A Buffer Design for Mitigation Downtime Effect in an Automated Transfer Line

S. Prombanpong, J. Kaewyu, N. Thanadulthaveedech, and M. Matwangsang

***Abstract*—One of the problems in an automated transfer line is line breakdown which has an adverse effect to overall production rate. The causes of line breakdown can be due to scheduled tool change, tool adjustment, quality problem, equipment malfunction, etc. which can occur anytime during the production. Due to the fact that these unavoidable breakdowns cause every workstations to completely stop until the repair is completed. As a result, the production output will be less than that of expected and the required production rate cannot be met. One of the common solutions to mitigate this effect is to provide buffer stocks between workstations. However, the determination of appropriate buffer capacity is quite complicated. This paper therefore demonstrates the design of buffer capacity between workstations to alleviate break down effect in an automated transfer line.**

***Index Terms*—Automated transfer line, Buffer design, breakdown analysis.**

I. Introduction

An automated transfer line is consisted of several workstations which are linked together by a material handling system where parts are transferred from one station to the next [1]. The operations at each workstation will be performed by an automated machine such as spot welding robots, computer numerical control machines, adhesive machines, and so on. Once the operations are completed, the part will be unloaded from the station and placed on the material handling system. The part then will be transferred to the next station. Typically, the automated transfer line is performed in a cycle and the number of parts in the line is equal to the number of work stations. The cycle time is determined by the bottleneck station and it is depending upon the service time of the bottleneck station and the transfer time. The ideal production rate is computed as the reciprocal of the cycle time. However, in an operation there will be downtime on the line causing by random breakdowns and scheduled stoppages. The examples of random breakdowns include tool failures at workstations, mechanical failure, electrical malfunctions, running out of stock parts, insufficient space for finished product or any inadvertent situations such as power failure. The scheduled stoppages are scheduled tool changes or adjustments, preventive maintenance on the line and so on. If any problem occurs and forces the workstation to cease, the entire stations must also stop until the problem is solved. As a consequent, the actual production quantity will be less than that of anticipated depending upon the duration and frequency of downtimes. Thus the efficiency of the automated transfer line is the proportion of cycle time to the summation of cycle time and expected beak down time as shown in (1). In order to alleviate this problem, buffer stocks between workstations are provided. The buffer storage separates the line into stages that operates independently for a number of cycles depending upon the storage capacity of the buffer [1].

In an analysis of workstation breakdown, there are two possible approaches named upper-bound and lower-bound approach [1]. In the upper-bound approach, the work-parts will not be damaged or receive any effect due to the breakdown problem. Thus, the work-parts can remain in the line for further processing until all operations are completed. The examples of break down suitable for upper-bound approach include tool changes, tool adjustments, minor mechanical or electrical malfunctions, preventive maintenance, and so on. It can be seen that these type of break down have no effect to the work-part, and therefore, it is not necessary to remove it from the line. Once the work-part continues to be processed on the line, it is possible that the work-part may involve more than one line stop during its production sequence. Thus, the frequency of failure per cycle is increasing which contributing upper limit of failure per cycle. The expected number of failure per cycle can be obtained by summing the probability of failure over the entire stations in the line [1]. Note that the upper-bound approach will be considered in this paper. On the contrary, in the lower-bound approach, the station malfunction causes damage to the work-part and the work-part becomes defective. Thus, it must be removed from the work station as a consequence [1]. The examples of these types of break down are tool broken and stuck in the work-part, work material melt and welded to the spot welding tip and so on. In this case the product will be damaged and must be removed from the station. The lower-bound approach provides an approximation of lower limit on the frequency of line failure. The probability of a work-part will jam at the current station depends on the probability of this particular work-part is not jammed in the preceding workstation. Thus, the probability a given part will jam at the workstation is the summation of probability a given part jamming at this work station and not jamming at all previous work stations. The number of outputs will be less than those of original launching onto the front line due to the fact that the defective work-parts are already removed from the production line.

Besides the frequency of failure or line break down per cycle, the characteristic of down time distribution must be taken into account. The characteristic of downtime

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distribution can also be expressed in two theoretical distributions as derived by Buzacott [2]. The first one is geometric downtime distribution. In this distribution, the downtime duration is quite varied. The repair completion time at each cycle is exponential and independent to the repair starting time. In addition, Groover also proved that with high variation in downtime, line efficiency will be jeopardized [1]. The second distribution is constant downtime distribution. The repair duration time of any cycle is constant. Therefore, there is no downtime variation. In this paper the upper-bound approach and the geometric downtime distribution are assumed due to the fact that the line failure does not harm the work-part. The product still remains in the production line. However, the geometric downtime distribution will be applied in this paper to reflect actual situation in the automobile part manufacturer from where all data are collected.

The determination of appropriate buffer capacity is not easy and little research has been conducted in this topic. Al-Momani et al. studied the buffer design for flexible transfer line using genetic algorithm. Different buffer capacities were trial. The throughput was then used as criteria to select the solution [3]. Burman and Gershwin analyzed the efficiency of transfer line production with different operation time and buffer size. The decomposition methodology was implemented and its results were later compared with those of numerical method to verify the accuracy of the program [4]. In addition, Shi and Gershwin applied nonlinear programming to obtain the optimal buffer size based on area expenses and inventory cost required by different buffer capacity [5]. Fu and Xie applied the simulation technique to analyze the perturbation in two-stage transfer line with finite buffer capacity [6]. Dallery et al. analyzed two-stage transfer line using an approximation method to compute the average production rate given by buffer [7]-[9]. Wijngaard analyzed two-stage transfer line with finite buffer. The comparison between constant downtime distribution and geometric downtime distribution was also conducted [10]. Lipset et al. analyzed performance of serial transfer line which is subjected to machine and buffer failure [11]. Enginarlar et al. investigates the minimum level of buffer to secure desired production rate in serial lines with unreliable machines [12]. A number of papers addressed numerical algorithms to calculate optimal buffer allocation [13]-[15]. Gershwin et al. applied decomposition methods with unreliable machines and finite buffers for small lines and then extended to the longer lines [16]-[19]. Park developed heuristic algorithm to determine buffer size in order to minimize buffer space in two-phase transfer line [20]. Hillier et al. studied an effect of machine breakdown and buffer capacity to the performance of the production line [21].

This paper applied numerical analysis to identify appropriate buffer allocation on the two-stage transfer line using algorithms developed by Buzacott [2] and Groover,[1] which will be described next.

II. Problem Scenario

A case study of a transfer production line to manufacture an automobile part is presented. This production line assembles the side panel of a pickup truck. It consists of five consecutive workstations which are mainly a robot spot welding operation. These five workstations are connected by an automated material handling system which transfers the work-part from one station to the next. When there is break down at any work station, the entire work stations will stop simultaneously. The causes of cessation can be due to cleaning of spot guns, changing tool tip, or sensor malfunction. Based on the collected data the frequency of failure of this line is 0.12 line stops per cycle. The average downtime of all workstations is 110 second per downtime. In an analysis of automated transfer line, the line will be divided into 2 stages by placing buffer stock between the second and the third station. Thus, the first stage is consisted of two workstations and the second stage is consisted of three workstations. This paper aims to analyze the ability of buffer capacity to the line efficiency in the two-stage transfer line and it will be described next.

III. Methodology

A. Performance Measurement

In the automated production line, if there is no break down or line stop, the line will ideally operate at 100 % uptime efficiency. Line efficiency can be referred to the proportion of uptime on the line and can be used as performance measurement. The line efficiency can be calculated from (1).

$$E_0=\frac{T_c}{T_c+FT_d} \tag{1}$$

where E_0 is an efficiency without buffer stock, T_c is cycle time (sec), F is frequency of downtime (stops/cycle), T_d is average downtime (sec per stop).

The efficiency at stage k can be calculated from the following equation.

$$E_k=\frac{T_c}{T_c+F_kT_{dk}} \tag{2}$$

where $E_{(k)}$ is the efficiency at stage k.

$$E_\infty=\text{Minimum}\{E_{(k)}\} \tag{3}$$

where E_∞ is the line efficiency which storage buffer is infinite capacity.

Thus, if buffer stock is implemented, the line efficiency must be improved. The efficiency improvement by buffer stock can be obtained from (4) to (6) based on the assumption of geometric downtime. In addition, it is assumed that the frequency of breakdown of each stage is equal. Thus

$$E_b=E_0+D'_1h_{(b)}E_{(2)} \tag{4}$$

$$D'_1=\frac{F_1T_d}{T_c+(F_1+F_2)T_d} \tag{5}$$

$$h_b=\frac{r(1-K^b)}{1-rK^b}\ ;\ r=\frac{F_1}{F_2},\ K=\frac{1+r-(T_c/T_d)}{1+r-r(T_c/T_d)} \tag{6}$$

Equation (4) shows the efficiency improvement gained from buffer b and D'_1 is the proportion of expected downtime of stage 1 to the total production time and can be shown in (5). Equation (6) shows the ability of buffer b in the improvement during down time. The term $h_{(b)}$ is multiplied with $E_{(2)}$; consequently, the rate of improvement obtained from buffer is mainly due to the value of $h_{(b)}$.

B. Data Manipulation

In order to obtain the appropriate buffer size, a number of data must be collected. In addition, the required production time is 96 second per piece. Thus, the calculated cycle time can be obtained from the following equation.

$$T_c = T_p - FT_d \quad (7)$$

thus

$$T_c = 96-0.12\times110 = 82.8 \text{ sec}$$

Then, the line efficiency without storage buffer can be calculated from (1). Thus

$$E_0 = \frac{82.8}{82.8+0.12\times110} = 86.25\ \%$$

Note that E_0 is the line efficiency without buffer stock. It can be seen that the efficiency is less than 100 percent due to the effect of down time. To mitigate this adverse effect, buffer stock between workstation is proposed. In this case the buffer is placed right after workstation 2 and divides the line into 2 stages. The first stage is consisted of two workstations and the second stage is consisted of three workstations.

Thus, with the assumption of equal down time frequency the frequency of downtime occurrence of each workstation is equal to 0.12/5 (0.024). Thus, F_1, F_2 the frequency of line stop in stage 1and 2 can be obtained from (8).

$$F_k = n_k \times p \quad (8)$$

where the subscript k identifies the stage and n_k is number of workstations in stage k. p is the frequency of breakdown per cycle. Thus

$$F_1 = 2\times0.024 = 0.048$$

$$F_2 = 3\times0.024 = 0.072$$

where F_1 is downtime frequency of phase 1, F_2 is downtime frequency of phase 2. The efficiency of stage 2 can be calculated from (2). Thus

$$E_{(2)} = \frac{82.8}{82.8+0.72\times110} = 0.913$$

Let substituteF_1, F_2, T_d, T_c in (5). Then

$$D'_1 = \frac{0.048\times110}{82.8+(0.048+0.072)\times110} = 0.055$$

In order to determine appropriate buffer capacity, different buffer sizes must be investigated. In this paper buffer capacity ranged from two to eight pieces is utilized to compute line efficiency for comparison. Both $h_{(b)}$ and E_b (efficiency of line with b buffers) can be computed from (6) and (4) respectively. Thus,

$$r = \frac{0.048}{0.072} = 0.667$$

$$K = \frac{1+0.667-\left(\frac{82.8}{110}\right)}{1+0.667-0.667\left(\frac{82.8}{110}\right)} = 0.785$$

$$h_{(2)} = \frac{0.667(1-0.667^2)}{1-(0.667\times0.785^2)} = 0.4346$$

$$E_2 = 0.8625+(0.055\times0.4346\times0.913) = 0.884 \quad (88.4\%)$$

$$h_{(3)} = \frac{0.667(1-0.667^3)}{1-(0.667\times0.785^3)} = 0.5084$$

$$E_3 = 0.8625+(0.055\times0.5084\times0.913) = 0.888 \quad (88.8\%)$$

$$h_{(4)} = \frac{0.667(1-0.667^4)}{1-(0.667\times0.785^4)} = 0.5540$$

$$E_4 = 0.8625+(0.055\times0.5540\times0.913) = 0.89 \quad (89.0\%)$$

$$h_{(5)} = \frac{0.667(1-0.667^5)}{1-(0.667\times0.785^5)} = 0.5844$$

$$E_5 = 0.8625+(0.055\times0.5844\times0.913) = 0.891 \quad (89.1\%)$$

$$h_{(6)} = \frac{0.667(1-0.667^6)}{1-(0.667\times0.785^6)} = 0.6054$$

$$E_6 = 0.8625+(0.055\times0.6054\times0.913) = 0.892 \quad (89.2\%)$$

$$h_{(7)} = \frac{0.667(1-0.667^7)}{1-(0.667\times0.785^7)} = 0.6205$$

$$E_7 = 0.8625+(0.055\times0.6205\times0.913) = 0.893 \quad (89.3\%)$$

TABLE I: THE LINE EFFICIENCY AT VARIOUS BUFFER CAPACITIES

Buffer Capacity(pc)	$H_{(b)}$	Efficiency (%)
2	0.4346	88.4
3	0.5084	88.8
4	0.5540	89.0
5	0.5844	89.1
6	0.6054	89.2
7	0.6205	89.3
8	0.6316	89.4

$$h_{(8)} = \frac{0.667(1-0.667^8)}{1-(0.667\times0.785^8)} = 0.6316$$

$$E_8 = 0.8625+(0.055\times0.6316\times0.913) = 0.894\ (89.4\%)$$

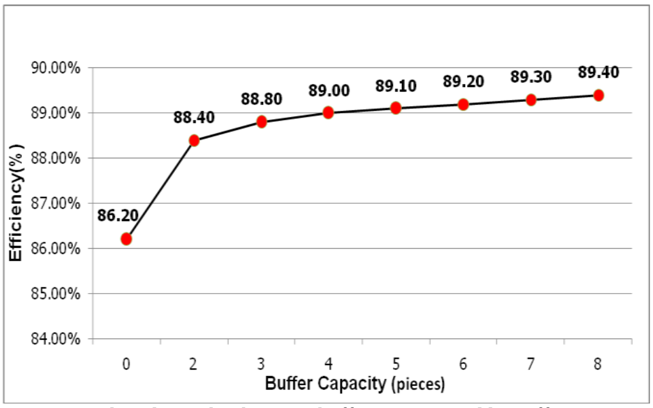

Fig. 1. The relationship between buffer capacity and line efficiency

IV. RESULT

As mentioned earlier, different buffer sizes are considered to calculate the line efficiency at various buffer capacities.

The result is summarized in Table I. It can be seen from the result that an improvement of line efficiency is gradually increased. This increment can be handily noticed from graph. The slope of the plotted curve can be used to determine appropriate number of buffer stocks that should be used. The graph of this result is shown in Fig. 1.

It can be seen from Fig 1 that the slope of the plotted curve from buffer capacity ranged from four to eight pieces is equal incremental. Although the number of buffer is increasing, the line efficiency does not change much. It is obvious that the buffer capacity at four seems to be an appropriate number for this problem.

V. Discussion

This paper demonstrates the numerical approach to determine an appropriate number of buffer stocks to mitigate the adverse effect of down time in an automated transfer line. The geometric downtime distribution with an upper-bound approach is utilized in the calculation. It can be seen that the appropriate number of buffer stocks can be determined from the plotted curve. This paper presents a numerical method to determine the appropriate number of buffer which is easy to obtain a solution.

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