APPLICATION OF THEORY OF CONSTRAINTS ON SCHEDULING OF DRUM-BUFFER-ROPE SYSTEM

S.S.Mahapatra[1] Amit Sahu[2]

[1] *Assistant Professor* [2] *M. Tech Student*

[1, 2] *Department of Mechanical Engineering, National Institute of Technology, Rourkela – 769008, INDIA*

[1] ssm@nitrkl.ac.in [2] amit_sahu@hotmail.com

Abstract: *The successful enterprises deliver products and services in shorter throughput time and turnover inventory as quickly as possible. Three important approaches to achieve these goals are Materials Requirements Planning (MRPI, MRPII), Just-in-Time (JIT), and Theory of Constraints (TOC). TOC seems to be a viable proposition because it does not require costly affair of system change; rather it is simply based on scheduling of the capacity constraint resources. The scheduling system of theory of constraints (TOC) is often referred as drum-buffer-rope (DBR) system. DBR systems operate by developing a schedule for the system's primary resource constraint. Based on simulation of a flow shop operation considering non-free goods, this study suggests that the performance of DBR results in lower in process inventory compared to conventional production system. In addition, the behavior of the system when bottleneck shifts its position has been studied. A methodology has been proposed using neural networks based on back propagation algorithm for accurate prediction of throughput considering mean processing time, coefficient of variation, buffer size, number of stations and signal buffer.*

Keywords: *TOC; DBR; Primary Resource Constraint; Simulation*

1.0 INTRODUCTION

Today's businesses are competing increasingly on time and quality. Companies can not survive if they fail to obtain competitive advantages by producing high quality products and services in shorter throughput time and quicker inventory turnover. Since the early 1970s, three important approaches have evolved for companies to achieve competitive advantages, each challenging old assumptions and ways of doing things. These are Materials Requirements Planning (MRP I and MRP II), Just-in-Time (JIT), and Theory of Constraints (TOC). Developed by Eli Goldratt in the mid-1980s [1], TOC evolved from the OPT (Optimized Production Timetable) system and was later known under the commercial name of Optimized Production Technology (OPT). As part of a marketing tool for the OPT system, Goldratt illustrated the concepts of OPT in the form of a novel in which the theory is gradually unraveled through the context of an everyday production situation. It presented a logistical system for the material flow called the drum-buffer-rope (DBR) and, gradually, the focus of the concept has moved from the production floor to encompass all aspects of business. By 1987, the overall concept became known as the theory of constraints (TOC) which Goldratt viewed as "an overall theory for running an organization". This refinement recognized that the main constraint in most organizations may not be physical but managerial-policy related. To address the policy constraints and effectively implement the process of on-going improvement, Goldratt [2] proposed a generic approach called the "thinking process" (TP). This is the current paradigm of TOC. Experts believe that it is the TP of TOC which will ultimately have the most lasting impact on business. The scheduling system of TOC is often referred as drum-buffer-rope (DBR) system. DBR systems operate by developing a schedule for the system's primary resource constraint. The aim of this paper is to focus on philosophy of TOC and study the behavior of DBR in a serial production line through simulation. Comparison of DBR system with conventional serial production line reveals that average work-in-process (WIP) and average wait time of items can be drastically reduced whereas utilization of machines can be significantly improved in a DBR system. Further, the effect of shifting of bottleneck in both systems is reported.

2.0 THE CONCEPT

The concept of the TOC can be summarized as:

• *Every system must have at least one constraint*. If it were not true, then a real system such as a profit making organization would make unlimited profit. A constraint therefore is anything that limits a system from achieving higher performance versus its goal

• *The existence of constraints represents opportunities for improvement*.

Contrary to conventional thinking, TOC views constraints as positive, not negative. Because constraints determine the performance of a system, a gradual elevation of the system's constraints will improve its performance.

The TOC has two major components. First, a philosophy which underpins the working principle of TOC. It consists of the five focusing steps of on-going improvement, the drum-buffer-rope (DBR) scheduling methodology, and the buffer management information system. These ideas are usually referred to as TOC's "logistics" paradigm. The second component of TOC is a generic approach for investigating, analyzing, and solving complex problems called the thinking process (TP).

2.1 PHILOSOPHY

The principle consists of five focusing steps [2]. The steps are:

(1) *Identify the system's constraint(s)*. These may be physical (e.g. materials, machines, people, demand level) or managerial.

(2) *Decide how to exploit the system's constraint(s)*. If the constraint is physical, the objective is to make the constraint as effective as possible.

(3) *Subordinate everything else to the above decision*. This means that every other component of the system (nonconstraints) must be adjusted to support the maximum effectiveness of the constraint. If nonconstraint resources are used beyond their productive capacity to support the constraint, they do not improve throughput but increase unnecessary inventory.

(4) *Elevate the system's constraint(s)*. If existing constraints are still the most critical in the system, rigorous improvement efforts on these constraints will improve their performance. As the performance of the constraints improves, the potential of nonconstraint resources can be better realized, leading to improvements in overall system performance.

(5) *Do not let inertia become the system constraint*

The first part of this step makes TOC a continuous process. Failure to implement step 5 may lead an organization to disaster.

3.0 DRUM-BUFFER-ROPE AND BUFFER MANAGEMENT

The logistics paradigm of the TOC has evolved from the scheduling software called Optimized Production Technology (OPT) which in turn, is based on the following nine rules [3]:

(1) Balance flow, not capacity.

(2) The level of utilization of a non-bottleneck is not determined by its own potential but by some other constraint in the system.

(3) Utilization and activation of a resource are not synonymous.

(4) An hour lost at a bottleneck is an hour lost for the total system.

(5) An hour saved at a non-bottleneck is just a mirage.

(6) Bottlenecks govern both throughput and inventories.

(7) The transfer batch may not, and many times should not, be equal to the process batch.

(8) The process batch should be variable, not fixed.

(9) Schedules should be established by looking at all the constraints simultaneously. Lead times are the result of a schedule and cannot be predetermined.

The implementation of the logistical system of TOC is governed by the drum-buffer-rope (DBR) methodology and managed through the use of time buffers (T-Bs). The *drum* is the system schedule or the pace at which the constraint works. *Rope* provides communications between critical control points to ensure their synchronization. *Buffer* is strategically placed inventory to protect the system's output from the variations that occur in the system.

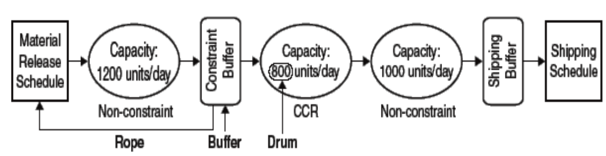

Figure 1 Drum-buffer-rope System

The DBR methodology synchronizes resources and material utilization in an organization. Resources and materials are used only at a level that contributes to the organization's ability to achieve throughput. Because random disruptions are inevitable in any organization, DBR methodology provides a mechanism for protecting total throughput of the system by the use of Time-buffers (T-Bs). Time-buffers contain inventory and protect constraint schedule from the effects of disruptions at non-constraint resources. The use of T-Bs as an information system to effectively manage and improve throughput is referred to as buffer management. It provides information based on planned and actual performance and is used for monitoring the inventory in front of a protected resource to compare its actual and planned performance.

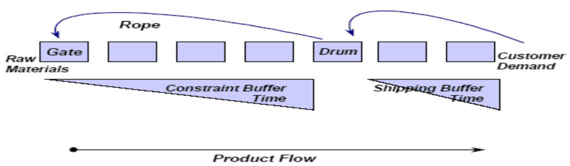

Figure 2 Synchronized flow

Three types of T-B are used in buffer management [8]:

(1) *Constraint buffers*: contain parts which are expected to wait a certain amount of time in front of a capacity constraint resource (CCR), thus protecting the constraint's planned schedule.

(2) *Assembly buffers*: contain parts/subassemblies which are not processed by a CCR, but need to be assembled with CCR parts.

(3) *Shipping buffers*: contain products which are expected to be finished and ready to ship at a certain time before the due date, thus protecting delivery date performance.

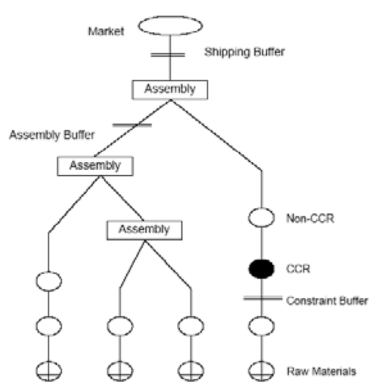

Figure 3 Different types of buffer

Figure3 shows the locations of these three T-Bs. Notice that an assembly buffer is not required before every assembly operation. It is required only before assembly operation that is fed by both CCR and non-CCR parts. The constraint buffer is located in front of the CCR and the shipping buffer is located at the end of the process. The use of T-Bs in buffer management can help spot the causes of disruptions without disrupting throughput. Moreover, by continually reducing buffer sizes, production cycle time can be reduced which in turn may reduce lead time.

4.0 TOC/JIT/MRP/LP COMPARISON

Several articles compared TOC with other production methods such as MRP and JIT. Swann (1986) advocated the use of MRP for net requirements and OPT for realistic shop schedules. Vollmann (1986) considered OPT as an enhancement to MRP II. Several studies argued that TOC (OPT), JIT and MRP are mutually exclusive inventory control systems. Gelders and Van Wassenhore (1985) expressed similar views and concluded that OPT would come first to plan the bottleneck facilities in the medium time horizon. MRP should be used to generate time-phased requirements while JIT should be used to maximize throughput. However, Plenert and Best (1986) concluded that both OPT and JIT are more productive than MRP, and the TOC system is more complete than the JIT system. Several studies compared the performances of TOC, JIT and MRP using computer simulations. A simulation study by Cook (1994) indicated that TOC outperformed JIT on a number of critical performance measures, including total output and standard deviation of flow time. From these studies, it is difficult to conclude with confidence that one system is better than the other. However, the general consensus derived from the comparisons is that an organization needs a combination of these production control methods to take advantage of each system's strength.

5.0 TRENDS OF TOC PHILOSOPHY

A comprehensive review of academic literature on the TOC, including papers published in referred and non-referred journals and books enables us to classify them on the basis of the TOC philosophy and its application in business disciplines. The review shows that the vast majority of the papers have concentrated on the concept and philosophy enhancement of TOC. Several articles have been published in the production sector also. But very little work has been done on service sector. In the application category a number of articles report the application of TOC concepts in the area of production and management accounting. Few papers have been published on the comparison of TOC with various existing theories such as TQM, JIT etc. Much work remains to be done in terms of developing measures of the three dimensions of the throughput orientation construct and empirically testing the hypothesis .Future research could be directed towards the simulation of the case studies of organizations by identifying the bottleneck stations and developing a detail schedule for it with the application of finite scheduling method .

6.0 MODELING TECHNIQUE

As pointed out in literature review an attempt has been made to address the issue of simulating a DBR system in this study. During model development, a serial production line having five machines and four intermediate buffer locations have been considered. The model has been developed using simulation software EXTEND 6. The processing time distribution of machines is assumed to follow Gamma distribution as it is one of the general types of distribution used for processing time generation.

$$f(x) = \begin{cases} \dfrac{\beta^{-\alpha} x^{\alpha-1} e^{\frac{-x}{\beta}}}{\Gamma(\alpha)} & \text{if } x > 0 \\ 0 & \text{otherwise} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where Ѓ (α) is the gamma function

The model for conventional serial production line is shown in Figure 4.

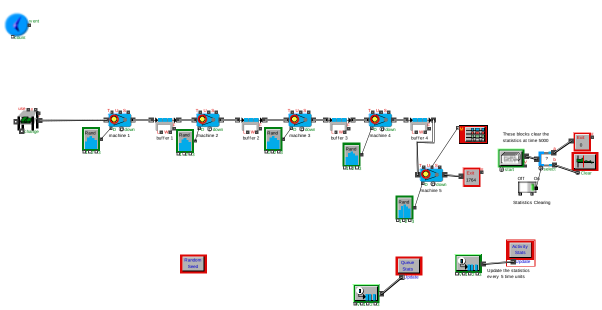

Figure 4 Model for Conventional Serial Production Line

The model for DBR system is shown in Figure 5. Note that a gate has been used to control the flow of items. In a conventional system, the inventories at buffer locations, particularly front buffer of CCR, go on increasing till the maximum limit of buffer capacity is attained. This results in excessive work-in-process (WIP) inventories. On the other hand, DBR system emphasizes on full capacity utilization of CCR. Therefore, adequate inventory must be maintained before the CCR so that it does not remain idle instead of building inventory in front of CCR. In order to achieve this, a back flow signal is introduced in the DBR model which prompts the generator to release a job into the system only when the level of buffer in front of CCR machine falls to a specified limit.

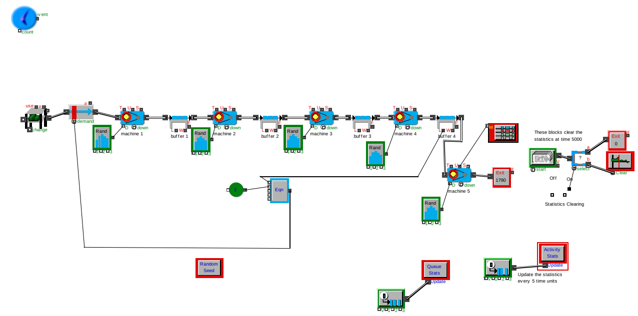

Figure 5 Model for Conventional Serial Production Line

In doing so, not only a constant level of inventory in front of CCR is ensured but also system inventory can be reduced.

7.0 MODEL VALIDATION

To validate the model developed for this study, comparison is made with the throughput obtained from the serial production line model and throughput calculated from Bluemenfield's formula. The percentage of error difference is calculated and is reported to be 0.01 which is within the acceptable limit (Table 1). Since analytical or simulation result for DBR system does not exist in the literature, it is difficult to validate simulation results of DBR system. The validation process carried out for serial production line is assumed to be extended for DBR system.

Table1 Throughput comparison

Sl. No.	Throughput calculated from Bluemenfield's Formula (B)	Throughput calculated from the model (S)	Percentage Difference ((B-S)/B)*100
1	0.098366	0.098365	0.01
2	0.099034	0.099033	0.01
3	0.099028	0.099027	0.01
4	0.097213	0.097212	0.01
5	0.096200	0.096200	0.00
6	0.096423	0.096423	0.00
7	0.094231	0.094213	0.00
8	0.098612	0.098612	0.00
9	0.99867	0.99867	0.00
10	0.99500	0.99500	0.00

8.0 RESULT & DISCUSSIONS

The steady state behavior of both the systems is studied. The model is run for 90000 time units and data is collected for 60,000 time units leaving 30,000 time units as warm-up period. The utilization of last machine in a DBR system having mean processing time of 10 units for all the machines with a coefficient of variation (CV) equal to 0.5 and intermediate buffer capacity of one is plotted in Figure 6 for estimating the warm-up period.

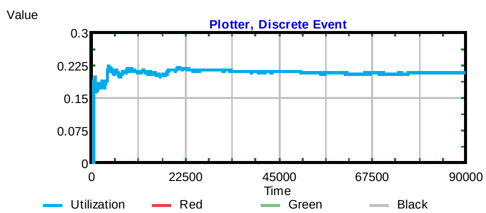

Figure 6 Estimation for warm-up period.

Each experiment is run for 10 times and performance parameters are noted down using 95% confidence interval.

8.1 Variation of Throughput with CV and Buffer Capacity

In DBR system, back flow signal for releasing items is taken from buffer 2. The variation of throughput in serial production line and DBR system with CV is reported in Figures 7 and 8 for intermediate buffer capacity (B) of one and three respectively. It has been observed that throughput decreases when CV increases for both the systems. However, throughput of DBR system is always less than that of serial production line for any value of CV. Again, for any value of CV, the throughput can be increased by increasing the buffer capacity in both the systems.

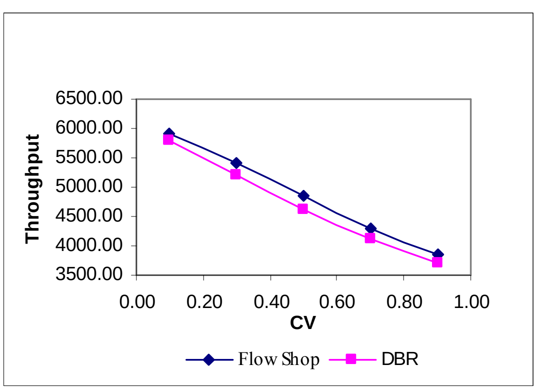

Figure 7 Throughput vs. CV (for B =1)

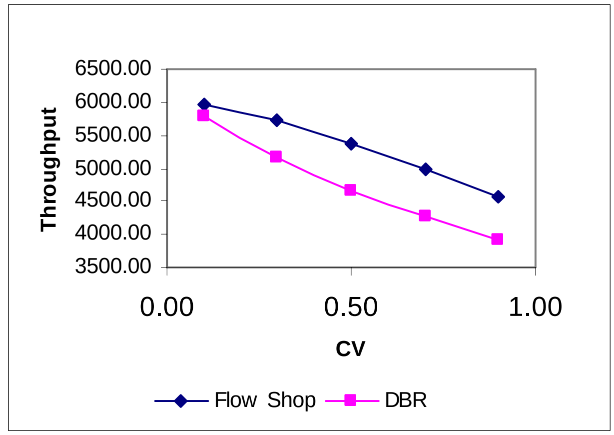

Figure 8 Throughput Vs. CV (for B =3)

8.2 Production Smoothing in DBR System

Although throughput of DBR system decreases in comparison to serial production line, it improves utilization of all the machines, reduces in-process inventory, reduces average wait time of items and percentage of blocking of the machines as shown in Table 2 for CV = 0.3 and B=3.

The mean processing time is assumed to be 10 time units for all the machines. In DBR system, back flow signal for releasing items is taken from buffer 2. The variation of throughput in serial production line and DBR system with CV is reported in Figures 7 and 8 for intermediate buffer capacity (B) of one and three respectively. It has been observed that throughput decreases when CV increases for both the systems. However, throughput of DBR system is always less than that of serial production line for any value of CV. Again, for any value of CV, the throughput can be increased by increasing the buffer capacity in both the systems. Although throughput of DBR system decreases in comparison to serial production line, it improves utilization of all the machines, reduces in-process inventory, reduces average wait time of items and percentage of blocking of the machines as shown in Table 3 for CV = 0.3 and B=3.

Table 2 Utilization of Machines

	FLOW SHOP		DBR	
m/c	Utilization	Blocked	Utilization	Blocked
1	1.000±0.01	0.0437	0.8649±0.001	0.0039
2	0.9860±0.2	0.0287	0.8620±0.002	0.0000
3	0.9780±0.2	0.0184	0.8618±0.000	0.0003
4	0.9685±0.2	0.0147	0.8626±0.002	0.0010
5	0.9529±0.2	0.0000	0.8601±0.002	0.0000

	FLOW SHOP		DBR	
B	Avg Length	Avg Wait	Avg Length	Avg Wait
1	1.84±0.045	19.2±0.484	0.654±0.0162	7.59±0.18
2	1.61±0.040	16.8±0.424	0.313±0.0025	3.36±0.02
3	1.37±0.029	14.4±0.308	0.382±0.014	4.43±0.16
4	1.11±0.02	11.6±0.30	0.383±0.009	4.45±0.1

8.3 Shifting of Bottleneck

In the next set of experiments, the mean processing time a machine is considered to be 10 except the bottleneck operation having processing time of 50 with CV = 0.5 and B = 3. The position of bottleneck (P) operation is systematically changed from 2 to 5 in the line. It has been observed that the system buffer in the flow line is always more than the DBR system. There is hardly any significant difference in both the systems as far as throughput is concerned. The utilization of bottleneck machine in DBR system is improved, Table 3. However, average wait time and average length of inter stage buffers prior to the bottleneck machine can be substantially reduced in DBR system. It is interesting to note that throughput can only be increased when bottleneck machine is placed at extreme ends of the line. If it is placed in the center of the line, system throughput is bound to decrease. The result is in consistent with well known “bowl phenomenon”.

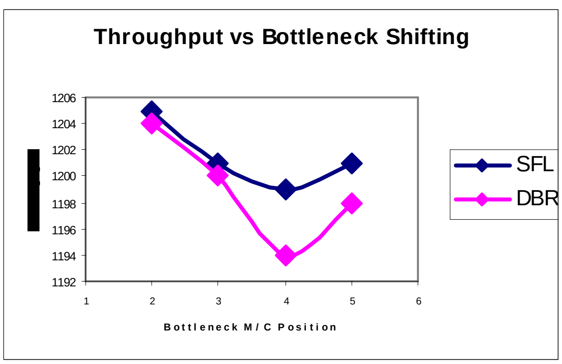

Figure 8 Throughput vs. Bottleneck Machine Shifting

8.4 Throughput vs. Buffer Size

A graph has been plotted between throughput and buffer size variation as shown in Fig 9 considering mean processing time of 10, CV = 0.1 and line length equal to 5. It is observed that throughput increases steadily as the buffer size increases up to a particular limit in case of serial production line model. After a particular level of the buffer size, the throughput almost remains constant irrespective of the increase in the buffer size.

In case of the DBR model, initially a slight increase of the throughput is observed when the buffer size increases but it remains more or less constant throughout the system irrespective of the increase in buffer size. The signal loop indicator is connected to machine 2 for DBR system.

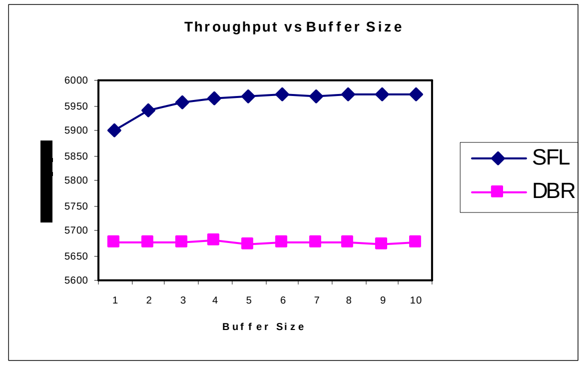

Figure 9 Throughput vs. Buffer Size

8.5 Throughput vs. change in Mean Processing Time

A graph has been plotted between throughput and variation in mean processing time as shown in Fig 10 considering CV = 0.1 and line length equal to 5. The signal loop is connected to machine 2 in all the cases .It is observed that in both the systems, i.e., the serial production line shop model and DBR model, it can be clearly concluded that as the mean processing time value increases, the throughput decreases.

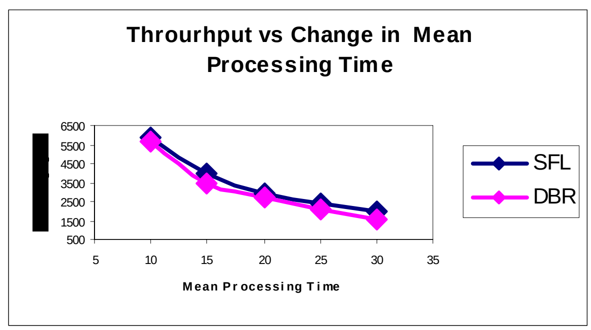

Figure10 Throughput vs. change in µ

8.6 Throughput vs. Change in Number of Machines

A graph has been plotted between throughput and change in number of machines as shown in Fig 11 considering CV = 0.1 and mean processing time 10. The signal loop is connected to machine 2 in all the cases. It is observed that in both the systems, i.e., the serial production line model and DBR model, as the number of machines increases, the throughput decreases. The decreasing trend is more prominent in case of serial production model.

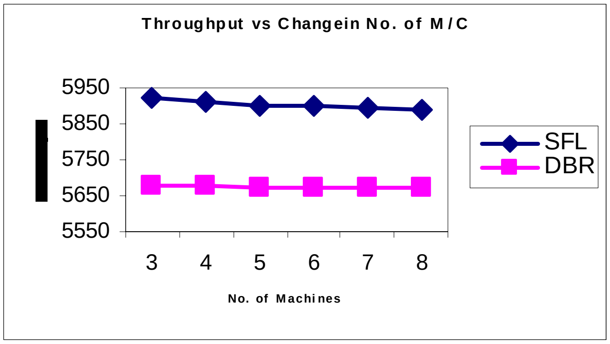

Figure 11 Throughput vs. No. of Machines

8.4 Throughput Estimation by the Application of Neural Network

A generalized analytical formula for throughput estimation (jobs per hour) of a DBR production line with variable processing times and limited buffer capacity happens to be difficult. Therefore, a methodology has been proposed using neural networks based on back propagation algorithm for accurate prediction of throughput considering mean processing time, coefficient of variation, buffer size, number of stations and signal buffer. In order to reduce training time, the five input parameters are converted into two principal components. This process of reducing the five input parameters to two principal components P1 and P2 is done with the help of a stastical software MiniTab. This is done mainly to reduce the neural network components and the computation time. Then the principal component P1 and principal component P2 are multiplied with two matrices and the output vectors are normalized. The output from the model is also normalized. The normalization is done by the following formula:

$$X_{i\,norm} = \frac{X_i - X_{i\,\min}}{X_{i\,\max} - X_{i\,\min}} \text{ ------------- (1)}$$

After the normalization, they are trained in the neural network program using the back propagation method written in C^{++}. The parameter set for the neural network training is as follows:

Error level = 0.1
Number of Cycles = 100000
Number of layers = 4
Number of Nodes = 2,7,7,1
After the training, the results obtained are:
Average error per cycle = 0.10011
Error last cycle = 0.10000
Error last cycle per pattern = 0.100000
Total cycles = 100000
Total patterns = 10000000

Seventy five percent of the data is used for training and twenty five percent of data is used for testing the network.
Since the error is within the acceptable limit, the neural network is accepted as well trained. Then testing the neural network model is done by taking some sample data and matching the results with the results obtained from actual simulation. The percentage error difference is reported to be within 0.1 which can be accepted. Therefore, it is concluded that neural network can accurately predict throughput of either flow lines or DBR system.

8.4 CONCLUSION

A simulation of a flow shop operation was done by the use of Extend 6 software. The model is allowed to run for 30000 time units as warm-up period and the data collection period consists of next 60,000 time units.
An attempt has been made to establish a relation between the system throughput and the parameters affecting it. The results are compared with the conventional production system and are reported to be matching with the literature. Simulation studies suggest that the performance of DBR results in lower in process inventory compared to conventional production system.
A generalized analytical formula for throughput estimation (jobs per hour) of a DBR production line with variable processing times and limited buffer capacity happens to be difficult. Therefore, a methodology has been proposed using neural networks based on back propagation algorithm for accurate prediction of throughput considering mean processing time, coefficient of variation, buffer size, number of stations and signal buffer. In order to reduce training time, the five input parameters are converted into two principal components and normalized principal components are used as inputs rather than actual parameters. The results obtained from the neural network training are found to be within the acceptable error limit. The throughput obtained from the neural network model almost matches with the throughput calculated from the DBR system using simulation.
Lastly it can be concluded that DBR system hardly demands the costly affair of organizational change prevalent in JIT or in lean system. It is simply based on scheduling of the capacity constraint resource.

8.5 References

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Table 3 Utilization of machines when bottleneck shifts

Flow shop

Position of bottleneck machine in the line	Utilization	Throughput	Avg. Length of corresponding buffer	Avg. Wait of corresponding buffer
2	0.9998±4.8950	1205±186.8	0.998±0.0002	49.6±0.2490
3	0.9990±0.0001	1203±186.0	0.998±0.0003	49.6±0.3450
4	0.9993±0.0001	1199±186.2	0.997±0.0003	49.9±0.2580
5	0.9930±0.0001	1201±186.0	0.997±0.0004	49.7±0.3220

DBR System

Position of bottleneck machine in the line	Utilization	Throughput	Avg. Length of corresponding buffer	Avg. Wait of corresponding buffer
2	0.9981±0.001 0	1204±186.7	0.799±0.0020	39.8±0.2850
3	0.9996±7.946 0	1205±185.7	0.993±0.0010	49.3±0.3550
4	0.9994±0.000 0	1194±185.0	0.993±0.0010	49.8±0.3270
5	0.9991±0.000 0	1198±184.9	0.993±0.0010	49.7±0.2840