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Interactive Decisions of Part Selection, Machine Loading, Machining Optimisation and Part Scheduling Sub-problems for Flexible Manufacturing Systems

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ABSTRACT

More often, the decisions of part selection, machine loading, machining optimisation and part scheduling sub-problems are made at different decision-making levels. As a result, part selection, machine loading and machining optimisation decisions at higher-production planning level may fail to interact with part scheduling decisions at lower-scheduling level. This paper presents a two-stage sequential methodology aimed at integrating the decisions of part selection, machine loading, machining optimisation and part scheduling sub-problems for flexible manufacturing systems (FMSs) and avoiding disparities of decisions which can be difficult to implement on the FMS shop floor. In this case, two mathematical models were presented and solved. Results from the models show that more interactive decisions and well-balanced workload of the FMS can be achieved when part selection, machine loading, machining optimisation and part scheduling sub-problems are solved jointly.

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1 Introduction

Flexible manufacturing systems (FMSs) are highly automated manufacturing systems that basically consist of computer-numerically controlled (CNC) machine tools, interconnected by automated material handling and storage systems all interfaced via a central computer. FMSs are associated with more complex decision making processes. Stecke (1985) identified four stages of FMS decision-making cycle as design, production planning, scheduling, and control. However, the decisions of production planning and scheduling problems are often made at two different levels achieving absolutely different objectives. While the production planning problems at higher level may be throughput or cost objective, scheduling problems at lower level are more concerned with time. Jang *et al.* (1996) pointed out that the optimal solution of higher-level production planning problems may not be feasible in the lower-level scheduling problems.

Because of the complexity of FMS planning problems, Stecke (1985) divided them into five sub-problems of part type selection, machine grouping, machine loading, production ratio, and resource allocation. Among these planning problems, Hwang (1986) found that part type selection and machine loading are the most important planning problems in the FMS. As such, these two problems have attracted many researchers. Stecke and Kim (1988), and Srivastava and Chen (1993) addressed part selection problems for the purpose of selecting a subset of part types for immediate processing in the FMS. Shanker and Srinivasulu (1989), Kim and Yano (1994), and Jang *et al*. (2005) accounted for machine loading problems concerning with the allocation of part operations and required tools amongst machine groups for a given product mix. Due to same production resource constraints such as available machine time and tool magazine capacity in the FMS, and in order to avoid possible conflicts between two sets of individually obtained solutions, some researchers have tried to solve the combined part selection and machine loading problems (Liang, 1994, Nayak and Acharya (1998), Yang and Wu, 2002, and Choudhary *et al*., 2006).

Scheduling of parts on machines in FMSs is a more complex task than in job shops and flow-line shops. Adams *et al*. (1988) approached the minimum makespan problem of job scheduling using a shifting bottleneck heuristic. Tung *et al*. (1999) employed a hierarchical approach to solve a scheduling problem of the FMS in two stages. Chen and Chen (2003) applied an adaptive scheduling approach to make coupled decisions about part/machine

scheduling and operation/tool assignments on a rolling horizon basis. Khayat *et al*. (2006) formulated an integrated production and material handling scheduling problem as mathematical programming and constraint programming models and solved the problems using ILOG OPL Studio commercial software.

As can be observed in the literature, studies on part scheduling problems at the lower scheduling stage (e.g. Tung *et al*., 1999, Chen and Chen, 2003, and Khayat *et al*., 2006) were addressed with isolation from part selection and machine loading problems at the higher production planning stage. On the other hand, most of the studies on part selection and machine loading problems (e.g. Liang, 1994, Nayak and Acharya, 1998, Yang and Wu, 2002, and Choudhary *et al*., 2006) were addresses without consideration of part scheduling decisions. Moreover, studies on part selection and machine loading problems tend to specify the values of machining parameters well in advance ignoring the analysis of machining parameters. These decision deficiencies from previous researchers may lead to conflicting situations where the optimal solution of part selection, machine loading and machining optimisation problems at higher-level production planning may contradict with the optimal solution of part scheduling problems at the lower level. It is therefore the purpose of this paper to achieve more effective and interactive decisions of part selection, machine loading, machining optimisation and part scheduling sub-problems. This is possible due to the fact that production planning and scheduling problems have common entities such as part processing time which can act as a linkage between the higher production planning stage and lower part scheduling stage.

2 Mathematical Models for Interactive Decisions of FMSs

The decisions of part scheduling problems at the FMS scheduling stage are often not linked to the decisions of part selection, machine loading and machining optimization problems at the FMS production planning stage. This might cause decision gaps leading to ineffective utilization of FMSs. In order to achieve more effective and interactive decisions of part selection, machine loading, machining optimisation and part scheduling problems in FMSs, two mathematical models are presented and solved in two stages as illustrated in Figure 1.

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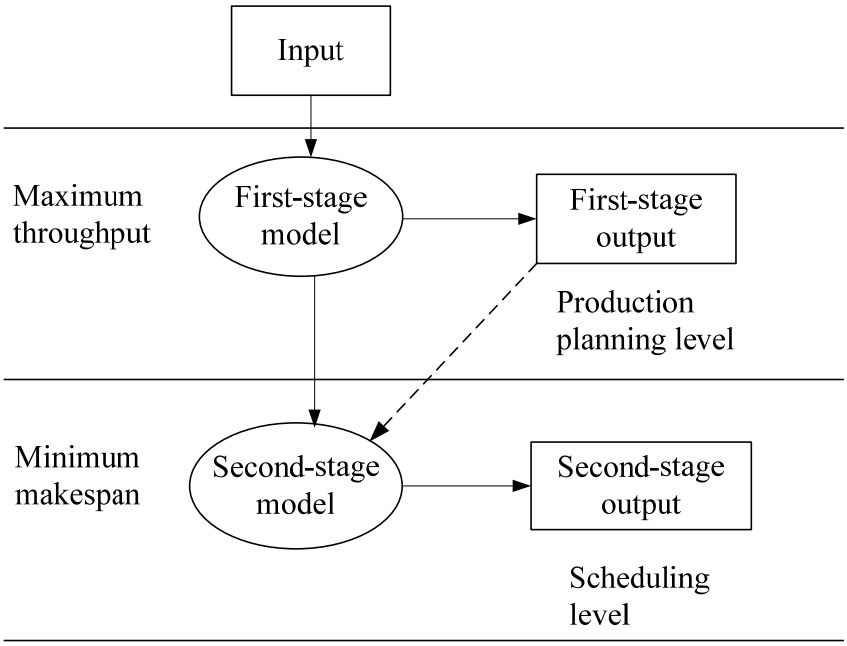


Figure 1: Interactive production planning and scheduling of FMS

In formulating the two mathematical models, the following notations of indices, decision variables, and parameters are used:

(1) Indices

i,q = 0, 1,..., n for scheduling sets of operations, 0 = start operation and n = finish operation

j = 1, …, J for part type

o = 1, …, O for operation

t = 1, …, T for tool type

k = 1, …, K for machine

(2) Decision variables

x_{jotk} = 1, if operation o of part j is processed using tool t on machine k

x_j = 1, if part type j is selected, 0 otherwise

y_{tk} = 1, if tool type t is assigned to machine k, 0 otherwise

v_{jotk} = cutting speed for combination j,o, t, k (m/min)

f_{jotk} = feed rate for combination j,o, t, k (mm/rev or mm/tooth)

$p_{i,q}$ = the processing time of operations i,q for part scheduling in the second stage (min)

p_{jk} = processing time of part j on machine k in the first stage (min)

$t_{i,q}$ = the start time of operations i,q (min)

t_n = makespan (min)

(3) Parameters

α_{jt} = tool life constant of the cutting speed for tool *t* on part *j*

β_{jt} = tool life constant of the feed rate for tool *t* on part *j*

γ_{jt} = tool life constant of the depth of cut for tool *t* on part *j*

δ_{jt} = tool life constant of the width of cut in milling operations for tool *t* on part *j*

ω_{jt} = tool life constant of the tool diameter in milling operations for tool *t* on part *j*

λ_{jt} = tool life constant of the number of tool teeth in milling operations for tool *t* on part *j*

A_k = available processing time at machine *k* (min)

a_{jot} = depth of cut (mm) for operation *o* on part *j* using tool *t*

B = available tooling budget ($)

C_t = cost per edge ($) of tool *t*

D_{jo} = tool diameter (mm) for operation *o* on part *j*

E_{jt} = tool life constant for tool *t* on part *j*

F^L_{jotk} = lower feed rate limit for combination *j*,*o*, *t*, *k* (mm/rev or mm/tooth)

F^U_{jotk} = upper feed rate limit for combination *j*,*o*, *t*, *k* (mm/rev or mm/tooth)

G_k = number of slots on the tool magazine of the machine *k*

T_{jt} = Tool life for part *j* and tool *t* combination

K_i = the machine on which operation *i* is to be processed

L_{jo} = length of cut for operation *o* on part *j* (mm)

M_{jot}, N_{jot} = machining constants for operation *o* on part *j* using tool *t*

Q_j = production quantity of part type *j*

R_t = replacement time for tool *t* (min)

S_t = number of slots required by tool type *t*

V^L_{jotk} = lower cutting speed limit for combination *j*,*o*, *t*, *k* (m/min)

V^U_{jotk} = upper cutting speed limit for combination *j*,*o*, *t*, *k* (m/min)

W_j = width of cut on part *j* (mm)

Z_t = number of teeth of the tool *t*

2.1 Maximum Throughput Model in the First Stage

In the first stage, part selection, machine loading and machining optimisation problems are jointly solved to maximise the throughput of the FMS. The model presented by Mgwatu *et al*. (2009) was modified in order to determine the maximum throughput of the FMS and to

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provide a linkage to the part scheduling model in the second stage. The modified model is formulated as follows:

Maximise $\sum_{j=1}^{J} Q_j u_j x_j$ (1)

Subject to:

$\sum_{t=1}^{T}\sum_{k=1}^{K} x_{jotk} = x_j, \forall(j, o)$ (2)

$\sum_{j=1}^{J}\sum_{o=1}^{O_j}\sum_{t=1}^{T} x_{jotk} \geq 1, \forall k$ (3)

$\sum_{o=1}^{O_j}\sum_{t=1}^{T} x_{jotk} \leq 1, \forall(j, k)$ (4)

$\sum_{j=1}^{J}\sum_{o=1}^{O_j} x_{jotk} \leq y_{tk}, \forall(t, k)$ (5)

$\sum_{t=1}^{T} S_t y_{tk} \leq G_k, \forall k$ (6)

$\sum_{j=1}^{J}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\left(N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} + M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t\right) Q_j x_{jotk} \leq A_k, \forall k$ (7)

$\sum_{j=1}^{J}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\sum_{k=1}^{K} M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} C_t Q_j S_t y_{tk} \leq B$ (8)

$\sum_{o=1}^{O_j}\sum_{t=1}^{T}\left(N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} + M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t\right) Q_j x_{jotk} = p_{jk} \forall(j, k)$ (9)

$V_{jotk}^{L} \leq v_{jotk} \leq V_{jotk}^{U}, \forall(j, o, t, k)$ (10)

$F_{jotk}^{L} \leq f_{jotk} \leq F_{jotk}^{U}, \forall(j, o, t, k)$ (11)

$x_{jotk} = 0$ or 1, $\forall(j, o, t, k)$ (12)

$x_j = 0$ or 1, $\forall j$ (13)

$y_{tk} = 0$ or 1, $\forall(t, k)$ (14)

The objective function (1) maximises the FMS throughput where the level of importance of part types can be in terms of dollar or due-date value coefficients. Constraint (2) states that the total proportion of a part processed at all alternative machines using all feasible tools should

be the same for all operations, either 0 or 1. To avoid starvation of machines and ensure that all machines are utilized in the shop floor, Constraint (3) binds every machine to perform at least one operation on a part. Constraint (4) disallows the recirculation of parts on machines in order to maintain the inherit flexibility of the system. Constraint (5) ensures that if a part is allocated to a machine, the required tool should be assigned to that machine. The capacity of tool magazine is restricted by constraint (6). Constraint (7) forces the total processing time at each machine not to exceed the available machine time on the shop floor. Constraint (8) assures that the total tooling cost is not beyond the available tooling budget. Constraint (9) specifies the processing time of each part at different machines. Constraints (10) and (11) give the lower and upper bounds for cutting speed and feed rate respectively. Constraints (12) through (14) represent binary restrictions on the decision variables.

Where: C_t is the cost per edge ($) and R_t is the time required for each tool replacement (min).

$$N_{jot} = \frac{\pi D_{jot} L_{jo}}{1000}, \text{ for drilling and tapping/reaming operations, and} \quad (15)$$

$$N_{jot} = \frac{\pi D_{jot} L_{jo}}{1000 Z_t} \text{ for milling operations.} \quad (16)$$

v_{jotk} is the cutting speed (m/min), f_{jotk} is the feed rate (mm/rev or mm/tooth), D_{jot} is the tool diameter (mm), L_{jo} is the length of cut (mm), and Z_t is the number of teeth. M_{jot} is a machining constant which is defined by Wang and Liang (2005) as:

$$M_{jot} = \frac{\pi D_{jot}^{1-\omega_{jt}} L_{jo}}{1000 E_{jt}} \text{ for drilling operations} \quad (17)$$

and,

$$M_{jot} = \frac{\pi D_{jot}^{1-\omega_{jt}} L_{jo} a_{jot}^{\gamma_{jt}}}{1000 E_{jt}} \text{ for reaming/tapping operations} \quad (18)$$

The machining constant for milling operations defined by Shnumugam *et al*. (2002) and Wang and Liang (2005) is:

$$M_{jot} = \frac{\pi D_{jot}^{1-\omega_{jt}} L_{jo} a_{jot}^{\gamma_{jt}} W_j^{\delta_{jt}} Z_t^{\lambda_{jt}-1}}{1000 E_{jt}} \quad (19)$$

E_{jt} is tool life constant, ω_{jt} is the tool life constant of the tool diameter, δ_{jt} is the tool life constant

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of the width of cut, and λ_{jt} is the tool life constant of the number of tool teeth in milling operations.

2.2 Minimum Makespan Model in the Second Stage

Based on the decisions of the first stage including the processing times of selected parts, the minimum makespan can be determined. The following constraint-based scheduling programming model is used to determine the minimum makespan (Adam *et al*., 1988):

Minimise t_n (20)

Subject to:

$$t_q - t_i \geq p_i, \forall (i, q) \in O_{iq} \quad (21)$$

$$\left(t_q - t_i \geq p_i\right) \vee \left(t_i - t_q \geq p_q\right), \forall (i, q) \in O_k, k \in K \quad (22)$$

$$t_i \geq 0, \quad \forall i \in O_j \quad (23)$$

The objective function (20) minimises the maximum completion time of the last operation of every part and hence the completion times of all operations i.e., the makespan. Constraint (21) gives a set of precedence (conjunctive) relations between two operations *i* and *q* and states that there is a precedence arc (*i*, *q*) at which operation *i* is the immediate predecessor of operation *q*. Constraint (22) is a set of disjunctive relations expressing the fact that operations *i* and *q* have non-overlapping durations such that each machine can only execute a single operation at a given time. Any feasible solution to Constraint (22) is called a schedule. Finally, Constraint (23) is the non-negativity condition for the start time variables. It should be noted that the solution of part processing time p_{jk} in Constraint (9) of the first-stage model becomes the input $p_{i,q}$ to Constraints (21) and (22) thus providing a major linkage between the first-stage and second-stage decisions.

3 Numerical Input Data

The numerical data which are used to test the formulated models are defined as follows (Mgwatu *et al*., 2009). The number of CNC machining centres in the FMS is four, each with a tool magazine capacity of G_k=10 tool slots. 20 types of tools are available and the number of slots S_t needed by each tool set is given. The tool replacement time is approximately R_t=1 min. The tool-operation and tool-machine compatibilities are pre-specified. There are 10 part types

waiting for immediate and simultaneous processing in the FMS. The production quantities of the ten types of parts are Q_j=450, 900, 480, 1300, 2000, 700, 1500, 2500, 1000 and 850 respectively. Part types have equal value coefficient u_j=1. The maximum tooling budget is B=$25,000 and available machine time is A_k=7200 min. Tool and empirical data are presented in Table 1. Part and machining data are given in Table 2. Limits of cutting speeds and feed rates are listed in Table 3 and Table 4 respectively. Tool life constants were taken from Shnumugam *et al*. (2002) and Wang and Liang (2005) while the tool costs per edge were obtained from McMaster-Carr Supply Company (2008). The limits of cutting speeds and feed rates were found in Chapman (2002).

Table 1: Tool and empirical data

Part Type	Operation No.	Tool Type	C_t ($)	S_t	α_{jt}	β_{jt}	D_{jot} (mm)	Z_t	γ_{jt}	δ_{jt}	ω_{jt}	λ_{jt}	E_{jt}
1	1	1	315	3	3.12	1.09	75	5	0.47	0.62	0.62	0	1.62E+08
		2	325	3	3.12	1.09	90	5	0.47	0.62	0.62	0	1.62E+08
	2	3	210	1	3.12	1.09	30	4	0.47	0.62	0.62	0	1.62E+08
		4	220	1	3.12	1.09	40	4	0.47	0.62	0.62	0	1.62E+08
	3	5	60	2	2.50	1.25	26	2			1.25		11640
2	1	6	40	2	3.03	1.51	25	4	1.51	0.3	1.36	0.3	148880
		7	80	2	3.03	1.51	30	6	1.51	0.3	1.36	0.3	148880
	2	8	25	4	3.03	1.51	16	4	1.51	0.3	1.36	0.3	148880
		9	35	4	3.03	1.51	20	4	1.51	0.3	1.36	0.3	148880
	3	10	20	1	3.03	1.51	12	2	1.51	0.3	1.36	0.3	148880
3	1	1	315	3	3.12	1.09	75	5	0.47	0.62	0.62	0	1.62E+08
		2	325	3	3.12	1.09	90	5	0.47	0.62	0.62	0	1.62E+08
	2	11	25	1	2.50	1.25	10.2	2			1.25		11640
	3	12	30	1	3.33	1.67	12		0.33		0.67		7774
4	1	6	40	2	3.03	1.51	25	4	1.51	0.3	1.36	0.3	148880
		7	80	2	3.03	1.51	30	6	1.51	0.3	1.36	0.3	148880
	2	13	15	2	3.03	1.51	10	2	1.51	0.3	1.36	0.3	148880
5	1	14	90	1	2.50	1.25	38	2			1.25		11640
	2	15	140	1	3.33	1.67	39		0.33		0.67		7774
6	1	1	315	3	3.12	1.09	75	5	0.47	0.62	0.62	0	1.62E+08
		2	325	3	3.12	1.09	90	5	0.47	0.62	0.62	0	1.62E+08
	2	5	60	2	2.50	1.25	26	2			1.25		11640
	3	16	75	1	3.33	1.67	27		0.33		0.67		7774
7	1	8	25	4	3.03	1.51	16	4	1.51	0.3	1.36	0.3	148880
		9	35	4	3.03	1.51	20	4	1.51	0.3	1.36	0.3	148880
	2	13	15	2	3.03	1.51	10	2	1.51	0.3	1.36	0.3	148880
8	1	17	85	1	2.50	1.25	36	2			1.25		11640
	2	18	160	1	3.33	1.67	39		0.33		0.67		7774
9	1	6	40	2	3.03	1.51	25	4	1.51	0.3	1.36	0.3	148880
		7	80	2	3.03	1.51	30	6	1.51	0.3	1.36	0.3	148880
	2	8	25	4	3.03	1.51	16	4	1.51	0.3	1.36	0.3	148880
		9	35	4	3.03	1.51	20	4	1.51	0.3	1.36	0.3	148880
10	1	19	235	1	3.12	1.09	50	4	0.47	0.62	0.62	0	1.62E+08
		20	245	1	3.12	1.09	60	4	0.47	0.62	0.62	0	1.62E+08
	2	5	60	2	2.50	1.25	26	2			1.25		11640

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Table 2: Part and machining data

Part	Operation	Tool	W_i (mm)	L_{io} (mm)	a_{jot} (mm)	N_{jot}	M_{jot}
1	1	1	68	540	5	25.45	3.15E-07
		2	68	540	5	30.54	3.37E-07
	2	3	26	180	8	4.24	6.36E-08
		4	26	180	8	5.65	7.10E-08
	3	5		32		2.61	3.82E-06
2	1	6	20	600	10	11.78	1.20E-04
		7	20	600	10	9.42	8.44E-05
	2	8	12	105	10	1.32	2.11E-05
		9	12	105	10	1.65	1.95E-05
	3	10	12	80	5	1.51	1.02E-05
3	1	1	68	630	4	29.69	3.31E-07
		2	68	630	4	35.63	3.54E-07
	2	11		45		1.44	6.80E-06
	3	12		45	0.9	1.70	3.99E-05
4	1	6	20	500	8	9.82	7.12E-05
		7	20	500	8	7.85	5.02E-05
	2	13	10	210	6	3.30	3.55E-05
5	1	14		50		5.97	5.44E-06
	2	15		50	0.5	6.13	6.77E-05
6	1	1	68	280	2.5	13.19	1.18E-07
		2	68	280	2.5	15.83	1.26E-07
	2	5		80		6.53	9.56E-06
	3	16		80	0.5	6.79	6.94E-04
7	1	8	12	400	3	5.03	1.31E-05
		9	12	400	3	6.28	1.20E-05
	2	13	10	160	5	2.51	2.06E-05
8	1	17		40		4.52	4.41E-06
	2	18		40	0.75	4.90	4.92E-05
9	1	6	20	420	4	8.25	2.10E-05
		7	20	420	4	6.60	1.48E-05
	2	8	12	360	4	4.52	1.81E-05
		9	12	360	4	5.65	1.67E-05
10	1	19	42	340	3	13.35	1.24E-07
		20	42	340	3	16.02	1.33E-07
	2	5		50		4.08	5.98E-06

Table 3: Upper and lower limits of cutting speeds

Part	Operation	Tool	V^U_{jot1} (m/min)	V^U_{jot2} (m/min)	V^U_{jot3} (m/min)	V^U_{jot4} (m/min)	V^L_{jot1} (m/min)	V^L_{jot2} (m/min)	V^L_{jot3} (m/min)	V^L_{jot4} (m/min)
1	1	1	152			152	91			91
		2	152			152	91			91
	2	3		152	152			91	91	
		4		152	152			91	91	
	3	5		45	45			12	12	
2	1	6	30			30	9			9
		7	30			30	9			9
	2	8		30	30			9	9	
		9		30	30			9	9	
	3	10		30	30			9	9	
3	1	1	152			152	91			91
		2	152			152	91			91
	2	11		45	45			12	12	
	3	12		19	19			6	6	
4	1	6	30			30	9			9
		7	30			30	9			9
	2	13		30	30			9	9	
5	1	14	45			45	12			12
	2	15	15			15	8			8
6	1	1	152			152	91			91
		2	152			152	91			91
	2	5		45	45			12	12	
	3	16	15			15	8			8
7	1	8		30	30			9	9	
		9		30	30			9	9	
	2	13		30	30			9	9	
8	1	17		45	45			12	12	
	2	18	19			19	6			6
9	1	6	30			30	9			9
		7	30			30	9			9
	2	8		30	30			9	9	
		9		30	30			9	9	
10	1	19	152			152	91			91
		20	152			152	91			91
	2	5		45	45			12	12	

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Table 4: Upper and lower limits of feed rates

Part	Operation	Tool	F^U_{jot1}	F^U_{jot2}	F^U_{jot3}	F^U_{jot4}	F^L_{jot1}	F^L_{jot2}	F^L_{jot3}	F^L_{jot4}
1	1	1	0.3			0.3	0.075			0.075
		2	0.3			0.3	0.075			0.075
	2	3		0.3	0.3			0.075	0.075	
		4		0.3	0.3			0.075	0.075	
	3	5		0.5	0.5			0.23	0.23	
2	1	6	0.152			0.152	0.102			0.102
		7	0.152			0.152	0.102			0.102
	2	8		0.127	0.127			0.063	0.063	
		9		0.127	0.127			0.063	0.063	
	3	10		0.089	0.089			0.038	0.038	
3	1	1	0.3			0.3	0.075			0.075
		2	0.3			0.3	0.075			0.075
	2	11		0.3	0.3			0.13	0.13	
	3	12		0.5	0.5			0.15	0.15	
4	1	6	0.152			0.152	0.102			0.102
		7	0.152			0.152	0.102			0.102
	2	13		0.089	0.089			0.038	0.038	
5	1	14	0.5			0.5	0.23			0.23
	2	15	0.5			0.5	0.25			0.25
6	1	1	0.3			0.3	0.075			0.075
		2	0.3			0.3	0.075			0.075
	2	5		0.5	0.5			0.23	0.23	
	3	16	0.5			0.5	0.25			0.25
7	1	8		0.127	0.127			0.063	0.063	
		9		0.127	0.127			0.063	0.063	
	2	13		0.089	0.089			0.038	0.038	
8	1	17		0.5	0.5			0.23	0.23	
	2	18	0.5			0.5	0.15			0.15
9	1	6	0.152			0.152	0.102			0.102
		7	0.152			0.152	0.102			0.102
	2	8		0.127	0.127			0.063	0.063	
		9		0.127	0.127			0.063	0.063	
10	1	19	0.3			0.3	0.075			0.075
		20	0.3			0.3	0.075			0.075
	2	5		0.5	0.5			0.23	0.23	
Feed rates for milling operations in mm/tooth and other operations in mm/rev.										

4 Results and Discussions

The first-stage model was solved using LINGO nonlinear programming solver. As can be seen from Table 5, the decisions of part selection, machine loading (including tool assignment, operation allocation and part routes), machining optimisation (cutting speeds and feed rates) and part processing time are simultaneously made while the throughput is maximized. It is evident that the part routes and part processing times so obtained in the first stage are the major linkages for part scheduling decisions in the second stage. In attaining maximum throughput of the FMS, it is noted that not all parts could be selected for immediate processing on the machines and not all tools could be assigned to machines. This is because of the limited

production resources such as the available machine time, the capacity of tool magazine and the tooling budget.

The results presented in this work indicate significant improvement of throughput over some of the reported results of similar studies. The throughput of 10,330 obtained in this study is comparatively higher than the throughput of 1440 reported by Liang (1994) and the throughput of 36 reported by Choudhary *et al*. (2006) with nearly the same problem sizes. In this study, the workload of the FMS is also well balanced with the total processing time on machines M1=629+3690+2401+500=7200 min; M2=555+1620+2599+1884+542=7200 min; M3=192+753+2577+3678=7200 min; and M4=3210+534+339+1664+1453=7200 min as shown in Table 5. The results reported by Liang (1994) and Yang and Wu (2002) showed unbalanced workload in FMSs. The effect of unbalanced workload is that, some machines on the manufacturing shop floor become more occupied than others. Since CNC machine tools employed in the FMS are rather expensive, it is mostly important to balance the workload so that all machines can be effectively utilized. It can be concluded that the balanced workload is achievable with maximum throughput objective when machining optimization, part selection and machine loading problems are solved concurrently. In this case, machining parameters are likely to adjust themselves within their allowable limits.

Table 5: Part selection, machine loading and machining optimisation decisions

Part	Operation	Tool	Machine	Cutting speed	Feed rate	Process Time (min)	Part Routes	Maximum Throughput
3	1	2	1	91	0.300	629	M1-M3-M2	
	2	11	3	12	0.300	192		
	3	12	2	6	0.245	555		
4	1	6	4	26.4	0.152	3210	M4-M2	
	2	13	2	30	0.089	1620		
5	1	14	4	45	0.500	534	M4-M1	
	2	15	1	8	0.420	3670		
6	1	1	4	91	0.300	339	M4-M3-M1	
	2	5	3	12	0.500	753		
	3	16	1	8	0.250	2401		
7	1	8	2	22.9	0.127	2599	M2-M3	
	2	13	3	16.4	0.089	2577		
8	1	17	2	12	0.500	1884	M2-M4	
	2	18	4	15.1	0.500	1664		
9	1	7	4	30	0.152	1453	M4-M3	
	2	9	3	12.1	0.127	3678		
10	1	20	1	91	0.300	500	M1-M2	
	2	5	2	12.8	0.500	542		10330

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The second-stage model was solved using ILOG OPL Studio computer software. The decisions of production planning and scheduling are interacted by utilizing the decisions of part processing times and part routes which were made in the first stage while maintaining the maximum throughput objective. Table 6 summarizes the decisions of the start and completion times for all parts on different machines with the associated makespan and is well represented by Figure 2 as a Gantt chart. A notable problem on the scheduling decisions is that even when the workload in the FMS was well balanced, it was not guaranteed that the idle time will be fully eliminated. Either a machine may become idle for a certain period of time waiting for a part to process or a part may be waiting to be processed by a machine which is busy during that time.

Moreover, all production schedules in Figure 2 are active such that any left shift or jump of the operation on the same machine may not improve the makespan. Moving some parts in the left into idle slots of other machines to start them earlier would affect the decisions that were made in the first stage. However, in order to utilise the idle times in the FMS without affecting other decisions, a trade-off between system utilisation and manpower utilisation can be sought. The suggestions would be to deploy workers only when they are required to be engaged on machines from the time a part is started on the machine until it is finished, or to utilise the idle times by assigning workers to other functions such as maintenance activities in the FMS.

A study conducted by Nayak and Acharya (1998) reported the makespans of 10,238 min and 29,654 min for 10 operations leading to unbalanced workload in the FMS. This is compared to the makespan of 8047 min reported in this work for 2-3 operations resulting in balanced workload in the FMS. Using the approach adopted in this work, it is possible to take advantage of the minimum makespan and balanced workload in the FMS.

Table 6: Decisions of part starting and completion times (in min) on machines

Available Time (min)	Tooling Budget ($)	Part	Machine 1	Machine 2	Machine 3	Machine 4	Makespan (min)
7200	25000	3	0-629	4483-5038	1092-1284	-	
		4		5536-7156		2326-5536	
		5	3993-7663			1792-2326	
		6	1092-3493	-	339-1092	0-339	
		7		0-2599	5470-8047		
		8		2599-4483		5536-7200	
		9			1792-5470	339-1792	
		10	3493-3993	7156-7698			8047

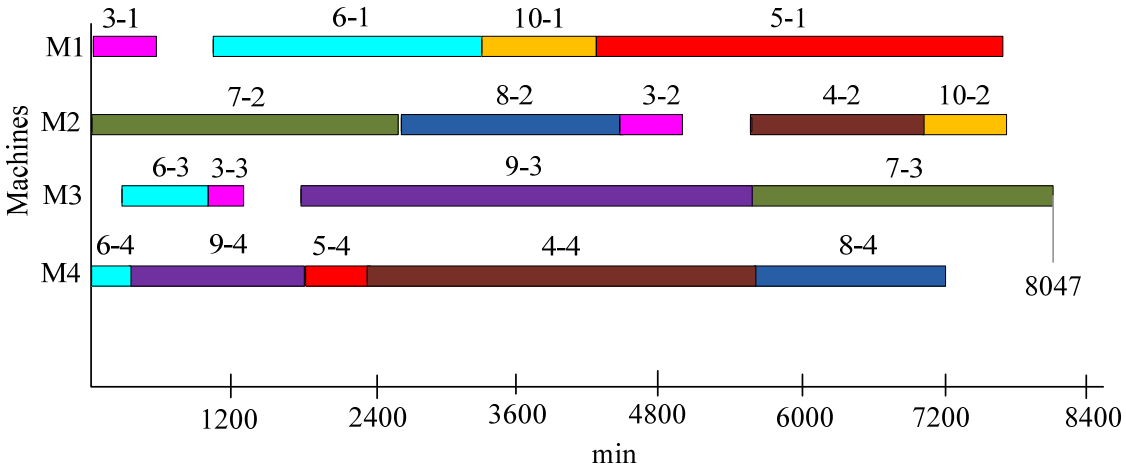


Figure 2: Part schedules on machines in the FMS

5 Conclusion

This study has achieved the purpose of integrating part selection, machine loading and machining optimisation decisions in higher-production planning level and part scheduling decisions in lower scheduling level. To achieve this purpose and make the decision problems to be more tractable, a two-stage sequential methodology was adopted. In the first stage, the combined part selection, machine loading and machining optimisation problem was solved for maximum throughput of the FMS. The second stage addressed the part scheduling problem to find the minimum makespan of the FMS for the selected parts. For interactive decisions, the main inputs for the scheduling problem were part-processing times and part routes that were obtained in the first stage. This approach allows holistic decisions which can easily be implemented on the FMS shop floor. Despite observing balanced workload in some cases, waiting time for parts and idling time for machines in the FMS could not be avoided. Such situations are inevitable especially in the presence of a variety of part types in the system each having different requirements.

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