boleh diharap. Peruntukan pemampan optimum (*OBA*) perlu dicari untuk talian pengeluaran seumpama ini. Subjek ini penting kerana kini syarikat dengan produk bersaiz kecil dan sederhana menggunakan talian pengeluaran tidak melangkah dan kaedah sesuai penentuan *OBA* diperlukan. *OBA* adalah merujuk kepada bilangan optimum pemampan yang diperuntukkan di dalam slot pemampan perantaraan di antara stesen untuk membolehkan kadar kecekapan (*throughput*) dapat dimaksimakan dan bilangan *kerja dalam proses* (*WIP*) di dalam talian dapat dioptimumkan. Kajian ini dibahagikan kepada dua fasa utama. Di dalam fasa 1, kaedah carian digunakan untuk mendapatkan kadar kecekapan untuk suatu set bentuk peruntukan pemampan yang diberikan di dalam talian pengeluaran menggunakan perisian simulasi *Arif's algorithm*. Beberapa *Konsep Asas OBA*

(BOC) yang mewakili ciri-ciri OBA disimpulkankan daripada kaedah carian. Dengan mengaplikasikan *BOC* ini, perkembangan *Aliran Penentuan OBA* dilakukan di dalam fasa 2. *Aliran Penentuan OBA* yang menggunakan perkakas *6 Langkah OBA* diaplikasikan untuk panduan pihak pengurusan di dalam memperuntukkan pemampan semasa merekabentuk susunatur, berdasarkan μ untuk setiap stesen di dalam talian pengeluaran tersebut. *Aliran Penentuan OBA* ini dihasilkan bagi meringkaskan aliran untuk mendapatkan *OBA* bagi talian pengeluaran seimbang dan ketidakseimbangan-μ. Dua kajian kes sebenar dengan bilangan stesen yang berbeza dijalankan di sebuah syarikat elektronik multinasional di kawasan utara Semenanjung Malaysia untuk membuktikan keputusan daripada *Aliran Penentuan OBA* yang dikembangkan. Daripada kajian kes yang dijalankan, terbukti *OBA* yang diperolehi menggunakan kaedah yang dikembangkan memberikan kadar kecekapan (produktiviti) yang tertinggi untuk talian pengeluaran. Secara umumnya, *Aliran Penentuan OBA* yang dibangunkan sesuai digunakan sebagai kaedah penentuan *OBA* untuk aliran pengeluaran tidak melangkah ketidakseimbangan-μ.

A DEVELOPMENT OF OPTIMAL BUFFER ALLOCATION DETERMINATION METHOD FOR μ-UNBALANCED UNPACED PRODUCTION LINE

ABSTRACT

This research deals with a buffer allocation problem in an unpaced (asynchronous) μ-unbalanced production line. Unpaced line is referred to a line with workstations act independently and the material is not pulled by demand but in push mode. In this research, the production line is considered unpaced, μ-unbalanced but reliable. The optimal buffer allocation (*OBA*) needs to be determined for this particular type of production line. This subject is importance since recently many small and medium sizes products' companies are utilizing unpaced production lines and a convenient method of determining *OBA* is required. *OBA* is referred to the optimum number of buffers to be allocated in the intermediate buffer slots between the workstations so that it can maximize throughput rate and optimize total number of *work in progress* (*WIP*) on the line. This research's problem statement is divided into two main phases. For phase 1, a searching method using *Arif's algorithm* simulation software is carried out to simulate the throughput rate for a given sets of buffer allocation shapes in the production line. Few *Basic OBA Concept (BOC)* represented the characteristics of *OBA* for a production line was summarized from the searching method. By applying these *BOC*, a development of *OBA Determination Flow* is carried out in phase 2. *OBA Determination Flow* which utilized *6 Steps OBA* tool is used to guide the management in allocating the buffer during designing a line layout, with reference to the μ of each station in the production line. This *OBA Determination Flow* will summarize the flow of determining *OBA* for both fully balanced and μ-unbalanced line. Then, two actual case studies with different numbers of stations carried out in one of the multinational electronic company in north region of Peninsular Malaysia to validate the result from *OBA Determination Flow* developed. From the case studies, it is proven that the *OBA* decided by using the flow established giving the highest performance to the production line. Generally, *OBA Determination Flow* developed could be utilized as an *OBA* determination method for μ-unbalanced unpaced production line.

CHAPTER 1 : INTRODUCTION

1.1 Background

Recently, there are many researches that have been carried out in improving the production line from the work in progress *(WIP)* perspective. This is due to a demand from a company's management to lead the global competition among manufacturing companies. One of the areas that focused by researchers is a study to maximize the production line throughput rate (efficiency), *X* and productivity. Throughput rate could be defined as an efficiency of the production line to produce one unit of completed product in a specified time period. Dennis (2001) defined line's throughput rate as the average number of jobs per unit time that can flow through a production line while station's throughput as the number of jobs the station can produce per unit time, taking account of failures. Fully efficient production line is said to be achieved when the throughput rate is equal to 1.00. For a few of the companies, sometimes the efficiency of the production line is determined by line productivity. Basically, line productivity is defined as a percentage of total units output produced in specified working hours and number of manpower in a calculated total standard time (*SST*). The line is said to be good if it achieves 100% productivity. However, it is quite a challenging task for a line to achieve more than 100% productivity.

The management is fighting for a better efficiency of their production lines due to a demand for manufacturing industries. It has become a challenge to a management to design the best and perfect production line layout that can maximize the output with the lowest investment. At the same time they also need to consider the space availability during designing the line layout, optimize manpower usage and selection of good machines and equipment to minimize (or even avoid) any downtime related to machine failure. Nowadays, unpaced production line (sometimes called cell line concept) is one of the direction for the management to reduce the investment cost during new product introduction. This line concept is suitable for small and medium size products such as computer peripheral and accessories products, home appliances products and small electrical products. Many multinational companies are using the cell line concept for their product assembly line.

In the real world, it is impossible for unpaced production line to achieve 100% perfect balance and reliable lines. This is due to many factors causing the lines to become unreliable and unbalance. The sources of unbalanced are mean processing time (μ), coefficient of variation (C_v) and buffer allocation that need to be considered for balanced production line. In an actual unpaced production line, μ for each station is difficult to be set at a perfectly balanced or distributed uniformly. As for an unreliable line, more factors need to be taken into consideration such as failure rate, machine downtime and repair rate.

One of the possible methods to optimize the line efficiency is by identifying the optimal buffer allocation (*OBA*) of the line. Buffer allocation is an important, yet intriguingly difficult issue in planning the physical layout and location of the production line layout. Optimal buffer allocation can optimize production line performances such as minimizing buffer (work in progress, *WIP*), cycle time, blocking probability and maximizing throughput rate.

There is a necessity between researchers, industrial engineers and managements to synchronize their understanding in buffer allocation at the actual production line. Therefore, the *OBA Determination Flow* need to be developed as a guideline for a management to set up a production line with the optimum buffer allocation, hence could lead to the best line efficiency.

1.2 Problem statement

As has been discussed in previous section, nowadays a majority of companies in Malaysia are practicing a cell line concept (unpaced line) particularly the manufacturing companies that produce small and medium size products. The production line in these companies usually is considered unpaced or asynchronous line, reliable but with μ unbalanced. The company's management unquestionably will put a goal of getting 100% reliable line. A good manufacturing company must move to a nearly perfect (reliable) production line. Generally, a reliable line is achieved by selecting good machines and well trained operators. There are also zero failure rates for the assembly process and inspection station which would be achieved by good equipment maintenance and a good support of engineering knowledge to avoid line machine's downtime and product (process) failures. Once a failure occurred, it must be fixed and repaired (corrected) as soon as possible. In addition to that it has become a norm in any manufacturing company to have a goal in maximising the production line's throughput rate (Efficiency), *X* and productivity. Even though various concepts and solutions have been proposed for realizing the goals stated such as lean concept, quality improvement methods and so on, still there is opportunity for better and simple solutions. As an example, one of the solutions is in identifying the accurate buffer in term of the quantity and the size to be used on the production line.

Therefore, it will be a revolution for companies especially in Malaysia to adopt the concept of arranging the correct number of buffers known as optimal buffer allocation (*OBA*) between the stations in the production line in order to achieve the best line's throughput rate, *X* and productivity. Even though various number of research has been carried out over the years relating to the *OBA* but most of the findings is convoluted to be adopted in real world. One of the possible reasons for the company management not to practice the *OBA* is due to an unavailability of easy guidelines to adopt the concept.

Hence, a better optimal buffer allocation *(OBA)* is needed to be developed for this particular type of production line so that it can maximize *X* and minimize (optimize) total number of buffer (*Work In Progress* (*WIP*)) on the line (both on workstation and on buffer slot). In addition to that there is a challenge for the researchers to convince the company management to adopt the findings from the concept of identifying the *OBA* of the production line. As a result a direct guidance to management on how to apply the *OBA* to the production line needs to be developed as well.

1.3 Research objective

The main objectives of this research are as follows:

a) To categorize the unpaced production line in order to have a better understanding of the criteria and characteristics of this production line. It will be achieved by reviewing the relevant literatures related to this subject matter.

b) To develop a methodology and a flow to determine the OBA of the μ-unbalanced unpaced production line. The flow is called *OBA Determination Flow*. This will be achieved by adopting and improving the previous work done by various authors identified in the literatures. Simulation, searching and mathematical approaches will be used during developing this flow.

c) To validate the findings concluded in the *OBA Determination Flow*. This flow will be tested in an actual unpaced production line at one electronics manufacturing company in the northern area of Peninsular Malaysia. Two different products (with different μ-unbalanced shapes, number of stations and buffers) produced by this company will be selected for the verification and validation purposes.

1.4 Layout of Thesis

This thesis is organized as follows. In chapter 2, all the literature review findings related to the discussed topic were highlighted. There are various papers discussing the combination between unbalanced, balanced, unreliable and reliable production line conditions. Each paper was studied in order to understand previous researchers' scopes, findings and limitations. Based on the literatures, there is still no any single study carried out to discuss the management guide to allocate buffer in the production line. Therefore this research will focus on the easy method to determine the *OBA* of the production line, once the total number of stations and buffers are decided.

Then in chapter 3, the production line model selected, methodology and approach used to complete the research was explained. The methodology used is broken down into two major phases; Phase 1 and Phase 2. In phase 1, searching method is used to find out few *Basic OBA concept (BOC)* which need to be followed during determining *OBA* of the production. Next in phase 2, based on the *BOC* results, *OBA Determination Flow* using a tool called *6 Steps OBA* is developed. The *OBA Determination Flow* concluded the finding as a management guidance to get *OBA* of the production line.

In chapter 4, details of findings in two different case studies were discussed. These case studies were carried out in actual production line for two different product models in one multinational company in northern Peninsular Malaysia. The purposes of these case studies are to confirm whether the method and approach developed would be applicable to the real world. The results (output) between *OBA Determination Flow* and actual production line throughput rate are compared in details. The two different models and conditions of production line layouts tested in a separate time frame. Case study 1 was tested for unpaced μ-unbalanced production line with eight stations line while case study 2 for 17 stations line. Chapter 4 will give detailed results of the case studies.

Finally, chapter 5 concludes the research besides indicating the proposed future works on the relevant topics.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

The literature review of this research revolved around Optimal Buffer Allocation (*OBA*) for a few combinations of unpaced production line conditions either it is fully balanced, mean process time (μ) unbalanced or coefficient of variation (C_v) unbalanced, reliable or unreliable. The overview of production line's throughput, unpaced production line, balanced and unbalanced production line was also elaborated in the next sections.

2.2 Production Line's Throughput Rate

Production line's throughput rate could be defined as an efficiency of the production line to produce one unit of completed product in a specified time period. It is widely used by management as a performance index of the production line. The highest performance for the production line is achieved when throughput rate value is equals to 1.0 . Dennis (2001) derived the equations to determine production line's throughput rate for two stations arranged in series (with buffer). The parameters involved are the speed (service rate) of a stn i (i=1,2) (jobs per unit time) (*S*), buffer size (number of jobs that can be held in the buffer) (*B*) and the throughput rate of the line (jobs per unit time) (*P*). The production line were assumed as follows :

(i) processing time at station-i are independent and exponentially distributed (with mean $1/S_i$, i =1,2)

(ii) stations are not subject to failures.

Then, the throughput rate of the line (average number of jobs per unit time) is given by :

$$P = S_1 S_2 \left((S_1^{B+2} - S_2^{B+2}) / (S_1^{B+3} - S_2^{B+3}) \right) \qquad (1)$$

In a special case of identical stations ($S1 = S2 = S$), this throughput result reduces to

$$P = \left((B+2) / (B+3) \right) S \qquad (2)$$

Elsayed (1994) represented line's throughput rate as line's efficiency (*LE*) which was defined as the ratio of total station time (*ST*) to the cycle time (*CT*) multiplied by the number of workstations (*N*). In equation, it was given by:

$$LE = \frac{\sum_{i=1}^{N} ST_i}{(N)(CT)} \qquad (3)$$

Station time (*ST*) is the sum of the times of work elements that are performed at the same workstation. Cycle time (*CT*) the time between the completion of two successive assemblies, assumed constant for all assemblies for a given speed. It is obvious that the station time (*ST*) should not exceed the cycle time (*CT*). The minimum value of the cycle time must be greater than or equal to the longest station time. Then, delay time of a station is the difference between the cycle time (*CT*) and the station time (*ST*) (that is the idle time of the station = *CT-ST*). In designing an assembly line, the following restrictions must be imposed on grouping of work elements:

i) Precedence relationship

ii) The number of work stations, cannot be greater than the number of work elements (operations) and the minimum number of work station is 1 ($1 \leq N \leq W$) where W = number of work elements to complete the assembly.

iii) The cycle time is greater than or equal to the maximum time of any station time and of any work element, T_i . The station's time should not exceed the cycle time ($T_i \leq ST_i \leq CT$).

Arif and Zahid (2003) defined throughput rate (X) as total number of items produced from the production line in a specific time. This is as stated in the *Arif's Algorithm* simulation software. The *Arif's Algorithm* was also utilized during completing methodology section in chapter 3.

2.3 Unpaced production line

A production line is an assembly line in which material moves continuously at a uniform average rate through a sequence of workstations where assembly work is performed. Elsayed and Thomas (1994) mentioned that an arrangement of work along the assembly line will vary according to the size of the product being assembled, the precedence requirements, the available space, the work elements, and the nature of the work to be performed on the job. There are two main problems in assembly lines; to balance the workstations and to keep the assembly line in continuous production.

A production line generally consists of several work stations in series, possibly with buffers in between. A work station is a group of (parallel) machines or operators performing one or more operations. Production line may be divided into two main groups; synchronous and asynchronous lines. In synchronous lines, the movement of jobs is coordinated. All jobs move to the next work station simultaneously. In asynchronous line, the movement of jobs is not coordinated. The operator or machine starts to process the next jobs as soon as one becomes available. Once the process completed the job immediately moves to the next work station, as long as there is a space for it. Thus an operator or machine can become starved (no job available) or blocked (no space to put a completed job). Asynchronous lines are also called unpaced where the number of jobs in the production line may fluctuate and buffers are needed to prevent starvation and blocking. Buffers between stations hold jobs that have been processed at one station and are waiting to be processed at the next station (Dennis (2001)). In a paced line, the time allowed for an operator or machine to work on the job is limited.

Basically the unpaced production line can be described as in Figure 2.1, considering total of N stations and $N-1$ intermediate buffer slots. Each station, S_i will have its own mean process time; μ_i. There is a finite buffer, B_i in between two stations.

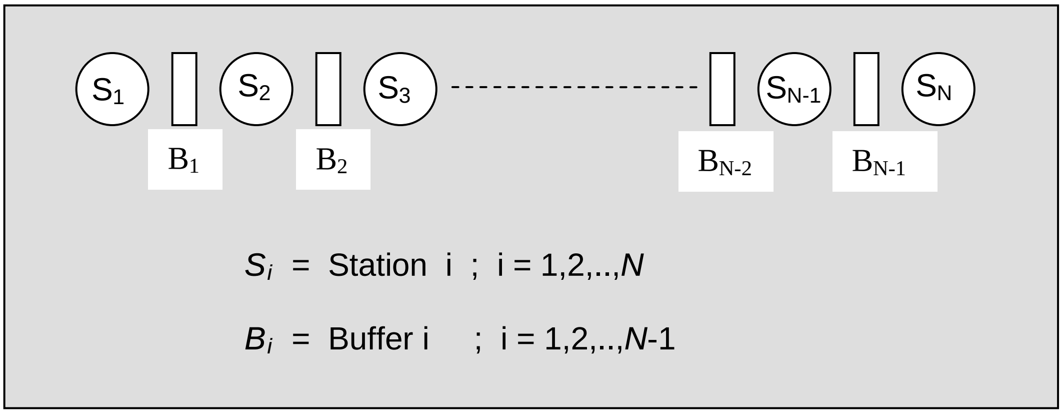

Figure 2.1: Unpaced production line general layout

For the unpaced production line, material is not pulled by demand but it is in a push mode. The total performance of this production line is affected by each station process time and overall line balancing. The station is considered in a starving condition if after completing its task, the buffer before it is empty. On the other hand, if there is no space to put the complete product in the next buffer slot, the station is considered in a blocking condition. Generally, few assumptions need to be made when studying the unpaced production line is; the raw material is always available before station-1, S_1 (first station never starved) and the completed assembled material can always be placed after station-N, S_N (last station never blocked). Therefore, there are infinite buffer slots at before station-1 and after station-N but limited buffer slots between stations, depending on management decision for the total number of buffers, B permitted in the whole production line.

2.4 Unpaced line with assembly and inspection processes

The production line also sometimes will consist of an assembly stations, an inspection stations or mixed between assembly and inspection. A real production line could be in a combination of both assembly and inspection factors together. Unpaced production line system have been divided by researchers into two categories, namely the automatic lines where operations are performed by automatic machines meaning that the operation times are deterministic and constant and the non-automatic lines where operations are performed manually and task times are random with possibly known probability distribution. By considering assembly (*A*) and inspection (*M*) factors inside the production line, the unpaced production line with finite buffers and exponential processing times; μ_i can be shown as in Figure 2.2.

Figure 2.2 shows the operator at station one is doing assembly process only, while station three's operator is doing inspection process. At station two, the operator is doing both assembly and inspection processes. For an example, in the assembly of a DVD Player production line, first operator may need to do the assembly process of the *Bottom Casing* follows by second operator who is doing assembly for *Top Casing* of the product together with inspection for parts alignment using alignment machine. Then, the third operator will continue with other inspection processes by using other type of checkers. Although a few of the stations only involve inspection processes (machine time), there is actually an effect of operator handling, for example to load and unload the product to the inspection machines. This means in a real unpaced production line, it is impossible to find a station with only inspection factor involved in its process.

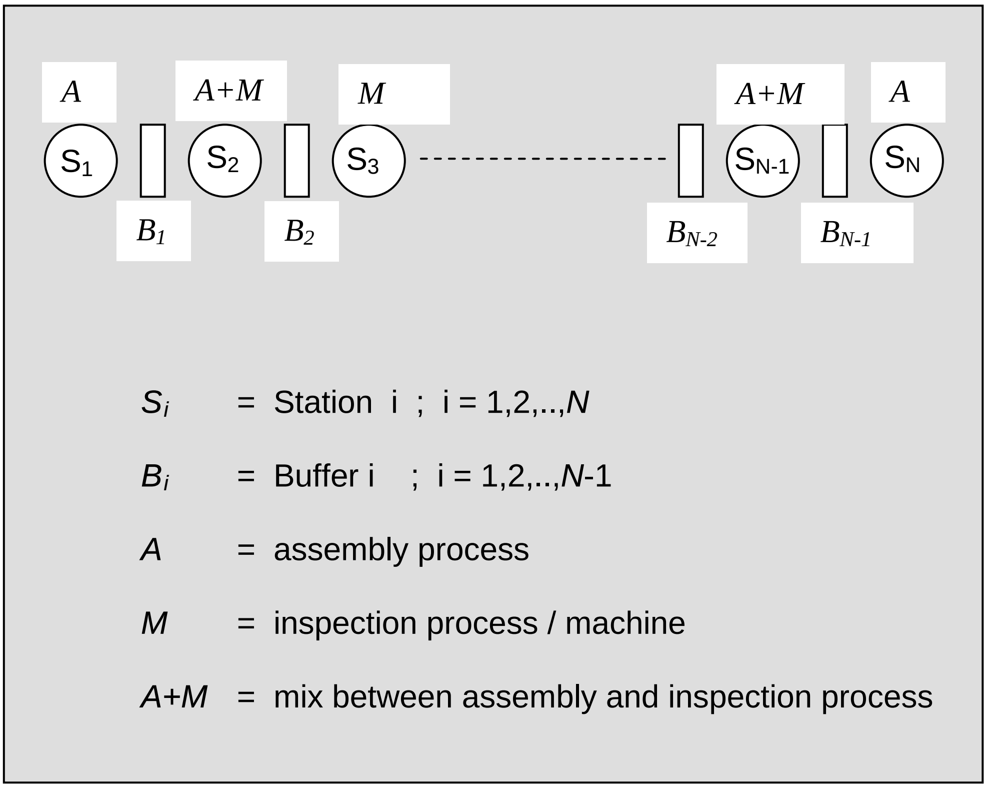

Figure 2.2: Unpaced line with assembly and inspection station

2.5 Balanced and unbalanced line

Each station has its own mean process time; μ and coefficient of variation; C_v, which will be random variables. For completely balanced production line, both μ and C_v, for every stations are exactly similar. According to Elsayed and Thomas (1994), a perfect balance line means to combine the elements of work to be done in such a manner that at each station the sum of the elemental times just equals the cycle time. Cycle time is referred to the amount of time a unit of product being assembled is normally available to an operator performing the assigned task.

It is almost unfeasible task for a management to design a production line with a perfectly balanced station. There will be a different on the process tact time from one station to another due to assembly process difficulty and complexity of the product to be produced. Therefore, the unbalanced production line consideration is more relevant to the real world production line circumstances. There are 3 types of unbalanced production line by considering each station's μ and C_v, as mentioned by Papadopoulos and Vidalis (2000):

(a) μ-unbalanced - mean service time, $\mu_i \neq \mu_{(i+1)}$ for at least one pair of i and (i+1) but $C_{vi} = C_{v(i+1)}$ for all i.

(b) C_v-unbalanced - coefficient of variation, $C_{vi} \neq C_{v(i+1)}$ for at least one pair of i and (i+1) but $\mu_i = \mu_{(i+1)}$ for all i.

(c) Fully unbalanced - $\mu_i \neq \mu_{(i+1)}$ and $C_{vi} \neq C_{v(i+1)}$ for at least one pair

of i and (i+1).

μ is a variable which is intricate to be fixed to a constant in an actual production line due to the complexity of the assembly processes. The μ-unbalance variance will become higher if the complexity level of the assembly process is higher. Sometimes the μ-unbalanced may occurs due to inequality of machine tact time. When this situation occurred, the management needs to invest additional machines to rebalance the line. However for a case of an expensive machine which require high capital investment, the management may possibly decided not to increase the number of machines. In this case, the μ-unbalanced ratio would be higher. Hence there is a need to find the trade in increasing the throughput by taking into consideration various factors in improving the throughput rate (efficiency), *X* and productivity of this type of production line. There are many researches that have been carried out on *OBA* for various types of production line conditions and could be divided into two groups; fully balanced and μ or C_v unbalanced.

2.6 Review on *OBA* for balanced production line

For balanced production line, there are two possibilities either it is reliable or unreliable. Most of the studies carried out in identifying *OBA* are by considering the line is balanced and reliable. Andijani and Anwarul (1996) came out with a method of determining an efficient allocation sets for a given buffer to maximize average throughput rate, minimize average Work in Progress (*WIP*) and minimize system time. The methodology used is called *Manufacturing Blocking Discipline (MBD)* which consists of three sub-methods; generating efficient buffer allocation sets (the scope narrowed down to eight buffers and three to four identical workstation), using *Analytic Hierarchy Process (AHP)* to identify most preferred allocation and by *Sensitivity Analysis* to get an *OBA*. The finding is to give the best buffer allocation for a management to decide based on a few different objectives, either to get maximum throughput rate, minimum *WIP*, minimum mean process time or a combination between the three objectives.

Papadopoulos and Vidalis (2000) focused on how to get *OBA* in order to minimize *WIP* inventory for a given required throughput. They used *Modified Hooke-Jeeves (H-J)* and *Heavey* algorithm to get the *OBA* for a short balanced line (up to 15 stations) once the required throughput is given. They used four simple steps; *Allocation Routine, Evaluation Method, generative Method* and *OBA* as the output. For a balanced reliable line, *OBA* follows inverse bowl phenomenon to get a maximum throughput rate. This meant buffer slots need to be equally allocated and remaining slots at central buffer

A few researchers discussed on balanced and unreliable production line condition. The algorithm is simpler in discussing an unreliable line by assuming it completely balanced. Michael and Kathryn (1995) studied on the buffer allocation for unpaced production lines with serial work stations (*S*) and parallel service facilities (*F*). Their finding is production line efficiency can be increased by reducing reliability of service and number of work stations and increasing amount of storage. A guideline for management to design a manufacturing system by selecting either single machine or multiple machines in parallel also given. Then, seven conjectures concluded their findings for general systems. For *N* number of stations and expected output rate for the production line (*R*), the seven conjectures consist of :

(i) For two stations, if $F_1 \neq F_2$, the optimal workload allocation is unbalanced by giving most work to the stations with fewer facilities.

(ii) For two stations, output rate is maximized by balancing the facilities per station and the workload per station as much as possible.

(iii) For any set of parameters that maximizes *R*, given fixed resources, the symmetrical allocation property holds.

(iv) For any set of parameters that maximizes *R*, the bowl phenomenon holds.

(v) A unit increase in the number of work stations decreases *R*, even if this is accompanied by unit increases in each of the resources.

(vi) As *S* or *F* → ∞ , the optimal distribution of workload approaches a balanced situation and *R* → 1.0. In addition, for large *S* and *F*, the balanced workload line is approximately equal to the optimal unbalanced distribution of workload.

(vii) If there is a choice between adding one facility or one storage space to a production line, while keeping the distribution of service constant, the expected output rate is always increased more by adding a storage space.

Another study is by Papadopoulos and Vidalis (1999) where the line is considered short μ-balanced and consists of machines subjected to breakdown. They used an enumeration method together with evaluative algorithm of Heavey et. al. (1991). The findings answered the effect of service time distribution and the availability of the unreliable stations, on the *OBA* and the throughput of the line. From the numerical experiment, they also conclude that *OBA* presents the shape of bowl, non-symmetric bowl or inverse bowl, depends on number of unreliable stations in the line either less than *N* and even, odd or equal to *N*, respectively.

2.7 Review on OBA for unbalanced production line

For production line with specifically unbalanced, there are also two combinations whether it is fully reliable or unreliable. For unbalanced but reliable line, only a few studies carried out so far. Papadopoulos and Vidalis (2001) included this combination of reliable and μ-unbalanced during their unreliable line study. They used *heuristic algorithm* (*PaV*i algorithm) and *complete enumeration* (*CE*) method for a number of stations up to six stations. The finding is divided into two basic principles :

(a) First basic principle: Two general design rules of thumb are used, as follows :

(i) Buffers that are close to the bottleneck stations (their upstream and downstream buffers) need preferential treatment. The buffer that is located toward the center of the line is getting more slots.

(ii) The central buffers are allocated some extra buffer slots as the central stations with their operation affect both the upstream and the downstream parts of the line.

(b) Second basic principle: Sectioning approach by using *PaVi* algorithm. The result obtained was compared the accuracy to *CE* method for four stations line. However, the discussion was based on the selected cases and no conclusion on the method of getting *OBA* for a known μ-unbalanced line.

Another related study was done by Spinellis and Papadopoulos (2000) by adapting a physical thermodynamic annealing principle to a buffer allocation problem solving approach. They used simulated annealing approach (decomposition method) followed by a search method to get *OBA* of the line. However, this new developed method still needs further investigation to determine its effectiveness.

There was also a study for a serial reliable production lines modeled as tandem queuing networks and formulated as continuous-time Markov chains to investigate how to maximize throughput rate or minimize the average *WIP*. The effect of process time distribution type on the optimal workload allocation was studied by Papadopoulus et.al. (2005). Production line with three, four and five stations was studied in details. They have introduced workload allocation and phase load allocation during their study. They included the workload and phase load allocation into the consideration of *OBA* (finite buffer) in order to maximize throughput and to minimize *WIP* of the perfectly reliable production line.

For unreliable and unbalanced production line, there are limited studies carried out might be due to a complexity of the model. During simulation, the researcher still needs to run unbalanced and unreliable conditions separately, by fixing one of the variables to constant. Papadopoulos et.al. (1991) developed on how to determine a maximum throughput rate for multi station unreliable production line. A methodology for generating the associated set of linear equations is presented. These sets of linear equations are solved by the use of the *Successive Over-Relaxation (SOR)* method with a dynamically adjusted relaxation factor. The finding concluded that the method used by generating the transition matrix could give an exact result for the production line *OBA*.

Tempelmier (2003) determined an *OBA* in a real life system data by considering an asynchronous production under stochastic condition. He extended the works by Burman (1995) using Accelerated Dallery-David Xie

(ADDX) algorithm, Geushwin (1994) using Decomposition Method and Buzacott (1995) using stopped arrival G/G/1/N queuing model. Based on the three extended works, he introduced '*FlowEval'* software as a tool for his research. He broke down the production line into three conditions of processing time; Deterministic, Stochastic and Mixed Deterministic/Stochastic. However, the production line is assumed to be μ and C_v balanced during the analysis. In deterministic process, μ vary from station to station and accurately can be analyzed by using *ADDX* algorithm. For stochastic process, station subjected to failure and repair. Decomposition Method (G/G/1/N) and Gaver Completion Time were used to analyze this type of station. Mixed deterministic/stochastic stations were solved either by using Denoted ADDX plus Gaver Completion Time approach or using Denoted GG1(C_v=0) plus G/G/1/N method. The result was compared to a simulation result by *SIMAN* software. The main finding are for a small buffer size (up to six pieces), approximation using ADDX(adj) is better but for a big buffer size (10 to 25 pieces), *GG1*(C_v=0) approximation is better.

Latest research on the unreliable and unbalanced line done by considering production line that consists of machines connected in series and separated by buffers was carried out by Nabil et.al. (2006). Each machine is described by three parameters: failure rate, repair rate and processing rate. The *degraded ceiling approach* is used as a local search technique then link to buffer allocation problem. Results obtained are compared to simulated annealing algorithm for production line with seven machines and total buffer of 30 units. The two approaches also have been tested on production lines with different sizes from 10 to 40 machines. The finding concluded that the result obtained by degraded ceiling method to solve the problem is more encouraging compared to simulated annealing algorithm.

There are also studies carried out for buffer allocation problem by using the analytical models and neural network approach. Hemachandra and Eedupuganti (2003) developed an analytical model of open assembly system that consists of two assembly lines and a single joining operation. In the study, they investigated parameters such as service time and arrival rates that affect the configuration of buffer. Recently, an artificial intelligence model had been used to solve this problem, especially for large solution space and when fast decision making is needed. Altiparmak et.al. (2006) demonstrated a simulation model based on *neural network approach*. They investigated the buffer allocation on asynchronous assembly system subjected to failure. Despite of their promising result, the neural network has a drawback. It is an empirical and data driven model, which means the approach depends heavily on data.

Arif and Zahid (2003) studied a real-time production-inventory control system using fuzzy control strategy and compared to a corresponding crisp control and no-control strategy. The system consists of a production shop having a number of identical processing machines which produce two products. The output goes into two bins whose inventory is required to be controlled at desired level by varying the number of machines allocated to the products. For performance measures, real time inventory variation, output, average inventory and machine usage, number of setups and stock-outs were used. The simulation results of the system with various configurations showed that the capability of fuzzy control is seriously inhibited by limited opportunities and responses delay although fuzzy has clear advantage over crisp.

In this research, it is important to know a type of production line model which will be used during the *OBA* study.

2.8 Production line model for *OBA* study

A type of production line used in this research is unpaced (asynchronous) with finite number of stations. However, unpaced line normally related to short line (number of stations,N less or equal to 20 stations). This type of short line normally known as cell line concept where there is no conveyor belt used. Each station's mean process time,μ is independent and not paced by a conveyor movement or specific given time. For the unpaced production line, material is not pulled by demand but it is in push mode. Many electronics companies with small and medium size products such as computer peripheral (for instance CD/DVD Drive, Floppy Disc Drive and Hard Disc Drive) and personal audio (for instance Discman, Walkman and MP3 player) are adopting this type of line for their assembly processes. Sometimes it is difficult for management to decide whether to design a few short cell lines or one flow line during setting up the production line. Basically, there are a few advantages and benefits for designing a production line layout with a few short cell lines compared to one flow line, such as:

i) Production is more flexible to run various types of models. It is possible to design a cell line layout and set up machines which can be used to run all models. Therefore, when there is any requirement to run many models simultaneously, the production manager or supervisor can easily allocate any line to run. Production is also flexible in term of if there is a low output requirement from a sales department for certain month forecast. The production can be planned to run at a few cell lines only to meet the low target capacity and just shut down other lines production. By this method, the line productivity will still be maintained besides easy to manage the manpower reduction plan.

ii) The effect from machine breakdown can be minimized. For a one flow production line, if one machine breaks down the output for the whole line will be affected. However, if the failure machine at one of the cell lines, only that particular line affected and other lines can still run as a normal production.

iii) Trouble shooting by production engineering support group will become easier. One of the famous concepts that could be adapted to the cell line layout is called a *Non-Spaghetti* concept. This concept is illustrated in Figure 2.3.