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Parameter sensitivity analysis for offset printing simulation model

***Abstract**. This paper focuses on parameter sensitivity analysis of an offset printing production system working under various dynamic dispatching rules. A discrete-event simulation model has been developed for the purpose of experimentation. Four dispatching rules from literature have been incorporated in the simulation model: EDD, LOR, SPT and FIFO. Proper management of orders' sequence can improve manufacturing system efficiency by several percent. Performed sensitivity analysis revealed that in case of applying dispatching rules to manufacturing system the key factors are utilization and product mix. Order parameters like number of copies and number of pages are much less significant.*

***Streszczenie.** W artykule zbadano wpływ doboru reguł priorytetowych na wybrane parametry druku offsetowego. Badania przeprowadzono korzystając z komputerowego modelu symulacyjnego. Przebadano cztery reguły priorytetowe: EDD, LOR, SPT i FIFO. Zarządzanie kolejnością zleceń w systemie może poprawić jego wydajność o kilka procent. Przeprowadzona analiza wrażliwości wykazała, że w przypadku zastosowania reguł priorytetowych do szeregowania zadań kluczowymi parametrami są poziom obciążenia sprzętu oraz produkt mix. Parametry zleceń takie jak nakład oraz liczba stron są znacznie mniej istotne. (**Wpływ doboru reguł priorytetowych na wybrane parametry druku offsetowego**)*

Keywords: Sensitivity analysis, simulation, dispatching rules
Słowa kluczowe: analiza wrażliwości, symulacja komputerowa, reguły priorytetowe.

Introduction

Offset printing facilities are organized as job-shop systems. Orders arrive from many independently acting customers for various kinds of final products: business cards, leaflets, brochures, folders, catalogues, books etc. A major problem in the control of such a manufacturing process is to synchronize the arrival of all required components for assembly [1] in the post press department. A production plan should take into account uncertainty inherent in the manufacturing system caused by processing time variability, processing time uncertainty, unanticipated demand, customized specifications, complex product structures, and long lead-times [2].

As customers act independently and request different or at least customized product, the arrival process over time has a strong stochastic nature [3]. Each job has a different content (text and illustrations) but could be roughly categorized (e.g. three groups: leaflet, booklet and book). Depending on the job category and other characteristic features like coating, number of colors and size, an appropriate technological itinerary could be determined. Customer orders have a stochastic nature in terms of their type and order quantity.

In situations where capital investments are difficult to finance, opportunities for manufacturing system performance improvement could be attained by better management, including dispatching rule assignments. Our task was to investigate both whether and how much a change in dispatching rules affects the system's performance. In order to do this we studied the mutual impact of system parameters:

- dispatching rule (FIFO – First-In-First-Out, EDD – Early Due Date, LOR – Least Operations Remaining, , SPT – Shortest Processing Time)
- system workload (by means of machine utilization)
- structure of order arrival streams, standard deviations of product characteristics

In this paper, we present a sensitivity study of the influence of several dispatching rules on profit and various performance parameters for a typical offset printing facility, such as:

- Profit function (defined later)
- Wait time in system (for each product type class independently)
- Work-in-progress (WIP) in system (for each product type class independently)
- Length of queue before printing machine

Literature review

The problem of job dispatching has been well studied in literature. However, the majority of studies are on priority queues with static dispatching rules, which means that the decision of selecting the next unit for service may depend only on the knowledge of the priority class to which the unit belongs. In many applications this discipline may not be an accurate modeling approach [4]. The alternative is dynamic priorities. The actual situation in the system, with dynamic priorities, is deciding about the sequence of unit servicing. The results obtained for these queuing systems can be used when several types of packets (or traffic, jobs, customers) share the same resources. In paper [5] the author carried out a simulation study to examine the trade-offs involved in changing a dispatching rule in a shop that can set due-dates subject to penalties for the length of tardiness from the quoted lead time.

Dynamic priorities have been considered in [6]. The authors proposed a neuro-genetic decision support system coupled with simulation to design a job shop manufacturing system to obtain the optimal amount of resources in each workstation in conjunction with the right dispatching rule for scheduling. Yildirim et.al. (2006) proposed a framework that utilizes parallel neural networks to make decisions on the availability of resources, due date assignments for incoming orders, and dispatching rules for scheduling. Jobs are scheduled in a work centre according to one of the following dispatching rules: SPT LPT, FCFS. In [7] they estimated the performance measures of two priority disciplines (FIFO, LIFO) in a re-entrant-flow queuing network model.

Since testing dispatching rules in real-world production is absolutely impossible, discrete-event simulation has often been adopted to evaluate the performance of dispatching rule selection [8]. Simulation experiments are carried out to test dispatching rules. Simulation modeling as an evaluative tool for stochastic systems has facilitated the ability to obtain performance measure estimates under any given system configuration [9].

Model formulations

Indices: i – workstation index ($i = 1, 2, \ldots, k$); j – product index ($j = 1, 2, \ldots, t$). Model parameters: $\gamma_{i,j}$ – the average arrival rate of customer jobs for product j at workstation i, $\sigma a^2_{i,j}$ – standard deviation of customer job inter arrival time for product j at workstation i; μ_i – average service rate at workstation i; σs^2_i – standard deviation of a technological operation duration at workstation i; n_i – the number of identical machines within a workstation i; Lq_i – average number of jobs at buffer i; *a* – profit coefficient associated with the production rate; c_i – cost coefficient associated with the buffer space for buffer *i*; d_i – cost coefficient associated with average inventory for buffer *i*. Decision variables: b_i – buffer capacity at workstation *i*; pr_i – dispatching rule at workstation *i*.

The basic performance measures in the analysis of production systems are throughput and average work-in-process or equivalently average production time. The objective is profit maximization. The developed criteria function below for profit maximization follows an example in [4]. In mathematical terms, our problem could be stated as follows:

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

subject to: $b_i \in$ N, $b_i > 0$; $pr_i \in${*FIFO, EDD, LOR, MOR, SPT, LPT*}; where $P(b_1, b_2, . . ., b_k, pr_1, pr_2, . . ., pr_k)$ is the production rate of a system. Although the production rate *P* is a function of the machines and their reliability, we vary only buffer sizes and dispatching rules. The first term can be seen as the total revenue of the production system; while the other two items together can be interpreted as the total cost of the production system. The coefficient c_i expresses the cost of space necessary for storing a maximum level of work-in-progress and coefficient d_i expresses the cost of working capital allocated to work-in-process. A production system was modeled using a discrete-event simulation. Consequently, modification of the dispatching strategy is capable of altering the functioning of the production system. Therefore, it is important to know the effects of the priority discipline problem on production, and optimal configuration of the studied system. Unfortunately, unexplained randomness is a common and unavoidable characteristic among real-world systems.

Results from simulation studies

The ARENA simulation package from Rockwell Software (version 9.0) was used for modeling the manufacturing system. A typical printing facility will serve as a test bench for the analysis. In the model there were 9 workstations (RIP, CTP, Offset printing machine, Reversing, Drying, Folding, 3-knife trimmer, Sticking cover, Sewing cover), all of them have the set processing time randomly distributed according to a general distribution (mean setup times and standard deviations of all operations are data from real world machines specifications). Three types of products existed in the system: leaflet, brochure, and book. Simulation runs parameters were selected in order to assure reliable results:

- warm-up time is 1 day,
- replication length is 100 days,
- number of replications is 7.

The performances of the 4 rules under study were evaluated with respect to mean flow time of jobs, work-in-progress, equipment utilization, wait time at the most critical input buffer in front of the offset machines, and profit. There were four control factors at three levels each. In addition four dispatching rules (FIFO, SPT, LOR, EDD) were analyzed in all experiments. All control factors (utilization level, input structure type, number of copies, type, and number of pages type) with analyzed levels are presented in table 1, 2 and 3. Table 1 shows input structure type for three utilization levels. Type A is characterized by equal arrival streams for leaflet - λ_1 and brochure - λ_2 and more frequently than for a book - λ_3 (input structure type C less frequent than a book). Input structure type B is characterized by frequent order of leaflets and less frequent for brochures or books). Table 2 shows stochastic parameters for each product class. Three types of standard deviation are analyzed for the number of copies and the number of pages: low variation (LV), mean variation (MV), high variation (HV).

Table 1. Utilization and input structure type levels

Utilization	Input type	λ_1[h]	λ_2[h]	λ_3[h]
95%	A	1/10	1/10	1/15
	B	1/5	1/15	1/20
	C	1/15	1/15	1/10
87%	A	1/14	1/14	1/18
	B	1/7	1/18	1/20
	C	1/25	1/25	1/16
80%	A	1/18	1/18	1/21
	B	1/8	1/20	1/23
	C	1/25	1/25	1/18

Table 2. Number of copies -type and number of pages - type levels

Variation	Product	# of copies		# of pages	
		Mean	Std. dev.	Mean	Std. dev.
Low (LV)	Leaflet	30000	10000		
	Brochure	5000	1500	10	4
	Book	3000	1000	200	50
Mean (MV)	Leaflet	30000	17000		
	Brochure	5000	3000	10	6
	Book	3000	1500	200	100
High (HV)	Leaflet	30000	25000		
	Brochure	5000	4500	10	8
	Book	3000	2500	200	150

For these parameters sensitivity analysis was performed according to DOE methodology [10]. Altogether 2268 ($3^4 \cdot 4 \cdot 7$ = 3 levels of number of copies type, 3 levels of number of pages type, 3 input structure type, 3 utilization levels, for 4 dispatching rules and 7 replications at each variant) simulation runs were carried out in ARENA. Results of ANOVA at 0.05 confidence level are shown in table 3.

Table 3 below shows which control parameters (Number of copies type, Number of pages type, Input structure type, Dispatching rule) have an impact on the profit function (eq. 1) at different levels of utilization. From the study, it appears that dispatching rules have a big influence on the profit function at all utilization levels (the biggest spread between F_0 from ANOVA, than from Snedecor distribution with a small p-value at the same time). The number of pages is also an important factor at all utilization levels. The number of copies is important only for 95% utilization level and input structure for 95% and 87% utilization levels. For lower levels of utilization when there are not as many orders (hence queues are not so long) these two parameters have a smaller impact on profit function. One can also observe that the p-value rises for dispatching rules with smaller values of utilization, meaning that influence is lesser (but still strong).

We now discuss some typical results of the experimental analysis for offset printing. Figure 1 shows the profit function versus number of copies type for different number of pages type, input structure and dispatching rule as a parameter for 95% level of utilization (vertical columns are 95% confidence intervals). It can be seen that for input structure type C (when arrival streams for leaflet and brochure are equal and less than book) some dispatching rules are markedly better than others, the best dispatching rule is SPT and the worst dispatching strategy seems to be EDD. For input structure type A (when arrival streams for leaflet and brochure are equal and more frequent than book) and lower values of standard deviations for number of pages, the worst strategy is FIFO, other strategies give quite similar results but the best is also SPT. For input structure type B (when arrival streams for leaflet is the most frequent) differences are not as explicit, but one can observe that it is preferable to use the EDD or SPT rule.

Table 3. Analysis of Variance for executed experiments

Source of Variation	Sum of Squares	Degrees of freedom	Mean Square	F_0	p-value
Utilization 95%					
{1}# of copies	2.42E+07	2	1.21E+07	14.7	0.000001
{2}# of pages	2.22E+08	2	1.11E+08	134.8	<0.000001
{3}Input structure type	2.96E+09	2	1.48E+09	1802.5	<0.000001
{4}Priority	4.01E+08	3	1.33E+08	162.4	<0.000001
1*2	2.29E+07	4	5.74E+06	7.0	0.000017
1*3	1.13E+07	4	2.82E+06	3.4	0.008654
2*3	2.52E+07	4	6.30E+06	7.7	0.000005
1*4	5.09E+07	6	8.48E+06	10.3	<0.000001
2*4	3.42E+07	6	5.71E+06	6.9	<0.000001
3*4	2.42E+07	2	1.21E+07	14.7	0.000001
Error	5.33E+08	648	8.23E+05		
Utilization 87%					
{1}# of copies	2.07E+06	2	1.03E+06	1.4	0.256223
{2}# of pages	1.51E+08	2	7.58E+07	99.9	<0.000001
{3}Input structure type	1.11E+09	2	5.51E+08	726.4	<0.000001
{4}Priority	3.85E+06	3	1.28E+06	6.7	0.001726
1*2	7.22E+06	4	1.80E+06	2.4	0.050729
1*3	2.69E+06	4	6.72E+05	0.9	0.472075
2*3	7.70E+06	4	1.92E+06	2.5	0.039241
1*4	1.02E+07	6	1.70E+06	2.2	0.037486
2*4	6.06E+06	6	1.01E+06	1.3	0.240971
3*4	1.32E+07	6	2.21E+06	2.9	0.008195
Error	4.92E+08	648	7.59E+05		
Utilization 80%					
{1}# of copies	4.35E+05	2	2.17E+05	0.4	0.693069
{2}# of pages	4.80E+07	2	2.40E+07	40.4	<0.000001
{3}Input structure type	2.97E+08	2	1.48E+08	100.3	0.072467
{4}Priority	8.01E+06	3	2.67E+06	4.5	0.003930
1*2	4.50E+06	4	1.12E+06	1.9	0.109915
1*3	8.26E+06	4	2.06E+06	3.5	0.008049
2*3	5.28E+06	4	1.32E+06	2.2	0.065167
1*4	8.87E+06	6	1.47E+06	2.5	0.021819
2*4	3.15E+06	6	5.25E+05	0.9	0.506379
3*4	3.92E+06	6	6.54E+05	1.1	0.359888
Error	3.85E+08	648	5.94E+05		

Some interesting characteristics of dispatching strategy influencing the parameters of the model are shown in figure 2. One can observe the influence of the dispatching rule on the wait time for leaflet product class. For all input structure types (the most expressly for input structure type A and C) it can be seen that the LOR strategy is the best. Wait time for this strategy is the smallest, while the EDD strategy also gives good results. The worst strategy is now SPT. The reason for this is that jobs with the least operations remaining (leaflet have less operations than brochure and book – no sticking or sewing cover) can be quickly operated and moved forward.

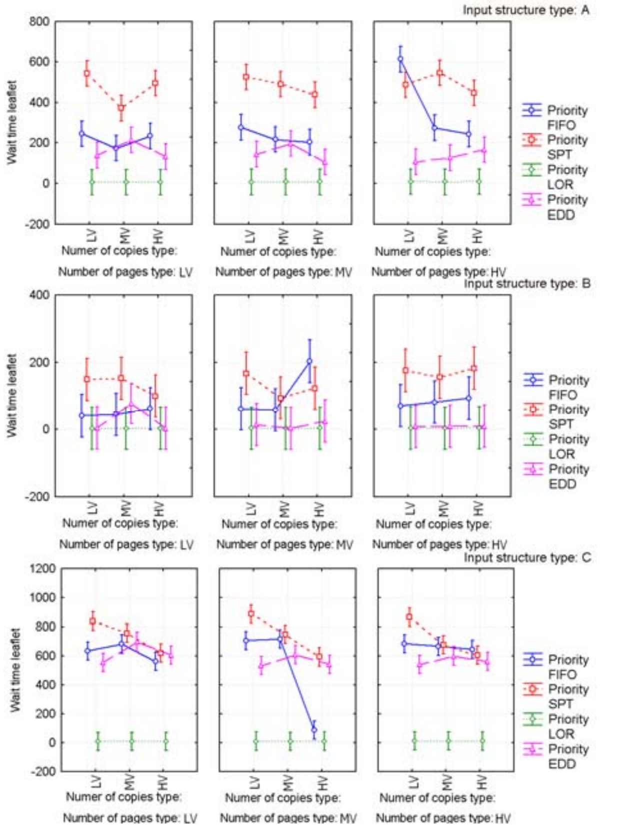

Fig.1. Profit function versus number of copies type for different number of pages type and dispatching rules for 95% level of utilization

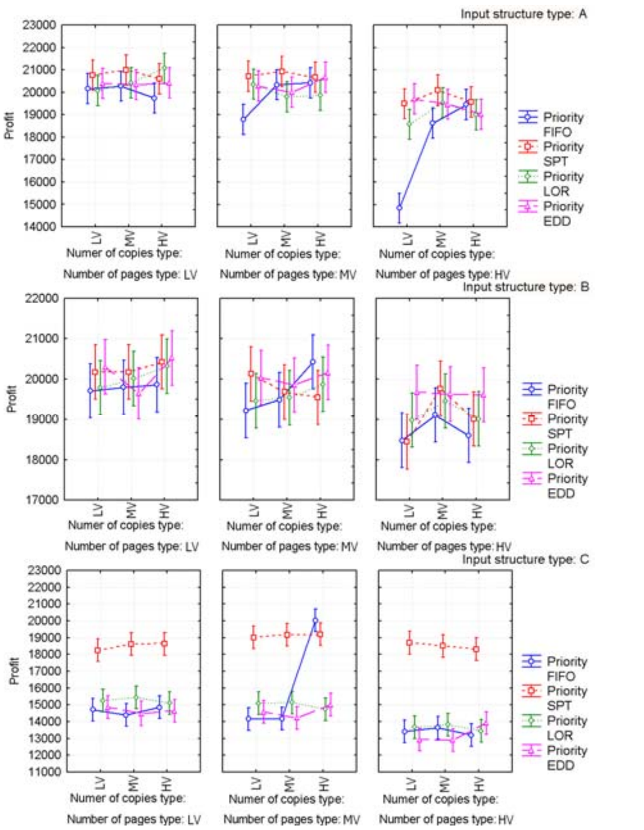

Fig.2. Wait time versus number of copies type for different number of pages type and dispatching rules for 95% level of utilization

Relevance analysis

Relevance analysis was executed to verify if there were dependencies between the dispatching rule and particular system output parameters. All calculations were done in Statistica 8.0 software.

Chi-square test for independence was used.

$$\chi^2 = \sum_{j=1}^{k} \frac{(O_j - E_j)^2}{E_j} \quad (2)$$

where O_j is the observed frequency in each category, a E_j is the expected frequency in the corresponding category.

Table 4. Chi-square and V-Cramer coefficients

	For all utilization levels		
System output parameter	χ^2	p	V Cramer
Queue at offset 1	230.284	0.1839712	0.2873
Queue at offset 2	210.83	0.41311	0.1760
WIP leaflet	1966.57	<0.00001	0.5376
WIP brochure	807.88	<0.00001	0.3446
WIP book	1495.45	0.02147	0.4688
Wait Time leaflet	3607.01	<0.00001	0.7281
Wait Time brochure	3541.20	<0.00001	0.7214
Wait Time book	4025.85	0.01317	0.7692
	At 95% utilization level		
System output parameter	χ^2	p	V Cramer
Queue at offset 1	216.15	0.02579	0.3087
Queue at offset 2	205.10	0.04071	0.3007
WIP leaflet	1192.12	<0.00001	0.7250
WIP brochure	468.70	<0.00001	0.4546
WIP book	1355.73	0.0036	0.7732
Wait Time leaflet	1660.81	<0.00001	0.8557
Wait Time brochure	1693.43	0.00309	0.8641
Wait Time book	2132.00	0.01093	0.9696

Null hypothesis H_0 is that the dispatching rule has no effect on the particular system output parameter being measured, whereas the alternative hypothesis, H_1, asserts that the dispatching rule has an impact on the system output parameter. For all utilization levels one can observe that with a confidence level of 95 % mean values of most of analyzed parameters lie in the confidence interval. Observing p-values for these parameters it can be seen that only the Queue at offset 1 and Queue at offset 2 do not lie in the confidence interval. This doesn't mean that dispatching rules have no impact on these three parameters. It only means that there is a failure to reject H_0. Observing p-values at 95% utilization level one can definitely say that hypothesis H_0 is rejected. It means that the dispatching rule has an impact on all system output parameters.

In addition, to estimate how strong this relationship is, a V-Cramer coefficient was used. It is used as a post-test to determine the strengths of association after the chi-square test

$$(3) \quad V = \sqrt{\frac{\chi^2}{N \cdot MIN(k-1, p-1)}}$$

where χ^2 is chi-square, N is the number of analyzed cases, k is the number of rows and p the number of columns in the table. When the value of this coefficient is less than 0.3, it that means there is a weak relationship between the analyzed characteristics, a moderate relationship if values are between 0.3 and 0.5 and strong relationship if it's more than 0.5. The V-Cramer coefficient is used when one of the analyzed variables is in a nominal scale. From table 4 one can observe that for all utilization levels, the V-Cramer coefficient denotes a moderate or strong relationship. From this it can be observed that the dispatching rule has the greatest impact on wait time for all products. At 95% utilization level one can observe that the V-Cramer coefficient is greater than 0.5 so dispatching rules have a strong impact on all system output parameters. The biggest impact is on wait time for all products, but also on WIP leaflet and WIP brochure.

Conclusions

Proper management of orders' sequence can improve manufacturing system efficiency by several percent. Performed sensitivity analysis revealed that in case of applying dispatching rules to manufacturing system the key factor is utilization level (the higher the more important) and product mix (proportions of order arrivals). Order parameters (number of copies and number of pages) from statistical point of view are important (p-value < 0.05) but in comparison with aforementioned parameters are much less significant.

The conducted experiments and analysis did not give a clear response to the question which dispatching rule best fulfills offset printing requirements.

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