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Workload Control in Flow Shops with Bottleneck Shifting and Process Time Variability

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Abstract
Manufacturing industries-struggle to devise precise planning and scheduling solutions due to unpredictable business situations. Additionally, uncertainties in production such as machine breakdowns, labour absenteeism, cycle time deviations, etc., would further deteriorate production plans and lead to uncertainty in decision-making processes. Flow shops with bottlenecks are particularly susceptible to these disturbances. Moreover, the random variations in cycle time variations can cause the bottleneck to shift between different stages. Literature indicates that conventional job release methods are ineffective in addressing these difficulties. In contrast, workload control methods would provide better solutions. Hence, a flow shop model has been developed and simulated using the variables like process time variations and bottleneck shifting on the discrete-event simulation software. The flow shop model incorporates realistic shop characteristics which are subjected to random process time variations, so as to assess the performance. The outcomes of the experimentation demonstrate that order release methods play a pivotal role in improving the performance of flow shops in more volatile situations.

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1. Introduction

In the current era of escalating competition, manufacturing industries are compelled to excel by minimizing costs, achievable through the optimal utilization of resources (Francas et al., 2011). Uncertainties in production such as unexpected fluctuations in demand patterns, scarcity of raw materials and quality-related issues in production would adversely affect manufacturing-related decisions (Betterton and Cox, 2009; Huang, 2017). Certain production systems have implemented Industry 4.0 which enables real-time process monitoring integrated with decision support systems. The simulation model is very relevant and a key role player as a decision-making tool for production systems design based on the Industry 4.0 paradigm (Kamble et al., 2020; Renna, 2022). In most cases, decision-making becomes complicated in shops that have a high level of uncertainty in accomplishing customer orders. Workload control (WLC) provides more promising solutions for effective manufacturing control (Huang, 2017). The WLC aids in organizing and guiding shop floor activities by addressing complexity issues, making the production environment more transparent and thereby reducing the likelihood of decision-making errors (Land et al., 1998; Stevenson and Hendry, 2006). Investigations have revealed that WLC policy implementations could bring down the total production time by 40-50 per cent (Bertrand and van Ooijen, 2002; Fredendall et al., 2010). Research in WLC is frequently found in three distinct forms such as i) developing new release rules, refining existing rules and comparing the rules, ii) Capacity control by applying order release rules and dispatching rules and iii) integrating customer enquiry management and release rules with dispatching rules to obtain optimum outcomes (Thürer et al., 2011). The present study investigates the performance of capacity constraint resources in a flow shop when processing time variability is initiated. A workload control approach is proposed for a flow shop model to mitigate the ill effects of bottleneck shifting phenomena. The flow shop with realistic shop characteristics was modelled and simulated on discrete event simulation to evaluate the performance under different experimental settings.

2. Literature review

This section presents a brief overview of WLC research that focuses on capacity and bottleneck aspects. A large part of the literature on WLC emphasizes either on designing new release policies or integrating release policies with production capacities. The WLC is exclusively practised to encounter complex situations yielding effective outcomes in the form of low flow time and maximum resource usage (Breithaupt et al., 2002; Land et al., 2014; Thürer et al., 2016, 2019). Land et al. (2015) claimed that the performance of a job shop under high load conditions could be improved by incorporating small adjustments in the capacity. Likewise, the timing of the capacity modification is more crucial than the amount of capacity adjustment. Further, research outcomes appealed to design a new control policy that focuses on capacity adjustments through the reduction of processing time of operations. Hence, Integrating Lancaster University Management School's corrected order release (LUMS COR) with the capacity adjustments has resulted in substantial performance benefits. In this policy, the amount of adjustment was recorded with a workload limit that was made to trigger the start and end of capacity adjustment (Thürer et al., 2016). Another research considered a dynamic environment and discovered that timing and degree of control adjustments play a vital role in judging performance. Additionally, if the dynamics were not considered then throughput time would become uncontrollable and resources remain underutilized (Soepenberg et al., 2012). Further, research correlated LUMS COR with a popular bottleneck-oriented Drum Buffer Rope (DBR) in different shop settings and observed that workload-controlled order release performs better in a shop with a moderate bottleneck. This was the advantage of the LUMS COR as it had a load-balancing function in it. However, bottleneck-oriented control release DBR was found to be superior in severe bottleneck situations (Thürer et al., 2017). Riezebos et al. (2003) noticed an efficient way to balance the flow of work in the manufacturing line by combining WLC with DBR. Kim et al. (2003) stated that the bottleneck flow control is exceptional in simple line scenarios having breakdowns and process time variability aspects. In another research, DBR showed extraordinary performance even in a job shop environment with multiple job routings (Chakravorty, 2001). Yet in another policy, Constant Work in Process (CONWIP) releases a new job when the number of jobs in the entire shop falls below the specified limit (Bullington, 2001; Spearman et al., 1990; Thürer and Stevenson, 2018). It is to ensure that the actual bottleneck of the system is always within the control. The CONWIP in a high variety of complex job shops earlier had faced load balancing issues, but research routed this problem by incorporating backlog sequencing rules and capacity slack-based rules (Thürer et al., 2017). Research confirmed that DBR performs exceptionally well in the stochastic environment such as bottleneck lines when compared with common release policies. However, in the presence of double bottlenecks, a policy called "pull from both bottlenecks" exceeds the CONWIP and other DBR interpretations from 10 to 20 per cent (Gilland, 2002). Also, CONWIP seems to be ineffective when the loop contains too many stations and no difference in job routings in terms of controlling utilization and throughput time (Bullington, 2001). Yet, with more stations in a CONWIP loop, less would control over the work in process (WIP) in the system (Thürer et al., 2016). A protective capacity placement in the vicinity of the bottleneck station is a sensible option to overcome bottleneck issues (Betterton and Cox, 2009). Kadipasaoglu et al. (2000) revealed that the placement of extra capacity upstream of the production line accommodating the random fluctuations diminishes the contrary effects of varying process parameters. Prabhu et al. (2022) observed that CONWIP outperforms other release methods like DBR, pull from a bottleneck (PFB) in unbalanced shops with dual bottlenecks having process time variability. However, DBR is consistently superior concerning flow time at certain levels of process time variability and CONWIP provided consistent throughput regardless of the bottleneck station in a four-station line with bottleneck shift phenomena. The theory of constraint principles too yielded better performance with shops that underwent random breakdown issues and process time variability (Betterton and Cox, 2009). Furthermore, Thürer and Stevenson, 2018 found a correlation between the direction of bottleneck shift and order release methods performance. Betterton and Silver, 2012 claimed that the throughput performance of a serial line entirely depends on the bottleneck station and proposed a novel approach for locating the bottleneck in a serial line having varying repair times and unusual buffers. Thürer, Qu, et al., (2017) found that bottleneck shiftiness has a negative impact on performance. However, the trade-offs between the bottleneck position and release control parameters would yield better results. The research observed deficient performance when the bottleneck shifted downstream rather than upstream. Literature on WLC revealed that enough studies have treated the flow shop with hypothetical characteristics and analysed the diverse kinds of uncertainties that lead to bottlenecks. However, the real process time variations with bottleneck shifting have not been considered in any of the research. Hence, this study considers real process parameters for the production of a windmill component which has considerable process time variations in distinct stages. The objective of this research is to apply the theoretical concepts of WLC to the flow shop with realistic process parameters. The question that is posed in the research is:

- What is the effect of bottleneck shifting in a flow shop with process time variability?

The research develops the simulation model and subjects it to experimentation with a proper experimental design to seek a solution to the research question.

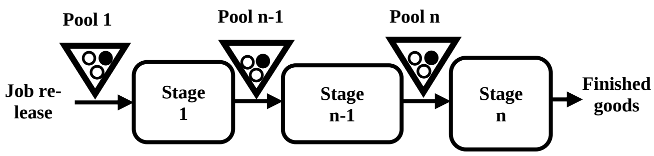

Fig.1. Conceptual Model

3. Experimental

This section discusses the methodology followed in experimentation such as the development of the conceptual model, simulation model, order release methods and design of experiments.

Table 1. Model Characteristics

Characteristics	Details
Shop modelled	Serial line production
Shop Characteristics	Realistic
Routing	Unidirectional flow
Number of stations	8
Station capacity	Equal
Inter arrival time (Hours)	Exponential distribution
Order release methods (ORR)	ARRIVAL, CONWIP, DBR, PFB
Processing time variability (PTV)	Three levels -Deterministic Level (1) and Random Levels (2)
Constraint Locations	Bottleneck shifting -8 stages

3.1. Conceptual Model

The model has been conceptualised based on manufacturing operations involved in the production of the rotor blade, a crucial part of the windmill. The conceptual model is shown in Figure 1. The process of rotor blade manufacturing consists of eight stages with operations in a particular sequence. Every stage has a pool, for the jobs that are waiting in line for the next process. Later jobs enter the corresponding stage once that machine becomes free. In this manufacturing line, the entities flow in a specific order beginning with material kit preparation, prefabrication, shell building, outer lamination, sawing and drilling, painting, balancing and inspection. The production activities start with releasing jobs and the jobs flow sequentially through the various stations from stage-1 to stage-n which represents a flow shop. In this, if one of the stages is disrupted, the entire system would come to a stop, which in turn results in production losses. A critical issue in this flow shop is the process time variability, i.e., random changes in process time to overcome quality-related issues. The accurate prediction of the process timings in stages is difficult as the severity of defects is unknown at the time of job release. These aspects in the flow shop would cause bottlenecks or lead to shifting the bottleneck among the stations. In available literature is rather scanty in this perspective and therefore, this research is intended to investigate the impact of bottleneck shifting on the performance of order release methods in a flow shop with process time variability.

3.2. Simulation Model

The characteristics of the simulation model are summarised in Table 1. The study considers the process characteristics of rotor blade manufacturing which resembles a flow shop. The simulation model has eight stages and was implemented using Arena V16 software. The minimum time required for the eighth stage is 105 minutes and the maximum time required for the second stage is 1680 minutes which becomes the constraint station. The research exercised four relevant order releases methods such as ARRIVAL, CONWIP, PFB and DBR which are described in section 3.3.

3.3. Order release methods

The order release methods hold a key control over the shop, designed to maintain a steady production rate along with meeting reliable delivery dates (Fernandes et al., 2017; M. Land and Gaalman, 1996). Most of the research in WLC is focused on designing appropriate order release methods, refining existing methods and comparing the performance (Lödding et al., 2003; Lu et al., 2011; Oosterman et al., 2000). In the present research, real process parameters are incorporated into the flow shop model and the performance of four ORRs have been experimented with process time variations and Bottleneck shifting (BNS).

3.3.1 ARRIVAL

ARRIVAL is a release policy that just releases the jobs continuously based on preliminary settings. It is an open-loop policy and the shop floor does not have any control over the policy. Earlier literature demonstrates the usage of this policy with different inter-arrival rates, arrival patterns and distributions. Given utilizing bottleneck capacity fully, an exponential arrival distribution with different inter-arrival times has been used.

3.3.2. Constant Work in Process (CONWIP)

Spearman et al. (1990) designed a release policy based on the total processing time required for the jobs that are under processing, i.e., a constant number of jobs waiting for the work to be completed is termed CONWIP. It controls the input based on the number of work-in-process workloads. CONWIP policy performs very effectively in simple serial lines. But its performance was poor in more complicated shops as it has a weak load-balancing function (Thürer, et al., 2017). CONWIP maintains the number of work-in-process units within the specified limit. It always monitors the number of work-in-process units in the entire system and sends the signal to release a new job only if the number of jobs in the system reaches the defined limit. The experimentation was conducted with the CONWIP at distinct levels of WIP to determine the best level.

3.3.3. Drum Buffer Rope (DBR)

The drum buffer rope (DBR) schedule, popular among researchers, was developed based on the theory of constraints principles laid by Goldratt and Cox. DBR schedules the release based on the status of the bottleneck and by limiting the buffer size in the bottleneck machine. Hopp and Spearman stated that lean production requires an upper level of WIP, which hence results in a pull system. DBR captures the information (rope) about the status of the bottleneck machine (drum), and resources (buffer) and accordingly controls input. DBR performance is exceptional in high bottleneck shops as it integrates input rate with the capacity of the bottleneck resource (Thürer et al., 2017).

3.3.4. Pull from Bottleneck (PFB)

PFB policy controls the input based on the workload present in selected bottleneck stations. The working mechanism of PFB is similar to CONWIP. The CONWIP maintains the constant work in the process throughout the system whereas PFB focuses exclusively on a bottleneck machine. Gilland (2002) executed PFB on a wafer fabrication facility with multiple bottleneck cases. The research resulted in an outstanding performance of PFB in multiple bottleneck cases as compared to single bottleneck cases.

3.4. Design of Experiments

In this experimentation, three variables have been considered such as ORR, PTV and BNS. The developed model reflects the real process time characteristics, experimented under different circumstances. Two different sets of experiments have been conducted. In the first set of experiments, four ORRs have been exercised namely ARRIVAL, CONWIP, PFB and DBR. The ARRIVAL ORR has experimented with eight different arrival parameters. The CONWIP has experimented with six levels of WIP. These levels of ARRIVAL and CONWIP were employed to determine the best-performing parameters of arrival rate and WIP limit. Thus, a 16x3 full factorial experimentation was selected. In the second set of experiments, the bottleneck location was shifted among eight distinct locations and was experimented with four ORRs. Hence, a full 8x4 factorial design was chosen. The replication length was chosen based on the assumption that the industry runs for 312 days in a year with 24 hours of work per day which determines the length of replication as 7848 hours. Initial 3744 hours were neglected as the warm-up period. In the simulation, 200 replications were run by changing one factor at a time.

4. Result and discussion

This section outlines the influence of each input at its selected level on the performance of the system and presents the outcomes in four diverse ways as summarised below.

4.1. Average performance of ORRs

The performance of ORRs was evaluated based on the flow time, throughput units and utilization of constraint resources at three levels of PTV. These outcomes are represented in charts as depicted from Figures 2 to Figure 4 shown in Appendix A. Figure 2 shows the average flow time for various ORRs when executed with PTVs. From the graph, the performance of PFB is observed to be exceptionally good. The flow time achieved is 78.79 hours, followed by CONWIP2 with 96.26 hours. The flow time performance under DBR and ARRIVAL are extremely poor. In ARRIVAL with different arrival rates, ARRIVAL4 shows satisfactory results. It was observed that the flow time performance was improved with the increase in inter-arrival time. On the contrary, performance degrades with an increase in WIP. Figure 3 shows the average throughput and it is seen that CONWIP2 and CONWIP10 yield a maximum throughput of 157 units followed by PFB with 156 units. The ARRIVAL and DBR performance were poor. Figure 4 shows the average utilization of bottleneck stations; the graph shows that resource utilization is highest at ARRIVAL i.e., usage ranges from 99 percent to 100 percent. In CONWIP, if the WIP level is restricted to a low limit the bottleneck resource results in starvation. If the WIP level is increased up to a certain extent utilization improves. Utilization was in the range of 85 per cent to 99 per cent. DBR method shows better performance concerning utilization. In the PFB method, the utilization of bottleneck resources drops to 74 per cent.

4.2. ORRs performance under PTVs

In this experimentation along with DBR and PFB, the top performing levels of the CONWIP and ARRIVAL, i.e, ARRIVAL4 and CONWIP2 were selected. ARRIVAL4 and CONWIP2 are labelled as ARRIVAL and CONWIP hereafter. The performance measures were plotted on the graphs from Figure 5 to Figure 7 shown in Appendix A. The parameters are the average (AVG) and standard deviation (STD) values of flow time, throughput and constraint resource utilization. In addition, to check the robustness of the model, the coefficient of variance (CV) for each output was plotted. The performance of ORRs under PTV-I is shown in Figure 5. PTV-I employs deterministic process time estimates and indicates no uncertainty. The maximum throughput of 155 Units and a minimum flow time of 73.78 hours is recorded for PFB. The values of CV are very small i.e., 0.09 and 0.05 respectively for throughput and flowtime. Figure 6 presents the ORR performance under PTV-II that uses random process time estimates with a low level of uncertainty. The maximum throughput of 157 units and a minimum flowtime of 72.51 hours were recorded for PFB, with smaller CV values i.e., 0.09 and 0.05 correspondingly for throughput and flowtime. Figure 7 presents the ORR performance under PTV-III that uses random process time estimates with a high level of uncertainty. In this, the maximum throughput of 157 units and a minimum flowtime of 87.2 hours were recorded for PFB, with smaller CV values i.e., 0.08 for both throughput and flowtime. Amongst other ORRs, PFB performs consistently better based on throughput and flowtime measures. However, utilization performance is poorer than other ORRs.

4.3. ORRs Performance with BNS and PTV

In this experimentation, the study assesses the performance based on flow time, throughput and utilization parameters under the bottleneck shifting for three levels of PTV. Results are illustrated in graphs depicted in Figure 8(a) to Figure 8(c) of Appendix A for PTV-I to PTV-III respectively with the X-axis indicating the bottleneck stations from station 1 to station 8. Considering PTV-I, in Figure 8(a) the flow time, throughput and utilization remain constant with BNS. CONWIP offered excellent performance with a flow time of 93.27 hours followed by ARRIVAL and DBR with a flow time of 94.17 hours. Flow time in PFB is remarkably high i.e., 954.39 hours, but records a high utilization of bottleneck resources. CONWIP also yielded the highest throughput of 157 units.

Figure 8(b) depicts the performance at PTV-II. It was observed that if the bottleneck is on station 1, PFB gives better results with a flow time of 72.13 hours, followed by CONWIP and DBR. In ARRIVAL, the flow time is 123.01 hours and increases with the BNS downstream. Based on throughput performance, if the constraint is on station 1, PFB gives better results with a maximum throughput of 157 units, followed by CONWIP. The throughputs achieved with ARRIVAL and DBR are 134 and 133 respectively, indicating weak performance. In ARRIVAL, the throughput is constant regardless of the position of the constraint. CONWIP showed consistence performance as the BNS moved forward. Although, PFB yielded the best flow time and throughput performance, the performance of the last station became the bottleneck. Also, with DBR, performance suffers as the constraint position moves downstream. Utilization performance of all the ORRs displays a similar pattern, however, utilization varies across the bottleneck positions.

Figure 8(c) illustrates the performance at PTV-III. It is observed that, when station1 is the bottleneck, PFB records the best flow time of 97.33 hours, followed by CONWIP with a flow time of 98.46 hours. CONWIP displays a greater performance consistently even when the constraint position moves downstream. PFB yields the best results with upstream BNS but performance deteriorates when BNS is at the last station. In ARRIVAL, the flow time is 541.67 hours when the constraint position is slightly upstream and increases as the bottleneck moves downstream. In DBR, the flow time at the upstream bottleneck is 360.61 hours and the flow time performance improves as the bottleneck moves downstream. When the constraint is station1, PFB and CONWIP give better results with a maximum throughput of 157 units. The throughput achieved with DBR and ARRIVAL are 132 and 129 respectively, indicating inferior performance. In ARRIVAL the throughput is constant regardless of the position of the condition. CONWIP shows consistent improvement in performance as the bottleneck moves forward. Initially, DBR yielded the best throughput performance but gradually declined as the BNS moved downstream. Further, the utilisation performance of the ORRs was suffering when BNS was downstream with random process estimates.

4.4. ANOVA Analysis

The simulation results have been statistically analysed by performing ANOVA to assess the significant relationship between the chosen factors. Table 2 in Appendix B, presents the main effects and interaction effects of BNS, PTV and ORR on the performance measures at a 5% significant level. First, considering the main effects of independent factors, based on a p-value less than 0.05, all the values are significant except for the effect of BNS on flow time. Next, considering the interaction effects between the factors based on a p-value less than 0.05, all the values show the influence on the performance except for the following two cases. One is the interaction effects of (BNS * PTV) for flow time and the second one is the interaction effects of (BNS * PTV) for throughput has shown non-significant results. When the PTV is introduced independently impact on the performance was observed. However, when BNS is executed either independently or by combining with the PTV, the model exhibits non-significant results. This specifies that PTV and ORR have a significant influence on the performance but no significant correlation was found between the BNS combined with either PTV or ORR.

5. Summary and conclusion

This study assesses the leverage of workload control methods in improving the performance of a windmill component manufacturing shop under process time variations. A simulation model has been developed with the real process time characteristics under random process time variations. Performance was evaluated under three different scenarios with four relevant order release methods. The employed measures were flow time, throughput and constraint machine usage along with the coefficient of variation for each performance parameter. In addition, the study examined the independent and combined effect of factors on performance using ANOVA. It was observed that PTV had more impact when it was enforced independently rather than when combined with other variables. The outcomes reveal that PFB was achieving consistently superior in certain PTV scenarios based on flow time and throughput. CONWIP records maximum and constant throughput regardless of operating conditions. Based on utilization, ARRIVAL was yielding remarkable outcomes over the other three ORRs regardless of constraint stations. With the real-time characteristics, the study observes that PFB performance was outstanding concerning flow time and throughput even with the presence of randomness in the system. Gilland (2002) also observes a similar performance in a study on bottleneck-oriented flowshop. In the experimentation on shifting the bottleneck with deterministic time estimates, the study observed that bottleneck shifting has a negligible impact on performance. Modelling BNS with random process estimates, the CONWIP showed consistently superior performance. PFB performed well only when the bottleneck stream is upstream. ARRIVAL and DBR exhibit deficient performance in all the cases of bottleneck shifting. In most of the previous studies such as Chakravorty (2001); Riezebos et al. (2003); and Thürer, Stevenson, et al. (2017) DBR was outperforming CONWIP and other ORRs. However, in this working environment, DBR failed to show consistent results. The reasons for the inferior performance of DBR could be due to over-emphasising the bottleneck machine, which requires approximately three times more than the average time required for non-bottleneck machines. In such situations, the release will entirely depend upon the bottleneck machine, thus leading to the starvation of remaining non-bottleneck machines. Hence, flow time increases and utilization of the non-bottleneck machines decreases gradually which leads to the weak performance of DBR. This indicates that bottleneck shifting downstream would deteriorate the performance as evident in the research by (Thürer et al., 2017). This study contemplates that the performance of the DBR would be improved by balancing the resource limit in both bottleneck machines and non-bottleneck machines. The present research compared the ORR performance under three scenarios. Future research may be extended in experimenting with the DBR with various levels of buffer limit at the bottleneck and minimizing starvation at non-bottleneck stations.

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Appendix

Appendix A

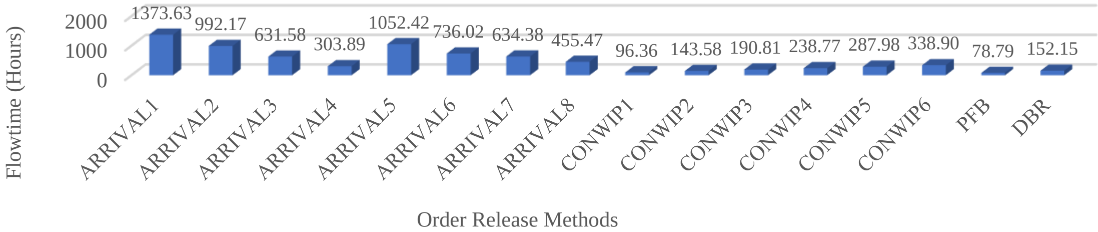

Fig. 2. Average flow time performance

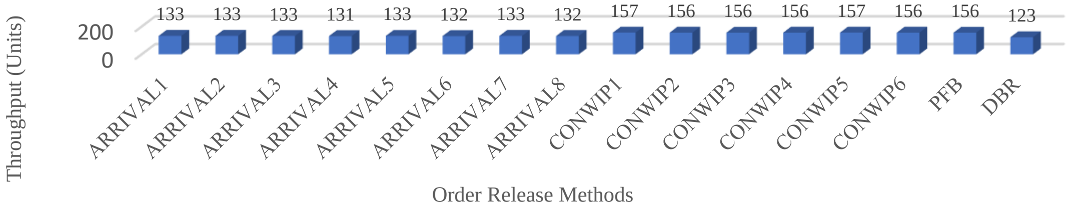

Fig. 3. Average throughput performance

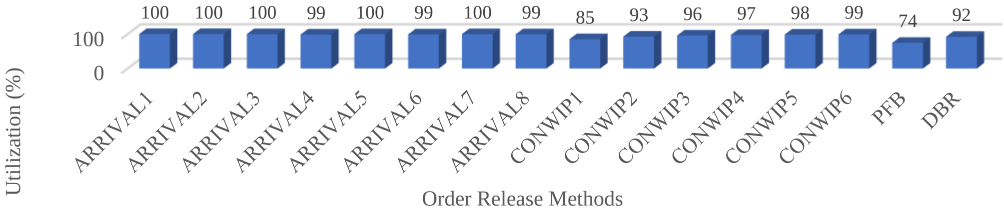

Fig. 4. Average utilization performance

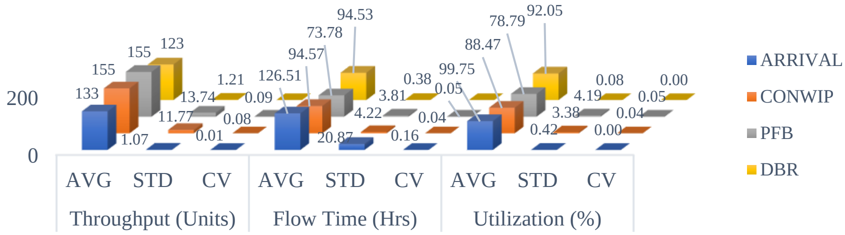

Fig. 5. Performance measures at PTV-I

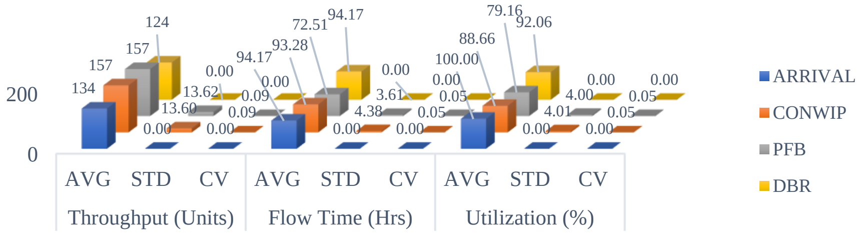

Fig. 6. Performance measures at PTV-II

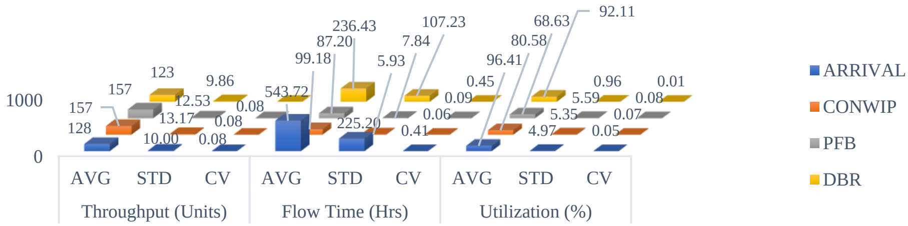

Fig. 7. Performance measures at PTV-III

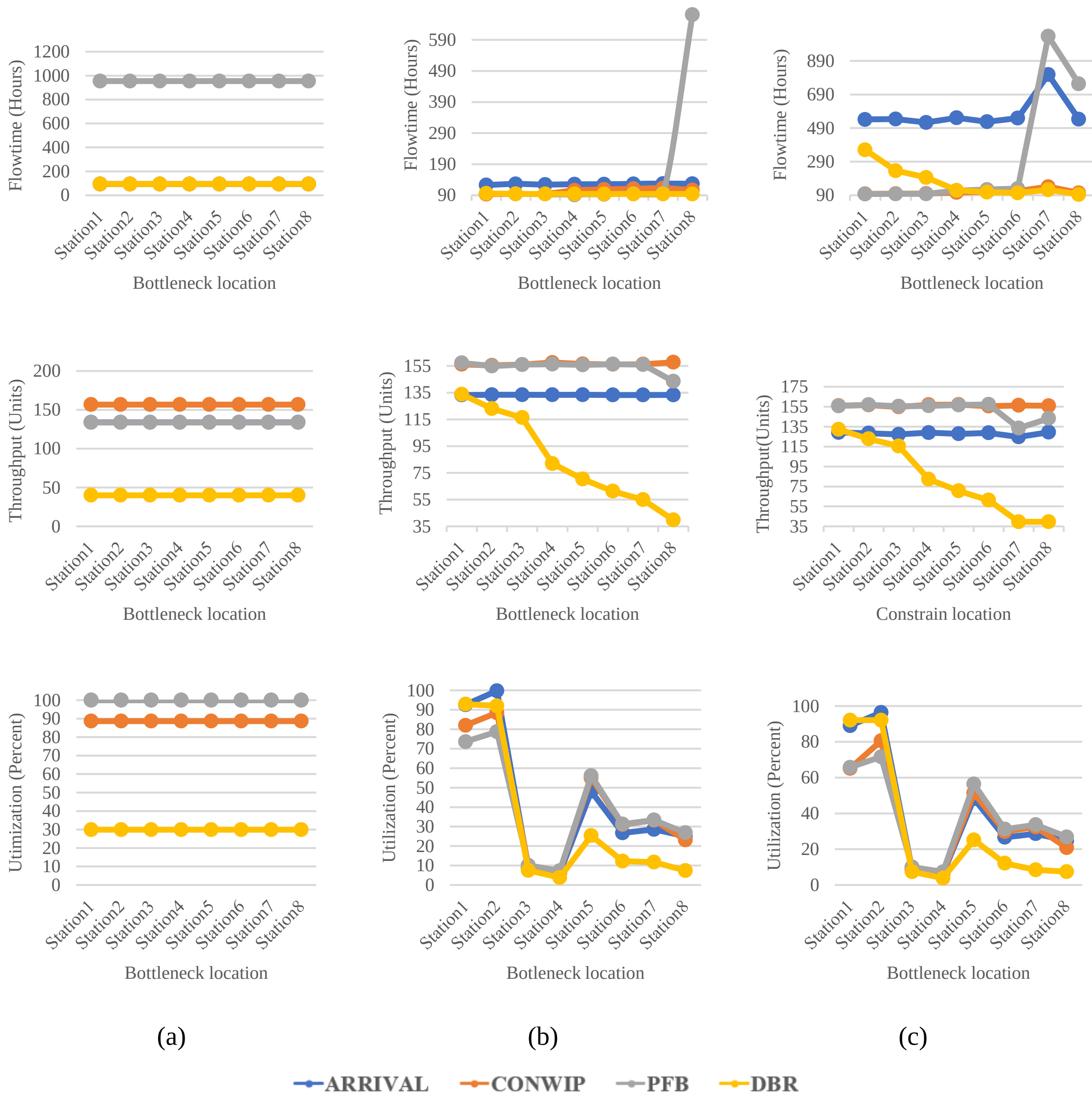

Fig. 8. ORRs performance with BNS under (a) PTV-I; (b) PTV-II; and, (c) PTV-III.

Appendix B

Table 2. ANOVA Results

Performance Measure	Source of variance	Sum of squares	Degrees of freedom	Mean square	F-ratio	p-value
Flow Time	BNS	173655.31	7	24807.90	2.06	0.070
	ORR	2130758.11	3	710252.70	58.86	0.000
	PTV	687326.12	2	343663.06	28.48	0.000
	BNS * ORR	473352.22	21	22540.58	1.87	0.042
	ORR * PTV	3358451.21	6	559741.87	46.39	0.000
	BNS * PTV	236716.28	14	16908.31	1.40	0.195
	Error	506793.48	42	12066.51		
Throughput	BNS	1530039.92	8	191254.99	1818.15	0.000
	ORR	110330.53	3	36776.84	349.62	0.000
	PTV	4743.81	2	2371.91	22.55	0.000
	BNS * ORR	8539.22	21	406.63	3.87	0.000
	ORR * PTV	7799.94	6	1299.99	12.36	0.000
	BNS * PTV	2021.52	14	144.39	1.37	0.209
	Error	4418.06	42	105.19		
Utilization	BNS	36737.84	7	5248.26	185.24	0.000
	ORR	14204.63	3	4734.88	167.12	0.000
	PTV	37562.88	2	18781.44	662.89	0.000
	BNS * ORR	2229.80	21	106.18	3.75	0.000
	ORR * PTV	13814.28	6	2302.38	81.26	0.000
	BNS * PTV	18465.40	14	1318.96	46.55	0.000
	Error	1189.97	42	28.33		