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INVESTIGATION OF WORKLOAD CONTROL METHODS FOR SHOPS WITH RE-ENTRANT FLOWS

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Abstract:
The re-entrant flow with an unpredictable nature of arrival would apparently harm production plans and schedules in flow type of shops. The re-entrant flow with varied arrival frequencies in rotor blade manufacturing is quite complicated and results in disproportionate workloads. Hence, an attempt has been made to study the significant influence of disproportionate workloads and research on an innovative order release method to enhance performance. The manufacturing process was observed thoroughly to incorporate the uncertain events that cause disturbance in the production. A simulation model was developed on a discrete event simulation platform by analysing problem phenomena right from the conceptualization phase. The model has been verified and validated to ensure the accuracy. The model was subjected to 288 experiments representing different scenarios that a flow shop undergoes in reality. The factors considered in the experimentation were re-entrant frequency, re-entrant proportions, order release methods and priority dispatching rules. A refined load release policy for disproportionate loads has been proposed to judge its effectiveness in terms of profit computation by comparing it with other relevant policies. Results of the experiment revealed that the order release methods contribute 95.93% to throughput performance, in addition, the use of the new re-entrant method policy in the above scenario was productive in improving the overall shop performance.

Key words: *ANOVA, Re-entrants, Rotor blade manufacturing, Simulation, Turkey's test*

INTRODUCTION

The workload control (WLC) concept has gained considerable attention among researchers for its superior ways of governing complex job shops [1, 2] which have been witnessing significant improvements both in simulation [3, 4] and in actual practice [5, 6]. The origin of WLC is with the idea of controlling the system performance through the use of order release methods, which consecutively yield lower levels of work-in-process (WIP) and maximum throughput [7]. In WLC, the key decision lies in order release that feeds the jobs into the system at a rate equal to the output rate. The WLC aims to have an input rate through a suitable release method that strikes a balance with the output rate by the use of capacity modification options. WLC is a mechanism that helps to integrate input and output [8, 9, 10], thereby improving delivery performance [11, 12]. Literature on WLC research has focused on complex flow shops having diverse kind of aspects such as breakdown aspects [13], bottleneck issues [1, 14] uncertain process times in production [15, 16] capacity adjustments [17, 18, 19], and due date settings that assimilate customer enquiry management [20]. The flow shop consists of workstations with materials flowing from upstream to downstream in a pre-defined sequence by approaching the workstation only once [7]. Although the process looks simpler than the job shop, but complications occur when workstations have disproportionate workloads. Though there has been a considerable amount of research on flow shop modelling, the disproportionate workloads in stations due to re-entrants have so far not been considered. The rotor blade production follows a simple flow shop, however, the occurrence of defects in multiple stages would lead to disproportionate loads. The requirement of extra time for rework, capacity and materials for different stages needs to be assessed and accordingly incorporated into production schedules. Subsequently, the increase in WIP generates the mandate for extra space for the storage of large blades. These uncertain chains of events make the flow shop complicated in production planning and execution. The research presents a unique and innovative mechanism which has hitherto not been proposed. The uniqueness in terms of the flow shop that gets converted into a partial job shop when re-entrants occur in different proportions has been considered. The re-entrants are the products being produced but might re-circulate in the same loop due to defects, which would further degrade the flow shop performance. The processes in flow shops are usually in a chronological manner, however, any unexpected interruption due to re-entrants in one or multiple stages of the shop would cause production difficulties. The research presents a workload-control strategy that releases the jobs on the basis of the limit set on aggregate loads of regular jobs and re-entrant jobs. The performance of flow shops having disproportionate workloads has been compared with other relevant techniques by experimenting with an efficient simulation model.

LITERATURE REVIEW

It is evident that simulation studies on workload control methods have shown tremendous improvements in flow shops, however, real-life aspects would make the shop floor a little more complicated leading to undesirable outcomes. Investigating the benefits derived from workload control methods in such uncertain environments would be more meaningful in today's competitive era. The planning and scheduling of the flow shops is not complex due to the arrival of similar types of jobs, however, bottleneck aspects, disproportionate workloads and re-entrants make the shop more complicated. The products that return to the same machine repeatedly until its operations are completed are termed re-entrant flow [21]. In production, re-entrants are the finished or semi-finished goods that would return to the previously visited stations of the line the second time. The re-entrants would enter any station once or multiple times and subsequently the rate of re-entrants and the stations that are needed is unpredictable, making the flow shops more complicated. A handful of researchers have highlighted the re-entrant aspects in the workload control literature, however, they have not modelled the re-entrants in their research studies [22]. Graves et al., [23] found improvements in throughput time by applying scheduling heuristics in an integrated circuit fabrication facility that has flows which are cyclic in nature. Also, in the dynamic manufacturing system containing re-entrant flows, the implementation of order release methods would be helpful in reducing manufacturing lead time variations [21]. Arzi & Raviv [24] suggested an approach for dispatching jobs in a line having re-circulated jobs with random arrival rates and sequence-dependent setup time. A majority of the production systems may not have the same product reentering the same machine except in the case of reworked products. However, recirculation is the core of the system in semiconductor manufacturing. Fowler et al., [25] state that re-entrant flow occurs due to quality issues which are quite common in the semiconductor industry. Enns & Costa [26] evaluated shop performance by considering the multiple visits to the station and compared job shops with high routing variability and flow shop with no routing variability. Their findings of the research conclude that bottleneck-oriented releases are more appropriate in complex job shops in comparison to aggregate load releases in a unidirectional flow shop. Kim et al., [27] outline that protective capacity plays a key role in improving performance and highlights the need for protective capacity to absorb variations in the line. Thürer & Stevenson [22] were of the opinion that earlier studies must have ignored the influence of re-entrant flows assuming no effect on performance, as re-entrant flows were not derived in past literature. The investigations revealed that re-entrant flows lead to a detrimental effect on the performance due to the increase in variability of arrivals and the effectiveness of dispatch rules could be found only if the jobs are released immediately. Additionally, research claims that if tight norms are being executed, there is a possibility that new jobs will never be released as the shop gets loaded with re-entrant flows. Neuner & Haeussler [28] compared the order release methods (ORR) performance for the shop with re-entrants and proved that Lancaster University Management School Corrected Order Release (LUMS COR) is better in yielding lower cost over the other two ORRs like constant load (ConLOAD) and starvation avoidance. ORRs such as immediate release (IMMD) and continuous release policies yield better outcomes when re-entrant flows are considered, however, LUMS COR and Lancaster University Management School order release (LUMS) showed detrimental effects with re-entrant flows Thürer & Stevenson [22]. Recently, Haeussler et al., [29] investigated the use of time limits in high and low load periods. A mechanism that works on dynamic time limits to balance the job release to respond to high or low load periods either spontaneously or by delaying the response. Costa et al. [30] investigated a hybrid MTS-MTO flow shop to compare the effectiveness of the load-based and bottleneck-based rules and found that the bottleneck-based rule was effective during high-severity cases. Fernandes et al. [31] developed a new policy which was very effective for large jobs that control direct loads and simplify workload calculations. Thürer & Stevenson [32] worked on integrating order release and sequencing rules by prioritizing jobs which were applied for the longest queue resources that showed the best performance. Thürer et al., [33] investigated the effect of lead time syndrome in MTO shops with independent demand cases which showed that decreasing the lead time during low loads would lead to an increase in workload during high loads. The principle of WLC has been widely recognized in complex job shops and a considerable amount of studies have incorporated re-entrant flows. The researchers have overlooked the influence of re-entrant flows in flow shops having diversified forms of uncertainties. The Literature on workload control has revealed that research on re-entrant flow is limited, also there is no appropriate order release method that would effectively subside the negative impact of re-entrant issues. In this context, the research undertakes this study by considering a flow shop environment with bottlenecks having unpredictable nature of re-entrant arrivals. The re-entrants flow due to the observation of defects is quite common in the rotor blade manufacturing process. However, in this case, the re-entrant destinations are multiple including both upstream and downstream.

Hence, the question being posed in this research is mentioned below.
How does the workload control strategy help to improve the performance of re-entrant flow shops with disproportionate workloads?
In order to obtain the answer to the above question, the research aims to develop a conceptual model, followed by a simulation with a suitable experimental design.

METHODOLOGY

The research uses a methodology which has been widely employed in simulation experimentation. The production process has been observed thoroughly to develop the conceptual model supported by information related to uncertain process timings and other resource requirements. This is followed by the development of a simulation model and validation. The experiments have been conducted on the simulation model with a suitable experimental design and result analysis.

Conceptual model

The conceptual model represents the flow shop with eight stations, which resembles the manufacturing setup of rotor blades which is a part of the windmill. The key processes of rotor blade production have been identified as material preparation (MatPrep), preform, shell making (ShellBuild), outer lamination (OverLam), dry finish (DryFinish), paint, balance and inspection [34] have been shown in Fig. 1.

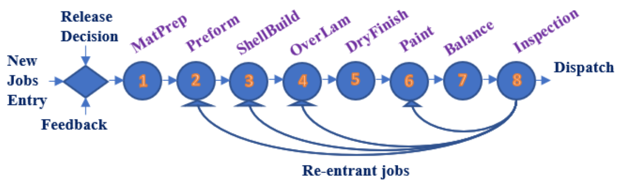

Fig. 1 Conceptual model

The first station of the flow shop is material preparation followed by seven stages in sequence with the final stage being inspection. In this line, once the job is released, it moves sequentially through the various stations from the first station to the last station and during the production process, WIP gets accumulated at every stage. It is obvious that flow shops are more susceptible to production disruptions, leading to production losses. In the last stage, the products are subjected to rigorous inspection, and the presence of non-conformities would require rework. These defective products would become re-entrants as they are required to be directed back to previous stations of the flow shop, thereby disrupting the production schedules.

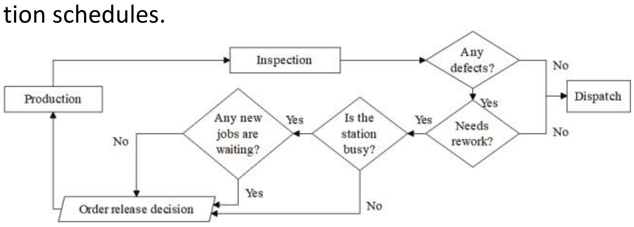

Fig. 2 Logical workload control model

The logical workload control model is shown in Fig.2, which depicts the decision-making involved in workload control methodology. All the stations of the production shop are usually occupied with the regular workloads and once the job reaches the inspection stage, if there are no defects observed by the surveyor the jobs would be dispatched. However, in case of defects, there would be several aspects that need to be looked upon, such as: which station does this defect belong to? Is the station currently free? and Is there any new job waiting for processing? Based on these aspects, an appropriate workload control strategy would be employed. The release decision in the re-entrant policy is determined by the total load on the system by considering the loads of new jobs as well as re-entrant jobs.

Simulation model

The rotor blade manufacturing line has been modelled using Arena 16 software. The simulated shop and job characteristics of the model have been shown in Table 1. The simulation model comprises a flow shop with eight stations having probabilistic process timings and three bottleneck stations. Job enters the shop with a specific arrival rate and order release methods filter these jobs based on the conditions and direct them for further processing. The released jobs would pass through the production line, however, in case of defectives, for carrying out rework same stations are made to accommodate these unexpected loads. In certain cases, these are the defective products that reenter the line after crossing the final station. All these complications would generate routing variability.

Table 1
Summary of the simulated shop and job characteristics.

Shop and Job Characteristics	
Shop Type	Flow shop
Characteristics	Real
Routing Variability	Yes
Number of workstations	Eight stages
Workstation capacity	Fixed
Inter arrival time (Hours)	Poisson distribution
Re-entrants Frequency (RF)	Two levels - Once and Twice
Re-entrant Proportions (PROP)	Six levels
Order release methods (ORR)	CONWIP, DBR, IMMD, PFB, RAND, REM
Priority dispatching rules (PDR)	FCFS, LCLS, PrioHigh, PrioLow

The model assumes fixed capacity stations in order to limit the complexity. Inter-arrival time for the product follows Poisson distribution except for the random (RAND) order release method. Two levels of re-entrants with six levels of re-entrant proportions, six order release methods and four priority dispatching rules have been considered. The re-entrant proportions indicate the combinations of various percentages of products with or without defects. The product with a defect needs to pass through single or multiple stages in the line.

Verification And Validation

The validation assesses the behaviour of the model with the requisite accuracy for the purpose that was intended over the domain of applicability. The internal validity test has been extensively employed for probabilistic models by subjecting them to distinct replications in order to gauge the output variations. This approach helps in evaluating the appropriateness of the model and the consistency in results [35]. The first step in validation process is to ensure that the developed model is appropriate with regard to its structure. The verification involves checking the model structure, logic and causal relationship between the entities and comparing them with the conceptual model. The research has employed a trace technique that includes tracking the events and activities of the entities that are released continuously. Consistency has been observed in the event timings of the simulated model when compared with the intended schedule.

The internal validity test of the simulated model has been conducted by recording the waiting time of one of the critical processes under different simulation replications. The model results have been shown in Table 2 and statistically analyzed with the help of a box plot as depicted in Fig. 3.

Table 2
Validity test results

Replications	Waiting Time (Hours)
20	10.14
40	10.39
60	9.90
80	9.85
100	9.75
120	9.45
140	9.43
160	9.21
180	9.44
200	9.25
220	9.39
240	9.42
260	9.39
280	9.27
300	9.27

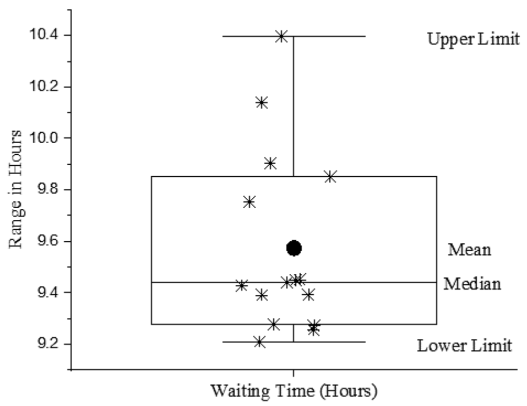

Fig. 3 Box plot for internal validity test

In the box plot, the data has been spread across both sides of the box, however, the median is closer to the bottom of the box. Also, the whisker is shorter on the lower end of the box and the distribution of data points is positively skewed. The data points are within the whiskers indicating that there are no outliers. This confirms that the data points are significantly not different from the rest of the data. Therefore, the results of the internal validity test validate that the model displays the desired level of accuracy.

Experimental Variables

The flow shop with disproportionate loading has been modelled with four critical variables like re-entrant frequency, re-entrant proportions, order release methods and priority dispatching rules that in combination represent the real flow shop.

Re-entrant frequency and proportion

The production shop usually has two types of loads, regular loads for new jobs and re-entrant loads for re-circulated jobs which are found to be defective. Regular jobs move in the same sequence, whereas re-entrant jobs enter only into the required stage. A certain number of new products are produced with the regular load which do not have any defects; hence they do not require any rework. Depending upon the type of loads occurring at different stages, seven types of products have been identified as shown in Table 3. For the purpose of carrying out experimentation, the total production load is assumed by considering seven products in six proportions. The research work assumes 25% of type-I loads have no defectives and the balance 75% of loads are apportioned from type-II to type-VII. In addition, two re-entrant frequencies have also been considered.

Table 3
Type of Re-entrant Jobs

Stages	Type
Regular Load-No Rework	Type - I
Regular Load-Rework in all Stages	Type - II
Re-entrant Load-Rework in all Stages	Type - III
Re-entrant Load-Rework in Preform	Type - IV
Re-entrant Load-Rework in ShellBuild	Type - V
Re-entrant Load-Rework in Overlam	Type - VI
Re-entrant Load-Rework in Paint	Type - VII

Order release methods (ORR)

Order release methods play a key role in managing the shop floor by keeping constant production rates with optimum usage of resources and meeting reliable delivery times [36], [37]. It is evident that several order release methods have been developed, refined and integrated with sequencing rules in order to get the desired results [38]. In the present study, a bottleneck-oriented flow shop having re-entrant flows has been considered, hence the most suitable order release methods are executed and discussed below:

Constant work in process (CONWIP)

CONWIP is a closed-loop policy that restricts the entry of new jobs into the system until the level of WIP drops to the predetermined level. The objective of CONWIP is to sustain a steady level of WIP [39]. The CONWIP policy has proven to outperform other order-release policies in simple flow shops, but it cannot be used in complex scenarios due to the lack of a load-balancing feature. This policy maintains a desired level of WIP throughout the system, which compels the system to release a new job only after the previous job has been completed. From Little's law, the average WIP is calculated as Average WIP = (Relase rate x Average flow time). The rule for CONWIP in the model is the total number of jobs currently processed in the system, $\Sigma W_n \leq 5$. The value is decided on the basis of 5 downstream stations with each job per station.

Drum buffer rope (DBR)

In Goldratt's theory of constraints, a policy referred to as Drum-Buffer-Rope (DBR) has been developed based on the principles of scheduling. This policy occupies a superior position in terms of its performance in bottleneck kind of operations [40]. In this release policy, the release of every job is determined by the status of the bottleneck machine (drum) which is treated as the heart of the production shop and is important for decision-making. All the other operations and sufficient resources (buffer) are channelled in line with the operations of the bottleneck machine, which is linked through effective feedback (rope). Thurer et al. [41] investigated the DBR performance in severe bottleneck cases and found effective synchronization with the capacity-constrained resources.

Immediate release (IMMD)

IMMD is a policy in which jobs are continuously being released into the shop without taking the shop floor conditions into account. It is a conventional open-loop policy that does not have any control over the process. The orders that are accepted at the job entry stage are immediately released for production which would have to wait near the respective machines. The waiting jobs naturally require more resources to handle, which may hamper the job performance.

Pull from bottleneck (PFB)

This is a bottleneck machine-centric policy in which the jobs are released only when the bottleneck station is free. This policy prevents a number of jobs from waiting near the bottleneck machines, thereby preventing the machine from getting overloaded which would in turn decrease efficiency. The PFB was executed by Hopp & Spearman which has witnessed a superior performance in multiple bottleneck cases [42].

Random release (RAND)

The random release policy is an open-loop policy in which the jobs are released randomly at the beginning of the specific production period. All the orders which the organization is capable of producing in a given time period are released at once. This policy appears to be a conventional policy; however, it has got its own advantages such as improving the utilization of resources.

Re-entrant method (REM)

REM is a modified version of CONSTBWL [43] which was used for determining the workload of batch production. In this case, the policy releases the jobs into the system on the basis of monitoring the average workload of the system instead of considering only the bottleneck stations. System workload accounts for regular load and the disproportionate workloads at different stations due to re-entrants. It holds the release of jobs until the re-entrant workload plus a load of already released jobs is less than or equal to the set workload limit. The set workload limit is decided based on the required throughput and utilization. The expression for the total workload at point "t" in time is given as follows.

$$W(t) = \sum_{n=1}^{N} \sum_{J=1}^{J_n} W_n\,(j)(t).\,p_n(j) + \sum_{n=1}^{N} O_n\,(t).\,p_n, \qquad (1)$$

where:
n = type of job n = 1...N (regular, re-entrant types),
J_n= Number of downstream stations for job type "n",
$p_n(j)$ = Processing time on j^{th} operation for n^{th} job,
$W_n(j)(t)$ = Number of jobs under processing and rework in stations at time "t",
$O_n(t)$ = Number of recently released jobs into a system of job type n at time "t".

The equation is derived from Little's law of queuing theory, i.e., the total workload is equal to the number of jobs to be processed multiplied by the processing time of jobs. In this shop, there are a series of processes, hence, upstream WIP definitely have an impact on the downstream stations and in turn increases the workload on the system.

Priority dispatching rules (PDR)

The jobs get accumulated near the respective machines after the release from the previous station which makes the shop floor overcrowded. The priority dispatching rule is a sequencing technique that helps to set the jobs in a particular order before they have to be processed in the station. Usually, jobs wait in the form of queues on the basis of sequencing rules. The literature demonstrates that these dispatching rules are not helpful when an ORR is productive in maintaining the queue length under a desired limit, however, the first come first served rule is helpful in such cases. The research considers four priority dispatching rules first come first served (FCFS), last come last served (LCFS), high priority (PrioHigh) and low priority (PrioLow). The basis for the priority in the last two rules is the priority on the length of the sequence. That means in PrioHigh, a high priority is given to the jobs that need to pass through a greater number of stations.

Design of experiments

The simulation model was experimented with the following four important factors such as re-entrant frequency, re-entrant proportions, order release methods, and priority dispatching rules. Two re-entrant frequencies were considered. Re-entrant proportions of the jobs are based on the percentage of defective products. Six different proportions were considered. Six order release methods were applied which are CONWIP, DBR, IMMD, PFB, RAND, and REM. Priority dispatching rules were FCFS, LCLS, PrioHigh, and PrioLow. Hence, 2 x 6 x 6 x 4 = 288 experiments with the full factorial design were chosen. The replication length of 7488 hours was used by considering 24 hours of working per day for 312 days in a year. The research neglects the initial 3744 hours as a warm-up period. In each experimental run one factor is changed at a time and a total of 100 replications were run.

Performance measures

The model outputs were chosen to evaluate the performance of the system such as flowtime in hours, throughput in units and utilization of resources in percentage terms. In addition, research models the profit by considering the costs associated with production and estimated revenue realized from sales. The research evaluates the effectiveness of the new order release policy on the basis of the relationship between throughput and flow time. The flowtime is obtained from the model from experimentation which accounts for the inventory cost. These are work-in-process inventory costs which are directly proportional to the flow time. Total flow time is the sum of the waiting time in the queue plus the processing time. An increase in flow time increases the cost of production in terms of the cost of work in process. The profit is determined by the difference between the total revenue and total cost. Total revenue is obtained by selling the throughput units with a selling price of 1.2$. For-profit analysis a 20% margin has been considered, only for the calculation purpose in the research. According to a rotor blade cost analysis conducted by [34], out of the total blade cost, 26.9% accounts for fixed costs per time units, inventory costs per time units and penalty cost per time units etc. The balance 73.1% accounts for variable costs such as material and labour costs.

RESULTS AND DISCUSSIONS

The performance characteristics

The flow time, throughput and utilization for six re-entrant proportions (PROP) at two re-entrant frequencies (RF) are shown in Figure 4(a) to Figure 4(f) and Figure 5(a) to Figure 5(f).

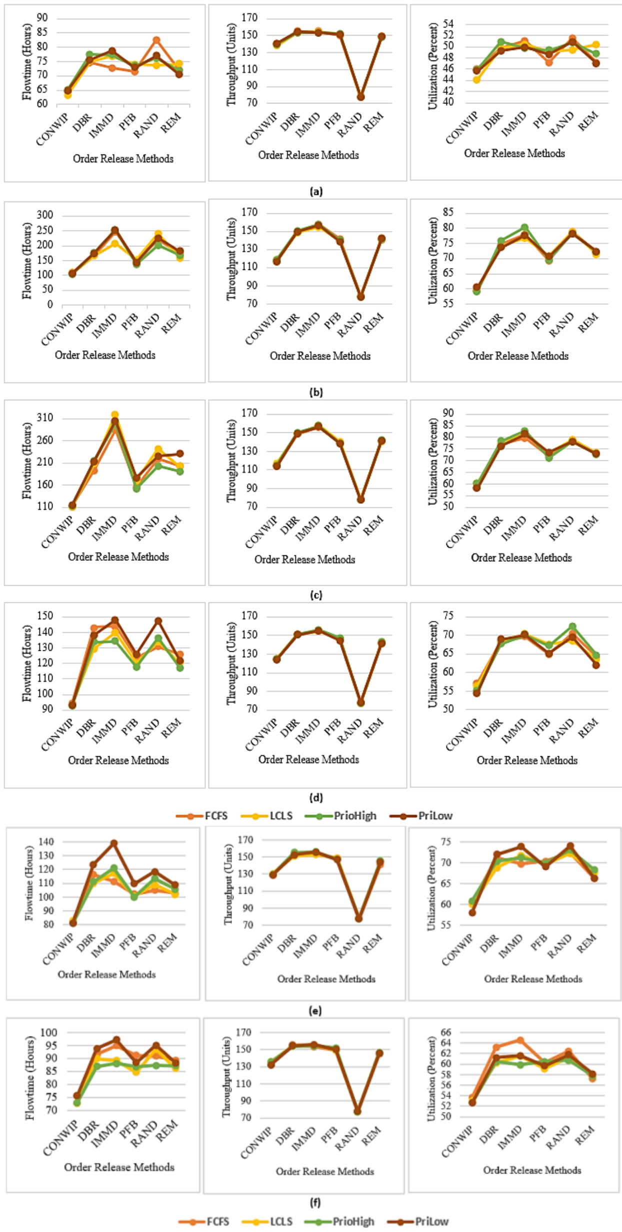

Fig. 4a-f ORRs performance with re-entrant once under (a) Proportion I; (b) Proportion II; (c) Proportion III; (d) Proportion IV; (e) Proportion V; and (f) Proportion VI

Fig. 5a-f ORRs performance with re-entrant twice under (a) Proportion I; and (b) Proportion II (c) Proportion III; (d) Proportion IV; (e) Proportion V; and (f) Proportion VI

It is observed that different patterns of outcomes exist for different combinations of ORRs and PDRs. Some of the prominent outcomes achieved from the analysis have been highlighted. The flow time rises with a rise in re-entrant frequency while throughput remains constant and a substantial increase in utilization was observed. This is in conformance with the principle of Little's law, a rise in variance in the process would increase the utilization [19]. The performance of the shop was assessed by increasing the re-entrant workload proportionately from proportion-I to proportion-VI.

The workload is proportionately increased in each proportion by increasing the rework in the form of a percentage increase in defective products. From the graphs, it is evident that the flow time characteristic curves behave erratically in different combinations of the ORRs and PDRs. By observing the substantial difference in the performance of ORRs, it can be concluded that CONWIP achieves the greatest flow time in all combinations. In CONWIP, the flow time values have minimal variance with respect to PDRs which indicates that CONWIP overrides the PDRs like one of the outcomes in research [44]. However, in the case of other ORRs, the minimal effect of PDRs was observed as these values are dispersed. The maximum and minimum values of flowtime to evaluate the significant difference in the performance among PDRs were recorded. The highest throughput performance was observed in all the proportions except for proportion-I where DBR outperforms [42, 45]. On the other hand, RAND yields poor throughput. In the utilization plots, slight changes were noticed in the performance of PDRs [43]. The flow time and utilization graphs follow the same pattern, except in a few cases where there exist tradeoffs between the ORRs and PDRs. For example, in Figure 4(e), for re-entrant once with proportion-V, the maximum flow time is 253.99 hours for IMMD with PrioLow and the minimum flow time is 207.27 hours for IMMD with LCLS. The difference of 46.72 hours could be saved with an effective PDR. With regard to the throughput in all the cases, the values are not scattered from the mean indicating PDRs have no influence on the throughput performance [22]. Similarly, in one of the cases, i.e., Figure 4(b) for re-entrance once with proportion-II, utilization is 64.53% for IMMD with FCFS and 59.89% for IMMD with PrioHigh resulting in 4.64% improvement by using proper PDRs. In addition, in proportion-VI, 83% utilization was recorded for IMMD with PrioHigh and the lowest of 58% for CONWIP with PrioLow. It is also noticed that an ORR performed extremely well with flowtime performance but lags in throughput performance and vice versa. On the basis of throughput performance, IMMD is superior to other ORRs but has poor flow time values. DBR, PFB, and REM policy records an average performance with respect to 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.

Statistical analysis using ANOVA

The ANOVA analysis shows the relative contribution of different process parameters on the flowtime, throughput and utilization in the flow shop. These outcomes have been recorded using experimentation for 288 combinations of all four factors and a statistical method was employed to get an understanding of the relative effects of the factors. By using the ANOVA module of the Minitab program, a four-factor ANOVA was conducted and the results are shown in Table 4. At 95% of confidence level, the F-ratio was compared with the associated critical p-values to figure out the relationships. When the flowtime measures are considered, associated p-values below 0.05 which meet the 95% confidence level are RF, PROP, ORR, and (PROP·ORR). Based on the calculations, factors, RF, PROP, ORR and (PROP·ORR) contribute 13.38%, 37.88%, 17.15% and 13.45%, to the flow time. Therefore, it is confirmed that PROP has a greater significant influence on the flow time than ORR followed by RF. Evaluating the throughput measures, associated p-values less than 0.05, are RF, PROP, ORR and (PROP·ORR) with the contribution of 0.47%, 1.4%, 95.93% and 1.11% respectively.

Table 3
ANOVA Results

Source	DOF	Flow time				Throughput				Utilization			
		Seq. SS	F-ratio	P-Value	Percent	Seq. SS	F-ratio	P-Value	Percent	Seq. SS	F-ratio	P-Value	Percent
RF	1	472352	122.5	0.00	13.38	982.4	81.69	0.00	0.47	0.222	193.73	0.00	6.71
PROP	5	1337154	69.4	0.00	37.88	2907.4	48.35	0.00	1.40	1.867	324.85	0.00	56.27
PDR	3	19716	1.71	0.169	0.56	9	0.25	0.86	0.00	0.009	0.06	0.98	0.01
ORR	5	605386	31.4	0.00	17.15	199251	3313.7	0.00	95.93	0.920	160.19	0.00	27.75
PROP* PDR	15	18240	0.32	0.993	0.52	74.4	0.41	0.97	0.04	0.003	0.2	1.00	0.10
PROP* ORR	25	474788	4.93	0.00	13.45	2304.7	7.67	0.00	1.11	0.118	4.13	0.00	3.58
PDR* ORR	15	14843	0.26	0.998	0.42	97.6	0.54	0.91	0.05	0.004	0.26	0.99	0.13
PROP* PDR* ORR	75	36376	0.13	1.00	1.03	362.7	0.4	1.00	0.17	0.016	0.19	1.00	0.50
Error	143	551040			15.61	1719.7			0.83	0.164			4.95

This implies that ORR alone has maximum weightage in judging the throughput performance and the effects of the other parameters are very minimal. Finally, by considering the utilization performance, p-values less than 0.05, are RF, PROP, ORR and (PDR·ORR) with a contribution of 6.71%, 56.27%, 27.75% and 3.58% respectively. Utilization has a more significant influence on PROP followed by ORR, RF and (PROP·ORR). Hence, it can be concluded that re-entrant proportions and order release methods play an important role in judging the performance of flow shops. The priority dispatching rules have no influence on any parameters either independently or in combination. Further, the PROP is an uncontrollable production factor; however, ORR can be significantly controlled by the management. Hence, it has been decided to evaluate the performance of different ORRs by conducting Post hoc multiple tests which is shown in the next section.

Profit evaluation

Post hoc analysis was carried out by employing Tukey's honestly significant difference test for the variable "ORR". The objective is to determine which means are significantly different from the rest of the means of ORRs. This is one of the superior ways to rank the ORRs on the basis of all performance measures appropriate for the re-entrant flow shops with disproportionate workloads. The results of Tukey's test results are tabulated in Table 5.

Table 5
Tukey's test results

Rank	1	2	3	4	5	6
ORR	CON-WIP	PFB	REM	DBR	RAND	IMMD
Mean Flow Time (Hours)	96.51	140.36	156.68	170.42	216.55	233.21
ORR	IMMD	RAND	DBR	REM	PFB	CON-WIP
Mean Throughput (Units)	155	152	144	140	122	78
ORR	IMMD	RAND	DBR	REM	PFB	CON-WIP
Mean Utilization (%)	72.82	72.72	70.41	67.2	65.48	56.38

First, on the basis of flow time performance, the policies are ranked from excellent policy to poor policy in the order: CONWIP, PFB, REM, DBR, RAND, and IMMD, which is shown in Fig. 6.

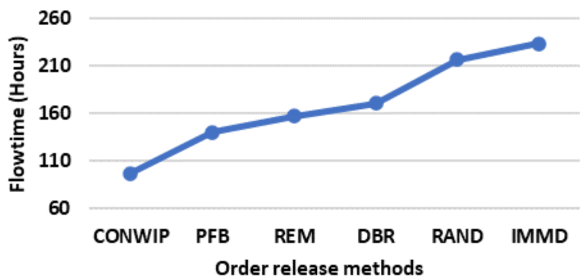

Fig. 6 Comparison of mean flowtime under different ORRs

Next, the performance on the basis of throughput and utilization is shown in Fig. 7 and Fig. 8 respectively and policies are ranked from excellent to poor performance in the following order: IMMD, RAND, DBR, REM, PFB, CONWIP. Though Tukey's test was adequate in determining a significant difference among ORRs, but could not conclude, which ORR is most appropriate for flow shops with disproportionate re-entrant workloads. Hence, a relationship was obtained between the throughput, flowtime and cost factors.

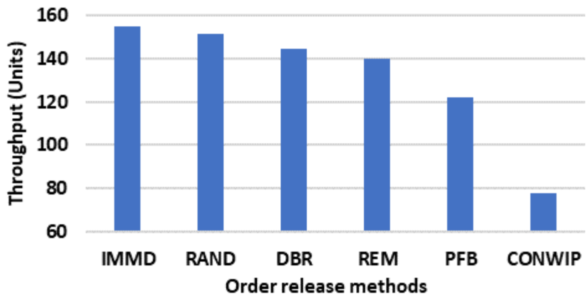

Fig. 7 Comparison of mean throughput under different ORRs

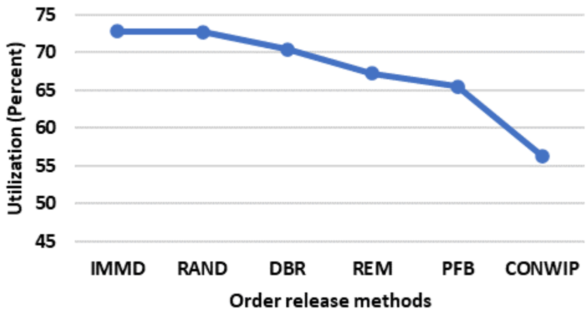

Fig. 8 Comparison of mean utilization under different ORRs

The costs have been considered in the research are production costs, WIP costs, flow time costs, and throughput loss costs. The approximate profits were calculated by substituting the mean throughout and mean flowtime from Tukey's result Table. The approximate profits are shown in Table 6 and plotted on the graph as shown in Fig. 9.

Table 6
Approximate Profit

Particulars	IMMD	RAND	DBR	REM	PFB	CON-WIP
Sold Turnover ($)	28475906	27921180	26626821	25887187	22558835	14237953
Production Cost ($)	25225883	24654464	23280491	22574244	19697889	12481322
WIP Cost ($)	299192	277363	218295	200318	179772	123272
Lost Throughput Cost ($)	1261294	1232723	1164025	1128712	984894	624066
Increased Flow time costs ($)	360909	331553	252118	227942	200313	124332
Total cost ($)	27147278	26496102	24914929	24131216	21062869	13352993
Approximate Profit ($)	1328628	1425078	1711892	1755972	1495965	884960

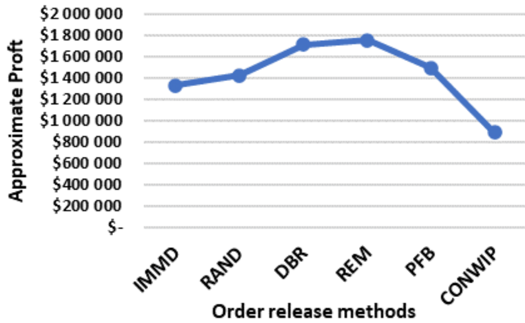

Fig. 9 Comparison of approximate profit under different ORRs

While evaluating the profits, the REM policy records maximum profits, followed by DBR and PFB. In addition, RAND, IMMD and CONWIP show poor profits. Finally, the outcomes of the experimentation confirm that the REM policy is an ideal policy that could be productively employed in scenarios of disproportionate workloads in flow shops.

CONCLUSION

The study presents a methodology for the selection of an optimal workload control strategy in flow shops with disproportionate workloads triggered due to the re-entrant nature of jobs. The flow shop was modelled to resemble the working of the rotor blade manufacturing plant by incorporating major factors causing disruption in it. The model was simulated with uncontrollable variables of production such as re-entrant frequency and re-entrant proportion and to counter the negative effect, the order release methods and dispatching rules have been included. To know the significant contribution of factors, a four-factor ANOVA was applied to the simulated results which were experimented using the design of experiments with 288 combinations. In addition, a new order release policy for re-entrant flow shops was designed and evaluated for its economic performance in comparison with the other relevant policies. On the basis of the results obtained in the work, the major observations made are:

– The re-entrant proportion is the major influencing variable on the flowtime and utilization to the extent of 37.88% and 56.27% respectively. The influence of order release methods is 17.15% on flowtime, 95.93% on throughput and 27.75% on utilization. The re-entrant frequency is 13.38% on flowtime and 6.71% on utilization. The priority dispatching rules do not have a significant influence on the performance.
– The significant difference among the order release methods was observed from Tukey's post hoc tests and it reveals that the order release method that has the lowest flowtime yields the lower level of throughput and vice versa.
– The REM policy demonstrates optimum outcomes in terms of profit measures. The profit obtained by REM is 2.5% more than that of DBR. Hence, it can be concluded that the REM policy is the most effective policy for the flow shop with bottleneck workloads and different re-entrant frequencies and proportions.

Re-entrant proportions have a major impact on flow time and utilization performance. An increase in re-entrant proportions increases the routing variability, hence flow shop becomes a partial job shop and further degrades the performance. Hence, the industry must focus on decreasing the rate of defectives from different stations by preventing defects in the shell build-up stage of rotor blade manufacturing. Although the present research has modelled the relevant features of the flow shop, however, a few applicable factors such as capacity modifications and profit variations at different throughput levels could be considered in future research work.

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REFERENCES

[1] C.E. Betterton & S.J. Silver, "Detecting bottlenecks in serial production lines - A focus on interdeparture time variance," *Int J Prod Res*, vol. 50, no. 15, pp. 4158-4174, Aug. 2012, doi: 10.1080/00207543.2011.596847.

[2] L.D. Fredendall, D. Ojha, J. Wayne Patterson, "Concerning the theory of workload control," *Eur J Oper Res*, vol. 201, no. 1, pp. 99-111, Feb. 2010, doi: 10.1016/j.ejor.2009.02.003.

[3] N.O. Fernandes, M. Thürer, T.M. Pinho, P. Torres, and S. Carmo-Silva, "Workload control and optimised order release: an assessment by simulation," *Int J Prod Res*, vol. 58, no. 10, pp. 3180-3193, May 2020, doi: 10.1080/00207543.2019.1630769.

[4] M. Thürer, M. Stevenson, & P. Renna, "Workload control in dual-resource constrained high-variety shops: an assessment by simulation," *Int J Prod Res*, vol. 57, no. 3, pp. 931-947, Feb. 2019, doi: 10.1080/00207543.2018.1497313.

[5] T. Hutter, S. Haeussler, & H. Missbauer, "Successful implementation of an order release mechanism based on workload control: a case study of a make-to-stock manufacturer," *Int J Prod Res*, vol. 56, no. 4, pp. 1565-1580, Feb. 2018, doi: 10.1080/00207543.2017.1369598.

[6] C. Silva, M. Stevenson, & M. Thürer, "A case study of the successful implementation of workload control: A practitioner-led approach," *Journal of Manufacturing Technology Management*, vol. 26, no. 2, pp. 280-296, Mar. 2015, doi: 10.1108/JMTM-10-2013-0144.

[7] N. Nahavandi, "CWIPL II, a mechanism for improving throughput and lead time in unbalanced flow line," *Int J Prod Res*, vol. 47, no. 11, pp. 2921-2941, Jan. 2009, doi: 10.1080/00207540701725059.

[8] N.O. Fernandes, C. Silva, & S. Carmo-Silva, "Order release in the hybrid MTO-FTO production," *Int J Prod Econ*, vol. 170, pp. 513-520, Dec. 2015, doi: 10.1016/j.ijpe.2015.03.025.

[9] N.O. Fernandes & S. Carmo-Silva, "Order release in a workload controlled flow-shop with sequence-dependent set-up times," *Int J Prod Res*, vol. 49, no. 8, pp. 2443-2454, Apr. 2011, doi: 10.1080/00207541003720376.

[10] N.O. Fernandes & S. Carmo-Silva, "Workload control under continuous order release," *Int J Prod Econ*, vol. 131, no. 1, pp. 257-262, May 2011, doi: 10.1016/j.ijpe.2010.09.026.

[11] M. Thürer, M.J. Land, M. Stevenson, & L.D. Fredendall, "On the integration of due date setting and order release control," *Production Planning and Control*, vol. 28, no. 5, pp. 420-430, Apr. 2017, doi: 10.1080/09537287.2017.1302102.

[12] M. Thürer, M. Stevenson, M.J. Land, & L.D. Fredendall, "On the combined effect of due date setting, order release, and output control: an assessment by simulation," *Int J Prod Res*, vol. 57, no. 6, pp. 1741-1755, Mar. 2019, doi: 10.1080/00207543.2018.1504250.

[13] R. Singh & M. Mathirajan, "Experimental investigation for performance assessment of scheduling policies in semiconductor wafer fabrication – a simulation approach," *International Journal of Advanced Manufacturing Technology*, vol. 99, no. 5-8, pp. 1503-1520, Nov. 2018, doi: 10.1007/s00170-018-2414-y.

[14] M. Thürer & M. Stevenson, "Bottleneck-oriented order release with shifting bottlenecks: An assessment by simulation," *Int J Prod Econ*, vol. 197, pp. 275-282, Mar. 2018, doi: 10.1016/j.ijpe.2018.01.010.

[15] S. Kim, K. Roscoe Davis, & J.F. Cox, "An investigation of output flow control, bottleneck flow control and dynamic flow control mechanisms in various simple lines scenarios," *Production Planning and Control*, vol. 14, no. 1, pp. 15-32, Jan. 2003, doi: 10.1080/0953728021000039416.

[16] A. Prabhu, K. Raghunandana, & P. Yogesh Pai, "Bottleneck shifting in serial line production: An investigation with different order release methods," in Materials Today: *Proceedings*, Elsevier Ltd, 2022, pp. 1714-1720. doi: 10.1016/j.matpr.2021.11.337.

[17] D. Corti, A. Pozzetti, & M. Zorzini, "A capacity-driven approach to establish reliable due dates in a MTO environment," *Int J Prod Econ*, vol. 104, no. 2, pp. 536-554, Dec. 2006, doi: 10.1016/j.ijpe.2005.03.003.

[18] M. Thürer & M. Stevenson, "The use of finite loading to guide short-term capacity adjustments in make-to-order job shops: an assessment by simulation," *Int J Prod Res*, vol. 58, no. 12, pp. 3554-3569, Jun. 2020, doi: 10.1080/00207543.2019.1630771.

[19] S.N. Kadipasaoglu, W. Xiang, S.F. Hurley, & B.M. Khumawala, "A study on the efffect of the extent and location of protective capacity in flow systems," *Int. J. Production Economics*. Vol. 63, 217-228, 2000.

[20] M. Thürer, M. Stevenson, C. Silva, M.J. Land, L.D. Fredendall, & S.A. Melnyk, "Lean control for make-to-order companies: Integrating customer enquiry management and order release," *Prod Oper Manag*, vol. 23, no. 3, pp. 463-476, 2014, doi: 10.1111/poms.12058.

[21] P.R. Kumar, "*Scheduling Manufacturing Systems of Re-Entrant Lines*," in Stochastic Modeling and Analysis of Manufacturing Systems, New York, NY: Springer New York, 1994, pp. 325-360. doi: 10.1007/978-1-4612-2670-3_8.

[22] M. Thürer & M. Stevenson, "Workload control in job shops with re-entrant flows: an assessment by simulation," *Int J Prod Res*, vol. 54, no. 17, pp. 5136-5150, Sep. 2016, doi: 10.1080/00207543.2016.1156182.

[23] S.C. Graves, H.C. Meal, D. Stefek, & A.H. Zeghmi, "*Scheduling of Re-Entrant Flow Shops*," 1983.

[24] Y. Arzi & D. Raviv, "Dispatching in a workstation belonging to a re-entrant production line under sequence-dependent set-up times," *Production Planning and Control*, vol. 9, no. 7, pp. 690-699, Jan. 1998, doi: 10.1080/095372898233696.

[25] J.W. Fowler, G.L. Hogg, & S.J. Mason, "Workload control in the semiconductor industry," *Production Planning and Control*, vol. 13, no. 7, pp. 568-578, Oct. 2002, doi: 10.1080/0953728021000026294.

[26] S.T. Enns & M.P. Costa, "The effectiveness of input control based on aggreǵate versus bottleneck work loads," *Production Planning and Control*, vol. 13, no. 7, pp. 614-624, Oct. 2002, doi: 10.1080/0953728021000026258.

[27] S. Kim, J.F. Cox, & V.J. Mabin, "An exploratory study of protective inventory in a re-entrant line with protective capacity," *Int J Prod Res*, vol. 48, no. 14, pp. 4153-4178, Jan. 2010, doi: 10.1080/00207540902991666.

[28] P. Neuner & S. Haeussler, “Rule based workload control in semiconductor manufacturing revisited,” *Int J Prod Res*, vol. 59, no. 19, pp. 5972-5991, 2021, doi: 10.1080/00207543.2020.1797208.
[29] S. Haeussler, P. Neuner, & M. Thürer, “Balancing earliness and tardiness within workload control order release: an assessment by simulation,” *Flex Serv Manuf J*, vol. 35, no. 2, pp. 487-508, Jun. 2023, doi: 10.1007/s10696-021-09440-9.
[30] F. Costa, K. Kundu, M. Rossini, & A. Portioli-Staudacher, “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*, vol. 16, no. 1, pp. 33-48, Mar. 2023, doi: 10.1007/s12063-022-00276-6.
[31] N.O. Fernandes, M. Thürer, & M. Stevenson, “Direct Workload Control: simplifying continuous order release,” *Int J Prod Res*, vol. 60, no. 4, pp. 1424-1437, Feb. 2022, doi: 10.1080/00207543.2020.1857451.
[32] M. Thürer & M. Stevenson, “Order release, dispatching and resource assignment in multiple resource-constrained job shops: an assessment by simulation,” *Int J Prod Res*, vol. 60, no. 12, pp. 3669-3681, Jun. 2022, doi: 10.1080/00207543.2021.1930240.
[33] M. Thürer, N.O. Fernandes, S. Haeussler, & M. Stevenson, “Dynamic planned lead times in production planning and control systems: does the lead time syndrome matter?,” *Int J Prod Res*, vol. 61, no. 4, pp. 1268-1282, Feb. 2023, doi: 10.1080/00207543.2022.2034193.
[34] P. Bortolotti et al., “*A Detailed Wind Turbine Blade Cost Model*,” 2019. [Online]. Available: www.nrel.gov/publications.
[35] R.G. Sargent, “Verification and validation of simulation models,” in Proceedings of the 2010 Winter Simulation Conference, *IEEE*, Dec. 2010, pp. 166-183. doi: 10.1109/WSC.2010.5679166.
[36] M. Land & G. Gaalman, “International journal of production economics ELSEVIER Workload control concepts in job shops A critical assessment,” 1996.
[37] M. Thürer, N.O. Fernandes, M. Stevenson, & T. Qu, “On the backlog-sequencing decision for extending the applicability of ConWIP to high-variety contexts: an assessment by simulation,” *Int J Prod Res*, vol. 55, no. 16, pp. 4695-4711, Aug. 2017, doi: 10.1080/00207543.2017.1281462.
[38] M. Thürer, M. Stevenson, & C. Silvaa, “Three decades of workload control research: A systematic review of the literature,” *International Journal of Production Research*, vol. 49, no. 23. pp. 6905-6935, Dec. 01, 2011. doi: 10.1080/00207543.2010.519000.
[39] M.L. Spearman, D.L. Woodruff, & W.J. Hopp, “CONWIP: A pull alternative to kanban,” *Int J Prod Res*, vol. 28, no. 5, pp. 879-894, May 1990, doi: 10.1080/00207549008942761.
[40] M. Thürer, M. Stevenson, C. Silva, & T. Qu, “Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation,” *Int J Prod Econ*, vol. 188, pp. 116-127, Jun. 2017, doi: 10.1016/j.ijpe.2017.03.025.
[41] M. Thürer, T. Qu, M. Stevenson, C.D. Li, & G.Q. Huang, “Deconstructing bottleneck shiftiness: the impact of bottleneck position on order release control in pure flow shops,” *Production Planning and Control*, vol. 28, no. 15, pp. 1223-1235, Nov. 2017, doi: 10.1080/09537287.2017.1362486.
[42] W.G. Gilland, “A simulation study comparing performance of CONWIP and bottleneck-based release rules,” *Production Planning and Control*, vol. 13, no. 2, pp. 211-219, Mar. 2002, doi: 10.1080/09537280110069784.
[43] R. Singh & M. Mathirajan, “*Investigation of different inputs and a new release policy in the proposed simulation model for wafer fabrication system*,” Sādhanā, vol. 44, no. 2, p. 41, Feb. 2019, doi: 10.1007/s12046-018-1006-8.
[44] M. Thürer & M. Stevenson, “Card-based delivery date promising in pure flow shops with order release control,” *Int J Prod Res*, vol. 54, no. 22, pp. 6798-6811, Nov. 2016, doi: 10.1080/00207543.2016.1177672.
[45] C.E. Betterton & J.F. Cox, “Espoused drum-buffer-rope flow control in serial lines: A comparative study of simulation models,” *Int J Prod Econ*, vol. 117, no. 1, pp. 66-79, Jan. 2009, doi: 10.1016/j.ijpe.2008.08.050

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