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LEAD TIME MANAGEMENT FOR PRODUCTION PLANNING IN JOB SHOPS

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Abstract

Short and reliable lead times are important to promote customer satisfaction and generate further orders, particularly in the case of make-to-order and engineer-to-order manufacturing. Moreover, accurate manufacturing lead times can greatly help production planning and allocation of capacities. The design of a manufacturing system refers to the configuration of elements such as the number of workstations, storage, capacity and movement of work through the system. The design of a manufacturing system can play a key role in manufacturing lead time. The purpose of this paper is to investigate the effects of the number of workstations, buffer sizes, processing capacities, number of entry workstations and layout of a system on manufacturing lead time, and to demonstrate how such an analysis can aid managerial decision making in production planning. Five sets of experiments, with a total of 19 cases, were conducted. An approximate model for arbitrary queueing networks is used to provide insights into the general behaviour of manufacturing systems. These experimental results suggest that the manufacturing lead time of a system is the most sensitive to layout of the system, i.e., configuration of the system (feed-forward or feed-backward topology) and the number of exit workstations.

Keywords: Job Shops, Queuing Network Modelling, Manufacturing Lead Time.

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ATÖLYE TİPİ SİSTEMLERİN ÜRETİM PLANLAMASINDA TEMİN SÜRESİ YÖNETİMİ

Öz

Kısa ve güvenilir temin süreleri, özellikle siparişe-özel-üretim ve siparişe-özel-tasarım şeklinde üretim yapan firmalarda müşteri memnuniyetini artırmak ve siparişlerde süreklilik sağlamak için kritik önem taşımaktadır. Ayrıca kesin ve güvenilir üretim temin süreleri, üretim planlamasına ve kapasite tahsisine önemli ölçüde katkı sağlamaktadır. Bir üretim sisteminin tasarımı iş istasyonu sayısı, bekleme alanlarının büyüklüğü, üretim kapasitesi ve işlerin sistem içindeki rotaları gibi unsurların yapılandırılmasını kapsamaktadır. Üretim sistemi tasarımı, temin süresinin belirlenmesinde önemli rol oynamaktadır. Bu çalışmanın amacı, iş istasyonu sayısının, iş istasyonları arasındaki tampon alanlarının büyüklüğünün, üretim kapasitesinin, giriş iş istasyonu sayısının ve sistemin yerleşim planının üretim temin süresi üzerindeki etkilerini araştırmak ve böyle bir analizin üretim planlamasında yönetimsel karar almaya nasıl yardım edebileceğini göstermektir. Çalışmada, 19 vakanın bulunduğu beş ayrı grupta denemeler gerçekleştirilmiştir. Üretim sistemlerinin performanslarının belirlenmesinde yapılandırılmamış kuyruk ağları için geliştirilen yaklaşık bir model kullanılmıştır. Deneme sonuçları üretim temin süresinin, sistemin yerleşim planından (sistemin yapılandırmasının ileri veya geri beslemeli oluşu ve çıkış iş istasyonlarının sayısından) önemli ölçüde etkilendiğini göstermektedir.

Anahtar Kelimeler: Atölye Tipi Üretim Sistemleri, Kuyruk Ağı Modeli, Üretim Temin Süresi.

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Introduction

Manufacturing systems are classified by various criteria in the literature. A classification can be based on how quickly the customers require the product relative to the time it takes to produce it. This categorizes manufacturing systems as make-to-stock, assembly-to-order, make-to-order and engineer-to-order (see Amaro, Hendry and Kingsman, 1999; Hill, 1993). In make-to-stock and assembly-to-order manufacturing, products are to be produced in advance of and anticipation of a customer order. In make-to-order and engineer-to-order, a product is designed and manufactured after an order has been received. The product must meet the specifications desired by the order. For make-to-order and engineer-to-order companies, product design can be included in the manufacturing process and considered as a remaining process to plan and control. For this reason, the company starts manufacturing a product only after it has received a customer order, and does not produce their products on mass and to stock. Hence, successive products made typically vary significantly from each other in the amount and type of product work required. Another characteristic of the make-to-order and engineer-to-order manufacturing is that the jobs involve a high level of variability with respect to the routings and processing times.

The design of a manufacturing system refers to the configuration of elements such as the number of workstations, storage, capacity and movement of work through the system. Static design definitions cannot realistically design and produce low volume and customized products. Instead, design development should continue during the product's life cycle. To take advantage of this, design changes must be made in a controlled manner and implemented quickly and efficiently (Ashton, 1993). According to Perera and Ratnayake (2015), the flexibility of a manufacturing system is one of the key parameters that determine the success of companies in today's highly competitive markets, and layout flexibility has a greater impact on manufacturing flexibility especially for demands with shorter lead-time. Wangari, Muchiri and Onyancha (2018) proclaims that facility layout plays a key role on manufacturing lead time and throughput. Moreover, Ab-Kadir et al. (2015) states that the decisions regarding layout of facilities are the determinant of long-term operational efficiency of companies for all type of manufacturing systems.

Azaron et al. (2006) and Perkgoz et al. (2007) point out that companies focus on the speed of customer response as well as cost and quality for competitive advantage, and short lead times are critical to win customer orders particularly in the case of make-to-order and engineer-to-order manufacturing. It is important to provide reliable lead times to promote customer satisfaction and generate further orders. Providing competitive lead times and managing to achieve a reliable delivery performance are typically as important as competitive prices. Moreover, accurate manufacturing lead times can greatly help production planning and allocation of capacities. Reliable and determinable manufacturing lead times are essential inputs for all production planning systems.

In the literature, a variety of methods for the estimation of manufacturing lead time have been proposed, including simulation, queuing theory, logistic study curves, statistics, stochastic analysis, artificial intelligent methods and hybrid methods (Mourtzis et al., 2014). Among them, simulation and queuing theory are probably the most commonly used modelling technique for manufacturing systems. Although simulation is useful in detailed description of manufacturing systems, it also has inherent shortcomings. The development and use of a simulation model usually require enormous information regarding the system and extensive time. 'What-if' analysis with simulation models requires running many replications, and hence a lot of computer time, to obtain valid results. The output of a simulation analysis requires sophisticated analysis to resolve the initial and transient effects from the effects of interest. Hence, simulation can be difficult and extremely time-consuming to analyse the system. Compared with simulation, queueing models can be much faster in achieving reasonable results. Though the initial development of queueing models is time-consuming and difficult, once developed they can generally be used to analyse the system in a very short time and to obtain quick feedback about system performance. Many 'what-if' analyses can be performed in a short time and do not require sophisticated statistical analysis of the outputs of the model.

This paper aims to investigate the effects of the number of workstations, buffer sizes, processing capacities and layout of a system on manufacturing lead time, and to demonstrate how such an analysis can aid managerial decision making in production planning. The remainder of this paper is organized as follows: the previous research on queueing network modelling of manufacturing systems is briefly presented in Section 2. Section 3 describes numerical experiments considered in this study, and the results of these experiments are discussed in Section 4. Finally, Section 5 summarizes the major findings of this paper.

A. Queuing Network Modelling

Queueing network models have been used to provide insights into the general behaviour of manufacturing systems, and queuing network modeling of manufacturing systems has been extensively studied by many researchers. A review of these works can be found in Papadopoulos and Heavey (1996) and Subba Rao et al. (1998). Queueing network models have also been used to give estimates of the manufacturing lead times, a good prediction of these being essential for efficient production planning. Manufacturing lead times are often long and unreliable, particularly in the make-to-order and engineer-to-order companies, almost entirely due to the large proportion of time that jobs spend waiting in the queues in front of the workstations needed. Stommel (1976) showed that 85% of the total manufacturing lead time is due to queueing whilst Stalk and Hout (1990) reported it as even higher at 95% to 99%. Kingsman et al.

(1989) and Stalk and Hout (1990) show that in this situation lead time should be considered as a variable to be controlled by management rather than treated as a constant, estimating by forecasting techniques. This requires an understanding of the behaviour of any manufacturing system as a queueing network, where jobs arrive randomly, each requiring different processing times and possibly different routes through the workstations of the manufacturing system.

In a queueing network with finite inter buffers, the flow of jobs in the system becomes dependent on the spaces at the buffers of the destination workstation. This has the effect that the flow of jobs through a workstation may be momentarily stopped if the buffer of a destination workstation has reached its maximum capacity. This situation is known as blocking, and the workstation having this blocking job is said to be blocked. Different types of blocking mechanism have been considered in the literature, see for instance, Perros (1994). Blocking-after-service is generally accepted as the most common type of blocking in manufacturing processes. The occurrence of blocking generally destroys the product-form solutions. Except for a few special cases queueing networks with blocking do not have product-form solutions (see for instance, Perros 1994). Hence, in general, queueing networks with finite buffer capacities are difficult to analyse, and involve numerical solutions for their exact analyses. However, the exact solution method is not feasible for most practical problems, which become computationally infeasibility as soon as the number of workstations or buffer capacities are increased. In fact, only small systems can be solved exactly (Perros, 1994). Therefore, most analyses of queuing networks with finite buffers are based on approximation methods, and many approximation methods have been proposed in the literature; see for instance Balsamo et al. (2001), Dallery and Gershwin (1992), Perros (1994), and Zhang et al. (2017) and the references therein.

B. Experiments

In this paper, job-shop systems are modelled as open queueing network where each workstation settled in a node of the network represents a manufacturing operation. External arrivals and completed departures from the system may occur at any workstation. The job arrives at any node according to a Poisson process. Then, it goes to the particular workstation in its routing sequence of the manufacturing operations, and transition probabilities are defined to represent the flow of jobs. After completing the manufacturing operations of the jobs, the final product leaves the system from any node. In each workstation, there is only one server at each workstation with exponential distribution of processing time. The time spent in a workstation is equal to the processing time plus waiting in the queue in front of the workstation. In almost all real physical systems, finite buffers exist. For this reason, all workstation buffers are assumed to be finite.

In a manufacturing system, the number of workstations, buffer sizes, processing capacities, and the number of entry workstations can be expected to affect its performance measures, as can its layout. This section reveals how manufacturing lead times change when the number of workstations is doubled from 4 to 8, buffer sizes are doubled from 3 to 6, the capacity to process work per unit time is decreased by %10, and the number of entry workstations is increased from 1 to 4; and also when a simpler job shop is contrasted with a pure flow shop.

In this range of experiments, the effects of numbers of workstations, buffer sizes, processing capacities and numbers of entry workstations in the case of various layouts have been analysed. For the systems with four workstations, three layouts are examined, namely ff4-1, ff4-2 and fb4, and the transition probabilities of these layouts are shown in Tables 1-3.

Table 1. Transition probabilities for ff4-1 layout

	1	**2**	**3**	**4**	**out**
1	0	0.5	0.5	0	0
2	0	0	0.5	0.5	0
3	0	0	0	1	0
4	0	0	0	0	1

Table 2. Transition probabilities for ff4-2 layout

	1	**2**	**3**	**4**	**out**
1	0	0.333	0.333	0.334	0
2	0	0	0.5	0.5	0
3	0	0	0	0.5	0.5
4	0	0	0	0	1

Table 3. Transition probabilities for fb4 layout

	1	2	3	4	out
1	0	0.333	0.333	0.334	0
2	0.3	0	0.35	0.35	0
3	0.15	0.15	0	0.35	0.35
4	0.1	0.1	0.1	0	0.7

Furthermore, four layouts (ff8-1, ff8-2, fb8-1 and fb8-2) are considered for eight-workstation systems, and transition probabilities of these layouts are presented in Tables 4-7.

Table 4. Transition probabilities for ff8-1 layout

	1	2	3	4	5	6	7	8	out
1	0	0.333	0.333	0.334	0	0	0	0	0
2	0	0	0.333	0.333	0.334	0	0	0	0
3	0	0	0	0.333	0.333	0.334	0	0	0
4	0	0	0	0	0.333	0.333	0.334	0	0
5	0	0	0	0	0	0.333	0.333	0.334	0
6	0	0	0	0	0	0	0.5	0.5	0
7	0	0	0	0	0	0	0	1	0
8	0	0	0	0	0	0	0	0	1

Table 5. Transition probabilities for ff8-2 layout

	1	2	3	4	5	6	7	8	out
1	0	0.2	0.2	0.2	0.2	0.2	0	0	0
2	0	0	0.2	0.2	0.2	0.2	0.2	0	0
3	0	0	0	0.2	0.2	0.2	0.2	0.2	0
4	0	0	0	0	0.25	0.25	0.25	0.25	0
5	0	0	0	0	0	0.333	0.333	0.334	0
6	0	0	0	0	0	0	0.333	0.333	0.334
7	0	0	0	0	0	0	0	0.5	0.5
8	0	0	0	0	0	0	0	0	1

Table 6. Transition probabilities for fb8-1 layout

	1	2	3	4	5	6	7	8	out
1	0	0.2	0.2	0.2	0.2	0.2	0	0	0
2	0.3	0	0.14	0.14	0.14	0.14	0.14	0	0
3	0.15	0.15	0	0.14	0.14	0.14	0.14	0.14	0
4	0.1	0.1	0.1	0	0.175	0.175	0.175	0.175	0
5	0	0.1	0.1	0.1	0	0.233	0.233	0.234	0
6	0	0	0.1	0.1	0.1	0	0.233	0.233	0.234
7	0	0	0	0.1	0.1	0.1	0	0.35	0.35
8	0	0	0	0	0.1	0.1	0.1	0	0.7

Table 7. Transition probabilities for fb8-2 layout

	1	2	3	4	5	6	7	8	out
1	0	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
2	0.3	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
3	0.15	0.15	0	0.117	0.117	0.117	0.117	0.116	0.116
4	0.1	0.1	0.1	0	0.14	0.14	0.14	0.14	0.14
5	0.075	0.075	0.075	0.075	0	0.175	0.175	0.175	0.175
6	0.06	0.06	0.06	0.06	0.06	0	0.233	0.233	0.234
7	0.05	0.05	0.05	0.05	0.05	0.05	0	0.35	0.35
8	0.043	0.043	0.043	0.043	0.043	0.043	0.042	0	0.7

The layouts of ff4-1, ff4-2, ff8-1 and ff8-2 are feed-forward topologies with all the transition probabilities above the diagonal, that is, these layouts are simpler job shops where jobs can only feed- forward by passing to higher numbered workstations. On the other hand, the layouts of fb4, fb8-1 and fb8-2 are more complicated job shops where jobs mainly pass to higher numbered workstations, but the transition probabilities of moving to lower-numbered workstations are also possible. It is assumed that 30% of jobs return to earlier workstations for further work, i.e., feed backward loops are allowed.

For these layouts, numerous scenarios regarding the number of workstations, buffer sizes, processing capacities and number of entry workstations are considered, and parameters of 19 different cases are explained in Table 8.

Table 8. Parameters of experiments

Cases	Layout	Number of workstations	Buffer sizes of each workstation	Processing rates of each workstation	External arrival rates
1	ff4-1	4	N_i=3	μ_i=1	λ_{01}=0.9
2	ff4-2	4	N_i=3	μ_i=1	λ_{01}=0.9
3	fb4	4	N_i=3	μ_i=1	λ_{01}=0.9
4	ff8-1	8	N_i=3	μ_i=1	λ_{01}=0.9
5	ff8-2	8	N_i=3	μ_i=1	λ_{01}=0.9
6	fb8-1	8	N_i=3	μ_i=1	λ_{01}=0.9
7	fb8-2	8	N_i=3	μ_i=1	λ_{01}=0.9
8	ff8-1	8	N_i=6	μ_i=1	λ_{01}=0.9
9	ff8-2	8	N_i=6	μ_i=1	λ_{01}=0.9
10	fb8-1	8	N_i=6	μ_i=1	λ_{01}=0.9
11	fb8-2	8	N_i=6	μ_i=1	λ_{01}=0.9
12	ff8-1	8	N_i=3	μ_i=0.9	λ_{01}=0.9
13	ff8-2	8	N_i=3	μ_i=0.9	λ_{01}=0.9
14	fb8-1	8	N_i=3	μ_i=0.9	λ_{01}=0.9
15	fb8-2	8	N_i=3	μ_i=0.9	λ_{01}=0.9
16	ff8-1	8	N_i=3	μ_i=1	λ_{01}=0.3, λ_{02}=0.3, λ_{03}=0.15, λ_{04}=0.15
17	ff8-2	8	N_i=3	μ_i=1	λ_{01}=0.3, λ_{02}=0.3, λ_{03}=0.15, λ_{04}=0.15
18	fb8-1	8	N_i=3	μ_i=1	λ_{01}=0.3, λ_{02}=0.3, λ_{03}=0.15, λ_{04}=0.15
19	fb8-2	8	N_i=3	μ_i=1	λ_{01}=0.3, λ_{02}=0.3, λ_{03}=0.15, λ_{04}=0.15

In the experiment cases, three layouts for four-workstation systems and four layouts for eight-workstation systems are considered, and these layouts are described in Tables 1-7. The layout used for any particular case is presented in the second column of Table 8. At the first three cases, the manufacturing system has four workstations, whereas the rest of cases considers the system with eight workstations. The cases excluding 8, 9, 10 and 11 assume that each workstation in the manufacturing system has buffer capacity of 3 units, including one on machine. The cases 8, 9, 10 and 11 assume buffer capacity of 6 instead of 3. In the cases excluding 12, 13, 14 and 15 the processing rates of jobs per unit time for each workstation are assumed to be 1 while the processing rates in the cases 12, 13, 14 and 15 are assumed to be 0.9 per unit time. For cases 1 thorough 15 external arrivals (jobs) can only occur at the first workstation with rate of 0.9 per unit time. Conversely, in the cases 16 through 19, external arrivals occur at workstations 1, 2, 3 and 4 with rate of 0.3, 0.3, 0.15 and 0.15 per unit time, respectively.

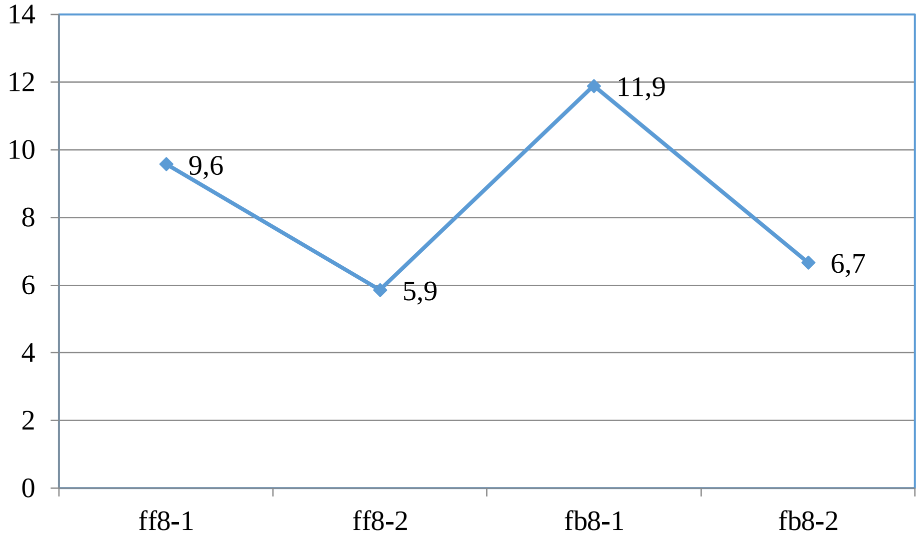
C. Results

In this section, the empirical results obtained using an approximate model are used to highlight provisional insights relevant for manufacturing system management, and the effects of system configuration (layout) on manufacturing lead time have been studied. The approximate model proposed by Haskose et al. (2004) allows to analyse arbitrary queueing networks with feed-forward and feed-backward topologies are possible, that is, both feed-forward and feedback loops are allowed. For this reason, the results are obtained using the approximate model of Haskose et al. (2004).

The effects of different layouts, number of workstations, buffer sizes, processing capacities and number of entry workstations are compared in separate graphs. Figure 1 explores performances of the system with eight workstations for the four layouts. Figure 2 examines the effect of the number of workstations on lead time. The comparisons for buffer sizes of 3 and 6 are presented in Figure 3 while two different processing capacities are evaluated in Figure 4. Finally, Figure 5 compares the two scenarios regarding the pattern of external arrivals to the system.

Of the layouts examined in Figure 1, two have feed-forward topology while other two are feed-backward systems. Both layouts of ff8-1 and ff8-2 are feed-forward layouts, and major difference between these two layouts is the number of exit workstations where jobs can leave the system. In the ff8-1 layout jobs can only leave the system from the last workstation (workstation 8) while the ff8-2 layout allows the jobs to leave the system from the last three workstations (workstations 6, 7 & 8). The lead times, on the other hand, are quite

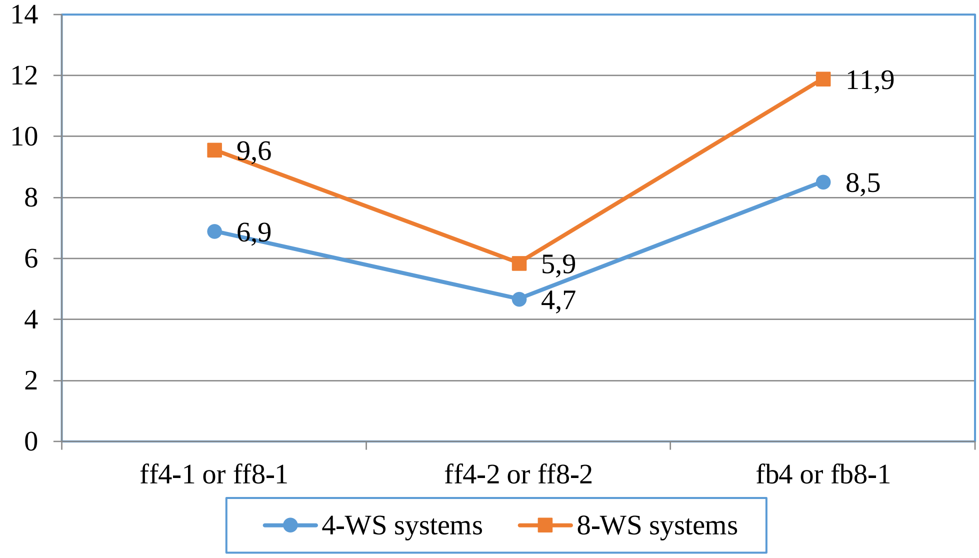
Figure 1. Manufacturing lead times for 8-workstation systems with various layouts, namely layouts of ff8-1, ff8-2, fb8-1 and fb8-2 (experiment cases of 4, 5 6 and 7)



different for these two layouts, and moving from ff8-1 to ff8-2 decreases the manufacturing lead times by 40%. Moreover, fb8-1 layout is similar to ff8-2, but it has feed-backward topology. The fb8-1 layout allows the job to leave from the last three workstation; but 30% of jobs returns to earlier stations for further work, i.e., feed backward loops are allowed in fb8-1 whereas backward loops are not allowed in ff8-2. Compared to ff8-2, the fb8-1 layout leads to increases in lead time double. The layout of fb8-2 is a pure job shop in which a job completed at one workstation can leave the system, or can go to either of the other workstations. As in feed-forward systems (ff8-1 and ff8-2), moving from fb8-1 to fb8-2 reduces the manufacturing lead time by 44% (see Figure 1).

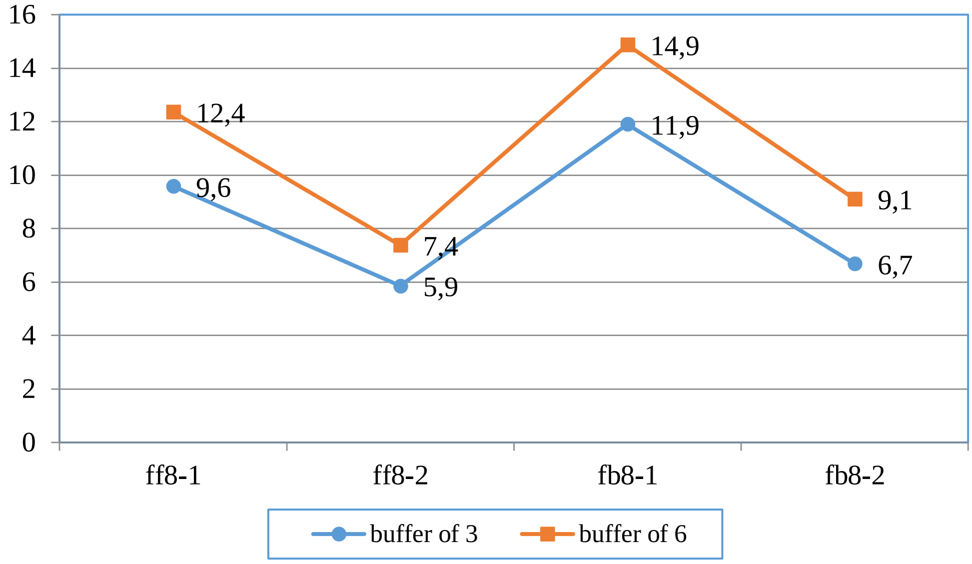
In Figure 2 the systems with eight workstations is compared against the four-workstation systems in order to examine the effect of size of the systems on lead time. These systems are compared in three groups. In the first group, simpler feed-forward configurations, namely ff4-1 or ff8-1, are considered. The layouts of ff4-2 or ff8-2 which are slightly complex feed-forward configuration are shown in the second group. The systems with feed-backward topology (ffb or fb8-1 layouts) are categorized as the third group. As seen in Figure 2 the greater the number of workstations the longer the lead time. Despite the fact that jobs tend to go through twice as many workstations and therefore the lead time is expected to increase twice, the increases in manufacturing lead time are between 25% and 40%.

Figure 2. *Manufacturing lead times for 4-workstation and 8-workstation systems with various layouts (cases 1, 2 & 3 vs. 4, 5 & 6)*



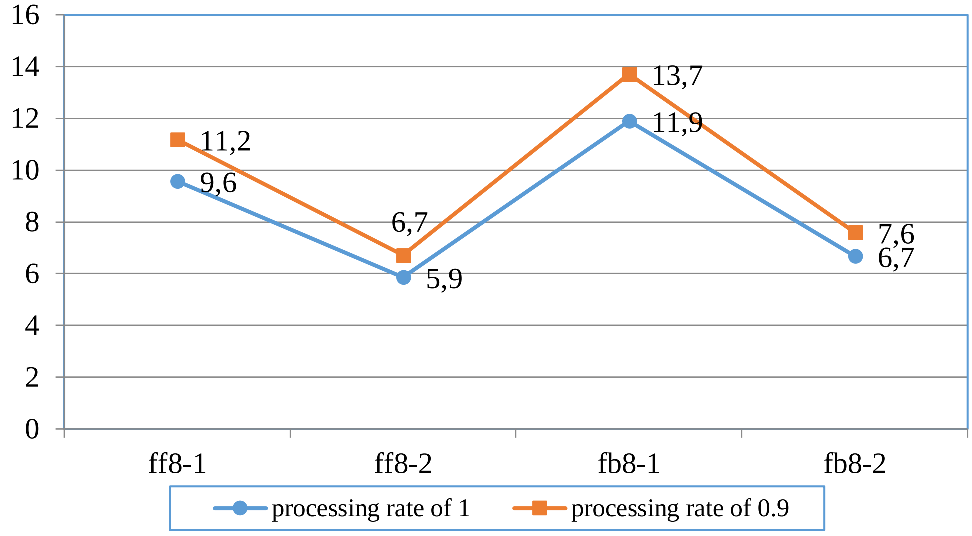
The amount of accepted jobs increases as the buffer capacities of workstations increase. This causes more congestion in the system; and hence leads to increases in manufacturing lead times. To investigate the effect of buffer sizes on lead time, the eight-workstation system is examined for four layouts, namely ff8-1, ff8-2, fb8-1 and fb8-2, and the results are shown in Figure 3. The buffer capacities of each workstation are assumed to be 3 and 6 units for the first and second sets of cases, respectively. Although manufacturing lead times for the cases where buffer sizes are 6 are longer than those of the cases with buffer of 3 in all cases, they are again sensitive to the layout. The lowest relative increment of lead time with 25% is observed in the case of fb8-1 layout while the highest increment is noticed in the layout of fb8-2 with 36%. However, the changes in quantity are slightly different, e.g., the lowest increment of lead time is 1.5 for ff8-2 layout whilst the highest increment is observed for fb8-1 layout with 3 unit-time.

Figure 3. *Manufacturing lead times for 8-workstation systems with various layouts in the cases of buffer sizes of 3 and 6 (cases 4, 5, 6 & 7 vs. 8, 9, 10 & 11)*



The two different scenarios for processing capacity of the system have been considered. The processing rates of each workstation per unit time are assumed to 1 and 0.9 for the former and latter scenarios, respectively. In other words, processing capacity of the system is reduced by 10% in the latter scenario for analysis of effect of processing capacity on lead time. For this situation, the manufacturing lead time is expected to increase due to reduction in processing capacity. As seen in Figure 4, no significant differences are observed between the results of first and second scenarios, and the relative changes of lead times for all layouts are between 14% and 17%.

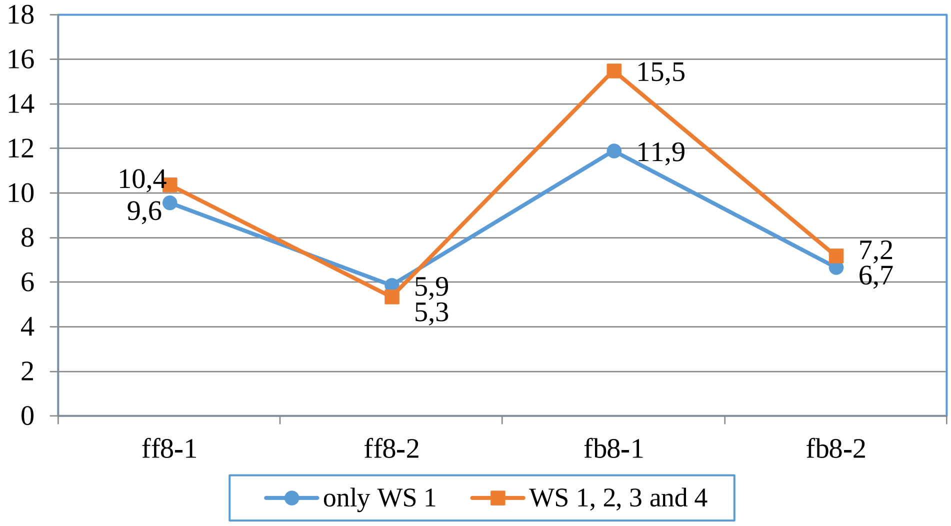
Figure 4. *Manufacturing lead times for 8-workstation systems with various layouts in the cases of processing rates of 1 and 0.9 per unit time (cases 4, 5, 6 & 7 vs. 12, 13, 14 & 15)*



Finally, the effect of the number of entry workstations on manufacturing lead time is examined. In the first group of cases, four different layouts (ff8-1, ff8-2, fb8-1 & fb8-2) are considered, and external arrivals (jobs) can only occur at first workstation with rate of 0.9 per unit time. However, in the second group, external arrivals can occur at four workstations instead of one. For the second group, external arrival rates at the first and second workstations are equal to each other and each is 0.3 per unit time whilst external arrival rates per unit time for the third and fourth workstations are 0.15 for each. Compared to the effects of the number of workstations, buffer sizes and processing capacities, the effect of the number of entry workstations is slightly different, and no pattern is observed. When the number of entry workstation is increased, the manufacturing lead time for ff8-2 layout decreases while it increases for the other layouts. Although the number of the entry workstations does not make a significant difference for the layouts of ff8-1, ff8-2 & fb8-2, the layout of fb8-1 causes an increase in manufacturing lead time by 30%.

As expected, increasing the number of workstations and buffer sizes causes longer manufacturing lead time. Similarly, reducing processing rate leads to an increase in lead time. The number of entry workstations also affects

Figure 5. *Manufacturing lead times for 8-workstation systems with various layouts in which entry workstations are only WS 1 and WS 1, 2, 3 & 4 (cases 4, 5, 6 & 7 vs. 16, 17, 18 & 19)*



the performance of the system. Moreover, the manufacturing lead time of a system is affected not only by the number of workstations, buffer sizes, processing capacities and the number of entry workstations, but also by the layout of the system. In fact, the most important factor affecting the manufacturing lead time seems to be the layout of a system.

Conclusions

Production planning has a great importance for the competitive position of a manufacturing firm. Accurate prediction of manufacturing lead times is important for determination of reliable delivery dates and reliable lead times thus are essential inputs for production planning systems. Setting the appropriate manufacturing lead time is critical for an efficient production planning, particularly in the make-to-order and order-to-order industries. Such a planning system supported with accurate lead times estimates should result in a better delivery date performance than planning systems with fixed lead times, ignoring the influence of possible interventions.

Five sets of experiments with a total of 19 cases were conducted. These experiment results suggest that manufacturing lead time of a system is the most sensitive to layout of the system, i.e., configuration of the system (feed-forward or feed-backward topology) and the number of exit workstations. However, it is difficult to estimate manufacturing lead time for any specific parameters, i.e., any configuration, number of workstations, buffer size, etc. Consequently, there appears to be no simple answer about how or to what degree it will affect performance, emphasizing the need for models capable of predicting the performance consequences of possible interventions and providing insights for production planning.

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