A Model for Contingent Manpower Planning: Insights from a High Clock Speed Industry

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Abstract - Intense competitive pressures have led to compressed product life cycles and frequent introduction of new products. This creates demand volatility and a consequent pressure on manufacturing to meet this variable demand. In this paper we model the manpower planning issues for a computer manufacturer during the product introduction phase when a quick ramp-up of production to meet rapidly increasing demand is a key requirement. A mix of permanent and contingent workers with different skill sets is considered. Some important issues addressed in this research are (a) how to assign workers with different skills to maximize production (b) what is the induction rate of contingent workers to achieve the desired ramp-up and (c) what are the key decision factors that impact manufacturing performance An LP model is proposed to minimize overall costs subject to complex scheduling, skills, and learning rate requirements. Our analysis indicates that cost of induction of contingent workers, overtime cost premium, and the amount of overtime have significant impact on performance. The findings of the study will be useful to managers in planning and allocation of workers of different skills to various manufacturing processes and to determine the optimal number of contingent workers to induct.

Key words: Contingent workers, Demand Ramp-up, manpower planning

I. INTRODUCTION

As global competition intensifies, managers in high clock speed industries (computer, telecommunications equipment, software etc.) face a multitude of challenges on several fronts (Fine, 1998). An important strategy in the high clock speed environment is the frequent introduction of new and improved products. However, frequent product introduction leads to excessive demand volatility creating pressure on manufacturing to respond quickly to changing demand. The product introduction phase is especially crucial as the firm may lose significant lifetime market share if customers defect to competing brands due to non-availability of products (Kurawarwala and Matsuo, 1996). An imperative for the firm during the crucial product introduction phase is to balance two key requirements – ramp up capacity to satisfy rapid demand increases and ensure cost control through effective resource utilization.

In labour intensive contexts such as the computer assembly firm that is the focus of this study, a common way to respond to demand spikes is through the use of *contingent* labour which is more economical. The challenge for the manufacturing managers is to find the best allocation of permanent and contingent workers effectively under varying daily production targets. Several other factors such as overtime capacity, overtime premium, flexibility etc complicate this decision-making problem. A limited number of workers of each skill type are available to man each stage of manufacturing process. Given distinct worker skills, managers need to know the value of different cross training strategies e.g., limited versus complete cross training, impact of learning or the rate at which the contingent workers can learn to perform jobs to full potential.

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The objective of this paper is to present a model that helps managers address the key issue of how many contingent workers to induct into different process phases in order to satisfy demand, while accounting for the differential rate of learning for different processes. We describe a real life case study pertaining to a Singapore based computer manufacturer that served as the backdrop of this research and provided us with several intuitions.

II. LITERATURE REVIEW

Workforce planning and scheduling encompasses decisions over several distinct time horizons ranging from the long term (a year or more) to immediate (next shift). In this section literature on workforce planning, scheduling and allocation is highlighted.

Hax and Candea (1984) have discussed several alternative production planning options that managers can use to deal with changing demand patterns, including use of variable workforce, overtime, subcontracting, seasonal inventory, planned backlogs, or complementary product lines. The authors presented several classical LP models incorporating the production, manpower and inventory related tradeoffs in each of the options above. Silva et al., (2000) presented an aggregate production-planning model that considered a constant level of employment. Using explicit costs for overtime and inventory holding from a real life case study, the authors showed that the model when applied to a construction material firm in Portugal achieved cost savings of 8.1%.

Lagodimos and Leopoulos (2000) proposed a mixed integer programming based greedy heuristic for the manpower shift-planning problem. The objective of this problem was to determine the minimum number of contingent workers needed to work in each available shift to meet pre-specified production targets. The heuristics proposed in this research, demonstrated satisfactory performance in terms of both solution time and quality. However, the numbers of contingent workers in any given shift were assumed fixed over the planning horizon. This policy may inflate costs in an industry where there are dynamic changes in demand levels from one period to another.

Kher and Fry (2001) studied the impact of labour flexibility, labour assignment policies and order dispatching rules on performance in a dual resource constrained job shop environment. Two classes of customers – vital (priority) and non-vital (normal) - are considered. The authors use various labour assignment and order dispatching rules to show that performance can be improved for the vital customers at the expense of poorer performance. In contrast, increasing labour flexibility provides many of the benefits for vital customers without diminishing the performance for the non-vital customers. The authors suggest that labour flexibility should be treated as an important tool for improving timeliness of deliveries as opposed to predominant focus on order dispatching rules.

Croci et al., (2000) found that even in manufacturing or assembly contexts where workers perform control and support tasks as opposed to direct production activities, workforce policies are an important design parameter. The authors used simulation to study the impact of workforce related policies on the operating performance of a real life automated printed circuit board manufacturing system. The results of this study indicated that performance improved if workforce policies are characterized by enlarged inter-functional tasks rather than by specialized tasks. However the authors suggest that optimal performance is achieved at a medium level of flexibility rather than complete flexibility (bounded mobility) as too much time is wasted in operator transfer when there is no constraint on allocation of a worker to an operation.

Bechtold et al., (1991) studied the labour tour-scheduling methods subject to a variety of labour demand requirements distributions, with the singular objective being the minimization of total labour hours scheduled. Campbell (1999) proposed a three level framework for workforce planning, scheduling and allocation decisions and developed a model for allocating cross-trained workers at the beginning of a shift in a multi-department service environment. The model was used in a series of experiments to investigate the value of cross utilization as a function of factors such as demand variability and levels of cross training. Nembhard (2001) proposed a heuristic worker-task assignment based on individual worker learning rate for long and short production run and suggested a methodology for identifying and assigning the necessary worker skills in manufacturing cells.

This brief literature review emphasizes the need for decision models pertaining to three types of decisions – planning, scheduling and allocation.

Other complicating issues such as effect of learning and workforce skills flexibility need to be incorporated in the decision-making problem. An important need identified in literature is that of integrating the three types of decisions. The model developed in this paper takes this direction and seeks to integrate decisions relating to permanent workforce, workforce skills, induction of contingent workers and learning rate with system related issues such as line capacity and output rate.

III. CASE STUDY

This research was motivated by a project carried out by the authors at a computer firm in Singapore. The firm is a niche global player in the computer industry with manufacturing facilities in US, Europe and Asia. Frequent introduction of new models is a cornerstone of the firm's strategy, and the average product life cycle is about six months. During the product introduction phase, demand rapidly increases, necessitating a "ramp up" of production. The ramp up continues till a peak production rate is reached, after which the demand stabilizes. As emphasized earlier, the ramp up phase is crucial as unfulfilled demand could be lost, negatively impacting the firm's market share and the product's success. Availability of sufficient permanent and contingent manpower is therefore important to ensure that throughput matches rapidly increasing demand. The manufacturing operations studied comprise four independent manufacturing lines, which can operate in parallel. The details of the manufacturing process are shown in Figure 1.

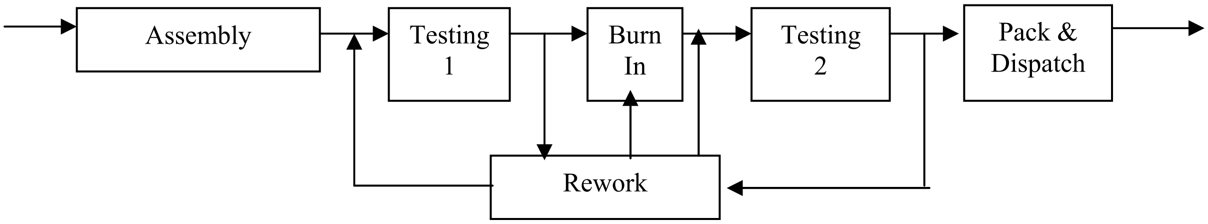

Figure 1: Manufacturing Process

Customer orders are released into assembly according to the daily production plan. After assembly, the units are tested (Testing 1) before they enter the burn-in for an endurance test. Burn-in is completely automated and merely requires the assembly workers to load the computers into the burn-in oven. A second set of testing (Testing 2) follows burn-in. Computers that successfully complete the second test are sent for packing and dispatch while computers that fail at any of the testing stages must undergo rework. The output from the packing stage determines the final throughput of the line. Though there are six stages, the manufacturing process essentially requires three main types of skills – assembly, testing and repair. The output at each stage depends on the number of skilled operators at that stage and the process yield. The assembly is designed to be fairly simple which enables the workers to acquire the requisite skills very fast according to learning curve. The fresh contractual workers go through a short classroom training session and on the job training. A new operator can reach the standard output rate on a given station within a certain period based upon a learning rate. The firm operates with a fixed core of permanent workers. The permanent workers can be categorized into four skill sets depending on their competences in one or more of the manufacturing processes – assembly, testing and repair (Figure 2). Workers in category *U* can only do assembly. Next come categories *V* and *W,* who possess competence in two processes (testing or

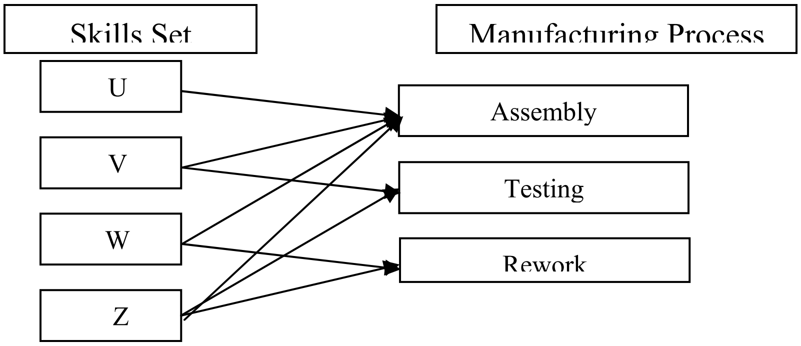

Figure 2: Skill Sets-Process Mapping

repair and assembly). Finally workers in category Z can perform all three processes - assembly, testing and rework.

Whenever a new product introduction necessitates a production ramp up, capacities can be increased through use of overtime and/or induction of contingent workers. Contingent workers are more cost effective as they are paid less as compared to the permanent workers. However, they have a limited set of skills and can only be engaged in certain processes. In this study, contingent workers are limited to the assembly process. Moreover, contingent workers being new to the manufacturing process, take a certain amount of time in reaching their standard output. This is depicted through differential learning curve rates and is given in Table 1 (Appendix B). The values in Table 1 represent the output level achieved by the contingent worker on a given day. The requirements during ramp-up could be met by increasing the pool of permanent workers, which increases capacity and results in higher labour costs during lean periods. Contingent labour provides more economic and flexible capacity. However the use of contingent labour is limited to specific processes and must incorporate the learning effect. Managers must resolve the cost tradeoffs between employing a larger set of permanent workers versus using contingent workers. Some of the key issues that were addressed in this study are: How to achieve the required production ramp up in an environment of high variability? How should workers of various skill levels be assigned to different production processes to maximize the production? At what rate should the contingent workers (having a specific learning rate) be inducted to minimize labour cost while achieving the desired ramp up?

An LP model has been proposed based on these issues and is given in Appendix-A.

IV ANALYSIS AND FINDINGS

The mathematical model for contingent manpower planning is given in Appendix A. Relevant data are given in Tables 1 – 4 in Appendix B. Measures of performance that were analyzed were the cost behaviour and the number of contingent workers inducted. Total cost comprised several components – cost of regular and overtime salary for permanent workers, cost of regular and overtime salary for contingent workers, induction cost for contingent workers, and idle time cost for permanent and contingent workers. The LP model was solved using LINGO 7.0.

Table 5 presents the results for the total cost for 162 different experiments representing unique combinations of each experimental factor. The cost figures in Table 5 are expressed as proportions of the least cost obtained in all experiments (the least cost outcome is defined as 1.000). The total cost is least for high overtime capacity (30%), low overtime premium (1.25 times regular hourly rate) and lowest cost of induction. Maximum total cost is obtained with low overtime capacity (20%), highest overtime premium (1.75 times regular cost) and highest cost of induction. The maximum total cost is around 32% more than the minimum cost. Our results indicate that the cases where cost of induction and idle time cost of permanent workers is minimum (maximum) also corresponds to the same combination of the parameters for which total cost is minimum (maximum).

In terms of number of contingent workers inducted, the maximum number of contingent workers is about 1.66 times minimum number of workers inducted. Further, our results indicate that the number of workers inducted decreases as cost of induction increases. Induction rate is delayed as cost of indcution decreases i.e., percent inducted in week 1 increases with increase in cost of induction and decrease in learning rate and increase in overtime premium.

The above findings represent a useful framework for managerial decision making in industries that make frequent use of contingent labour. Future work will focus on extending the basic model to include a fixed cost for inducting workers as well as a multi-stage model in which induction decisions can be taken at two epochs and the demand is stochastic.

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APPENDIX A

MODEL FOR CONTINGENT MANPOWER PLANNING

Index

I	worker skills category {1 = U, 2 = V, 3 = W, 4 = Z}
J	processing stages {1 = Assembly, 2=Testing, 3=Rework }
K	shifts {k = 1, 2, 3}
L	production lines {l = 1, 2, 3, 4}
M	products (M= 1,2,3,4)

Parameters

$\mathrm{D}_{\mathrm{t}}^{\mathrm{m}}$	demand for model m on day t
y_t^m	yield for model m on day t
D_{jt}^m	workload for model m at processing stage j on day t
	$= \quad \mathrm{D}_{\mathrm{t}}^{\mathrm{m}}$ for j=1 (assembly)
	$= \quad \mathrm{D}_{\mathrm{t}}^{\mathrm{m}} \left\{ 2 - y_t^m \right\}$ for j=2 (testing)
	$= \quad \mathrm{D}_{\mathrm{t}}^{\mathrm{m}} \left\{ 1 - y_t^m \right\}$ for j=3 (re-work)
WP^i	number of permanent workers of skill category i
a_{ij}	= 1 if workers of skill category i can work at processing stage j = 0 otherwise
$\mathrm{UH}_{\mathrm{J}}^{\mathrm{m}}$	Standard output rate for model m at processing stage j
$\aleph_J$	Maximum number of workers allowed at processing stage j
LI_t	Learning index for contingent worker t days after starting work (Table 1)
CI	Cost of induction of contingent workers
α_k , $\alpha_k^{'}$	RT and OT hourly rate for permanent workers during shift k
β_k , $\beta_k^{'}$	RT and OT hourly rate for contingent workers during shift k

Decision Variables

$X_j(l,k,t)$	Number of permanent workers allocated to stage j, on line l, shift k, day t
$Y_j(l,k,t)$	Number of contingent workers allocated to stage j, on line l, shift k, day t
$X'_j(l,k,t)$	Total number of overtime hours done by permanent workers at stage j, on line l, shift k, day t
$Y'_j(l,k,t)$	Total number of overtime hours done by contingent workers at stage j, on line l, shift k, day t
$X^i_J(l,\ k,\ t)$	Number of permanent workers from skills category i, allocated to process stage j, on line l, shift k, day t under regular time
$X'^i_J(l,\ k,\ t)$	Number of permanent workers from skills category i, allocated to process stage j, on line l, shift k, day t under over time
YI_t	Number of contingent workers inducted on day t of ramp up phase

Objective function

Minimize Total cost =

$$\sum_{j\in J}\ \sum_{l\in L}\ \sum_{k\in K}\ \sum_{t\in T}\left\{\begin{matrix} X_J(l,k,t)\} * \alpha_k + X'_J(l,k,t) * \alpha'_k + \\ Y_J(l,k,t) * \beta_k + Y'_J(l,k,t) * \beta'_k \end{matrix}\right\}$$

$$+ \sum_{t\in T} YI_t * CI$$

$$+ \sum_{i\in I}\ \sum_{t\in T}\left\{WP^i - \sum_{j\in J}\ \sum_{k\in K}\ \sum_{l\in L} X^i_j(l,k,t) * a_{ij}\right\} * \alpha_1$$

$$+\left\{ \sum_{l\in L}\ \sum_{k\in K} Y_j(l,k,t) - \sum_{p=1}^{p=t} LI_{t-p+1} * YI_p \right\} * \beta_1$$

subject to

$$X_j(l,k,t) - \sum_{i\in I} X^i_j(l,k,t) * a_{ij} = 0 \qquad \forall\ j,l,k,t \qquad \textbf{........... (1)}$$

$$\sum_{j\in J}\ \sum_{l\in L} X^i_j(l,k,t) * a_{ij} = WP^i_{kt} \qquad \forall\ i,k,t \qquad \textbf{......... (2)}$$

$$\sum_{k \in K} WP^{i}_{kt} \le WP^{i} \qquad \forall \quad i, t \qquad \text{..........} \ \mathbf{(3)}$$

$$WP^{i}_{k+2,\,t} + WP^{i}_{k,\,t+1} \le WP^{i} \qquad \forall \ i, t, k = 1 \qquad \text{.......} \ \mathbf{(4)}$$

$$\sum_{l \in L} \sum_{k \in K} \{X_j(l,k,t) + Y_j(l,k,t)\} * 8 + \{X'_j(l,k,t) + Y'_j(l,k,t)\} \ge \sum_{m \in M} \left\{ \frac{D^{m}_{jt}}{UH^{m}_{j}} \right\} \qquad \forall \quad j, t \qquad \text{.........................} \ \mathbf{(5)}$$

$$\sum_{l \in L} X'_j(l,k,t) - \sum_{l \in L} \sum_{i \in I} X'^{\,i}_j(l,k,t) * a_{ij} \le 0 \qquad \forall \ j, k, t \ \text{.......} \ \mathbf{(6)}$$

$$\sum_{j \in J} \sum_{l \in L} X'^{\,i}_j(l,k,t) * a_{ij} - WP^{i}_{k-1,\,t} * 4 * 0.5 \le 0 \qquad \forall \, i, k, t \ \text{...} \ \mathbf{(7)}$$

$$\sum_{l \in L} Y'_j(l,k,t) - \sum_{l \in L} Y_j(l,k-1,t) * 4 * 0.5 \le 0 \quad \forall \quad k, t, j = A \ \text{.............} \ \mathbf{(8)}$$

$$X_j(l,k,t) + Y_j(l,k,t) + \{X'_j(l,k,t) + Y'_j(l,k,t)\} / 8 \le \aleph_j \qquad \forall \quad j, l, k, t \qquad \text{...............} \ \mathbf{(9)}$$

$$\sum_{l \in L} \sum_{k \in K} Y_j(l,k,t) - \sum_{p=1}^{p=t} LI_{t-p+1} * YI_p = 0 \qquad \forall \quad j = A, t \ \text{......} \ \mathbf{(10)}$$

Constraint 1 defines the number of permanent workers of skill set i who should be allocated to processing stage j. Constraint 2 ensures that total number of permanent workers allocated from each skill set i to all feasible processing stages j, lines l in each shift. Constraint 3, represents the number of workers allocated cannot exceed the available number. Constraint 4 represents the non-overlap of workers in shifts. The right hand side of constraint 5 defines the total workload required at each processing stage j to fulfill daily demand, and depends on the daily demand and the standard hourly output at each processing stage. This workload requires deployment of sufficient permanent and contingent workers during the regular shift and overtime. Constraint 6 and 7 link the amount of overtime performed by permanent workers at each processing stage in a given shift, to the number of permanent workers of appropriate skill category who were working in the previous shift. Both constraints are necessary in order to ensure that overtime limits are not exceeded. The overall limit for overtime work is 4 hours per worker for at most 50% of the workers in the previous shift. Similarly constraint 7 and 8 defines limits on the amount of overtime that can be performed by contingent workers. Constraint 9 defines the upper limit on the total number of workers (permanent and/or contingent) that can man a given production line. Finally, constraint 10 incorporates the characteristics of the learning curves for contingent workers at each processing stage.

APPENDIX B

Day\ Learning Curve	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Fast learning (%)	50	83	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Slow learning (%)	50	59	65	69	73	76	79	81	86	88	90	91	93	94	96	97	98	100

Table 1: Differential Learning Curve Rates

		Shift 1	Shift 2	Shift 3
1	Regualr Rate for Contingent	$ 4.00	$ 4.20	$4.40
2	Overtime Rate for Contingent	$ 6.00	$ 6.30	$6.60
3	Regular Rate for Permanent	$ 5.00	$ 5.25	$5.50
4	Overtime Rate for Permanent	$ 7.50	$ 7.90	$8.25

Table 2: Regular and Over time Hourly Rate

Week	**W1**	**W2**	**W3**	**W4**
Demand	29550	40100	52000	67500
%Lcap	0.55	0.75	0.97	0.98

Table 3. Demand in terms of line capacity (weekly level)

Parameter (factor)	Number of Varaints	Description
Cost of Induction	3	Cost of induction of contingent workers[1]
Learning Curve	2	Fast and Slow learning rates[2]
Assembly Yields	3	Constant, Variable and aggregate yields[3]
Overtime Cost	3	OT Premium 25%, 50%, and 75% of RT hourly rate[4]
Overtime Capacity	3	20%, 25% and 30% of regular capacity[4]

Table 4: Experimental factors and levels used in the study

[1] Cost of induction is equivalent to 1 week, 3 week and 5 week salary.

[2] New contingent workers assumed to reach standard output according to fast (65%) and slow learning (85%) rates (given in table 2)

[3] Model yield are assumed as constant (95%). For the second case, the yield for each modeled varied randomly between 90% and 100%. For the last case, an aggregate yield was determined on a daily basis and this applied to all models on that day. The aggregate yields on all days were uniformly distributed between 90% and 100%. Thus in all cases, average yields over the entire period was 95%

[4] Overtime cost and OT capacity reflect the typical firm practice and variants around it

			Constant Yield		Variable Yield		Aggregate Yield	
			L1	L2	L1	L2	L1	L2
Max OT = 20% of Regular Capacity	OT Cost Premium = 25 %	C1	1.00	1.01	1.00	1.01	1.00	1.01
		C2	1.14	1.15	1.14	1.15	1.15	1.16
		C3	1.27	1.28	1.27	1.29	1.29	1.30
	OT Cost Premium = 50 %	C1	1.01	1.02	1.01	1.02	1.02	1.02
		C2	1.16	1.17	1.16	1.17	1.17	1.18
		C3	1.29	1.31	1.29	1.31	1.31	1.32
	OT Cost Premium = 75 %	C1	1.01	1.02	1.01	1.02	1.02	1.03
		C2	1.17	1.19	1.17	1.19	1.18	1.19
		C3	1.31	1.33	1.31	1.33	1.32	**1.34**
Max OT = 25% of Regular Capacity	OT Cost Premium = 25 %	C1	1.00	1.01	1.00	1.01	1.00	1.01
		C2	1.13	1.14	1.13	1.14	1.14	1.14
		C3	1.25	1.26	1.25	1.26	1.27	1.28
	OT Cost Premium = 50 %	C1	1.01	1.02	1.01	1.02	1.02	1.02
		C2	1.16	1.17	1.16	1.17	1.16	1.17
		C3	1.28	1.29	1.28	1.29	1.29	1.30
	OT Cost Premium = 75 %	C1	1.01	1.02	1.01	1.02	1.02	1.03
		C2	1.17	1.19	1.17	1.19	1.18	1.19
		C3	1.31	1.32	1.31	1.32	1.31	1.32
Max OT = 30% of Regular Capacity	OT Cost Premium = 25 %	C1	**1.00**	1.01	1.00	1.01	1.00	1.01
		C2	1.12	1.13	1.12	1.13	1.13	1.13
		C3	1.23	1.24	1.23	1.24	1.25	1.26
	OT Cost Premium = 50 %	C1	1.01	1.02	1.01	1.02	1.02	1.02
		C2	1.15	1.16	1.15	1.16	1.16	1.16
		C3	1.27	1.28	1.27	1.28	1.28	1.29
	OT Cost Premium = 75 %	C1	1.01	1.02	1.01	1.02	1.02	1.03
		C2	1.17	1.18	1.17	1.18	1.18	1.18
		C3	1.30	1.31	1.30	1.31	1.31	1.31

Table 5: Relative Total cost for 162 Cases