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DEADLOCK ANALYSIS IN FMS IN THE PRESENCE OF FLEXIBLE PROCESS PLANS – A SIMULATION STUDY

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Abstract
The increased use of FMS to provide customers with diversified products efficiently has created a significant set of operational challenges for managers. This technology presents a number of decision problems to be solved by researchers and practitioners. There have been a number of attempts to solve design and operational problems in FMS. A special attention has been given to batch scheduling when flexible process plans (FPPs) remain available on the shop floor. An extensive simulation study under two manufacturing environments is performed to study the system performance in the presence of FPPs. Several interesting conclusions have been drawn from deadlock, makespan and mean flow time criteria.

Key Words: FMS Scheduling, Flexible Process Plans, Deadlock Avoidance

1. INTRODUCTION

In recent years there has been considerable interest in the developments of control theory and methods for design, scheduling operations and performance evaluation of flexible manufacturing systems (FMSs). FMSs combine the efficiency of mass production and flexibility of a job shop to best suit the batch production of mid-volume and mid-variety of products. The flexibility of an FMS is mainly due to the capability of performing different operations within the same station and material handling system, which provides fast and flexible transfer of parts with in the system. Since FMSs are capital intensive, an effective management and control system is needed for their successful implementation.

For smooth operation of an FMS, there are several problems such as aggregate planning, resource grouping, disaggregate planning and scheduling that are to be solved in a hierarchical manner. Among them, scheduling has been researched over past several years and it is concerned with decisions that have to be taken when the system is in operation. FMS scheduling is quite different from that in conventional job shop because of its integrated hardware and its operating conditions such as (1) presence of flexible (multiple) process plans (FPPs), (2) limited buffer space availability, (3) considerations of transportation time and transportation capacity, (4) deterministic processing times, (5) reduced set-up time between consecutive operations (6) limited pallet and fixtures availability and (7) considerations of constraints on tool changing facilities [1]. These factors make most FMS scheduling problems NP-hard as they become intractable and complex [2]. Thus real time scheduling approach is advocated as appropriate approach for FMS scheduling problems by many researchers [3, 4].

In FMS, flexible process plans (FPPs) are common due to the presence of versatile machines that provide alternatives for adapting to dynamic environment and improve system performance [5]. FPPs can be generated with the consideration of operation flexibility (possibility of performing an operation on more than a machine), sequencing flexibility (possibility of interchanging the sequence in which required manufacturing operations are

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performed) and processing flexibility (possibility of producing the same manufacturing feature with alternative operations, or sequence of operations) [6]. It is important to mention that a computer controlled flexible automation system is essential to implement FPPs in practice [7].

In FMSs/automated manufacturing systems (AMSs), deadlock free operation is an essential control requirement. A deadlock is a situation where each of a set of two or more parts keeps waiting indefinitely for the other parts in the set to release resources. Deadlock occurs when various parts with different routings compete for finite number of resources. When a deadlock occurs in a manufacturing system, part flow is inhibited, no activity/event occurs in the system and system comes to a stand still. [8] stated that a deadlock occurs if and only if the following four conditions exist in the system simultaneously: *mutual exclusion, hold and wait, no pre-emption* and *circular wait*. Resolving a deadlock thus amounts to relaxing at least one of these conditions. In manufacturing systems, the first three conditions are generally satisfied. Thus only the fourth condition determines whether a deadlock occurs [8]. Therefore, if system controller can predict the occurrence of circular wait, deadlock can be avoided.

This paper, initially, provides a literature review of manufacturing research on deadlock and FPPs. Subsequently, an extensive simulation study is carried out using Petri nets (PN) model of an example FMS, to study the system performance in two manufacturing environments viz., VBM (virtual batch manufacturing) and VLM (virtual line manufacturing) from deadlock, makespan and mean flow time viewpoints. VBM represents the manufacturing scenario in which operation times are higher and not comparable with transportation times while VLM represents the manufacturing scenario in which operation times are comparable with transportation times.

2. LITERATURE REVIEW

This section provides a review of relevant literature in the areas of deadlock and FPPs. Review of literature indicates that two approaches are advocated for eliminating deadlocks in FMS/AMS. One emphasizes on designing an inherently deadlock free manufacturing system [9, 10, 11] while other approach eliminates possible deadlocks through proper operational control [12, 13, 14, 15]. Researcher community advocated following three strategies for eliminating the deadlock occurrence through operational control approach: *deadlock prevention, deadlock detection/recovery* and *deadlock avoidance*. Deadlock prevention is a simple approach in which predetermined rules are followed that ensures that at least one of the four necessary conditions does not hold. In case of a manufacturing system, system controller must determine in advance all possible routes of the parts in the manufacturing system to prevent occurrence of deadlock. Thus this approach is based on static resource allocation policy and easy to implement but results in poor resource utilization as well as system throughput. Deadlock detection/recovery strategy allows the system to enter a deadlock state and then initiate system recovery. It can be an expensive strategy since it might involve removal of some semi-finished parts from system or resource preemption [16]. Deadlock avoidance is a more practical approach for real-world manufacturing system [17]. It refers to dynamic resource allocation policies and examines the system’s state dynamically and by passes deadlock state carefully, in real time, resulting in better resource utilization and system throughput. Deadlock prediction is an essential part of the deadlock avoidance procedure to ascertain the locations of deadlocks in advance. In general, a system with dynamic routings require an algorithm to predict and avoid deadlocks in real-time. It is important to mention that deadlock resolution algorithms are dependent on system configuration and the way the system operates [15]. Several deadlock avoidance policies

(DAP) such as Banker's algorithm [18, 19], resource upstream neighborhood (RUN) [20, 21], resource order (RO) [22] have been developed by various researchers. However, authors found only a single paper that addresses the issue of DAP in the presence of flexible routing (operations flexibility) [23].

For FPPs and FMS scheduling, [24, 25] cover the published work in this area and this review includes only important published papers. [26] studied the impact of varying level of routing flexibilities on the makespan of a FMS and concluded that increase in routing flexibility, when made at the cost of an associated penalty on operation processing time is not always beneficial. There is an optimal flexibility level beyond which system performance deteriorates. [27] developed and evaluated computationally efficient procedures for scheduling jobs in a large-scale manufacturing system in the presence of FPPs for maximum lateness performance measure and concluded that **(i)** there are substantial differences in schedule performance between scheduling with alternative and scheduling without alternatives. Scheduling with alternatives can greatly improve the ability to satisfy due-date under various shop floor conditions and **(ii)** there are substantial differences in schedule performance between scheduling with alternative routing, operation and sequencing. Scheduling with alternative operations had the largest schedule improvement and scheduling with alternative sequences had the smallest schedule improvement. [28] developed a simulation software (OOSimFlex) that is capable of modeling different alternative systems design and analyzing a manufacturing system using multiple performance measures under different manufacturing flexibility levels. [29] carried out scheduling of FPPs in a mould manufacturing shop instead of FMS using branch and bound procedure to optimize priority weighted earliness of jobs. [30] used genetic algorithm for FMS scheduling/rescheduling and observed that routing flexibility has a significant impact in case of disruptions (machine breakdown, rush order arrival, order cancellation and increased order priorities). Literature review on dispatching rules is beyond the scope of this paper. [31] reported that in FMS, PT2 (smallest ratio of processing time to number of remaining operations), MOPNR (most operations remaining), MWR (most work remaining) and PWR (smallest ratio of processing time to remaining work) rules perform better than other dispatching rules for makespan. [25] proposed four dispatching rules (%CW, CW1, CW2, CW5) and presented several interesting conclusions on performance of dispatching rules.

Literature review reveals there are several studies to assess the impact of flexibility on system performance but few studies have been conducted by researcher community to study the system performance with FPPs for identifying various deadlock avoidance policies. The objective of the present paper is to study the system performance from deadlock viewpoint in the presence of FPPs that will assist operations managers to device deadlock avoidance algorithms. This paper also assesses the system performance from makespan and mean flow time performance measures in order to identify variables affecting them.

3. SYSTEM DESCRIPTION AND MODEL CHARACTERISTICS

The FMS considered in the present study is shown in Fig. 1 [24]. This system consists of four machines (M1, M2, M3, and M4) with work-in-process buffers, two robots, system input (B-IN) and output (B-OUT) buffers and a load/unload (L/UL) station. Each machine has individual input and output buffer of capacity three and two respectively. A giant robot R-2 serves all the four machines. It is assumed that L/UL station is of infinite capacity and B-IN/B-OUT have a capacity of ten and eight respectively. Another robot R-1 operates between L/UL station and B-IN/B-OUT for part transfer. Travel times of R-1 and R-2 while serving other system resources are given in Table I [24].

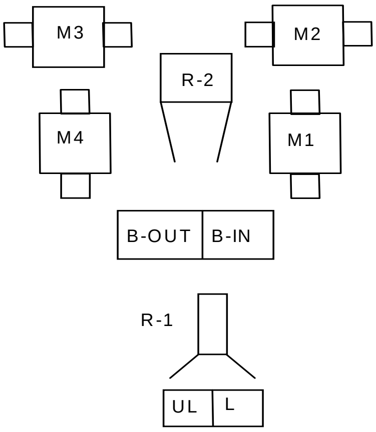

Figure 1: Taken FMS configuration [24].

Table I: R-1 and R-2 unit travel times [24].

		L/ UL	**B-IN/ B-OUT**	**M1**	**M2**	**M3**	**M4**
Robot R-1	**L/UL**	0	2	-	-	-	-
	B-IN/ B-OUT	2	0	-	-	-	-
Robot R-2	**B-IN/ B-OUT**	-	0	3	5	5	3
	M1	-	3	0	3	5	7
	M2	-	5	3	0	3	5
	M3	-	5	5	3	0	3
	M4	-	3	7	5	3	0

Legend: - Not Applicable.

The occurrence of manufacturing activity in the FMS is as follows. Initially, a raw part is loaded onto pallet at load station by manual operation. The palletized part is transported by R-1 to B-IN. R-2 then moves parts from B-IN to various machines according to their process plans. When FPPs are available, a part can switch over to alternate process plan to overcome the non-availability of machine due to limited buffer space. The sequence of part flow at a machine is: machine input buffer → machine table → machine output buffer. When a part is completed, R-2 transports it back to B-OUT. R-1 again transports finished parts from B-OUT to unload station, where part is unloaded from the pallet manually. This empty pallet is again loaded with raw part of same part type, if available, and sent into the system. At any time, three-job types viz., raw jobs, semi-finished jobs and finished jobs are circulating and compete for the same resources (machines/robots). Thus, several operational decisions such as part selection decision (at B-IN, B-OUT, input and output buffer of each machine) and machine selection decision (at B-IN and output buffer of each machine in case of FPPs) are required for the smooth functioning of the FMS. These decisions are not described here for want of space and discussed in [24, 25]. Assumptions such as (i) operations and transportation times are deterministic and known in advance, (ii) each machine is continuously available for processing jobs, (iii) part preemption is not allowed, (iv) pallet and fixture availability is limited and it can load one part at the most, (v) All parts are available for processing at the start, although part entry into the system is dependent on the pallet availability and (vi) number of pallets available for each part type is in same proportion of the total pallets available as the proportion of their required production quantity with respect to the total production requirement that are in line with previous studies have been made in this work.

The FMS is modeled using Petri nets (PN) modeling approach and execution code is written in C programming language under Windows environment. The PN model of the example FMS is large and not included for want of space. However, a simplified version of PN model in the form of flow process diagram is shown in Fig. 2. This diagram depicts the information and material flow in the system. Part loading/unloading, part transfer and operations are pictured as circles. Waiting time and delays are same and pictured as letter D. Delays occur due to non-availability of machines and/or material handling equipment. When machines and/or material handling equipment are available, waiting time/delay is zero. All decision blocks are represented by diamonds and play a crucial role in regulating the flow of material and information in the manufacturing system. Here, D1 and D3 represent part selection at load station and B-IN respectively. Similarly, D5, D8, and D11 represent part election at M1, M2, and M3 respectively. A brief discussion of nodes is given in Table II.

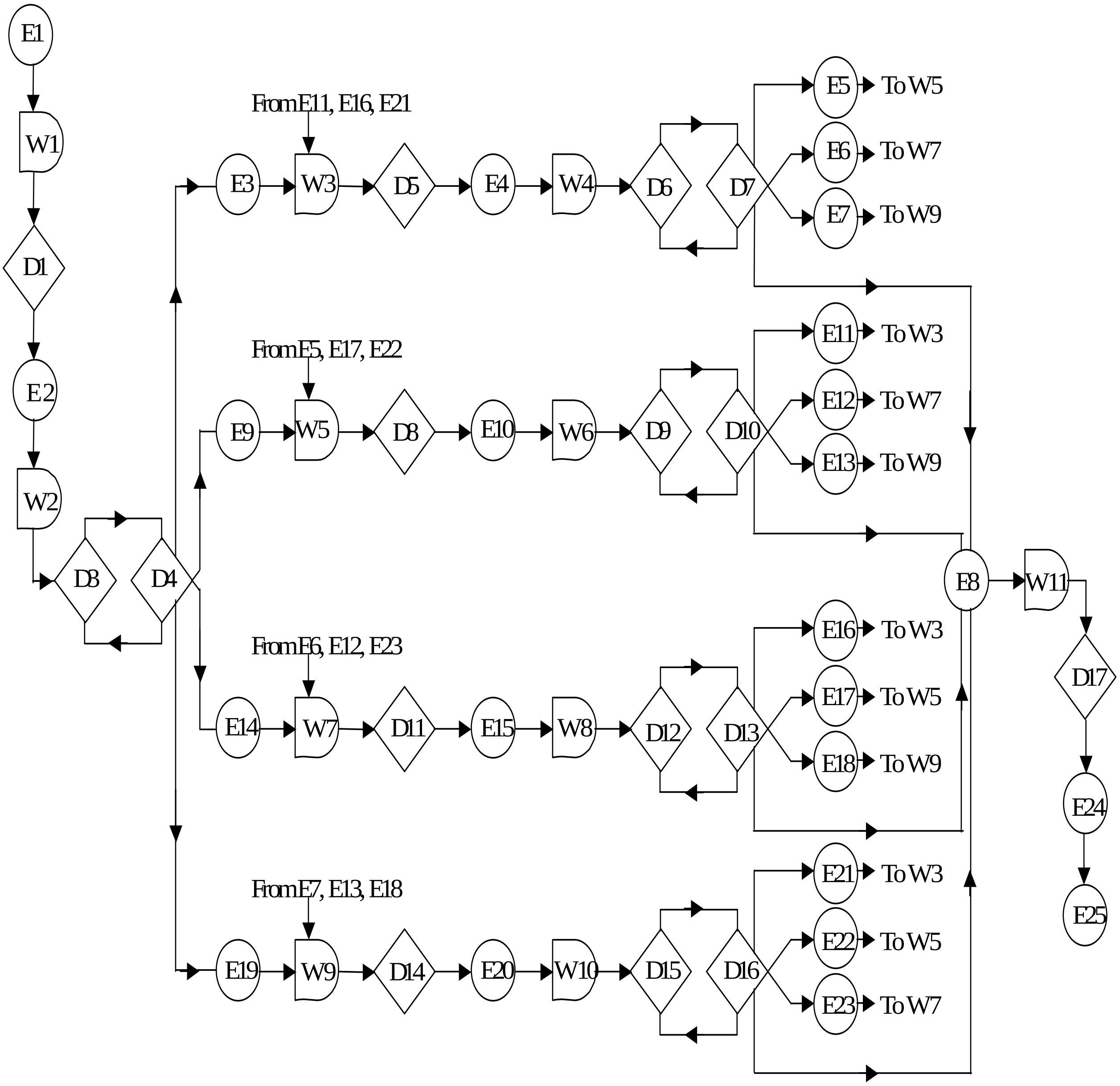

Figure 2: Process diagram of system controller.

4. EXPERIMENTAL INVESTIGATIONS

Experiments are designed and conducted by simulating the PN model of FMS in two manufacturing environments viz., VBM and VLM. Table III shows the flexible process plans of various part types that are considered in the present study. A production order belongs to either of manufacturing environment i.e. VBM or VLM. The number of pallets released to the system is taken as variable and it varies from six (30 % of work-in-process) to twenty (100 % of work-in-process). The various variables with their range/values considered are summarized in Table IV.

Table II: Description of nodes of system flow diagram.

Node	**Description**
D1	Part selection at load station
D3	Part selection at B-IN
D4	Machine selection at B-IN
D5	Part selection at input buffer of machine 1
D6	Part selection at output buffer of machine 1
D7	Machine selection at output buffer of machine 1
D8	Part selection at input buffer of machine 2
D9	Part selection at output buffer of machine 2
D10	Machine selection at output buffer of machine 2
D11	Part selection at input buffer of machine 3
D12	Part selection at output buffer of machine 3
D13	Machine selection at output buffer of machine 3
D14	Part selection at input buffer of machine 4
D15	Part selection at output buffer of machine 4
D16	Machine selection at output buffer of machine 4
D17	Part selection at B-OUT
E1	Part loading on pallet
E2	Part transfer to B-IN (by R-1)
E3	Part loading in input buffer of machine 1 (by R-2)
E4	Part processing on machine 1
E5	Part transfer to input buffer of machine 2 (by R-2)
E6	Part transfer to input buffer of machine 3(by R-2)
E7	Part transfer to input buffer of machine 4 (by R-2)
E8	Part transfer to B-OUT (by R-2)
E9	Part loading in input buffer of machine 2 (by R-2)
E10	Part processing on machine 2
E11	Part transfer to input buffer of machine 1 (by R-2)
E12	Part transfer to input buffer of machine 3(by R-2)
E13	Part transfer to input buffer of machine 4(by R-2)
E14	Part loading in input buffer of machine 3 (by R-2)
E15	Part processing on machine 3
E16	Part transfer to input buffer of machine 1 (R-2)
E17	Part transfer to input buffer of machine 2 (R-2)
E18	Part transfer to input buffer of machine 4 (R-2)
E19	Part loading in input buffer of machine 4 (by R-2)
E20	Part processing on machine 4
E21	Part transfer to input buffer of machine 1 (by R-2)
E22	Part transfer to input buffer of machine 2 (by R-2)
E23	Part transfer to input buffer of machine 3 (by R-2)
E24	Part transfer to unload station (by R-1)
E25	Part unloading from pallet
W1	Part at load station
W2	Part at B-IN
W3	Part in input buffer of machine 1
W4	Part in output buffer of machine 1
W5	Part in input buffer of machine 2
W6	Part in output buffer of machine 2
W7	Part in input buffer of machine 3
W8	Part in output buffer of machine 3
W9	Part in input buffer of machine 4
W10	Part in output buffer of machine 4
W11	Part in B-OUT

Table III: Process plans of various part types.

Part Type Number	VLM –FPP M_i (T_I)	VBM –FPP M_i (T_I)
1.	1(4) – 3(7) – 1(3) – 4(2) 1(4) – 3(7) – 2(5) – 4(2) 2(6) – 3(7) – 1(3) – 4(2) 2(6) – 3(7) – 2(5) – 4(2)	1(60) – 3 (75) – 2 (60) – 4 (30) 1(60) – 3 (75) – 1 (58) – 4 (30) 2(65) – 3 (75) – 2 (60) – 4 (30) 2(65) – 3 (75) – 1 (58) – 4 (30)
2.	2(4) – 1(3) – 2(2) – 4(10) 2(4) – 1(3) – 2(2) – 1(12) 2(4) – 1(3) – 3(3) – 4(10) 3(7) – 1(3) – 2(2) – 4(10)	2(60) – 1 (45) – 2 (41) – 4 (90) 2(60) – 1 (45) – 3 (45) – 4 (90) 3(65) – 1 (45) – 2 (41) – 4 (90) 3(65) – 1 (45) – 3 (45) – 4 (90)
3.	1(5) – 4(2) – 3(2) – 2(3) 1(5) – 3(2) – 4(3) – 2(3) 1(5) – 2(4) – 3(2) – 2(3) 1(5) – 2(4) – 4(3) – 2(3)	1(60) – 4 (45) – 3 (40) – 2 (30) 1(60) – 3 (41) – 4 (45) – 2 (30) 1(60) – 3 (41) – 2 (45) – 4 (33) 1(60) – 4 (45) – 2 (45) – 1 (32)
4.	2(3) – 1(6) – 2(5) – 1(3) 2(3) – 1(6) – 2(5) – 3(4) 3(6) – 4(5) – 2(5) – 1(3) 3(6) – 1(6) – 2(5) – 1(3)	1(60) – 2 (82) – 3 (100) – 2 (100) 1(60) – 4 (80) – 3 (100) – 2 (100) 3(65) – 2 (82) – 1 (98) – 4 (100) 3(65) – 4 (80) – 1 (98) – 4 (100)
5.	4(4) – 3(4) – 2(4) – 4(8) 2(5) – 1(3) – 2(4) – 4(8) 2(5) – 3(4) – 2(4) – 4(8) 2(5) – 1(3) – 3(8) – 4(8)	4(97) – 3 (54) – 2 (40) – 1 (99) 4(97) – 1 (50) – 3 (42) – 4 (100) 2(100) – 3 (54) – 2 (40) – 1 (99) 2(100) – 1 (50) – 3 (42) – 4 (100)
6.	4(6) – 2(3) – 3(2) – 1(3) 3(7) – 2(3) – 3(2) – 1(3) 4(6) – 2(3) – 3(2) – 2(4) 4(6) – 2(3) – 4(2) – 1(3)	2(60) – 1 (100) – 2 (100) – 3 (80) 2(60) – 1 (100) – 4 (97) – 3 (80) 3(63) – 4 (100) – 2 (100) – 1 (78) 3(63) – 4 (100) – 2 (100) – 3 (80)
7.	3(4) – 4(4) – 3(5) – 4(5) 1(3) – 2(5) – 3(5) – 2(6) 1(3) – 4(4) – 3(5) – 4(5) 3(4) – 2(5) – 3(5) – 4(5)	4(57) – 1 (95) – 2 (62) – 4 (40) 4(57) – 1 (95) – 2 (62) – 1 (42) 1(60) – 2 (100) – 3 (60) – 4 (40) 1(60) – 2 (100) – 3 (60) – 1 (42)

Legend: M_i - Machine Number T_i - Operation Time

Table IV: Parameters and their range considered in the present work.

S. No.	Parameter	Range/Value Employed
1.	Production quantity of each part type in a production order	20-50
2.	Number of part types in a production order	3-4
3.	Number of operations per job	4
4.	Manufacturing system environment	VBM and VLM
5.	Transportation time	2-7 units
6.	Operation time	2-15 units (for VLM environment) and 20-100 units (for VBM environment)
7.	Number of pallets released to the system	6-20 in steps of 2 i.e. 6, 8, 10, 12, 14, 16, 18, 20
8.	Dispatching rule	SPT, PT2, %CW, CW1, CW2, CW5
9.	Performance measure	Makespan, mean flow time

Six case studies in each manufacturing environment (total twelve case studies) are considered. Figs. 3 and 4 show variation of makespan and mean flow time with *np* for case study 1 (in VBM) and Figs. 5 and 6 show the above variations for case study 7 (in VLM). For other case studies, results are summarized in Tables V and VI for VBM and VLM respectively.

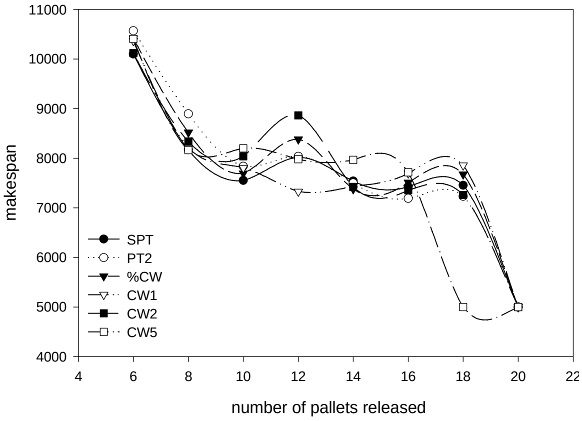

Fig. 3 Variation of Makespan with np (VBM)
(5000 shows deadlock state)

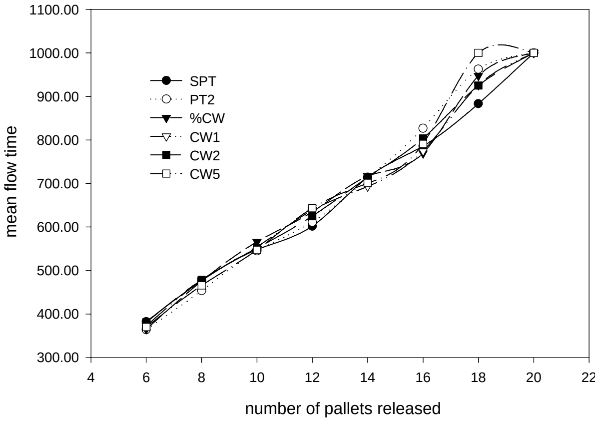

Fig 4 Variation of Mean Flow Time with np (VBM)
(1000 shows deadlock state)

Table V shows that for case study 2 in VBM at *np* = 16, system reaches to deadlock state for PT2 and CW1 rules and other rules do not give rise to deadlock state at *np* =16. Similarly, the Table V shows that for case study 2 in VBM at *np* = 16, system reaches to deadlock state for PT2 and CW1 rules and other rules do not give rise to deadlock state at *np* =16. Similarly, at *np* = 18, deadlock state of system is reached for SPT, PT2, CW1, CW2 and CW5 rules and other rule i.e. %CW does not give rise to deadlock state of system (at *np* =18). For case study 4 at *np* = 14, CW2 give rise to deadlock state while other rules avoid it i.e. for a given production order and *np*, deadlock state of system can be avoided by changing the dispatching rule. This observation is also true for other case studies in VBM (Table V and Fig. 3). This phenomenon may be attributed to the fact that during FMS scheduling, at B-IN and output buffer of each machine, part selection is performed using a dispatching rule. The selected part may be different due to different DRs at these stations and it may happen that the selected parts due to one DR can’t be allocated to any machine according to their flexible process plans and system reaches to deadlock state. Thus, it can safely be concluded that for a given production order and *np*, deadlock state of system can be avoided by changing the DR.

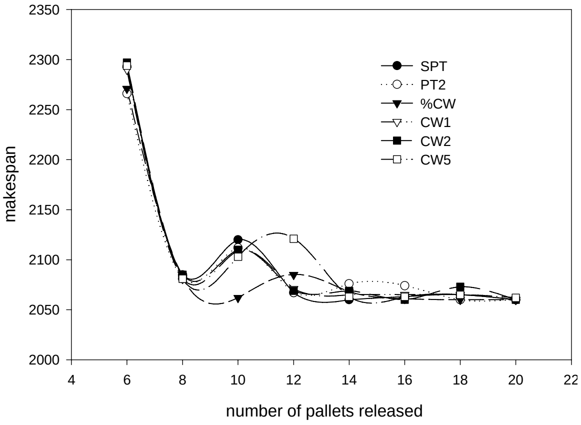

Fig. 5 Variation of Makespan with np (VLM)

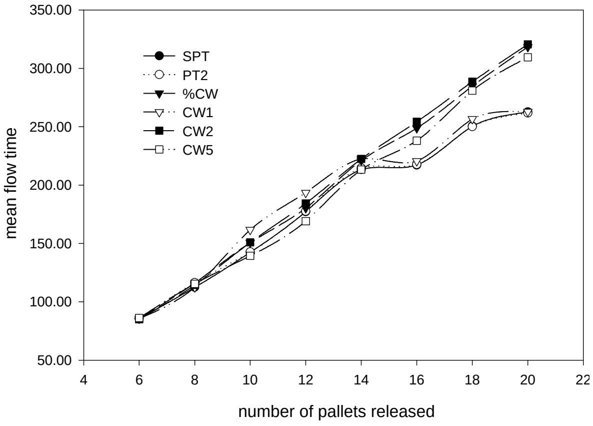

Fig. 6 Variation of Mean Flow Time with np (VLM)

Table V: System performance in VBM manufacturing environment.

		Performance measure when number of pallets released to system							
		6		8		10		12	
		Makespan	MFT	Makespan	MFT	Makespan	MFT	Makespan	MFT
Case study 2	SPT	11194	357.44	11237	471.88	10236	527.46	10608	616.39
	PT2	11426	358.43	10670	478.37	11120	532.22	10371	655.30
	%CW	11215	360.13	11127	475.36	12425	586.73	10133	715.96
	CW1	11326	362.17	11065	472.51	10802	588.96	9790	680.49
	CW2	11313	358.23	11145	473.17	11878	614.93	10683	666.33
	CW5	11227	358.17	10975	472.18	13441	568.95	13661	712.12
Case study 3	SPT	8423	325.97	7806	426.46	8225	540.43	8732	618.29
	PT2	7649	331.13	7564	424.50	7674	516.37	8447	612.36
	%CW	7964	328.13	7752	428.62	10114	571.32	9813	701.62
	CW1	7979	330.42	7672	430.73	8354	525.70	8293	656.02
	CW2	8323	330.14	7785	431.67	9820	597.29	9415	676.43
	CW5	8267	327.71	7802	427.62	10114	572.11	9892	706.02
Case study 4	SPT	17777	568.29	16119	618.02	15656	759.03	16113	915.21
	PT2	18984	591.16	15755	647.17	16815	854.48	16978	954.55
	%CW	18098	575.67	16200	630.13	13892	749.32	13153	918.47
	CW1	17876	570.62	15975	627.72	13015	776.98	16339	1012.44
	CW2	18975	580.17	16423	633.43	16264	879.01	15993	1003.89
	CW5	17795	577.32	15968	621.13	13738	751.95	15758	920.42
Case study 5	SPT	11950	420.62	11688	447.41	10105	530.52	9871	575.17
	PT2	11805	410.03	12327	438.90	10213	522.35	9442	617.57
	%CW	11815	422.13	11700	450.13	10293	536.59	9084	646.81
	CW1	11825	412.72	11823	440.14	9760	548.75	9047	629.85
	CW2	11952	421.31	11915	450.47	10083	552.34	9497	673.05
	CW5	11940	418.71	12227	448.63	9447	573.35	10033	612.94
Case study 6	SPT	7827	281.32	7774	300.69	7646	380.01	7652	453.93
	PT2	7787	285.84	7759	317.37	7732	379.96	7897	467.36
	%CW	7821	281.62	7773	310.01	9137	406.74	8615	493.50
	CW1	7835	285.73	7760	302.32	8734	412.76	8045	475.21
	CW2	7817	283.27	7780	312.52	8546	437.50	8325	512.64
	CW5	7822	284.72	7780	305.56	9007	444.79	8164	490.00

Table V (Contd.): System performance in VBM manufacturing environment.

		Performance measure when number of pallets released to system							
		14		16		18		20	
		Makespan	MFT	Makespan	MFT	Makespan	MFT	Makespan	MFT
Case study 2	SPT	10537	746.69	10803	832.18	DL	DL	DL	DL
	PT2	9499	757.48	DL	DL	DL	DL	DL	DL
	%CW	10457	850.92	9288	910.90	10719	1044.54	DL	DL
	CW1	9668	813.52	DL	DL	DL	DL	DL	DL
	CW2	10287	815.46	10539	896.44	DL	DL	DL	DL
	CW5	11373	899.69	11408	913.21	DL	DL	DL	DL
Case study 3	SPT	8310	754.10	7837	899.12	DL	DL	DL	DL
	PT2	8407	741.42	DL	DL	DL	DL	DL	DL
	%CW	7984	769.59	DL	DL	DL	DL	DL	DL
	CW1	7966	812.42	7629	903.17	DL	DL	DL	DL
	CW2	8615	858.86	DL	DL	DL	DL	DL	DL
	CW5	8666	820.68	7653	876.71	DL	DL	DL	DL
Case study 4	SPT	14638	1060.95	14800	1200.82	DL	DL	DL	DL
	PT2	14660	1109.53	14458	1186.19	13340	1233.75	DL	DL
	%CW	13836	1036.5	12974	1181.69	13553	1306.67	DL	DL
	CW1	14821	1152.94	13191	1200.25	13568	1325.66	DL	DL
	CW2	DL	DL	14294	1279.55	13670	1361.94	DL	DL
	CW5	13928	1119.94	15328	1319.28	14729	1430.73	DL	DL
Case study 5	SPT	9217	680.23	9007	783.50	9227	952.08	9137	1012.97
	PT2	9394	677.09	DL	DL	9275	865.39	DL	DL
	%CW	9598	701.45	DL	DL	DL	DL	DL	DL
	CW1	9180	670.60	9085	800.78	DL	DL	DL	DL
	CW2	9957	704.63	DL	DL	DL	DL	DL	DL
	CW5	9419	722.32	DL	DL	DL	DL	DL	DL
Case study 6	SPT	7456	501.64	7643	545.05	7609	672.01	DL	DL
	PT2	7642	508.38	7392	583.33	7564	683.14	DL	DL
	%CW	8291	546.83	7647	690.59	7565	779.10	DL	DL
	CW1	7951	578.56	7729	612.23	7358	716.47	7513	820.77
	CW2	8118	603.98	7808	682.54	DL	DL	DL	DL
	CW5	8197	564.32	7582	697.02	7847	776.99	DL	DL

Legend: MFT - Mean Flow Time DL - Deadlock State of System

Table VI: System performance in VLM manufacturing environment.

		Performance measure when number of pallets released to system							
		6		8		10		12	
		Makespan	MFT	Makespan	MFT	Makespan	MFT	Makespan	MFT
Case study 8	SPT	1770	87.35	1759	119.33	1754	151.02	1754	169.68
	PT2	1767	86.91	1758	128.79	1755	152.92	1754	175.11
	%CW	1767	88.73	1760	120.12	1756	150.72	1755	170.52
	CW1	1764	87.43	1763	122.73	1752	151.63	1754	173.61
	CW2	1770	88.64	1758	121.14	1751	152.71	1756	172.21
	CW5	1772	87.77	1762	126.52	1754	152.72	1754	173.42
Case study 9	SPT	1963	86.00	1843	113.33	1823	145.24	1820	158.57
	PT2	1986	88.83	1857	114.16	1823	145.22	1824	159.94
	%CW	1970	86.72	1845	113.73	1824	146.01	1824	158.12
	CW1	1965	87.67	1855	115.21	1821	144.89	1822	159.72
	CW2	1972	88.14	1852	112.79	1822	145.72	1822	158.02
	CW5	1984	86.72	1850	115.12	1824	145.12	1824	159.23
Case study 10	SPT	2428	114.04	2424	160.11	2440	183.32	2419	216.04
	PT2	2437	115.31	2440	152.63	2449	169.57	2420	213.49
	%CW	2429	114.14	2426	160.00	2455	169.58	2418	217.73
	CW1	2430	115.12	2440	155.32	2460	169.12	2422	210.96
	CW2	2436	114.42	2432	158.71	2433	182.22	2420	216.79
	CW5	2433	114.63	2430	153.32	2493	169.42	2417	214.55
Case study 11	SPT	1764	112.61	1762	135.72	1758	156.66	1734	196.44
	PT2	1758	114.84	1752	140.12	1748	161.27	1734	197.69
	%CW	1758	112.65	1753	140.03	1720	159.27	1723	201.01
	CW1	1764	113.42	1762	135.93	1721	167.29	1724	206.73
	CW2	1765	113.61	1761	138.72	1729	172.22	1737	191.41
	CW5	1754	114.32	1758	139.52	1723	173.01	1726	188.26
Case study 12	SPT	2036	99.54	2025	122.32	2030	147.14	2019	161.67
	PT2	2031	100.31	2026	130.67	2026	156.71	2017	175.71
	%CW	2032	100.11	2025	123.12	2026	155.52	2019	161.23
	CW1	2031	99.73	2026	129.52	2026	148.12	2017	162.32
	CW2	2031	99.44	2025	126.12	2030	149.17	2018	169.12
	CW5	2033	99.62	2025	127.32	2030	156.22	2018	173.73

Table VI (Contd.): System performance in VLM manufacturing environment.

		Performance measure when number of pallets released to system							
		14		16		18		20	
		Makespan	MFT	Makespan	MFT	Makespan	MFT	Makespan	MFT
Case study 8	SPT	1753	185.33	1750	208.26	1747	208.06	1747	257.09
	PT2	1751	198.12	1750	216.96	1747	238.69	1752	258.94
	%CW	1754	187.12	1752	215.62	1747	283.89	1745	316.19
	CW1	1754	196.23	1751	210.63	1747	281.62	1745	276.82
	CW2	1758	188.67	1750	212.12	1747	279.72	1745	316.19
	CW5	1754	192.42	1750	214.62	1747	262.42	1745	316.19
Case study 9	SPT	1821	188.86	1820	215.16	1820	244.12	1817	264.38
	PT2	1821	184.83	1817	212.89	1817	237.66	1820	258.76
	%CW	1821	212.66	1815	251.44	1817	289.27	1820	308.66
	CW1	1821	208.42	1817	250.83	1816	259.49	1819	278.46
	CW2	1821	212.66	1820	249.78	1817	289.27	1820	308.66
	CW5	1825	213.03	1817	249.54	1817	288.93	1820	309.08
Case study 10	SPT	2417	259.09	2420	272.83	2417	305.78	2417	333.06
	PT2	2420	244.74	2420	278.27	2420	305.28	2417	332.24
	%CW	2418	282.13	2417	308.32	2420	334.65	2420	383.07
	CW1	2420	246.02	2420	271.84	2420	296.67	2420	306.07
	CW2	2413	284.76	2413	317.65	2415	345.09	2416	381.09
	CW5	2417	274.19	2420	306.83	2420	337.14	2417	375.03
Case study 11	SPT	1742	206.41	1754	218.97	1732	231.72	1732	245.67
	PT2	1740	208.41	1745	220.71	1740	235.54	1732	248.67
	%CW	1740	208.13	1754	219.93	1735	235.13	1732	246.12
	CW1	1743	206.73	1752	220.13	1738	233.72	1733	247.32
	CW2	1739	207.13	1746	218.99	1732	234.54	1732	245.73
	CW5	1742	206.84	1749	219.14	1739	233.16	1733	248.12
Case study 12	SPT	2018	182.67	2015	215.67	2024	225.32	2021	268.67
	PT2	2019	195.25	2010	231.42	2026	241.27	2023	280.54
	%CW	2018	183.52	2015	216.32	2024	227.42	2021	267.67
	CW1	2018	186.13	2016	230.12	2024	230.61	2021	280.12
	CW2	2019	187.63	2017	229.42	2025	240.41	2023	275.42
	CW5	2017	186.63	2017	225.61	2024	235.42	2023	276.12

Legend: MFT - Mean Flow Time

A close observation of the system state at deadlock reveals that deadlock is reached due to non-availability of buffer space in the input buffer of next destination machine of the selected part i.e. deadlock occurs due to circular wait condition. It is important to mention that for the taken case studies in VLM (Table VI), system does not reach to deadlock state. This may be attributed to the fact that in VLM, operation times are comparable to transportation times. So by the time, R-2 transports a part to the input buffer of a machine, the machine completes the processing of under processed part. Since the input buffer capacity of the machine is three, it is very likely that there is always a vacancy in the input buffer of the machine. Thus, the parts available at B-IN and output buffer of each machine can be allocated to the next destination machine easily.

Table V also shows that for case study 2 in VBM, for PT2 and CW1rules at *np* = 16, 18 and 20, system reaches to deadlock state and other values of *np* viz., 6, 8, 10, 12, 14 do not give rise to deadlock state of PT2 rule. Similarly, for SPT, CW2 and CW5 rules, system reaches to deadlock state for *np* = 18 and *np* = 20 and other values of *np* do not give rise to deadlock state of system i.e. for a given production order and dispatching rule, deadlock state of system can be avoided by changing the *np*. This observation is also seen for other case studies in VBM (Table V and Fig. 3). This phenomenon may be attributed to the fact that as *np* is increased from six to twenty in steps of two, shop load increases. The increase in shop load reduces the possibility of availability of buffer space in the input buffer of a machine. Thus, it may happen that the parts at B-IN and output buffer of each machine can not be allocated to their next destination machine according to the available flexible process plans as the input buffer of the next destination machine is full to its capacity. Thus, it can safely be concluded that for a given production order and DR, deadlock state of system can be avoided by changing the *np*.

Table V and Fig. 3 reveal that irrespective of DR used, no deadlock is observed for taken case studies in VBM when number of pallets released to the system is less than fourteen. This may be attributed to the fact that when number of pallets released to the system is less than fourteen, shop congestion is less and it is very likely that there is always a vacancy in the input buffer of the machine. Therefore, the parts at B-IN and output buffer of each machine can be allocated to their next destination machine according to their flexible process plans easily. Thus, it can safely be concluded that for a given production order, irrespective of DR, system does not reach to the deadlock state when number of pallets released to the system is less than fourteen.

This study also reveals some interesting aspects of system performance as measured by makespan and mean flow time. Table VII shows the impact of dispatching rule on makespan with minimum and maximum variations are shown in bold for VBM and VLM respectively. The impact of DR on makespan is computed as given below:

$$\%\text{ change in the makespan due to DR} = \frac{\mathrm{Ma}_2 \sim \mathrm{Ma}_1}{\mathrm{Ma}_1} \times 100 \qquad (1)$$

where Ma_1 = Minimum makespan that occurs for a DR
Ma_2 = Maximum makespan that occurs for another DR
~ = Difference

Table VII: Effect of dispatching rule on makespan.

Manufacturing environment	Case Study No.	%age change in makespan when number of pallets released is							
		6	8	10	12	14	16	18	20
VBM	1	4.65	8.93	8.58	21.00	8.01	7.32	8.64	*
	2	2.07	5.31	31.31	**39.54**	19.72	22.83	**	*
	3	10.12	3.20	31.80	19.28	8.79	2.73	*	*
	4	6.79	4.24	29.20	29.08	7.12	18.14	10.41	*
	5	1.25	5.45	5.46	10.90	8.46	0.87	0.52	**
	6	0.62	**0.27**	19.50	12.58	11.20	5.63	6.65	**
VLM	7	1.37	0.19	2.81	2.61	0.78	0.68	0.63	**0.10**
	8	0.45	0.28	0.29	0.11	0.40	0.11	0.00	0.40
	9	1.17	0.76	0.17	0.22	0.22	0.28	0.22	0.17
	10	0.37	0.67	**2.47**	0.21	0.29	0.29	0.21	0.17
	11	0.63	0.57	2.21	0.81	0.23	0.52	0.46	0.06
	12	0.25	0.05	0.20	0.15	0.05	0.25	**0.10**	**0.10**

Legend: * - Effect can not be computed as all DRs give deadlock state.
** - Effect cannot be computed as all DRs except one give deadlock state.

Table VIII shows the effect of *np* on makespan with minimum and maximum changes are shown in bold for each manufacturing environment. The effect of *np* on makespan is computed as given below:

$$\%\text{ change in the makespan due to np} = \frac{Ma_4 \sim Ma_3}{Ma_3} \times 100 \qquad (2)$$

where Ma_3 = Minimum makespan that occurs at one *np*
Ma_4 = Maximum makespan that occurs at another *np*

Fig. 3 clearly reveals that in VBM, for a given *np*, makespan is different for various DRs. This observation is also seen for other case studies in VBM and VLM (Fig. 5 and Tables V, VI). Table VII clearly reveals that variation in makespan due to DR is in the range of 0.275 % to 39.54 % for VBM and 0.10 % to 2.47 % for VLM respectively. This is due to the fact that different parameters are used by various DRs for part selection. Thus, it can safely be concluded that for a given production order and *np*, makespan is dependent on DR used.

Table VIII: Effect of number of pallets released to system on makespan.

Manufacturing environment	Case Study No.	%age change in makespan when dispatching rule is					
		SPT	PT2	%CW	CW1	CW2	CW5
VBM	1	35.97	**47.03**	41.95	41.53	39.41	34.87
	2	5.93	20.29	33.77	17.15	15.47	24.47
	3	12.25	11.67	30.47	9.50	26.14	32.16
	4	21.45	42.31	39.49	37.35	38.81	29.53
	5	32.67	32.91	30.06	30.71	25.88	29.81
	6	**4.97**	6.83	20.78	18.70	9.85	18.79
VLM	7	11.31	10.00	10.24	11.17	**11.51**	11.25
	8	1.32	1.15	1.26	1.09	1.49	1.55
	9	8.04	9.30	8.54	8.20	8.53	9.19
	10	0.95	1.32	1.57	1.65	0.83	3.14
	11	1.85	1.50	2.21	2.50	2.08	2.03
	12	1.04	1.04	0.84	0.74	**0.69**	0.79

Fig. 3 also reveals that in VBM, for a given DR, makespan varies as *np* is varied from six to twenty in steps of two. This observation is also seen for other case studies in VBM and VLM (Fig. 5 and Tables V, VI). Table VIII reveals that variation in makespan due to *np* is in the range of 4.97 % to 47.03 % for VBM and 0.69 % to 11.51 % for VLM respectively. This phenomenon may be attributed to the fact that as the number of pallets released to the system is increased, shop load increases. Thus, it can safely be concluded that for a given production order and dispatching rule, makespan is dependent on *np*.

Figs. 4 and 6 clearly show that as *np* is increased from six to twenty in steps of two, irrespective of dispatching rule, mean flow time (MFT) increases in VBM as well as in VLM. This observation is also seen for other case studies in VBM and VLM environment (Tables V, VI). This phenomenon may be attributed to the fact that as *np* is increased in the taken range, shop load increases. Thus, it can safely be concluded that in the considered manufacturing environments, as *np* is increased in the taken range, MFT increases gradually and minimum MFT in each environment is achieved by releasing six pallets to the system.

5. CONCLUSIONS

This paper investigates the performance of an example FMS in VBM and VLM environments in the presence of FPPs from deadlock, makespan and mean flow time viewpoints. The following conclusions are drawn from the simulation results for the taken case studies.

- **(i)** Deadlock state of system can be avoided either by changing the dispatching rule or number of pallets released to the system.
- **(ii)** The system will not reach to deadlock state, irrespective of dispatching rule, when number of pallets released to the system is less than fourteen.
- **(iii)** For a given production order, makespan is dependent on number of pallets released to the system. Variation in makespan is in the range of 4.97 % to 47.03 % in VBM and 0.69 % to 11.51 % in VLM respectively.
- **(iv)** Choice of dispatching rules is important in FMS and affects the system performance. The variation in makespan is in the range of 0.27 % to 39.54 % in VBM and 0.10 % to 2.47 % in VLM respectively. This conclusion is in line with previous study [25, 31].
- **(v)** In each manufacturing environment (i.e. VBM and VLM), as the number of pallets released to the system is increased from six to twenty in steps to two, mean flow time

increases gradually. Thus, six numbers of pallets should be released (minimum number considered in the present study) in order to have minimum flow time.

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