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PERFORMANCE ANALYSIS OF COMMERCIAL OFFSET PRINTING UNDER DYNAMIC PRIORITY RULES

A profit analysis of a commercial offset printing production system working under various dynamic priority rules has been undertaken. The task is to investigate both whether and how a change in priority rules affects the system's performance. A mutual impact of the dynamic priority rule utilized (EDD, LOR, MOR, SPT, and LPT), system workload (by means of machine utilization) and input buffer capacities have been studied.

Keywords: *dynamic priority rules, commercial offset printing, simulation*

1. Introduction

Commercial offset printers are constantly under pressure to reduce cycle time, improve delivery performance, and decrease overall costs. Usually, offset printing facilities are constructed as job-shop systems, whereby similar tools are grouped together as one toolset to perform similar processes. High variation is introduced through multiple products being processed on the same toolset. Offset printing machines are often a bottleneck due to their cost. Scheduled and non scheduled downtimes also decrease the availability and increase variability of the toolset. Process flows vary. A process flow in offset printing usually involves several operations with some re-entrant processes. Even for a fixed process route, the traffic is highly dynamic due to the following varying from order to order: batch size, work on-hold, and rework. The stochastic process flow also results from the integration of multiple products accompanied with lot splits and merges. Furthermore, rapidly changing market demand and the random

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order of arrivals make additional contributions to the stochastic variability of flow lines in a make-to-order environment.

In offset printing, at some stages the phenomenon of re-entrance appears. The principal characteristic of a re-entrant job shop is that a job may visit certain machines more than once during the process flow, whereas in the classic job shop, each job visits a machine only once [32]. In a re-entrant system almost every product is unique and produced in a different way, products may spend significant time waiting for an available machine, resulting in long cycle times and low production volumes. From a theoretical standpoint, a re-entrant manufacturing system requires approaches which differ substantially from those traditionally used in flow and job shops [19]. This is due to the cost of running machines and the requirements of technological processes.

Commercial printing functions in a make-to-order manner, due to customers requiring a wide assortment of products, usually in small quantities, which necessitates customization and satisfying various needs [14]. As customers act independently and require different, or at least customized, products, the arrival process over time has a strong stochastic nature. Each job has different content (text and illustrations) but can be roughly categorized (e.g. into three groups: leaflet, booklet, and book). Depending on the job category and its other characteristic features like coating, number of colours and size, an appropriate technological itinerary can be defined. Customers' orders have a stochastic nature in terms of type and order quantity.

As a result, commercial offset printing is a typical multi-class facility, where parts for various kinds of final products are processed simultaneously within a single manufacturing system. When dealing with more complicated products, like booklets and books, an assembly operation is needed. One major problem in the control of component manufacture is to synchronize the arrival of all the components required for a particular assembly process [29]. A production plan should take into account the uncertainty inherent in the manufacturing system caused by variability and uncertainty in processing time, unanticipated demand, the specification of customized products, deep and complex product structures, and long lead-times [37]. Long queues may be created, especially to an assembly station. This requires a different approach to modelling an assembly station than in the case of a typical work station. One more characteristic of such a system is important to highlight, i.e. the parallel nature of the processes satisfying some classes of customers' orders. For example, printing a book will be split into a cover and interior. The job is split at the very beginning of the technological process and is only assembled at the very end. Moreover, parts of a job may follow various technological itineraries. This complicates modelling of such a system.

A typical structure for commercial offset printing is presented in Fig, 1. Reentrance emerges at offset printing machines which usually cover one side of a sheet with inks. In order to cover the other side of a sheet, a pile of sheets has to be left to dry and then reversed. Next, the same pile of sheets, already printed on one side, re-enters the offset printing machine. A similar procedure is required for folding machines, with the exception of drying and reversing, which are usually not necessary.

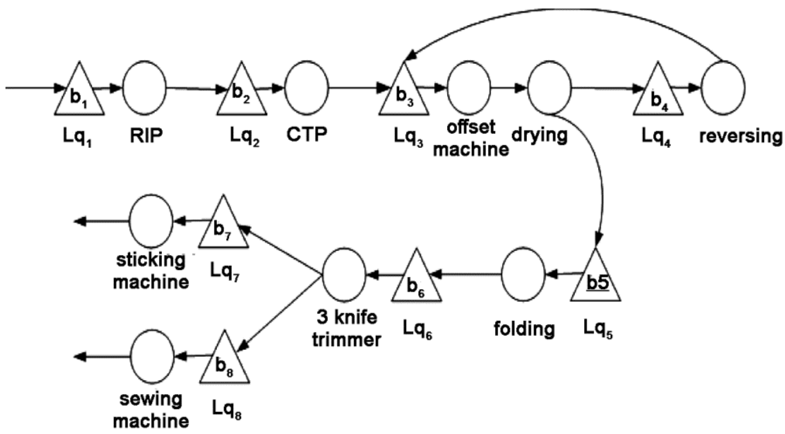

Fig. 1. A typical structure of a commercial offset printing system

In the paper, a study of the influence of various dynamic priority rules on the profit of a typical commercial offset printing facility has been presented. When capital investments are hard to finance, opportunities for improving manufacturing system performance can be attained by better management, including priority rule assignment. In general, printers employ the first-in-first-out rule and from time to time give higher priority to urgent or behind schedule jobs. Our task is to investigate both whether and how changing priority rules affects a system's performance. We have studied the mutual impact of the dynamic priority rule utilized (FIFO – First-In-First-Out, EDD – Early Due Date, LOR – Least Operations Remaining), system workload (by means of machine utilization) and input buffer capacities. Optimum input buffer capacities are taken out from our recent paper [18]. In the next stage of our research, more dynamic priority rules were compared taking into account three levels of work load.

The remaining part of the paper is organized as follows. In the following section a literature review on static and dynamic priority rules has been presented. An approach to estimate overall profit with the use of discrete-event simulation is given in the third section. Computational results and a discussion are provided in the forth section.

2. Literature review and formulation of the problem

Buffers utilizing a priority scheduling regime have been discussed in the literature on priority queues (cf. books [10, 31] and papers [2, 11, 21, 15], or [30]). All these treat the priority of objects in queues using static priority rules, which means that the decision of selecting the next unit for service may only depend on the priority class to which a unit belongs. However, in many applications such a regime may not be an appropriate approach [20]. The alternative is to assign dynamic priorities. The present situation of the system, together with these priorities, decides the sequence in which units are serviced. The results obtained for these queuing systems can be used when several types of packets (or traffic, jobs, customers) share the same resources. Priority regime queuing systems are of two types [25]:

- Systems with pre-emptive priorities, where a unit that is being served cannot be displaced if a higher priority unit arrives at the queuing system and any unit must be completely served without interruption once service has started.
- Systems with non-preemptive priorities, in which a lower-ranking unit that is being served is displaced back to the queuing area whenever a higher priority unit arrives at the system. The displaced unit re-enters service where it was left off.

Systems with two classes and pre-emptive priorities have been studied in [28]. The authors distinguish between two groups of priority classes that consist of multiple customer types, each having their own arrival and service rate. In papers [8] and [5], the authors analyze an M/M/1 queue with two classes of customers. In [34] a discrete-time, pre-emptive repeat priority queue with resampling is analyzed. The authors of [12] present the first near-exact analysis of an M/PH/k queue with $m > 2$ pre-emptive-resume priority classes. Multi-server systems are also compared with single server systems with respect to the effect of different prioritization schemes—“smart” prioritization (giving priority to smaller jobs) versus “stupid” prioritization (giving priority to larger jobs). In [17] a discrete-time two-class discretionary priority queuing model with generally distributed service times is considered. The authors of [15] study problems with two classes utilizing either the pre-emptive or non-preemptive type of servicing. They obtain steady-state performance measures for each class by exploiting the method of crossing levels. Another approach related to non-preemptive priorities is presented in [19]. The authors consider dynamic self-generated priorities with non-preemptive service applied in health care systems. The authors of [2] use matrix -analytic methods to construct a novel queuing model called the dual queue, in order to solve problems in which a pre-emptive priority system is utilized.

Systems with a larger number of priority classes are presented in [33]. It is demonstrated how tree-like processes can be used to analyze a general class of priority queues with three service classes, creating a new method to study priority queues. Also, [24] examines a typical manufacturing facility involving the production of several classes of products belonging to three priority levels. Multi-class priorities are presented in [13], where the priority assignment (PA) problem is considered for a discrete-time single-server queuing system, and the objective function (or performance criterion) is an infinite horizon discounted cost. The authors of [3] considered the cycle time distribution, waiting times for each customer type and the joint distribution of queue length for all priority classes. In [16], a multi-class priority queuing system is studied with non-preemptive time-limited service controlled by an exponential timer and multiple (or single) vacations. The authors of [25] provide a more realistic description of priority-discipline queuing models using fuzzy set theory.

Dynamic priorities are considered in [6]. The authors propose a neuro-genetic decision support system coupled with simulation to design a job shop manufacturing system, in order to obtain the optimum amount of resources at each workstation in conjunction with the right dispatching rule for scheduling. Four different priority rules are used: Earliest DUE DATE (EDD), Shortest Processing Time (SPT), Critical Ratio (CR) and First In First Out (FIFO). A framework is proposed in [36] that utilizes parallel neural networks to make decisions on the availability of resources, due date assignment for incoming orders, and dispatching rules for scheduling. Jobs are scheduled in a work centre according to one of the following priority rules: SPT LPT, FCFS. In [9] performance measures of two priority disciplines – FIFO, LIFO – are estimated for a network model of re-entrant-flow queuing that is particularly relevant to semiconductor manufacturing lines.

Some priority rules can lead to an unstable system. Indeed, in [22] and [4] the authors give examples which show that networks can be unstable under some apparently sensible buffer priority policies, even though the system workload is lower than 1. In [1] the authors use simulation to demonstrate, but not to prove, that many commonly dispatching rules, including FIFO, shortest-mean-processing time-first, shortest-mean-remaining-time-first and buffer priority rules, can be unstable. The authors of [35] deal with a multi-class priority queuing system with customer transfers that occur only from lower priority queues to higher priority queues. Conditions for the queuing system to be stable/unstable are obtained.

Systems with priorities are considered by many authors for various applications in computer science, telecommunication and production. Priorities, which are given to particular jobs/units, enable one to increase profit by more efficient resource utilization or decreasing cycle time. Thanks to a suitable priority strategy, the appropriate sequence in which jobs should be executed is assigned for queues to workstations. Consideration of a suitable priority strategy is a practical problem in production systems like commercial offset printing.

3. Formulation of the model

Subscripts

i – workstation ($i = 1, 2, \ldots, k$)
j – product ($j = 1, 2, \ldots, t$)

Parameters of the model

$\gamma_{i,j}$ – average arrival rate of customers' jobs for product j at workstation i
$\sigma a_{i,j}^2$ – standard deviation of customers' jobs inter-arrival time for product j at workstation i
μ_i – average service rate at workstation i
σs_i^2 – standard deviation of technological operation duration at workstation i
n_i – number of identical machines within workstation i
Lq_i – average number of jobs at buffer i
a – a profit coefficient associated with the production rate
c_i – a cost coefficient associated with the buffer space for buffer i
d_i – a cost coefficient associated with the average inventory for buffer i

Decision variables

b_i – buffer capacity at workstation i
pr_i – priority rule at workstation i

The basic performance measures in the analysis of production systems are the throughput and the average work-in-process or equivalently the average production time. The objective is profit maximization. The objective function for profit maximization developed below follows an example given in [27]. In mathematical terms, our problem can be stated as follows:

$$\zeta = aP(b_1, b_2, ..., b_k, pr_1, pr_2, ..., pr_k) - \sum_{i=1}^{k} b_i c_i - \sum_{i=1}^{k} Lq_i d_i \rightarrow \max \tag{1}$$

subject to:

$$b_i \in N, \quad b_i > 0, \quad pr_i \in \{\text{FIFO, EDD, LOR, MOR, SPT, LPT}\}$$

where $P(b_1, b_2, ..., b_k, pr_1, pr_2, \ldots, pr_k)$ is the production rate of a system. Although the production rate P is a function of the machines and their reliability, we only vary buffer sizes and rules for ascribing priority. The first term of Eq. (1) can be interpreted as the total revenue of the production system, while the two other items together can be interpreted as the total cost of the production system. The c_i coefficient expresses the cost of the space necessary for storing the maximum level of work-in-progress and the d_i coefficient expresses the cost of working capital allocated to work-in-process.

A production system was modelled using discrete-event simulation. Analysis of large and complex stochastic systems is a difficult task, due to the complexities that arise when randomness is embedded within a system. Unfortunately, unexplained randomness is a common and unavoidable characteristic in real-world systems. The emergence of discrete-event simulation, being an evaluative tool for stochastic systems, facilitated the estimation of performance measures under any given system configuration [26].

4. Computational results

Experiments were conducted to determine the mutual relationship between buffer capacities, dynamic priority rules and work loads for a typical commercial offset printing facility. The ARENA simulation package from Rockwell Software (version 9.0) was used for modelling the manufacturing system. The design of the experiment is described in the following section followed by a discussion of the results. The fixed parameters of the model are shown in Table 1. Table 2 presents the parameters for customers' orders.

Parameters for the simulations are as follows:

- warm-up time – 1 day,
- replication length –100 days,
- number of replications – 5.

Table 1. Processing times for the machinery

Work station	Mean setup time per job	Std deviation of setup time	Mean operation time per sheet	Std deviation of operation time per sheet	Time unit
RIP	0	0	20	0.2	min
CTP	0	0	0.5	0	
Printing	40	10	0.005	0	
Reversing	15	2	0	0	
Drying	60	15	0	0	
Folding	15	3	0.0075	0	
3-Knife trimmer	20	5	0.0075	0	
Sticking cover	30	8	0.006	0	
Sewing cover	30	5	0.005	0	

Table 2. Input parameters for each type of product

Parameter	Product class		
	Leaflet	Brochure	Book
Number of copies			
minimum	1000	100	500
average	5000	1000	3500
maximum	100 000	10 000	5000
Page format	A4, A5, A6	A4, A5, A6	A4, A5, A6
Number of copies			
minimum	1–2	8	100
average		12	300
maximum		16	512
Cover type	–	sew	stick or sew

4.1. Three factor experiment

A full 3^3 factorial experiment was conducted with the following parameters:

1. Input buffer capacity for the respective workstations (the RIP station has an infinite buffer capacity):

a) 81, 126*, 108, 81, 81, 108 (L),

b) 90, 140*, 120, 90, 90, 120 (M),

c) 99, 154*, 132, 99, 99, 132 (H).

Case b) uses the optimum buffer capacities found in [18]. The capacities in case a) are by 10% lower than optimum ones and in case c) they are by 10% higher.

2. Workload:

a) 60%,

b) 70%,

c) 85%.

3. Priority rule:

a) FIFO,

b) EDD,

c) LOR.

A sensitivity analysis was performed for these parameters according to DOE methodology [23]. Altogether, 135 simulations were carried out in Arena, 5 replications for each of the 27 observation points. The results of ANOVA at a significance level of 5% are shown in Table 3.

Table 3. Analysis of variance for the 33 factorial experiment

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_0	p-Value
B	7.79×10^{11}	2	3.90×10^{11}	1.8537	0.161606
U	$\mathbf{1.45\times10^{12}}$	**2**	$\mathbf{7.27\times10^{11}}$	**3.4561**	**0.035083**
P	$\mathbf{1.57\times10^{12}}$	**2**	$\mathbf{7.85\times10^{11}}$	**3.7333**	**0.027055**
BU	1.74×10^{12}	4	4.34×10^{11}	2.0662	0.090245
BP	1.25×10^{12}	4	3.11×10^{11}	1.4813	0.212910
UP	$\mathbf{2.83\times10^{13}}$	**4**	$\mathbf{7.07\times10^{12}}$	**33.6235**	**<0.0001**
BUP	2.55×10^{12}	8	3.18×10^{11}	1.5139	0.160685
Error	2.27×10^{13}	108	2.10×10^{11}		

It appears that the buffers' capacities (*B*) have little influence on the profit in comparison with the assigned priority rule (*P*) and workload (*U*) (the highest F_0 scores from the ANOVA tests and simultaneously the smallest p-value). One can observe this fact in Fig. 2. The surface plot presents predicted values of the objective function (Eq. (1)) according to the buffer capacities and level of resource utilization. Whatever the workload, the best values of the objective function are always obtained for the optimal level of buffer capacity. The significant two-factor interaction between workload and priority rule (*UP*) is also an important result (see Fig. 3); the vertical columns give 95% confidence intervals.

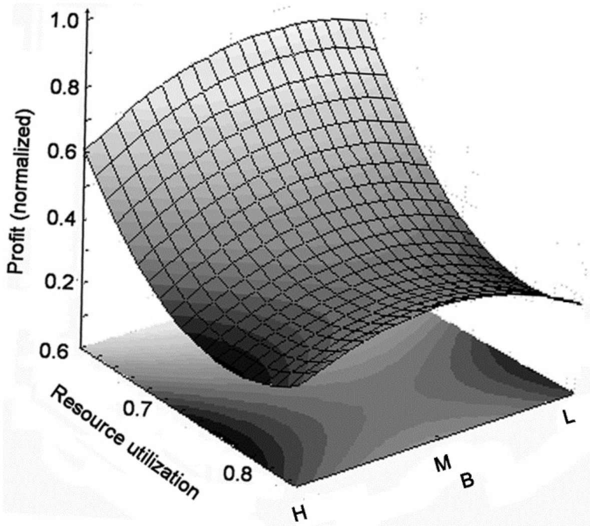

Fig. 2. Predicted values of the objective function according to buffer capacities and the level of resource utilization

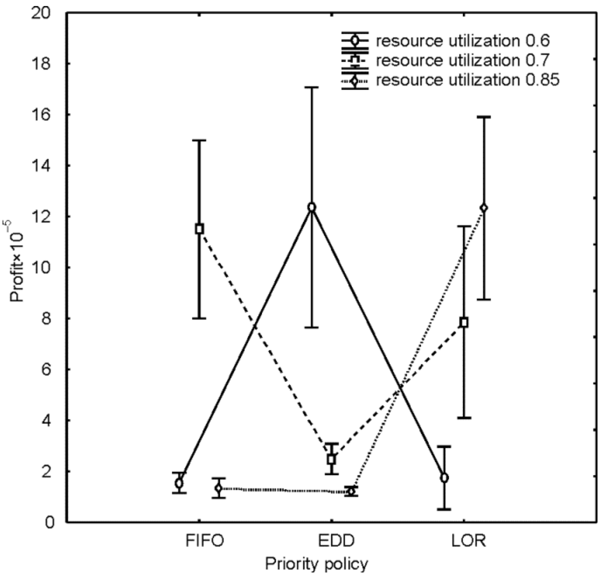

Fig. 3. Two-factor interactions between the level of resource utilization and priority regime for the 3^3 experiment

4.2. Dynamic priority rules

In the following experiment, the average profit obtained using other priority rules was examined according to workload. The following additional (to the previous experiment) dynamic priority rules were included in the experiment: MOR – most operations remaining, SPT – shortest processing times, LPT – longest processing times.

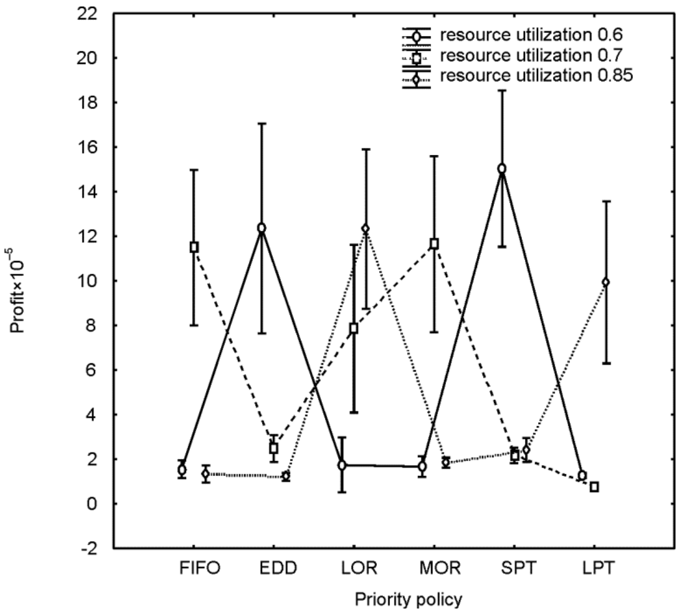

Fig. 4. Two-factor interactions between the level of resource utilization and priority regime for the experiment with six priority rules

Figure 4 presents two-factor interactions between workload level (resource utilization) and priority regime for these six priority regimes. One can observe that for some levels of utilization some rules work better, i.e. the EDD and SPT rules achieve higher profits for utilization at the 60% level, for utilization at 70% the FIFO and MOR rules work well and for utilization at 85% the SPT and EDD rules are efficient. It is interesting that none of the examined priority rules work well under the range of workload considered. This leads to the conclusion that priority rules should be selected on the basis of the workload at present and in the near future.

5. Conclusion

An analysis of the impact of various dynamic priority rules on the profits of a commercial offset printing firm has been presented. To define the objective function, we considered the costs of both buffer space and average inventory level and assigning different cost coefficients to different buffers. In addition, we include a production rate constraint in our problem.

From the tests performed, it appears that non-capital investment can lead to a significant rise in profit. First the buffer capacities should be optimized and then the appropriate dynamic priority rule should be selected. For companies with a moderate workload, EDD or SPT would be suitable and for those with a high workload LOR is the best choice.

The analysis is limited to ideal shop conditions, such as no breakdowns of the machines and no random reworks. In real-world situations such as the commercial offset printing process, failures occur. More realistic and extended conditions may be included in both modelling and computational procedures in further research.

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