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Constraint time buffer determination model

Y.-M TU† and R.-K. LI†*

In today's competitive environment, reducing Work in Process (WIP) to improve cycle time, delivery and product quality has become the key to maintaining profitability. However, due to conservative attitudes and conceptual mistakes, WIP has spread along the entire production pipe line. Although intended to maximize the utilization of resources, WIP can be caused to become over-sized. This maximum utilization of resources syndrome has been proved incorrect by the Theory of Constraint and WIP should be queued only in front of constraint machine, thereby ensuring the constraint machine not starvation. Although this concept has been proved correct and despite many reported examples of successful implementation in many companies, in practice, the WIP level is still determined by the trial and error approach. Therefore, a WIP computation model is deemed necessary. In this paper, a constraint time buffer determination model is proposed. The model first proposes a machine-view's bill of routing representing a structure that serves as a fundamental structure for formulating and computing the maximum time buffer. The machine-view's bill of routing is a tree structure, the constraint machine is the root node and its feeder machines are entry nodes (or subtrees) of the root node. With this tree structure, the behaviour (or stability) of the constraint machine and its feeder machines can then be studied and formulated. By incorporating the MTTR of each feeder machine, a mathematical relationship can then be formulated and the time buffer computed. Furthermore, to validate the proposed constraint time buffer determination model, an example is illustrated and a simulation model is also developed.

1. Introduction

Work In Process (WIP) is the converse of a product or products at various stages of completion throughout the plant. It includes all the materials employed from the raw material after release for initial processing up to the completely processed material awaiting final inspection and acceptance as a finished product (APICS 1995). It can be extensively applied to any type of production system. The positive side of WIP provides for resources to be put to full economical use and prevents unpredictable events from disturbing maximum output rate. This maximum output rate is particularly prevalent in capital intensive factories such as a semiconductor fab. The negative aspects of WIP are an increase in cycle time, impaired delivery performance and quality degradation (Chen *et al.* 1988, Glassey and Resende 1988, Wein 1992). In today's competitive environment, reducing WIP to improve cycle time, delivery performance and product quality has become the key to maintaining profitability (McNair *et al.* 1989). Figure 1 illustrates the relationships among WIP level, output rate, and cycle time. When the WIP level falls below Q1, increasing the WIP level causes the output rate to increase because the WIP in this situation can help prevent

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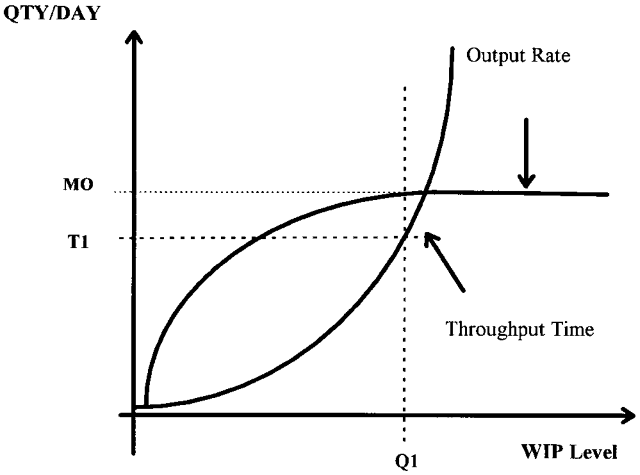


Figure 1. The relationship between WIP level and output rate/throughput time.

unpredictable events. However, when the WIP level exceeds the Q1 level, the output rate does not increase accordingly, because the maximum output rate is limited. The cycle time, however, increases sharply. Therefore, the Q1 of Fig. 1 is the desired maximum WIP level. However, the question arose: How can it be determined?

Two problems have been addressed in previous WIP management studies (Chen *et al.* 1988, Askin and Krisht 1994, Kuroda and Kawada 1994): (1) these studies assumed that the system under study was one of steady state and that the WIP level was an average level rather than a maximum WIP level. This average WIP level concept has a 50% likelihood of causing a machine to become idle and of impairing the output rate. Therefore, a confidence factor must be included in determining the maximum WIP level; (2) these studies focused on keeping every machine busy to attain maximum output. With this concept, WIP is then put in front of every machine to ensure they are kept busy when their feeder machines break down. This syndrome causes WIP to spread along the entire production pipeline. Maximum WIP level determination based on this syndrome becomes too high. Fortunately, this syndrome has been proved incorrect by the Theory of Constraints (TOC) (Goldratt 1990) and starvation avoidance at the constraint machines (key machines or bottleneck machines) (Lozinski and Glossey 1988). Starvation avoidance is accomplished by maintaining a relatively high WIP level with the constraint machine to ensure the availability of material in virtually any circumstances, including the occurrence of any extraordinary and unpredictable events. The Theory of Constraints views production as being restricted by the constraint machine. Therefore, by definition, any non-constraint machine has excess capacity. This excess capacity means that some utilization will be sacrificed by the machine. As long as this lost utilization does not restrict the flow of the material to the constraint machine or reduce capacity to below the level of the constraint machine, production output will thereby not be reduced.

According to the Theory of Constraints, a WIP level to protect the constraint machine is defined as a time buffer concept (termed the constraint time buffer). The time buffer is defined as an amount of processing time plus setup time plus an estimate of the aggregated amount of protective time required to ensure that the released product will get to the constraint machine when needed. It is a time mechanisms to offset those things which can go wrong. The reason for selecting time buffer instead of volume buffer is that the time buffer WIP level does not need changing when the product mix is changed. Therefore, focusing on the parts which are physically queued in front of constraint machine is irrelevant. Instead, emphasis should be placed on the time when the parts should be released and they arrive at the constraint machine. Although the time buffer concept is justifiable and practicable, unfortunately, according to the Theory of Constraints, determining the time buffer is a trial and error approach. This approach requires a test period in order to derive the desired maximum time buffer. In practice, simulation is frequently employed in determining the desired maximum time buffer. However, since simulation (Dayhoff and Atherton 1986, O'Neil 1991) is a heuristic approach with the results depending on an individual simulated case, it cannot serve as a generic solution.

Flowtime estimation in due date assignment rules has been researched (Vig and Dooley 1991, 1993). It can be viewed as a similar concept to that of time buffer determination. In such research, a regression approach is the used way of estimating flowtime. The input in the regression model is the flowtime of the completed jobs. This predictive approach is similar to the simulation approach, the only difference being that the input data in which historical time buffer data are the input variables.

As discussed above, the time buffer protects the utilization of the constraint machine and is the amount of time required to reach the constraint machine after the product is released. Therefore, the size of time buffer varies according to the degree of the stability of the feeder machines in front of the constraint machines. However, this stability is caused by unpredictable events, such as machine breakdown, material shortage and random processing time. Among these, machine breakdown is the most influential factor on the stability of feeder machines. This is particularly obvious in a semiconductor fab. Therefore, the maximum time buffer for protecting the constraint machine closely corresponds to the stability of the feeder machines of the constraint machines. Basically, MTBF and MTTR are the two indicators of machine stability behaviour. Of these, MTTR is critical to determining the maximum time buffer required to protect the constraint machine from a shortage of parts from its feeder machines.

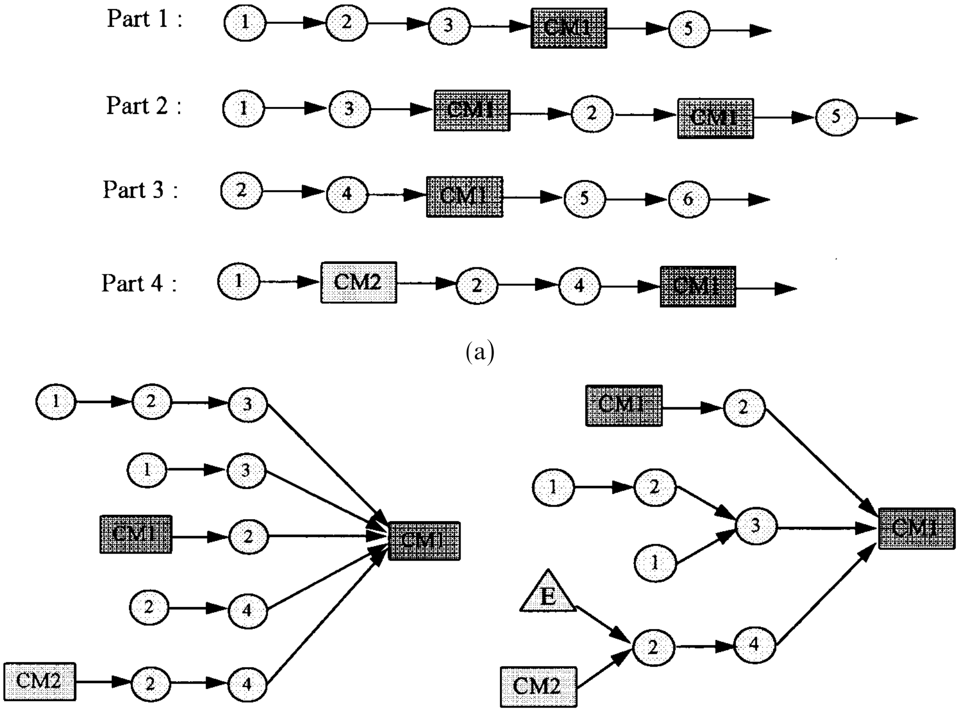
The maximum time buffer for protecting the constraint machine closely correlates with the stability and MTTR of its feeder machines. Therefore, to determine the maximum time buffer required for this protection, a representation of the relationship between the constraint machine and its feeder machines should first be developed. This representation serves as a fundamental structure for studying the behaviour in the feeder and fed machines relationship and from incorporating the MTTR of each feeder machine so that the protective time buffer can be expressed as a mathematical relationship. If the relationship is mathematical, the maximum time buffer can be computed.

In this paper, therefore, a constraint time buffer determination model is developed. The model first proposes a structure representing a machine-view's bill of routing to serve as a fundamental structure for formulating and computing the maximum time buffer. The machine-view's bill of routing is a tree structure, the constraint machine is the root node and its feeder machines are entry nodes (or subtrees) of the root node. With this tree structure, the behaviour (or stability) of the constraint machine and its feeder machines can then be studied and formulated. Incorporating the MTTR of each feeder machine, a mathematical relationship can then be formulated and the time buffer computed. However, the time buffer determined in the proposed model is still not a maximum time buffer, it is a mean time buffer, therefore, a confidence factor is incorporated with the determined time buffer for calculating its maximum.

Finally, to test the validity of the proposed time buffer determination model, an example is illustrated and a simulated model is developed for verification purposes.

2. A machine-view's bill of routing

Conventionally, a bill of routing, as illustrated in Fig. 2a, is employed to represent the process flow of manufactured products. It focuses on the operational flow of a product and provides valuable information for production planning and control (this type of bill of routing is termed a process-views' bill of routing). Although it illustrates the relationship between the constraint machine and its feeder machine, the relationship is quite complex. (Its complexity is greater when the number of products being processed is increased.) The behaviour between the constraint machine and its feeder machines has hardly been studied and formulated. Therefore, the need arises for a compact representational structure that can illustrate the relationship between the constraint machine and its feeder machines, with this structure the behaviour between the constraint machine and its feeder machines can then be studied and formulated as well. Figure 2c presents an example of the desired representational structure. It is a tree structure. The root node is the constraint



(a)

(b)

(c)

Figure 2. (a) Process-view's bill of routing; (b) machine-view's bill of routing (I); (c) machine-view's bill of routing (II).

machine and the rest of the machines are the root nodes' entry nodes. The structure focuses on the constraint machine and its relationship with its feeder machines. Therefore, it is termed a machine-view's bill of routing. Since a structure of both bill of routings are quite different, a transformation from process-views' bill of routing to machine-view's bill of routing is required. The transformation procedure is described as follows:

Step 1. Identifying constraint machines. A constraint machine is defined as a machine that does not allow for any loss in capacity due to heavy loading or to other management constraints. It may be a bottleneck machine or a machine that managers regard with importance. If the constraint machine is a bottleneck machine, it can be identified by performing a loading computation or simply by informed observation.

Step 2. A machine-view's bill of routing construction. Since several constraint machines may exist, the transformation starts by randomly selecting one of them from the process-views' bill of routing. The selected constraint machine is assigned as the root of a tree. The feeder flows of this constraint machine will be taken as subtrees and placed in front of the root. Two kinds of machines can serve as the entry point of the subtrees: (1) the selected constraint machine itself or other constraint machines. If the selected constraint machine itself is the entry machine, the process involved is a reentrant process; (2) the first machine of the process-view's bill of routing. In this case, the source of the entry machine is external (raw material). No backlog of raw material is assumed and the entry machine is not idle. Therefore, the external circumstances can be neglected.

Figure 2a illustrates an example of process-views' bill of routing for four products, and a reentrant process. CM1 and CM2 are identified as the constraint machines. The transformation first selects CM1 machine as the constraint machine and assigns it as the root of the machine-view's bill of routing. Other machines such as 1, 2, and 3 of product 1, etc. are the feeder machines of the CM1 constraint machines in front of which they are placed. Figure 2b illustrates the machine-views' bill of routing transferred from Fig. 2a.

Step 3. A machine-view's bill of routing modification. In Step 2, the only action required is to place all machines related to the CM1 in front of it. However, each fed machine allows for only one type of feeder machine. Whenever fed machines have more than one of the same type of feeder machine (for example, machines 2 and 4 for CM1), these must be combined into one node. The combination procedure is as follows:

(1) Add a dummy machine, representing the external resource, to the beginning of each subtree in which the entry node is the first machine of the process-view's bill of routing.

(2) Begin the procedure of combining the redundant machines to make one machine at the root node, by employing Breadth First Search to travel each node and execute the following rule:

If any redundant feeder machines exist, combine them to make one machine.

(3) Remove the dummy node which is now the only supply source for its fed machine.

Figure 2c illustrates the transformed machine-views' bill of routing following the Step 3 modification. It is a tree structure. The root is the selected constraint machine CM1, the child nodes of the root are the feeder machines and each one of these is also its own feeder machine.

3. The behaviour of feeder and fed machines

The time buffer required to protect a fed machine depends on the excess capacity and MTTR of its feeder machine. A fed machine may either have one feeder machine (termed a one-to-one feeder and fed machine relationship) or more than one (termed a many-to-one feeder and fed machine relationship). For example, in Fig. 2c, machine 4 has only one feeder, machine 2, but machine CM1 has three feeder machines, 2, 3, and 4. For a one-to-one relationship, the time buffer required to protect the fed machine is 100% determined by the MTTR of its feeder machine. However, for a many-to-one relationship, the time buffer required to protect the fed machine is determined by the MTTR of all the feeder machines. In this latter case, since each feeder machine has different output rate (or excess capacity), its MTTR has a different percentage of influence on the WIP determination of its fed machine. This percentage of influence of a feeder machine to its fed machine is termed the influence ratio and can be expressed by the following equations:

$$IR_{ij} = \frac{OR_{ik_{ij}}}{OR_{jk_{ij}}} \tag{1}$$

$$OR_{ik_{ij}} = \frac{NM_i}{APT_{ik_{ij}}} \tag{2}$$

$$OR_{jk_{ij}} = \frac{NM_j}{APT_{jk_{ij}}} \tag{3}$$

Where

IR_{ij}	influence ratio of feeder machine i to fed machine j
$OR_{ik_{ij}}$	output rate of part k_{ij} on machine i
k_{ij}	products which process from feeder machine i to fed machine j
NM_i	number of machine i
$APT_{ik_{ij}}$	average process time of part k_{ij} on machine i.

In addition to these two relationships, a one-to-many relationship also exists in the machine-views' bill of routing. A one-to-many relationship is where one feeder machine feeds more than one fed machines (for example, machine 2 feeds machines CM1, 3, and 4). In this situation, the capacity of the feeder machine must be allocated to support its fed machines. This capacity allocation is termed the Capacity Occupation Rate (COR) and can be expressed by the following equation.

$$COR_{ik_{ij}} = \frac{RH_{ik_{ij}}}{AH_i} = \frac{MQ_{k_{ij}} * APT_{ik_{ij}}}{30 * 24 * A_i} \tag{4}$$

$$A_i = \frac{MTBF_i}{MTBF_i + MTTR_i}.$$

Where

COR_{ij}	capacity occupation rate of feeder machine i which processes parts for fed machine j
$RH_{ik_{ij}}$	required process time of part k_{ij} on machine i
AH_i	monthly available machine time of machine i
$MQ_{k_{ij}}$	monthly required production quantity of part k_{ij}
A_i	availability of machine i.

Incorporating the COR, the $OR_{ik_{ij}}$ should be modified as following.

$$OR_{ik_{ij}} = \frac{NM_i}{APT_{ik_{ij}}} \times COR_{ik_{ij}}. \tag{5}$$

Theoretically, in a balanced capacity environment the value of $\sum IR_{ij}$ should be equal to one. This means the total feed rate of the feeder machine(s) is equal to the demand rate of its fed machine. However, this hardly holds true in a job shop environment. Even if the capacity of the job shop can be designed to balance, the designed balanced capacity is still out of balance, due to the change of product mix and unpredictable events. Therefore, when $\sum IR_{ij}$ is not equal to one normalizing IR to one is deemed necessary. This normalization is represented by the following expression:

$$IR_{ij} = \frac{IR_{ij}}{\sum_{i=1}^{n} IR_{ij}}. \tag{6}$$

Where

n the number of feeder machines of fed machine j.

4. The mathematical relationship of maximum time buffer determination

With respect to the machine-view's bill of routing, by considering the behaviour of fed and feeder relationship and the MTTR of each feeder machine as the input, the time buffer required to protect the constraint machine can be expressed by following recursive mathematical relationship:

$$B_{CM} = \sum_{j \in children-of-CM} MTTR'_j \times IR_{jCM} \tag{7}$$

```
if $j \in leaves\_of\_tree$
then $MTTR'_j = MTTR_j$ and stop this subtree$_j$
else if $i \in leaves\_of\_subtree_j$
        then $MTTR'_j = \sum_{i \in children-of-j} MTTR_i \times IR_{ij} + MTTR_j$
        else $MTTR'_j = \sum_{i \in children-of-j} MTTR'_i \times IR_{ij} + MTTR_j$
        endif
endif.
```

Where

B_{CM}: Time buffer of constraint machine CM.

As mentioned before, MTTR is the mean value of machines' down time; that is to say, around 50% of the machines will fail to surpass this mean value. This emphasizes that the maximum time buffer determined by the mathematical relationship is only a safe value not the desire Q1 maximum time buffer. Therefore, in order to

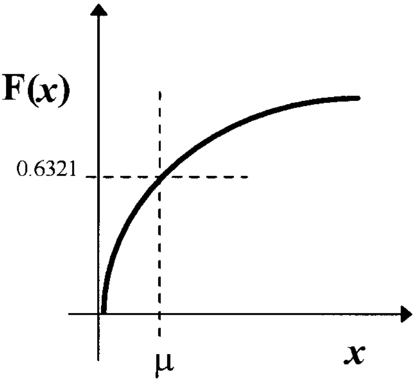


Figure 3. Cumulative probability function for exponential distribution.

determine this buffer, a confidence level must be incorporated in the maximum time buffer determination to ensure that the constraint machine is fully protected. Assume that the MTTR is exponentially distributed and that its cpf is as shown in Fig. 3. With this distribution, there is only a 63·21% chance of the constraint machine not being idle. To lower the chance of it being idle, managers can increase the time buffer of the constraint machine by employing the desired confidence level. With this concept, the maximum time buffer can be expressed as follows:

Assume

Confidence Level= α, then

$$B'_{CM} = \ln\left(\frac{1}{1-\alpha}\right) \times B_{CM} \tag{8}$$

$$\alpha = F(x) = F(X \le x) = 1 - e^{-\lambda x}$$

where

$$\lambda = \frac{1}{\mu} \text{ and } B_{CM} = \mu = \frac{1}{\lambda}$$

$$\Rightarrow e^{-\lambda x} = 1 - \alpha$$

$$\Rightarrow x = \ln\left(\frac{1}{1-\alpha}\right) \times \frac{1}{\lambda}$$

$$\therefore B'_{CM} = \ln\left(\frac{1}{1-\alpha}\right) \times B_{CM}.$$

5. An algorithm for the constraint time buffer determination model

In light of the above discussion, the constraint time buffer determination model can be summarized by the following steps:

Step 1. Transfer the process-view's bill of routing to the machine-view's bill of routing. Apply the transformation concepts and steps discussed in § 2.

Step 2. The Capacity Occupation Rate (COR) computation. In the case of the many-to-one feeder and fed machines relationship, the COR for each feeder and fed machine relationship should be determined before going to the next step. Equation 4 is applied in this step. For the non-many-to-one relationship, the COR should be equal to one.

Step 3. An influence ratio computation. Equation 1 is applied here.

Step 4. An influence ratio modification. In this step, those $\sum IR_{ij}$ that are not equal to one, the influence ratio determined in Step 3 should be modified in this step. Equation 6 is applied in this step.

Step 5. A time buffer computation. Equation 7 is applied in this step.

Step 6. A maximum time buffer determination. Since the time buffer determined in Step 5 is a mean value not a maximum time buffer required to protect the constraint machine, modification by the desired confidence level is necessary. Equation 8 is applied in this step.

6. A numerical example and simulation validation

Here, a numerical example is illustrated to demonstrate the validity of the constraint time buffer determination model and a simulation model is constructed to verify the determined time buffer size.

6.1. *Example*

Table 1a, Fig. 4 and Table 1b illustrate the preliminary data of the example which consists of information about the machines, a process-views' bill of routing and a production product mix, respectively. First, as illustrated in Fig. 5, the time buffer determination algorithm is employed to transform the process-views' bill of routing into a machine-views' bill of routing. Machines 2 and 1 belong to a one-to-many relationship, which means one feeder machine feeds more than one fed machine. In this situation, the Capacity Occupation Rate (COR) for each feeder and fed machine

Machine	Quantity	MTTR	MTBF	Availability
M1	1	2·50	10·00	0·80
M2	1	1·60	10·00	0·86
M3	1	2·66	10·00	0·79
M4	1	4·29	10·00	0·70
M5	1	3·00	10·00	0·77
M6	1	7·85	10·00	0·56
CM1	1	1·36	10·00	0·88
CM2	1	10·40	10·00	0·49

Table 1a. Machine groups.

Product	Quantity
Part 1	800
Part 2	1000
Part 3	800
Part 4	700

Table 1b. Product mix (parts/month).

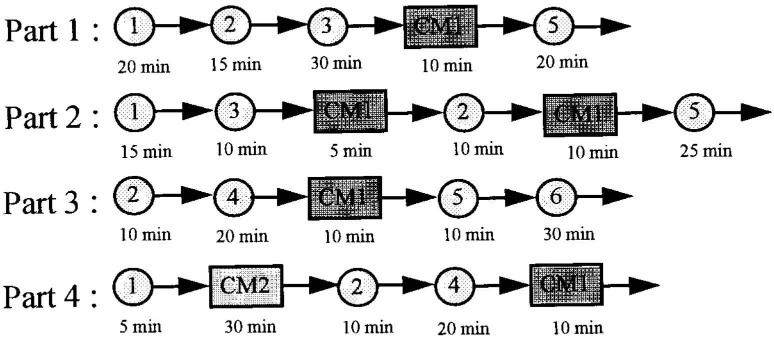


Figure 4. Process-view's bill of routing.

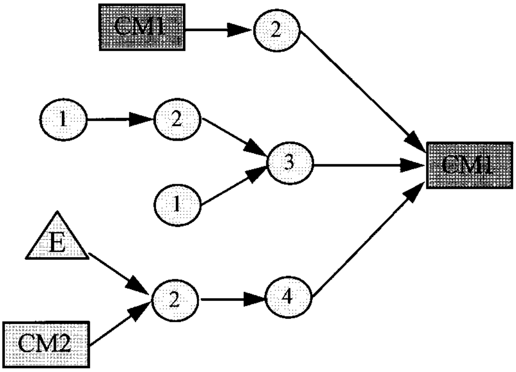


Figure 5. Machine-view's bill of routing.

i	j	$COR_{ik_{ij}}$
2	3	0·3243†
2	CM1	0·2703
2	4	0·4054
1	2	0·4638
1	3	0·4338
1	CM2	0·1014

† COR_{23}: $(800 * 15/60)/(30 * 24 * 0{\cdot}86) = 200/619{\cdot}2 = 0{\cdot}3243$

Table 2. Machine capacity occupation rate (COR_{ij})

relationship must first be determined. Table 2 illustrates the computed COR for each feeder and fed machine relationship.

Once the COR is determined, the influence ratio for each feeder and fed machine relationship can then be determined. Table 3 illustrates the computed influence ratio result. Each influence ratio result, if it is not equal to one, needs to be future normalized. Table 4 illustrates the normalization result. Once the influence ratio of each feeder and fed machine relationship is determined, the time buffer of the constraint

i	j	OR_{ij}	OR_{ji}	IR_{ij}
2	KM1	1·622†	6·000†	0·270†
3	CM1	3·176	8·308	0·382
4	CM1	3·000	6·000	0·500
1	3	1·739	3·170	0·549
2	3	1·297	3·170	0·409
CM2	2	2·000	6·000	0·333
E	2	#	#	0·667

† $OR_{2k_{2CM1}} = 1/(10/60) * 1 * 0{\cdot}2703 = 1{\cdot}622$
† $OR_{CM_{1k_2CM1}} = 1/(10/60) * 1 = 6{\cdot}00$
† $IR_{2CM1} = 1{\cdot}622/6{\cdot}00 = 0{\cdot}270$

Table 3. Machine influence rate (IR_{ij})

i	j	IR_{ij}	IR'_{ij}
2	CM1	0·270	0·225†
3	CM1	0·382	0·332
4	CM1	0·500	0·433
1	3	0·549	0·573
2	3	0·409	0·427
CM2	2	0·333	0·333
E	2	0·667	0·667

† $IR_{2CM1} = (0{\cdot}270)/(0{\cdot}270 + 0{\cdot}382 + 0{\cdot}500) = 0{\cdot}225$

Table 4. Modified machine influence Rate (IR'_{ij}).

machine CM1 can then be computed by the following expression:

$$\begin{aligned} B_{CM1} &= \left[(1{\cdot}36 * 1 + 1{\cdot}6) * 0{\cdot}225\right] + \left[((2{\cdot}5 + 1{\cdot}6) * 0{\cdot}427 + 2{\cdot}5 * (0{\cdot}573) * 0{\cdot}332\right] \\ &\quad + \left[(((10{\cdot}4 * 0{\cdot}333 + 0 * 0{\cdot}667) + 1{\cdot}6) * 1 + 4{\cdot}29) * 0{\cdot}433\right] \\ &= 5{\cdot}8 \text{ (hr)} \end{aligned}$$

The computed time buffer of CM1 is 5·8 h. The computed time buffer is a mean value, so, if a 99% confidence level is selected, then the time buffer is modified as follows:

if $\alpha = 0{\cdot}99$ is assumed.

$$B_{CM} = Ln\left(\frac{1}{1-\alpha}\right) B_{CM} = \text{Ln}(1/0{\cdot}01) * 5{\cdot}8 = 26{\cdot}7 \text{ (h)}$$

$$\Rightarrow B'_{CM1}$$

The final determined time buffer is equal to 26·7 h, which means that all products processed by the constraint machine CM1 have to be released 26·7 h early at the time being processed by the constraint machine. The same computation procedure is

Time buffer (h)		Output								Cycle time (h)		
CM1	CM2	Mon1	Mon2	Mon3	Mon4	Mon5	Mon6	Avg. outs (4–6)	Avg. outs (All)	Avg. WIP	Mean cycle	Cycle dev.
2	1	2375	2520	2473	2235	2398	2464	2366	2411	12	3·6	2·9
3	2	2468	2597	2461	2616	2759	2623	2666	2587	18	5·1	3·6
4	2	2551	2802	2921	2735	2728	2882	2782	2770	24	6·2	3·7
5	3	2484	2777	2988	2739	2717	2908	2788	2769	29	7·6	4·1
10	5	2980	3065	3105	2951	3110	3140	3067	3059	57	13·5	5·1
15	7	3161	3287	3207	3152	3166	3178	3165	3192	84	19·0	6·4
20	9	3104	3282	3277	3217	3205	3239	3220	3221	110	25·0	7·7
27	*12*	*3099*	*3171*	*3269*	*3267*	*3339*	*3227*	*3278*	*3229*	*147*	32·7	9·8
30	14	3173	3229	3269	3309	3278	3257	3281	3253	166	36·4	8·3
40	18	3282	3304	3345	3245	3324	3225	3265	3288	218	47·4	10·1
50	23	3319	3227	3120	3208	3200	3326	3245	3233	271	60·6	12·8
60	27	3256	3225	3185	3378	3224	3315	3306	3264	324	70·3	13·6
70	32	3267	3230	3305	3172	3299	3239	3237	3252	374	83·4	18·4
80	36	3253	3322	3213	3130	3199	3381	3237	3250	430	94·0	17·3
90	40	3247	3193	3254	3182	3194	3373	3250	3241	783	105·5	18·4
100	45	3288	3296	3342	3159	3164	3273	3199	3254	533	115·2	21·3

Table 5. Simulation results.

applied to the constraint machine CM2, giving its determined maximum time buffer as 11·5 h.

6.2. *Validation*

A simulation model based on the illustrated example is developed by use of a ManSim simulator (Tyecin 1995) to validate of the determined maximum time buffer size by the proposed time buffer determination model. The time buffer size of the constraint machines CM1 and CM2 is maintained as an independent variable in the simulation model. The simulation outputs include product output rate and production cycle time. To avoid the bias caused by the empty factory in simulation, the model is set in advance to run until steady state is reached. All scenarios are based on this initial simulated state. The simulation results are summarized in Table 5. The relationships of time buffer vs. output rate and cycle time is plotted in Fig. 6. The output rate is the average for the last three months, based on the simulation results, and the cycle time is the mean value of the products. Figure 6 reveals that the cycle time increases sharply when the time buffer increased. However, the output rate does not obviously increase when the time buffer exceeds 27 h and 12 h of CM1 and CM2. This finding proves that the 27 h and 12 h time buffers determined by the developed time buffer determination model and the maximum time buffer WIP level for CM1 and CM2 constraint machines.

7. Conclusion

In this paper, a constraint time buffer determination model for protecting a constraint machine is developed. The model consists of a machine-views' bill of routing which is a tree structure to represent the relationship between the constraint machine and its feeder machines. The tree structure serves as the fundamental structure for formulating and studying the behaviour between the feeder and fed machines. With this tree structure and its behaviour in relation to the MTTR of each feeder machine, a mathematical relationship to compute the time buffer can then be expressed. The validity of the determined time buffer result is further verified by the simulation model. Although the developed model focuses on the time buffer determination at the constraint machine, it can also be expanded to serve as a flowtime estimation approach for due-date assignment rules research.

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