PRODUCTION ENGINEERING ARCHIVES 2025, 31(4), 455-465

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

Workload control in a bottleneck-oriented flow shop with capacity adjustments

Aruna Prabhu[1], Raghunandana K[1*], Ramakrishna Vikas Sadanand[1], Augustine B.V. Barboza[1]

[1]Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India; aruna.prabhu@manipal.edu (AP); raghu.bhat@manipal.edu (RK); ramakrishna.vikas@manipal.edu (RVS); a.barboza@manipal.edu (ABVB)
*Correspondence: raghu.bhat@manipal.edu

Article history
Received 19.07.2025
Accepted 28.11.2025
Available online 12.12.2025

Keywords
Workload control,
Order release methods,
Rotor blade manufacturing,
Analysis of variance,
Tukey's test.

Abstract
The rotor blade manufacturing industry struggles to devise precise planning and scheduling approaches due to uncertainties in production situations. Bottleneck workloads, process time variations and re-entrant flows with varied arrival frequencies would interrupt production schedules and adversely affect the shop's performance. Hence, an attempt has been made to study the significant impact of disproportionate workloads and the influence of innovative order release methods integrated with capacity adjustment features to enhance performance. The rotor blade manufacturing process has been thoroughly observed to incorporate the uncertain events that cause disturbance in production. A simulation model was created on a discrete event simulation platform incorporating problem phenomena through the conceptualization phase. The randomness present in the process was assessed using an input modelling approach which has resulted in probabilistic equations. The model has been verified and validated to ensure accuracy and was then subjected to 576 experimentations representing different scenarios that occur in a flow shop. Relevant workload control policies are executed to judge their effectiveness followed by Analysis of Variance Techniques. In addition, order release methods were ranked with the help of Tukey's tests for contribution computation. Outcomes of experimentations revealed that order release methods have a major share of 80.2 percent to the throughput and 42.84 percent to flow time performance indicating the benefits of workload control strategies in decision-making during uncertain situations.

DOI: 10.30657/pea.2025.31.42

1. Introduction

In recent years, workload control (WLC) strategies have been offering promising solutions in manufacturing industries by mitigating the high variability of both human and machine resources. The WLC has three-layer filters especially designed for high-variety job shops, with its prominent features offering potential for Industry 5.0 (Ma et al., 2025). The WLC strategies have been implemented through three key control points of production, which include job entry, job release, and dispatching to synchronize the processes, thereby protecting throughput against any fluctuations (Thürer et al., 2014). Huang (2017) stated that the WLC is one of the well-known production planning and control concepts established for effective manufacturing flow control in production shops. The ultimate objective of the WLC strategies is to improve the overall performance of the shops by diminishing the effect of uncertainty, thereby meeting the delivery needs of the customers. Several shop floor issues in production were addressed by various researchers, like loss of productivity, human errors, planning issues, and thereby resulting in increased financial burdens. Chiara Leva et al. (2022) stated that human errors in production shops, before examining human performance, caused many errors resulting in financial costs and loss of productivity. Wang et al. (2024) claimed that models that have been implemented in the past are traditional, and they have a limitation that the root cause of the process variations was not well addressed and incorporated in the operational planning. Liu et al. (2019) demonstrated that every manufacturing organization aims to obtain cost advantages through improved efficiency, and operating costs have been greatly increased by up to 150 percent compared to decades ago. Considerable literature is available on WLC that focuses on either the development of novel release policies or the integration of these policies with production capacities. WLC is predominantly applied in complex manufacturing environments, where it consistently delivers favorable outcomes, notably in terms of reduced flow time and optimized resource utilization (Breithaupt et al., 2002; Land et al., 2014; Land et al., 2015; Thürer et al., 2016, 2019). The simulation studies on workload control methods have shown the possibility of tremendous improvements in both job shops and flow shops. However, some of the important real-life aspects of production are not considered, such as re-entrant flows and capacity fluctuations in terms of the reallocation of workers. Additionally, the literature on WLC is highly regarded in job shop applications, and researchers have referred to job shops as complex and dynamic in nature. However, the applicability of WLC is very limited in the context of flow shops, except for a few bottlenecks-affected shops. In addition, researchers have considered only hypothetical conditions, thereby ignoring the production parameters that occur in reality. The flow shops are also equally complex in some scenarios where critical parameters, such as uncertain environments, are considered. Moreover, most flow shops are dedicated to single products with a unidirectional flow involving high initial investment for specialized equipment. These shops have no scope for change in product types as they are not flexible. Though the production scheduling appears to be a simple task, it becomes complicated when uncertain parameters are involved. Hence, considering the above, the present research attempts to bridge the gap by varying the capacity of resources of the flow shops in terms of the application of manpower and machine capacity expansion.

2. Literature review

A brief overview of WLC research that emphasises capacity and bottleneck aspects is presented in this section. A considerable amount of the WLC literature is available either on designing job release methods or integrating those with dispatching rules to tune up the production capabilities. Kingsman & Hendry (2002) evaluated the ultimate benefits by executing input control and output control together rather than executing them independently. There have been enormous improvements in terms of optimum due date and flow time in the shops that considered decision points at release stage or delivery stage either independently or sequentially (Lu et al., 2011). The design of control policies is necessary in two level multistage job shops in order to determine the right time and the right place of exercising the release decision to obtain desired results. In addition, a control policy with an optimum combination of time and place would fetch better results in hybrid shops (Thürer et al., 2013). A hybrid make-to-stock and make-to-order flow shop was explored to compare the effectiveness of load-based and bottleneck-based rules, and it was discovered that the bottleneck-based rule was effective in high-severity scenarios (Costa et al., 2023).

Research outcomes in the past have observed the benefits of surplus capacity in different ways to help in production during uncertainty. Kadipasaoglu et al. (2000) revealed that the placement of extra capacity upstream of the production line helps in accommodating the random fluctuations and diminishes the contrary effects of varying process parameters. Kim et al. (2010) highlighted that protective capacity plays a key role in improving performance and demonstrated the need for protective capacity in absorbing the variations in production lines. Betterton & Cox (2009) proved that protective capacity placement in the vicinity of the bottleneck station is a sensible option to overcome bottleneck issues. Additionally, a properly modelled Drum-Buffer-Rope (DBR) system is essential to investigate the role and influence of protective capacity in terms of constraint location and magnitude. Sagawa et al. (2023) developed a proof of concept that converts the closed loop system into an open loop discrete event system incorporated with capacity adjustment policies. These models are found to be very responsive to connect dynamic events and help in achieving more cost-effective capacity plans. It has been observed that the operational performance of a job shop under high-load conditions can be enhanced through minor capacity adjustments. Notably, the timing of these capacity modifications proves to be more critical than the magnitude of the adjustments. Building on these findings, recent research has supported the development of a control policy that implements capacity changes by reducing the processing time of operations (Land et al., 2015). In response, the Lancaster University Management School Corrected Order Release (LUMS COR) policy was formulated, integrating capacity adjustments to yield significant performance improvements. Within this framework, the workload limit serves as a trigger mechanism to initiate and terminate capacity adjustments and consequently record the extent of these adjustments (Thürer et al., 2016). Research conducted in dynamic environments has demonstrated that both the timing and degree of control adjustments are critical determinants of system performance. Moreover, neglecting the dynamic nature of the environment can lead to uncontrollable throughput times and underutilization of resources. These findings underscore the importance of incorporating adaptive control mechanisms that respond effectively in changing system conditions (Soepenberg et al., 2012). Prior research conducted by Betterton & Cox (2009) assumed that having unlimited buffer space is unrealistic; hence, further investigation is needed to discover the relationship between buffer size to the generation of protective work in process by considering future consumption of constraints. However, the research is necessary to analyse the capacity adjustments during high load conditions and integrate policies for outsourcing, order acceptance, and process planning when there are changes in due dates and mixed routings (Land et al., 2015; Thürer, Land, et al., 2017). As complexity in the shop floor production parameters increases, the workload needs to be adjusted according to the realized job progress. However, research is required for controlling capacity adjustments in the case of the finite loading approach, and most of the studies have neglected the constraints with respect to practical situations like: (i) when operators with overtime are not applicable; and (ii) when operators are not transferable, etc. (Thürer et al., 2016). In addition, research must investigate shop performance under the influence of the interaction between WLC and shop design with capacity adjustments (Germs & Riezebos, 2010) in terms of rearrangement of workers and provision of overtime, etc. (Fredendall et al., 2010). Hence, considering the above knowledge gaps in capacity adjustments, the present research attempts to bridge the gap by varying the capacity of resources in the bottleneck-oriented flow shops in terms of the application of manpower and capacity expansion of machines. Hence, a research question has been framed: "How does capacity modification in terms of operator reallocation influence workload control performance in a pure flow shop during quality-related blockages?" To address the above question, a simulation model of real rotor blade manufacturing has been developed and experimented with different scenarios, and outcomes have been discussed in the subsequent sections.

3. Methodology

The methodology employed in the research has been widely used in simulation experiments. It begins with the construction of a conceptual model, which is supported by data regarding random process timings and other resource requirements collected through close observation of the rotor blade production process. The next process was developing a simulation model, followed by verification and validation. An appropriate experimental design was set up to carry out experiments on the simulation model, followed by an analysis of results.

3.1. Conceptual model

The conceptual model shown in Fig. 1 represents the manufacturing of the rotor blade, a crucial part of the windmill. It depicts eight processes employed in production, and each process must be completed in a specific order. The production activities start with releasing jobs and the jobs flow sequentially through the various stages from station-1 to station-n, which represents a flow shop. In the final station, the products are subjected to inspection, and the presence of defects would require rework, hence entering the respective intermediate stations, which disrupts the production of already released jobs. The workload control strategies are employed by keeping the uncertain workloads into account; in addition, the research incorporates capacity adjustments, such as the application of manpower and machine capacity at different levels.

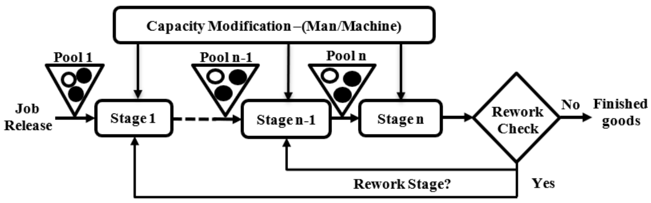


Fig. 1. Conceptual model

3.2. Experimental variables

The flow shop has been modelled on logical and quantitative factors. Quantitative factors depict production conditions like re-entrant proportions (PROP) and the capacity of shops. The production shop usually has two types of loads, regular loads for new jobs and re-entrant loads for the jobs that are found to be defective. Regular jobs move in the same sequence, whereas re-entrant jobs enter only into the required stage. In the experimentation, six different proportions of loads have been considered to generate uncertain scenarios, with different percentages of regular load and re-entrant loads to various stations. When the capacity modification factor is considered, there are two options such as (i) increasing the capacity of bottleneck stations (Machine); and (ii) the method of assignment of technicians (Stage) to eight stations. The logical variables are chosen from literature, such as order release methods (ORR) and priority dispatching rules (PDR), to overcome complex working conditions and make the shop floor more productive. The ORR holds key control over the shop, designed to maintain a steady production rate along with meeting reliable delivery dates (Fernandes et al., 2017; Land & Gaalman, 1996). Relevant ORRs that have been employed are discussed. The Constant Work in Process (CONWIP) policy performs very effectively in simple serial lines, and it maintains the amount of work in process (WIP) units within the specified limit. The DBR schedules the release based on the status of the bottleneck and by limiting the buffer size in the bottleneck machine. The DBR performance is exceptional in high-bottleneck shops as it integrates input rate with the capacity of the bottleneck resource (Thürer, Qu, et al., 2017). The Immediate Release (IMMD) is a policy in which jobs are released without considering the status of the machines, whether free or occupied; the released jobs are made to wait in different workstations. The Pull from Bottleneck (PFB) policy controls the input based on the workload present in selected bottleneck stations. In the Random Release (RAND) policy, all the jobs for a specific period are released instantly, which would help the technicians to know the required amount of workload for processing orders. The Re-entrant method (REM) is a modified version of Constant Batch Machine Workload (CONSTBWL) (Singh & Mathirajan, 2019), which was used for determining the workload of batch production. In this approach, the policy governs the job release into the system by monitoring the average system workload rather than focusing solely on bottleneck stations. The system workload encompasses both the regular load and the disproportionate workloads across stations caused by re-entrant flows. Job release is deferred until the combined re-entrant workload and the workload of already released jobs do not exceed the preset workload limit. This workload limit is determined based on the desired throughput and utilization levels. The PDR is a sequencing technique that helps to set the jobs in a particular order before being processed in a station. Usually, jobs wait in the form of queues based on sequencing rules. The research considers four priority dispatching rules first-come first-served (FCFS), last-come first-served (LCFS), high priority (PrioHigh), and low priority (PrioLow). The basis for priority in the last two rules is priority based on the length of the sequence.

3.3. Experimental modeling

The flow shop operates with probabilistic process timings and comprises eight stations, three of which are identified as bottleneck stations, as illustrated in Fig. 2.

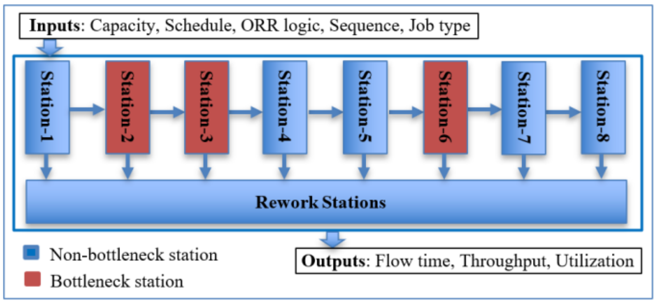


Fig. 2. The structure of flow shop

Release methods logically select jobs based on prevailing shop conditions and route them for further processing upon arrival. Each newly released job progresses sequentially from Station 1 to Station 8. In the event of defects, the same stations are equipped to manage the resulting additional rework loads, ensuring continuity in processing. These unforeseen circumstances make the shop floor complicated due to the introduction of randomness in the model. The production model takes different inputs, such as capacity, schedule, release logic, and type of job, and generates outputs such as flow time, throughput, and utilization. The discrete event simulation software Arena 16 V6 has been employed to model the production line of rotor blades. Table 1 shows the summary of simulated shops and job characteristics.

Table 1. Summary of the simulated shop and job characteristics

Characteristics	Details
Shop Type	Flow shop
Characteristics	Real
Routing Variability	Yes
Number of workstations	Eight stages
Inter arrival time in h	Poisson Distribution
Machine Setting (Machine)	Two Levels -One Machine, Two Machine
Manpower Setting (Stage)	Two Levels-Centralized, Decentralized
Re-entrant Proportions (PROP)	Six Levels – Increased Uncertainty
Order release methods (ORR)	CONWIP, DBR, IMMD, PFB, RAND, REM
Priority dispatching rules (PDR)	FCFS, LCFS, PrioHigh, PrioLow

Inter-arrival time for the product follows a Poisson distribution except for the RAND release method. In this experimentation, two levels of capacity, each in manpower and machine settings, six different levels of PROP were considered in the order of increasing uncertainty, six relevant ORRs were applied, such as CONWIP, DBR, IMMD, PFB, RAND, and REM, and four different PDRs were considered, namely FCFS, LCFS, PrioHigh, and PrioLow. Hence, $2 \times 2 \times 6 \times 6 \times 4 = 576$ experiments with the full factorial design were chosen. The replication length has been chosen based on the assumption that the industry runs for 312 days in a year with 24 h of work per day, which determines the length of replication as 7488 h. The initial 3744 h has been neglected as the warmup period, which is 50 percent of the replication length. The literature suggests 30 percent to 50 percent of the warmup period, and the research considered 50 percent of the replication length as the warmup period (Singh & Mathirajan, 2019). Each experimental trial has been repeated 100 times as replications. The model outputs were chosen to evaluate the performance of the system, such as flowtime in hours, throughput in units, utilization of resources in percentage terms, and approximate contribution.

3.4. Verification and validation

The trace technique and degeneracy tests are two powerful techniques for the verification and validation of a simulation model (Sargent, 2010). The trace technique is used to debug the discrete event simulation program (Qi et al., 2009). The behaviour of entities is traced throughout the model to determine whether the logic is precise and accurate. A certain number of jobs is released into the system continuously, and the occurrence of each operational event is traced during the simulation run. Accordingly, the status of every job and the timings of the succession events are recorded and compared with the estimated event schedules. In the verification process, consistency is observed in the event schedule, and the results correlate with the intended schedule as shown in Table 2.

Table 2. Trace Technique for Verification

Station	Start Time (h)	End Time (h)	Duration (h)
Station 1	0.00	2.43	2.43
Station 2	2.43	34.47	32.04
Station 3	34.47	60.43	25.96
Station 4	60.43	67.42	6.99
Station 5	67.42	75.45	8.03
Station 6	75.45	82.98	7.53
Station 7	82.98	96.36	13.38
Station 8	96.36	98.12	1.76

In addition, a paired t-test is conducted to determine whether the mean difference between the pairs is equal to zero or not. The output indicates the mean for the actual as 11.77 and for the simulation as 12.27. There are 7 degrees of freedom (DOF), and the p-value is 0.362, which is greater than 0.05 at a 5 percent significance level, indicating that there is no significant difference between the pairs. The paired t-test results are shown in Table 3.

Table 3. Paired t-Test Results

Source	Mean	DOF	t-Value	p-Value
Actual	11.77	7	0.974	0.362
Simulation	12.27			

The degeneracy test was conducted by changing one input variable with appropriate internal parameters. The behaviour of the model was tested by increasing the throughput rate in the form of decreasing inter-arrival time. An increase in capacity utilization due to an increase in the throughput rate was observed, as shown in Table 4. The results confirm that the model possesses a satisfactory range of accuracy based on principles of queuing theory and John D. C. Little's law of relation between throughput rate and WIP.

Table 4. Degeneracy Test

Factors	1	2	3	4	5
IAT (min)	1920	1860	1800	1740	1680
Utilization (percent)	81.24	83.82	86.63	89.65	92.83

4. Result and discussion

The research evaluates the influence of a few critical inputs on the performance of flow time and throughput. The flow time is a significant measure, which is the time elapsed for a job when it enters the system to that it leaves the system (Singh & Mathirajan, 2019). The total number of products that come out of the last stage within a considerable period is taken as throughput in units. The significant impact of various uncertain factors on performance has been determined by statistical analysis. Thereafter, the effectiveness of WLC policies has been evaluated for its economic performance with the help of Tukey's test.

4.1. Graphical analysis of ORR performance

The performance of different ORRs in a bottleneck-oriented flow shop which are assessed in this experiment under two levels of system uncertainty (low versus high) and two resource assignment settings (centralized versus decentralized) under low machine capacity, is depicted in Fig. 3 & Fig. 4 in Appendix A. The following are the main inferences drawn from the flow time values. Due to increased uncertainty across both centralized and decentralized manpower settings, a significant rise in flow time is observed when changing from low to high uncertainty.

This is particularly noticeable as the IMMD rule increases approximately from a range of 75 h to 86 h to more than 300 h to 470 h. Even in the RAND, rapidly increasing from a range of 106 h to 144 h to above 420 h to 627 h. This shows the widening gap in the performance under RAND and IMMD policies, indicating their high sensitivity to uncertainty. With respect to performance based on centralized and decentralized team assignment is concerned, at the lower levels of uncertainty, centralized shows better performance over the decentralized one among most policies. Like, in CONWIP, flow ranging between 62 h to 68 h in centralized increases to 71 h to 73 h in decentralized, indicating that the flow time is 5 h to 10 h shorter as compared to the centralized setting. The decentralized configurations for the IMMD can rarely perform better than centralized ones, like 267.08 h versus 306.51 h under the LCFS rule. This indicates that in certain scenarios, the decentralized setting could incorporate randomness without affecting performance. However, this advantage of centralized assignment diminishes at high levels of uncertainty.

The performance of different ORRs in a bottleneck-oriented flow shop, which are assessed in this experiment under two levels of system uncertainty (low against high) and two resource assignment settings (centralized against decentralized) under two machine capacities, is depicted in Fig. 5 & Fig. 6 in Appendix A. CONWIP and PFB have consistently achieved lower flow times under all priority dispatching rules at both levels of uncertainty. Their performance was also found to be stable under the centralized capacity setting. At the same time, the IMMD and RAND have delivered poor flow time performance at both uncertainty levels. The influence of priority dispatching rules is very minimal compared to release methods. At lower levels of uncertainty, the centralized settings outperformed with savings of approximately 10 to 12 h, which is recorded with the CONWIP. Under high levels of uncertainty, centralized setting performance was not consistent. Like, the IMMD performance was inferior in a decentralized setting, with flow time ranging from 267.64 h to 470.58 h as compared to 183.13 h to 234.32 h in a centralized setting. The IMMD yields lower flow times at lesser uncertainty levels, but the performance becomes unpredictable as the level of uncertainty increases.

The throughput performances at the two scenarios are shown in Fig. 7 in Appendix A. Throughput reduces as uncertainty increases. However, this reduction could be partially compensated for by doubling the bottleneck machine capacity. Like, during a lower level of uncertainty, when the throughput performances of one machine and two machine settings are considered, the IMMD results improved from 154 to 157 units. However, it is seen that team assignments have no role in improving throughput performance across various combinations. The highest throughput recorded was 157 units in the IMMD method with two machine centralized combinations under low uncertainty. Similarly, the lowest throughput of 114 units was recorded under a high uncertainty case with the combination of two machines centralized in the PFB method.

The research presented various scenarios with different levels of uncertainties in the form of varied percentages of defects and shop capacities. The changes in performance measures due to the input variations are noticed in the graphs. At both levels of uncertainty under centralized settings, the PFB & CONWIP showed a higher level of performance. These release methods still offered relatively significant results at a higher level of uncertainty. Under stable conditions, the decentralized manpower setup was found to be inferior; however, it can be more resilient under unpredictable production situations. Performance drastically degraded in the

IMMD and RAND when the level of uncertainty increased. Under higher levels of uncertainty, flow time performance declined with decentralized settings, indicating that centralized control is prominent and more robust during randomized process situations. Generally, centralized setups showed consistently better performance under both levels of uncertainty. The centralized setup, especially at higher levels of uncertainty, showed poor performance. The doubling of the bottleneck capacity has been supportive in improving flowtime and throughput measures. The CONWIP, PFB, and RAND are at the extreme ends, with either the best throughput or the flowtime. DBR and REM policies have recorded an average performance concerning all measures. To get a clear understanding of the influence of factors, statistical analysis was conducted using the analysis of variance (ANOVA) technique, which is described in the next section.

4.2. ANOVA analysis

A relative contribution of different variables to the flow time and throughput performance of the flow shop is shown by the ANOVA analysis. A statistical method was employed to determine the relative effects of five factors which were obtained through experimentation with 576 combinations. A five-factor ANOVA analysis was performed using the Minitab program, and the outcomes are shown in Table 5 in Appendix B. To examine the associations, the F-ratio was compared with corresponding p-values at a 95 percent confidence level.

When the main effects are considered, ORR contributes 42.84 percent to flow time and 80.2 percent to throughput, which are more significant with respect to both performance metrics. The PROP has a share of 28.56 percent, which is significant, and a moderate share of 7.16 percent on throughput. Similarly, the Stage factor has a moderate share of 2.99 percent and 2.78 percent on flow time and throughput, respectively. The main effect of other factors, i.e., Machine and PDR, is less than 1 percent, which is not significant. When the interaction effects are considered, the (PROP × ORR) has a moderate share of 13.38 percent and 5.02 percent, respectively, on the flow time and throughput. Likewise, the combined effect of (Stage × ORR) has a low effect of 2.38 percent on flow time and 1.25 percent on throughput.

The ANOVA analysis showed the significance of the impact of chosen parameters on flowtime and throughput performance. The study uses the relationship between throughput and flow time to assess the effectiveness of different policy combinations. For further investigation of effects, a Tukey post-hoc test was performed to rank these factors based on the magnitude of the impact. Remarkably, the results showed a contradiction between flow time and throughput, as shown in Fig. 8 in Appendix A. The ORR, which has yielded the lowest flow time, resulted in the highest throughput and vice versa. Hence, an economical model has been strategically developed to evaluate optimum release methods.

4.3. Profit computation

According to a cost analysis of a 63 m rotor blade by Bortolotti et al. (2019), the total manufacturing cost of a rotor blade is \$154,090.4. The proportion of variable cost in the form of material, labour, and utilities totals \$112,646.33 which accounts for 73.1 percent of the blade cost. Similarly, the fixed costs are attributed to equipment, building, tooling and maintenance amounts to \$ 41,444.07, representing 26.9 percent of the blade cost. In addition to the manufacturing cost of the blade, other costs attributed are WIP costs, lost throughput costs, and increased flow time costs. In the simulated production environment, the bottleneck station operates under a target cycle time of 24 h. Based on a replication length of 3744 h per year, the standard throughput is established at 156 blades per year. Any throughput below this benchmark incurs a penalty of 5 percent of the blade cost per unit shortfall. The standard flow time is 101.4 h per blade, which is observed as the minimum flow time in one of the ORRs. This value serves as the benchmark for evaluating flow time performance. Any increase in flow time beyond this benchmark contributes to additional fixed plant costs, calculated on a daily basis. Furthermore, WIP inventory is associated with a holding cost and is assumed to be equivalent to 20 percent of the blade cost. These cost components are integrated into the profit model to assess the economic efficiency of the production system. The yearly contribution, P, is given by:

$$P=\left\{(T_{act} \times C_m \times B_c) - \left[(n \times B_c) + (w \times 0.2B_c) + \left((T_{std} - T_{act}) \times 0.05B_c\right) + \left(\frac{(FT_{act}-FT_{std})}{24} \times F_c\right)\right]\right\} \quad (1)$$

Where,
T_{act}= Actual throughput (blades/year)
C_m = Contribution margin
B_c= Blade cost (\$/unit)
n = Number of blades produced (units)
w = WIP inventory (units)
T_{std} = Standard throughput (blades/year)
FT_{act}= Actual flow time (h)
FT_{std} Standard flow time (h)
F_c= Fixed cost per day (\$/day)

The yearly contribution is depicted in Table 6 in Appendix B. The contribution has been determined to find an optimum policy during critical situations shown in Fig. 9 in Appendix A. According to the findings, it is revealed that the DBR method is ideal since it offers balanced performance with maximum profit.

4.4. Practical implications

In queuing theory, it is clear that an increase in variance in the system increases the waiting time for the products and average performance decreases (Hurley & Whybark, 1999). In such situations, it is advisable either to remove the variability or provide a buffer that absorbs the variability in order to restore the system's performance. In the case of rotor blade manufacturing, the variability is caused due to the appearance of defects that require reworking. The rework time usually depends on the size and severity of the defects. Each type of defect requires different procedures based on depth, criticality, and location of the defect. In such cases, the process timings become unpredictable, resulting in queues and hampering production. Hence, it is essential to determine the size of WIP in order to make arrangements for a capacity buffer, such as additional storage space, resources to handle, and capital, especially the arrangements needed to transport and store 63 m long rotor blades.

5. Conclusion

Research outcomes have demonstrated that capacity modifications have a positive impact on performance, both in terms of capacity expansion through the addition of machines and manpower reallocation. Based on the flow time values, it can be inferred that PFB has consistently excelled at lower levels of uncertainty, while CONWIP surpassed it at higher levels. This means that CONWIP overrides PFB, indicating its ability to sustain itself at uncertainty levels. The research in (Chakravorty, 2001; Riezebos et al., 2003; Thürer, Stevenson, et al., 2017) also witnessed similar performance regarding CONWIP. Such outcomes have been established with different PDRs, mostly with FCFS and PrioHigh. Though the PFB and CONWIP are productive for flow time, but failed concerning throughput values. On throughput, policies like IMMD and RAND achieved outstanding throughput units, but on the contrary, yielded poor flow time values. This signifies that a policy that yields the greatest flowtime values produces the poorest throughput results and vice versa. Doubling the capacity of bottleneck machines showed consistent improvements in throughput and reduction in flowtime under higher uncertainty. In general, centralized technician assignments outperformed in terms of flow time, particularly under low uncertainty. These outcomes have significantly reinforced the literatures by (Betterton & Cox, 2009) that nurtured the benefits of the capacity cushion. The decentralized assignments provided a slight throughput gain for certain release methods, like IMMD, under higher uncertainty. Higher uncertainty has resulted in longer flow times and lower throughputs in all scenarios. The CONWIP and PFB are more robust than the IMMD and DBR, which are more sensitive to uncertainty. Based on the statistical analysis, the ORR has a 42.84 percent contribution to flow time, an 80.2 percent contribution to throughput. Similarly, the PROP has a 28.56 percent on flow time and 7.16 percent on throughput. The stage factor contributes to flow time by 2.99 percent and throughput by 2.78 percent. The PDR does not influence any of the performance measures. From Tukey's test results, the best mean flow time performance of 100.4 h was recorded, and a maximum throughput of 155 units was also observed. However, tests confirmed that flow time and throughput have more conflicting outcomes, which makes it difficult to choose the optimum release method. An economic model was employed to evaluate contribution measures, and the DBR method was used as the optimal approach, yielding the highest profit margins. In DBR, the release decision is governed by the status of the bottleneck station, specifically in relation to the availability of a minimum sufficient buffer for critical resources. The present research has considered a few factors that cause uncertainty to limit the complexity of modelling. However, industries often face challenges in terms of demand fluctuations, machine breakdowns, and labour absenteeism could be explored in future research.

Acknowledgement

The authors are grateful to the Department of Mechanical and Industrial Engineering of M.I.T Manipal for providing the computing facilities.

References

Betterton, C. E., & Cox, J. F., 2009. Espoused drum-buffer-rope flow control in serial lines: A comparative study of simulation models. International Journal of Production Economics, 117(1), 66–79. DOI: 10.1016/j.ijpe.2008.08.050

Bortolotti, P., Berry, D., Murray, R., Gaertner, E., Jenne, D., Damiani, R., Barter, G., & Dykes, K., 2019. A Detailed Wind Turbine Blade Cost Model. www.nrel.gov/publications.

Breithaupt, J. W., Land, M., & Nyhuis, P., 2002. The workload control concept: Theory and practical extensions of load oriented order release. Production Planning and Control, 13(7), 625–638. DOI: 10.1080/0953728021000026230

Chakravorty, S. S., 2001. An evaluation of the DBR control mechanism in a job shop environment. In Omega, 29. www.elsevier.com/locate/dsw

Chiara Leva, M., Demichela, M., Comberti, L., & Caimo, A., 2022. Human performance in manufacturing tasks: Optimization and assessment of required workload and capabilities. Safety Science, 154. DOI: 10.1016/j.ssci.2022.105838

Costa, F., Kundu, K., Rossini, M., & Portioli-Staudacher, A., 2023. Comparative study of bottleneck-based release models and load-based ones in a hybrid MTO-MTS flow shop: an assessment by simulation. Operations Management Research, 16(1), 33–48. DOI: 10.1007/s12063-022-00276-6

Fernandes, N. O., Thürer, M., Silva, C., & Carmo-Silva, S., 2017. Improving workload control order release: Incorporating a starvation avoidance trigger into continuous release. International Journal of Production Economics, 194, 181–189. DOI: 10.1016/j.ijpe.2016.12.029

Fredendall, L. D., Ojha, D., & Wayne Patterson, J., 2010. Concerning the theory of workload control. European Journal of Operational Research, 201(1), 99–111. DOI: 10.1016/j.ejor.2009.02.003

Germs, R., & Riezebos, J., 2010. Workload balancing capability of pull systems in MTO production. International Journal of Production Research, 48(8), 2345–2360. DOI: 10.1080/00207540902814314

Huang, Y., 2017. Information architecture for effective Workload Control: an insight from a successful implementation. Production Planning and Control, 28(5), 351–366. DOI: 10.1080/09537287.2017.1288278

Hurley, S. F., & Whybark, D. C., 1999. Inventory and capacity trade-offs in a manufacturing cell. In Int. J. Production Economics (Vol. 59).

Kadipasaoglu, S. N., Xiang, W., Hurley, S. F., & Khumawala, B. M., 2000. A study on the effect of the extent and location of protective capacity in flow systems. In Int. J. Production Economics (Vol. 63).

Kim, S., Cox, J. F., & Mabin, V. J., 2010. An exploratory study of protective inventory in a re-entrant line with protective capacity. International Journal of Production Research, 48(14), 4153–4178. DOI: 10.1080/00207540902991666

Kingsman, B., & Hendry, L., 2002. The relative contributions of input and output controls on the performance of a workload control system in make-to-order companies. Production Planning and Control, 13(7), 579–590. DOI: 10.1080/0953728021000026285

Land, M., & Gaalman, G., 1996. Workload control concepts in job shops A critical assessment. In Int. J. Production Economics (Vol. 46).

Land, M. J., Stevenson, M., Thürer, M., & Gaalman, G. J. C., 2015. Job shop control: In search of the key to delivery improvements. International

Journal of Production Economics, 168, 257–266. DOI: 10.1016/j.ijpe.2015.07.007
Land, M., Stevenson, M., & Thürer, M., 2014. Integrating load-based order release and priority dispatching. International Journal of Production Research, 52(4), 1059–1073. DOI: 10.1080/00207543.2013.836614
Liu, R., Li, X., & Chen, S., 2019. Extension Analysis of Manufacturing Cost and Construction of basic-elements Model. Procedia Computer Science, 162, 156–165. DOI: 10.1016/j.procs.2019.11.271
Lu, H. L., Huang, G. Q., & Yang, H. D., 2011. Integrating order review/release and dispatching rules for assembly job shop scheduling using a simulation approach. International Journal of Production Research, 49(3), 647–669. DOI: 10.1080/00207540903524490
Ma, L., Zhong, R. Y., Yuan, M., Ding, K., Thürer, M., Pan, Y., Qu, T., & Huang, G. Q., 2025. A human-centric order release method based on workload control in high-variety make-to-order shops towards Industry 5.0. Robotics and Computer-Integrated Manufacturing, 94. DOI: 10.1016/j.rcim.2024.102946
Qi, C., Sivakumar, A. I., & Gershwin, S. B., 2009. An efficient new job release control methodology. International Journal of Production Research, 47(3), 703–731. DOI: 10.1080/00207540701455335
Riezebos, J., Korte, G. J., & Land, M. J., 2003. Improving a practical DBR buffering approach using Workload Control. International Journal of Production Research, 41(4), 699–712. DOI: 10.1080/0020754031000065485
Sagawa, J. K., Oliveira, A. F., Mušič, G., Land, M. J., & Maluf, A. S., 2023. Smart workload input-output control of production systems: A proof of concept. European Journal of Operational Research, 309(1), 286–305. DOI: 10.1016/j.ejor.2022.12.034
Sargent, R. G., 2010. Verification and validation of simulation models. Proceedings of the 2010 Winter Simulation Conference, 166–183. DOI: 10.1109/WSC.2010.5679166
Singh, R., & Mathirajan, M., 2019. Investigation of different inputs and a new release policy in the proposed simulation model for wafer fabrication system. Sādhanā, 44(2), 41. DOI: 10.1007/s12046-018-1006-8
Soepenberg, G. D., Land, M. J., & Gaalman, G. J. C., 2012. Workload control dynamics in practice. International Journal of Production Research, 50(2), 443–460. DOI: 10.1080/00207543.2010.539277
Thürer, M., Land, M. J., Stevenson, M., & Fredendall, L. D., 2017. On the integration of due date setting and order release control. Production Planning and Control, 28(5), 420–430. DOI: 10.1080/09537287.2017.1302102
Thürer, M., Qu, T., Stevenson, M., Li, C. D., & Huang, G. Q., 2017. Deconstructing bottleneck shiftiness: the impact of bottleneck position on order release control in pure flow shops. Production Planning and Control, 28(15), 1223–1235. DOI: 10.1080/09537287.2017.1362486
Thürer, M., Stevenson, M., & Land, M. J., 2016. On the integration of input and output control: Workload Control order release. International Journal of Production Economics, 174, 43–53. DOI: 10.1016/j.ijpe.2016.01.005
Thürer, M., Stevenson, M., Land, M. J., & Fredendall, L. D., 2019. On the combined effect of due date setting, order release, and output control: an assessment by simulation. International Journal of Production Research, 57(6), 1741–1755. DOI: 10.1080/00207543.2018.1504250
Thürer, M., Stevenson, M., Silva, C., Land, M., & Filho, M. G., 2013. Workload control and order release in two-level multi-stage job shops: An assessment by simulation. International Journal of Production Research, 51(3), 869–882. DOI: 10.1080/00207543.2012.676685
Thürer, M., Stevenson, M., Silva, C., Land, M. J., Fredendall, L. D., & Melnyk, S. A., 2014. Lean control for make-to-order companies: Integrating customer enquiry management and order release. Production and Operations Management, 23(3), 463–476. DOI: 10.1111/poms.12058
Thürer, M., Stevenson, M., Silva, C., & Qu, T., 2017. Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation. International Journal of Production Economics, 188, 116–127. DOI: 10.1016/j.ijpe.2017.03.025
Wang, Y., Liu, J., Zhou, L., Cong, L., & Sutherland, J. W., 2024. Integrated operation planning and process adjustment for optimum cost with attention to manufacturing quality and waste. Journal of Manufacturing Systems, 73, 241–255. DOI: 10.1016/j.jmsy.2024.02.004

Appendix

Appendix A

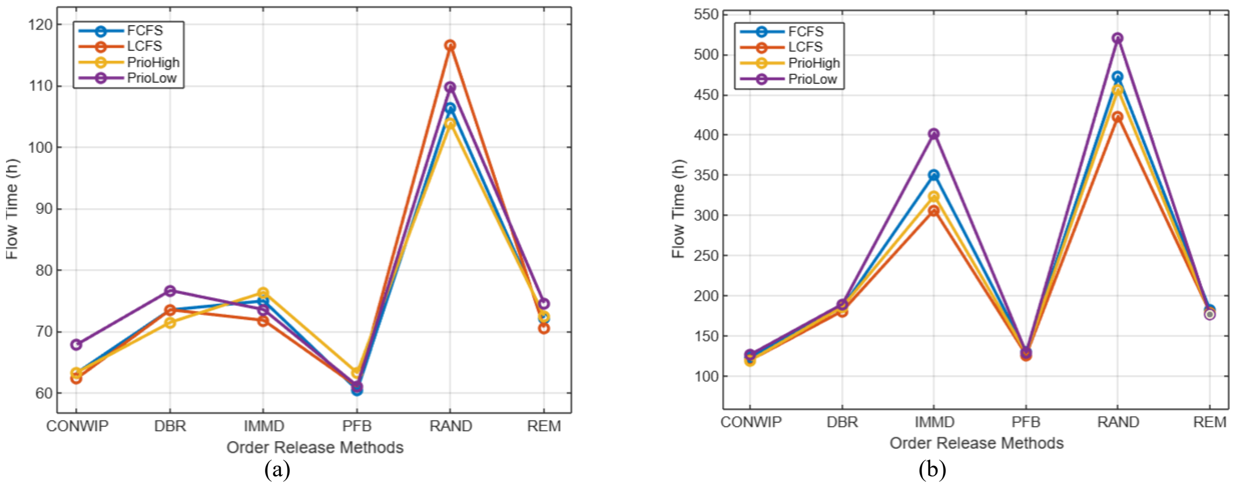


Fig. 3. Flow time performance of one Machine- centralized Stage under (a). Low Uncertainty; (b). High Uncertainty

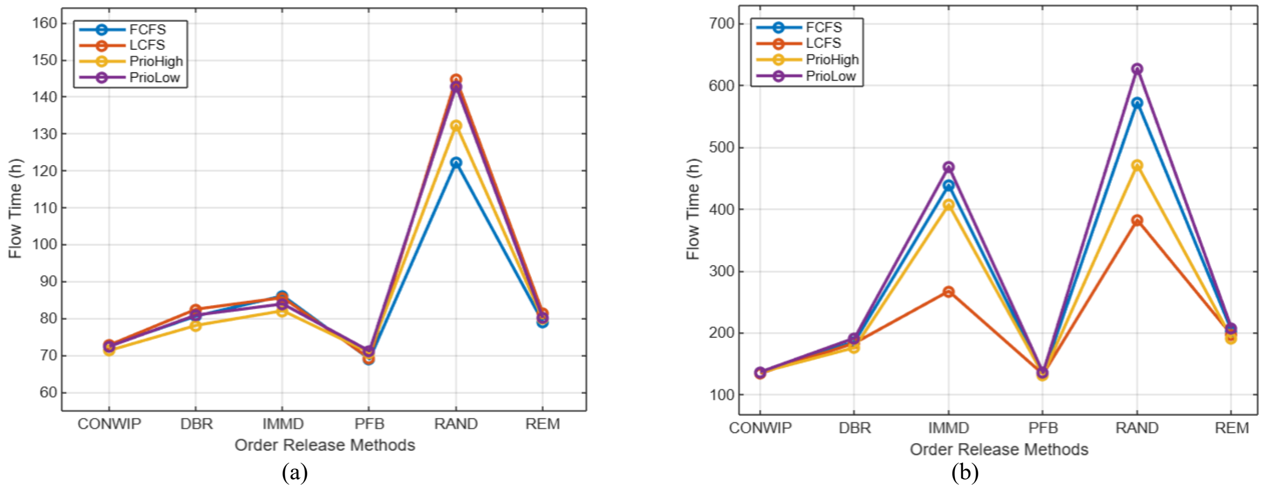


Fig. 4. Flow time performance of one Machine- decentralized Stage under (a). Low Uncertainty; (b). High Uncertainty

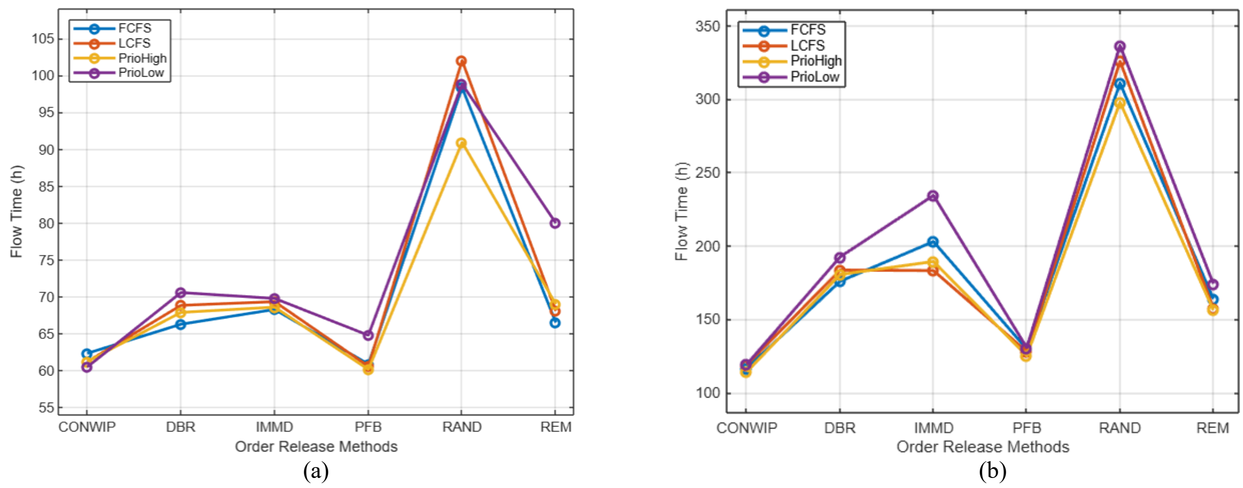


Fig. 5. Flow time performance of two machines - centralized stage under (a). Low uncertainty; (b). High uncertainty

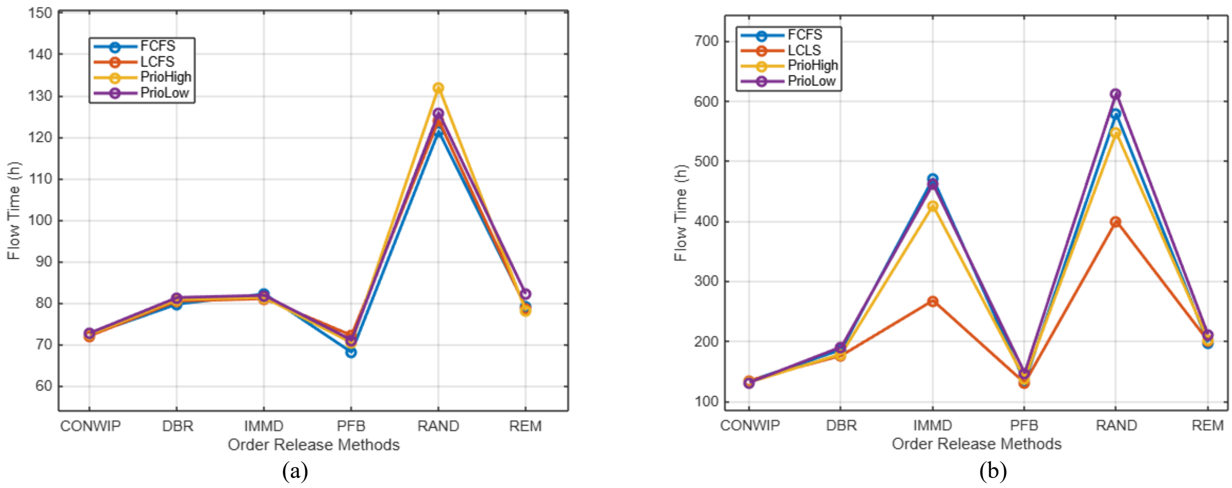
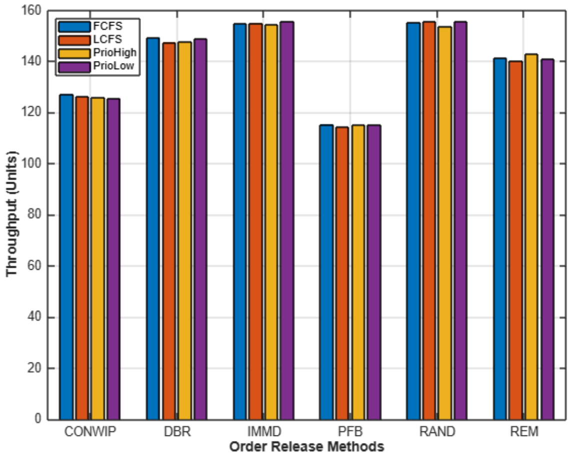
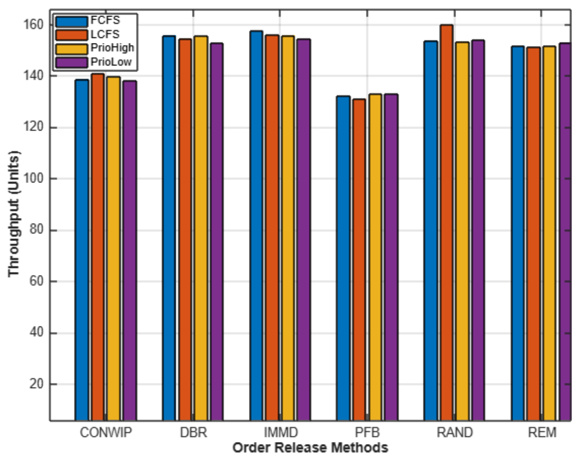


Fig. 6. Flow time performance of two Machine- decentralized Stage under (a). Low Uncertainty; (b). High Uncertainty

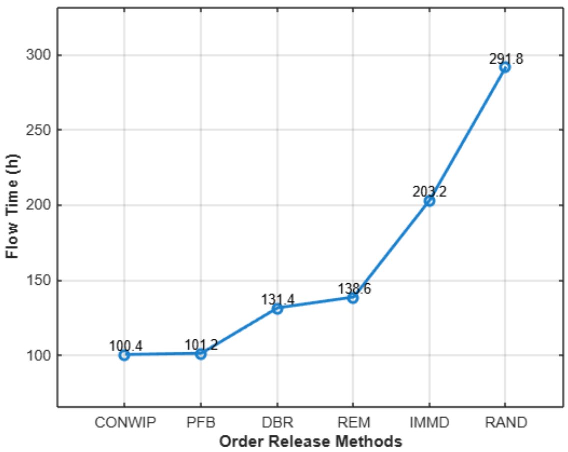


(a)

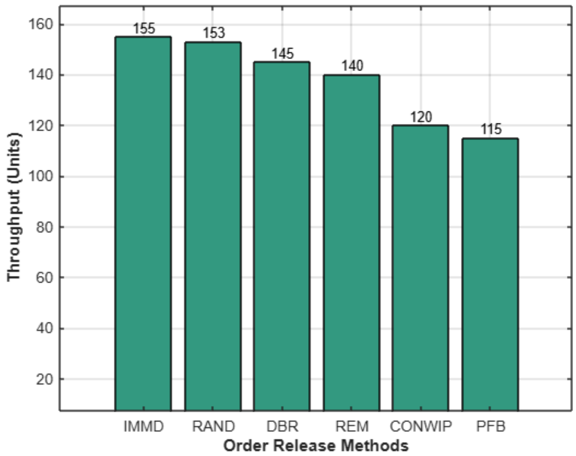


(b)

Fig. 7. Throughput performance under (a). Low Uncertainty; (b). High Uncertainty



(a)



(b)

Fig. 8. Tukey test results (a) Flow time; (b) Throughput

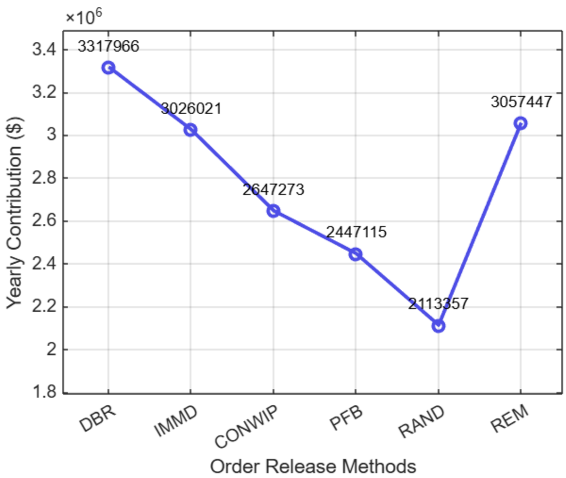


Fig. 9. Comparison of approximate yearly contribution under different ORRs

Appendix B

Table 5. ANOVA Results

Source	DF	Flow time				Throughput			
		SS	F	p-value	Percent	SS	F-value	p-value	Percent
Machine	1	41698	68.84	0.000	0.68	1097.3	470.54	0.000	0.64
Stage	1	184042	303.85	0.000	2.99	4778.3	2049.04	0.000	2.78
PROP	5	1760562	581.34	0.000	28.56	12323.9	1056.96	0.000	7.16
ORR	5	2641347	872.17	0.000	42.84	138084.2	11842.81	0.000	80.20
PDR	3	31303	17.23	0.000	0.51	55.1	7.88	0.000	0.03
Machine*Stage	1	31229	51.56	0.000	0.51	648.1	277.93	0.000	0.38
Machine*PROP	5	9827	3.24	0.007	0.16	70.3	6.03	0.000	0.04
Machine*ORR	5	50341	16.62	0.000	0.82	369.9	31.73	0.000	0.21
Stage*PROP	5	35580	11.75	0.000	0.58	586.8	50.33	0.000	0.34
Stage*ORR	5	146649	48.42	0.000	2.38	2152.3	184.60	0.000	1.25
PROP*ORR	25	824848	54.47	0.000	13.38	8640.9	148.22	0.000	5.02
Machine*Stage*PROP	5	13992	4.62	0.000	0.23	52.0	4.46	0.001	0.03
Stage*PROP*ORR	25	59112	3.90	0.000	0.96	1796.0	30.81	0.000	1.04
Machine*PROP*ORR	25	19448	1.28	0.164	0.32	161.6	2.77	0.000	0.09
Machine*Stage*ORR	5	40509	13.38	0.000	0.66	299.0	25.64	0.000	0.17
Error	454	274986			4.46	1058.7			0.61

Table 6. Yearly Contribution

Particulars	DBR	IMMD	CONWIP	PFB	RAND	REM
Sold Turnover ($)	26811730	28660814	22189018	21264475	28290997	25887187
Production Cost ($)	23186753	25188644	19135460	18370144	25449314	22462528
WIP Cost ($)	168729	260926	128922	129950	374696	177974
Lost Throughput Cost ($)	84750	7705	277363	315885	23114	123272
Increased Flow Time Cost ($)	53532	177519	0	1381	330516	65965
Total Cost ($)	23493764	25634794	19541745	18817360	26177640	22829740
Approximate Profit ($)	3317966	3026021	2647273	2447115	2113357	3057447