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**Labour Pooling: Impacts on  
Capacity Planning**

By

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**ABSTRACT:** Cross-training workers to perform multi-skilled jobs is one of the modern trends in job design. As companies engage in downsizing, the remaining workforce is expected to do more and different tasks. This paper presents a formal definition and a practical solution for optimizing the size and cost of the pool of multi-skilled workers for production units operated under batch manufacturing. The pool size is optimized through a search procedure applied separately to just-in-time (JIT) and Level production plans, which are derived from the stones heuristic. The method allows direct calculation of the cost savings from labour pooling. This paper was inspired by consulting in the food industry, where implementation of these results has significantly reduced labour costs.

**KEY WORDS:** *Capacity planning, production scheduling and load planning.*

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## 1. Introduction

Ernest Adams Ltd., New Zealand, is a successful food manufacturing company with a major share of the market in New Zealand and the Asia-Pacific region. It produces over 400 different kinds of fresh and frozen food products.

From the shelf life point of view, the company manufactures three types of products:

1. Shelf-stable and frozen food with practically infinite shelf life (up to one year),
2. Chilled products with a medium shelf life (from three to six month),
3. Short shelf life products (from one week to six weeks).

All products are manufactured on several highly automated lines. Every line had its own staff, headed by a line manager.

For years Ernest Adams Ltd built a reputable brand name and had enjoyed a stable market. Permanent customers, such as supermarkets, shops, and restaurants placed orders either for the next week, or for longer intervals with a regular delivery, and the company provided good customer service both in quality and delivery time.

The planning procedure was performed weekly and produced schedules for all production lines for the following week. The company's production and sales strategies were "make-to-order" (MTO). The input to the planning procedure consisted of orders, placed during the current week, less current stocks. The stocks of finished goods might exist because of the differences between batch sizes and order volumes in the past. Thus the volumes of each product, which should be produced next week were defined, as a basis for line scheduling. These volumes, rounded by batch sizes, were manually checked against the demonstrated capacity, and if the capacity seemed sufficient, were approved for scheduling. If the capacity was insufficient, then either overtime was added or some of the orders were shifted to the following weeks. The scheduling procedure was concentrated on the development of Gantt-charts according to established sequencing rules, defining the most economical way of resetting the equipment.

The type of production at Ernest Adams Ltd. is called batch manufacturing (also known as post-mass production). It appeared as the result of a pursuit of market share through an increase in variety across product lines. It occurs when basic products are produced in a modest variety of types and models. Demand volumes are not sufficient to justify dedicated plant and equipment as under mass production, and, at the same time, demand volumes are not so small as to warrant irregular job shop production. Examples of basic products, which commonly fall into the batch manufacturing production category, include hand tools, small electrical appliances, and food industry products. One or several highly automated lines producing a modest variety of products each, typically represent the processing shop in food industry. For example, a frozen meal line produces over forty different meals, a pie line produces fresh and frozen pies with several different fillings.

As inherited from the flow shop, a crew mans the production line, the number of workers and the duration of the production process depending on the product.

The dominant production planning system for this type of production is demand-pull, or just-in-time (JIT), as inherited from the flow-shop. However, JIT ignores capacity costs, and, in that sense, is too simplistic for this type of production. As MacCarthy and Wilson (2001) point out: “over the last two decades there have been numerous manufacturing ‘revolutions’, accompanied by clarion calls for universal adoption of some new paradigm...There is now greater realization across business and industry of the limitations of simplistic ‘magic bullet’ or ‘one size fits all’ solutions. It is clear that effective solutions must address the complexity of environment” (MacCarthy and Wilson, 2001, p. 451-2). Analysis shows (e.g. Portougal and Robb, 2000) that this type of production requires special capacity planning procedures. Neither JIT, efficient for flow shops, nor other planning procedures like OPT have produced a correct recipe for capacity planning in post-mass production.

This type of production is relatively stable. Apart from seasonal changes in demand, there are few introductions of new products. That is why from the capacity point of view the production through the year may be considered as a sequence of regimes with practically constant capacity utilization. At the same time mid-term and short-term capacity use will be uneven, with the periods of under-utilisation and periods of overloading. When the regular staffs are not used up to their maximum capacity, this involves losses, eg no work is being done, but the wages are paid. However, sometimes it is more profitable to produce nothing than to produce unnecessary things. This is the main idea of Just-In-Time (JIT) strategy. An alternative production strategy is disregarding the inventory holding costs and produce whenever there is spare capacity. This strategy is called “level”. Adan and van der Wal (1998) considered moving away from JIT planning to improve capacity utilisation, and they used a Markov process approach to quantify the trade-off between low inventories and low workload variance. In Houghton and Portougal (2001) the trade-off is quantified and this demonstrates the nature of the problem and the solution.

So, uneven workload, losses of capacity and the need for additional capacity are natural traits of this production type.

## **2. Suggested Business Process Re-engineering**

However, recently there was a decline of the company’s market share in many of the traditional markets. The marketing analysis showed that the main reason for the drop in sales was high production costs, and as a result competitors offered lower prices on similar products. The famous brand name did not attract customers so that they would pay higher prices. An attempt was made to compete on low retail prices with the results of slightly increasing sales volumes, but significantly decreasing profit. An analysis produced surprising results on low capacity utilisation. Working in volatile market conditions, organising multiple promotions and catching unexpected opportunities required carrying a significant capacity cushion both in labour and equipment. It was necessary for providing stable customer service while the demand was uneven, sometimes with huge lumps. The company was accustomed to seasonal variations and Christmas sales lumps, and coped with them accumulating stock. Daily and weekly variations, though, lead to losses in production time in low periods and to excessive use of overtime during peak periods. High labour cost variances (as compared to the standards) and low machine capacity utilisation were usual. The ability to perform to

any sales staff promises required not only keeping extra equipment and staff, but also using significant amount of overtime.

Management consultants after analysing the situation, had recommended two ways of business process reengineering:

1. To change the production and sales strategies from “make-to-order” (MTO) to “make-to-stock” (MTS). This change usually affects the “speed to market” factor, which allows expanding the market share by attracting new customers and by catching unexpected opportunities. The MTS strategy costs more in inventory than MTO, but it has an additional benefit of higher capacity utilisation by using inventory “cushions” instead of capacity cushions. This change was performed and the results are discussed in Portougal (2000).
2. To create a pool of cross-trained workers able to work at all the production lines.

This change and its implications on the performance of a batch manufacturing company is discussed in this paper.

The paper is structured as follows. Next three sections represent the main theoretical results (mathematical model and its analysis). In the section that follows, the heuristic procedure for labour pool planning is described. Then the theoretical results are applied to the example facility. The last section is conclusion.

### 3. The Mathematical Model

The processing parameters of the batch manufacturing model are the set of products, processing times, batch sizes, and market demands. The processing line  $l$  is single stage and is assumed to operate under a production planning matrix

$$\mathbf{Y} = \{y_{l,i,t}\} \tag{1}$$

where

$l = 1, \dots, L$  (index of production line),

$i = 1, \dots, n$  (index of the product),

$t = 1, \dots, T$  (index of the period),

$L$  is the number of lines,  $n$  is the number of products;

$T$  is the planning horizon;

$$y_{l,i,t} = \begin{cases} 1, & \text{if processing of the } i\text{th product is planned for period } t \text{ on line } l; \\ 0, & \text{otherwise;} \end{cases}$$

In this type of production all the production lines are dedicated (each product  $i$  is produced on a single line only). A set  $S_l$  of products  $i$  is specified for each line  $l$ , and

$$y_{l,i,t} = 0, \quad \text{if } i \notin S_l.$$

Processing planning must satisfy soft capacity constraints:

$$\sum_i^n p_i y_{l,i,t} \leq R_{l,t} + x_{l,t}, \quad \dots \text{ for } t = 1, 2, 3, \dots, T. \quad (2)$$

Here,  $R_{l,t}$  is the available regular capacity in line  $l$  in period  $t$ ,  $p_i$  is the production time (set-up inclusive) of a batch of item  $i$ , and  $x_{l,t}$  is the overtime incurred in line  $l$  in period  $t$ ,  $x_{l,t}$  may be either positive, or zero, or negative; all parameters are measured in the same time units.

Another set of constraints are the flow conservation equations:

$$I_{i,t} + r_i y_{l,i,t-1} - d_i = I_{i,t+1}, \dots \text{ for } i = 1, 2, \dots, n; t = 1, 2, \dots, T. \quad (3)$$

where  $d_i$  is the demand rate for product  $i$ , assumed constant;  
 $r_i$  is the batch size for product  $i$ ;  
 $I_{it} = d_i$ , is the opening stock of product  $i$  in period  $t$ .

We assume that for each product  $i$ :  $r_i > d_i$ , thereby removing from the analysis all batches required in every period. Further, all  $I_{it}$  are restricted to exceed demand, thereby precluding backlogging of demand for products.

Since all production lines are dedicated, the three-dimensional matrix  $Y$  may be separated into  $L$  two-dimensional matrices  $Y_l$ . For every matrix  $Y_l$  the columns are taken in order of  $t$ ; in column 1, values of  $y_{l,i,1} = 1$  identify those products to be processed in period  $t = 1$ , etc. Assume that a product  $i$  is always scheduled to be produced in period  $t$  only because otherwise the level of stock will fall below the demand level. This will be done to satisfy flow conservation constraint (3). In this case the spacing between unit elements will be equal to  $T_i = r_i / d_i$ . We shall call  $T_i$  the product cycle, because it gives the maximum spacing to satisfy (3). The unit element can be moved to an earlier period, if required by capacity restrictions, but not to a later period. Producing with the interval  $T_i$  is consistent with JIT philosophy, and it minimizes holding costs, however capacity utilization and capacity cost may suffer. The shop cycle,  $T$ , is given by the lowest common multiple of the  $T_i$ . Processing is cyclical in the sense that when processing for period  $t=T$  is complete, the next processing period is  $t=1$ . Since the shop cycle is repeated in this way, it becomes the horizon for purposes of optimizing the processing plan. The number of batches  $n_i$  of product  $i$  produced during the shop cycle is  $n_i = T/T_i$ . If they are equally spaced in the schedule, then the schedule is JIT and the holding costs are minimum. However, for reasons of better capacity utilization any spacing can be used, and then the constraints (3) will be satisfied for each product,  $i$ , if and only if  $n_i = T/T_i$ .

The solution to the basic model gives an optimum plan in the form of (1), with an associated optimum workload profile,  $x_{l,t}$ .

To standardise our comparisons of production plans we will compare the workload of any production plan to a perfect level-loading plan that meets demand requirements. Perfect level-loading exists when the workload for each period is constant at

$$P_l = \sum_{i \in l} p_i \frac{d_i}{r_i} \quad (4)$$

where  $P_l$  is the average workload of the line  $l$ .

The usual approach to capacity determination, sets the minimum design capacity, or regular capacity, to  $P_l$  for line  $l$ . It will be demonstrated below that  $P_l$  might be very misleading as a capacity benchmark, saying nothing as a means of regular capacity determination. In this type of production each batch of any product is produced in one period, independent of batch size. Because of the discrete nature of the batches the actual workload swings can be huge, and the average will have no significant meaning. The levelling of capacity requirements might be valid if the number of items is large. But, in this case the number of items is so large and  $P_l$  is useful only as a benchmark. Although  $P_l$  clearly implies a perfect level-loading production plan, in practice it is usually applied to general production plans with unfortunate cost implications, as demonstrated below. Overtime processing in (2) enables regular capacity to be exceeded.

We shall assume that the regular capacity  $R_l$  has not been fixed yet, but rather is a variable for optimizing the summary cost of regular and overtime labour. We shall reserve  $P_l$  for average workload.

Define:

1) the actual capacity utilization vector  $\mathbf{Q}$  of a plan as:

$$Q_{l,t} = R_l + x_{l,t} \dots \text{ for } t=1,2,3,\dots,T$$

... where  $x_{l,t}$  may be either positive, or zero, or negative.

2) overtime utilization, OT, as:

$$OT_1 = \sum_{t=1}^T \max(0, Q_{l,t} - R_l) = \sum_{t=1}^T \max(0, x_{l,t}).$$

3) overtime cost,  $COT_1$ , as:

$$COT_1 = c * OT_1, \text{ where } c \text{ is per hour overtime rate, here equal for all lines.}$$

4) regular capacity cost,  $CR_1$ , as:

$$CR_1 = c_1 * R_l * T, \text{ where } c_1 \text{ is per hour regular capacity cost (equal for all lines), } c_1 < c.$$

5) total cost, TC, as the sum of regular labour, overtime labour, and inventory costs  $CH_1$  over all lines:

$$TC = \sum_l (CR_1 + COT_1 + CH_1)$$

We need to minimize TC under restrictions (1-4).

The basic model may be viewed as a variant of the traditional sequencing problem as defined by Berkley and Kiran (1991). The primary difference is that regular processing within a regime replaces a system of due dates. Fixed batch sizes recognize the practical batch manufacturing procedure of computing batch sizes once, based on a compromise between the processing shop cost structure and other convenience criteria based on technical peculiarities of the process. But in the context of this paper, fixed batch sizes define a stable workload regime with capacity-requirements-planning cost management that minimizes the costs of production above regular capacity, including overtime, subcontracting, and inventory. This approach is appropriate for processing facilities where plant capacity is a tight restriction on processing. No attempt is made, therefore, to develop discrete lot sizing and scheduling as presented for other production environments, eg Salomon (1991).

Kogan and Lou (2002) explored a similar process. Their production environment includes a one-product, multiple-stage production system with periodic demand and an infinite capacity buffer after each machine. Properties of optimum solutions were identified, which bear similarities to those found in Houghton and Portugal (1995a). Based on those properties, optimum policies for a system with two restricting machines were developed, giving insights into the optimal behaviour of the production system with multiple restricting machines.

Planning usually was performed for a production unit characterised by regular capacity and the ability to use additional capacity. Regular capacity always was a part of the planning environment, and the possibility of its changes was considered only on a higher level of the planning hierarchy with much longer planning horizons (a year or more). In this context only the cost of additional capacity had to be minimized.

Now the planning environment has changed dramatically. MacCarthy and Wilson (2001) note that expensive machinery and high cost of labour, as well as recent developments in business environments including flexible manufacturing and the multi-skilled movable workforce, have made it necessary to treat regular capacity as much an object for optimization as capacity supports like overtime or sub-contracting.

In the production planning and scheduling literature though, regular capacity  $R$  is still a fixed parameter of the production unit, set to a level that meets average workload requirements  $P$ . However, the optimum level of regular capacity is equal to  $P$  only in very exceptional circumstances. Generally, optimum  $R \neq P$ , and it is a variable of the planning problem. Thus the model has the following variables:

$$\mathbf{Y} = \{y_{l,i,t}\}$$

and  $R_l$ ,

and a criterion TC.

Actually, there is another important criterion that is  $R = S_l R_l$  – the use of regular labour that is the preferred by managers option. Overtime staff is paid on a higher rate, and the productivity of casuals is much lower as they frequently have not adequate training. However, these benefits are very difficult to quantify, and therefore we shall treat it as a secondary criterion.



It is easy to see that the described model is completely intractable for problems of practical size. So, instead of solving it directly, we offer an operational analysis that would help in developing workable heuristics.

## 4. Analysis

### 4.1 JIT Strategies

Before we mentioned that the dominant production planning strategy for this type of production was JIT. It is easy to show that all JIT cyclic schedules ensure minimum holding costs over the shop cycle,  $T$ , thus reducing the criterion TC to labour costs:

$$TC=CR + COT.$$

There exists a whole set of JIT plans with different workload profiles. A secondary optimization of the JIT plans with regard to workload profile over this set gives a production planning matrix that defines an optimally phased JIT processing plan that we will refer to as an optimum JIT plan. The temptation is strong to use only JIT schedules, however this can be recommended only if the holding costs are much more significant than capacity costs. Due to the increasing capacity costs this situation becomes for batch manufacturing extremely rare.

### 4.2 Level Strategies

When the capacity costs are much higher than inventory holding costs (as in most practical cases), then schedules with workload profiles as level as possible should be used, disregarding the JIT property. We shall call such schedules *level plans*. If we can find a schedule with a workload profile constant over time, we shall call it the absolutely level plan (ALP).

In the following analysis we shall assume that the results are formulated for any of the production line, thus we shall skip the line index  $l$ .

PROPOSITION 1. If plan is ALP, then TC is minimum when  $R=P$ .

Proof. If a plan is ALP, then all  $Q_t = P$ .

- (a) Let us set  $R < P$ , then we shall need additional overtime  $(P-R) > 0$  every period that for  $T$  periods will cost

$$COT = c * T * (P - R) > 0.$$

The alternative is to set  $R = P$ . Then cost of regular capacity

$CR = c_1 * T * (P - R)$ .  $CR < COT$ , as  $c_1 < c$ , thus the second option is better.

- (b) Let us set  $R > P$ . This means we shall have unused regular capacity with extra cost.

COROLLARY. If a JIT plan exists that is ALP, then this plan is optimum by both criteria (minimum TC, including HC and maximum  $R$ ).

The following characteristic of a plan we shall refer to as workload relative deviation (WRD):

$$\text{WRD} = (\max Q_t - \min Q_t)/P.$$

Clearly, for the ALP

$$\text{WRD}(\text{ALP}) = 0.$$

Unfortunately, due to the nature of batch manufacturing, absolutely level plan exists only in a very special case, when the batch sizes allow packing them in periods evenly. There are some other special cases when optimum  $R=P$ , but these cases are even more exotic than an ALP case.

In reality, the planners are looking for a plan with minimum WRD that we shall call optimum level (OL) plan.

It can be expected that the more level is a plan (the lower is its WRD), the smaller are the capacity cost  $\text{CC} = (\text{CR} + \text{COT})$ , and that for the OL plan it is if not minimum, then very close to it. Then the OL plan would be (and in most practical cases is) the preferred option.

However, the procedure for finding an optimum level plan is NP-hard, that is why heuristic approaches are used to develop a reasonably level plan. We shall use the stones heuristic suggested by Houghton and Portugal (1995b) that gives an asymptotically optimum solution.

The stones heuristic has been developed for the solution of the stones problem:

Suppose we have  $m$  stones. Each stone is to be allocated to one of  $n$  heaps. Each stone has a weight not exceeding  $W$ . The objective is to form heaps in a way that equalizes, as near as possible, the heap weights. It is easy to see the connection between the stones problem and level planning problem. Here the stones are batch processing times (not exceeding  $W$  hours) which have to be allocated to processing periods in a way that equalizes, as near as possible the workloads  $Q_t$ .

The *stones heuristic* makes allocation decisions sequentially. The heuristic considers the stones in any order, and allocates the next stone to the lightest heap. When the allocation is done according to the stones heuristic,

$$(\max Q_t - \min Q_t) = W.$$

The heuristic gives an asymptotically optimum solution, as

$$\text{WRD} = (\max Q_t - \min Q_t)/P = W/P,$$

And

$$W/P \rightarrow 0, \text{ when } m \rightarrow \infty.$$

The application of the stones heuristic is as follows. In chapter 3 we have shown that for the continuity of supply the number of batches  $n_i$  of product  $i$  produced during the shop cycle should be  $n_i = T/T_i$ . So, we form the heap, representing every product  $i$  as  $n_i$  stones with the weight  $p_i$  each, and then, using the stones heuristic, allocate the stones to  $T$  heaps.

We shall refer to a plan  $\mathbf{Y}$  developed using the stones heuristic as the best level plan. It is easy to see there may be many *best level* plans (eg. depending on the initial order of jobs).

Suppose we have  $L$  lines (WC), manned by separate teams. They have an equal common cycle  $T$ . We assume that we have already defined our planning strategies and have already performed the scheduling. The WCs were scheduled independently of each other. We shall call them partial schedules  $S_1, S_2, \dots, S_L$ . As a result for every WC $_l$  we have optimum  $\mathbf{CC}_l$  and  $\mathbf{R}_l$  ( $l = 1, 2, \dots, L$ ).

Now suppose that we have organized a pool of multi-skilled workers, and everyone can work in every WC. Now the scheduling should be performed simultaneously for all WC, as every schedule depends on the other schedules. After producing a pool schedule of all WCs using the pool of labour we can define  $\mathbf{R}$  - the optimum level of regular labour in the pool and  $\mathbf{CC}$  - total optimum cost of pooled labour.

Now it is clear that there exists a pool schedule with

$$\mathbf{R} = \sum_l \mathbf{R}_l, \text{ and } \mathbf{CC} = \sum_l \mathbf{CC}_l,$$

and equalities are reached if all partial schedules are ALP.

This fact provides a theoretical validation of labour pooling. According to it the pooled schedule might require (and in reality nearly always does) less labour than the sum of partial schedules. The case study example demonstrates this result in following sections.

## 5. Scheduling Heuristics

Because the mathematical model is completely intractable, heuristic solutions are considered as a practical means of scheduling. There are two possible ways of practical pool scheduling, both for JIT and level strategies:

1. Simultaneous scheduling, when all the products are scheduled in one common schedule with the objective to minimize total cost, and then the line schedules are “cut out” of the common schedule.
2. Two-stage scheduling:
  - first stage: partial scheduling
  - second stage: partial schedules merging to compose a unified schedule.

Two-stage scheduling is more common in practice than simultaneous scheduling. At Ernest Adams Ltd line managers who know well the peculiarities of the process perform partial (line) scheduling. They can pack the jobs daily in the most efficient way (minimizing changeover time losses). Then the Master Production Scheduler unifies the partial schedules. Such practice is common in batch manufacturing companies. However, simultaneous scheduling gives more possibilities for optimization.

Scheduling for JIT strategy is performed as follows. In a planning context, the JIT property is satisfied when batches are processed as late as possible to meet the requirements without backlog. Correspondingly, a JIT processing plan is derived from the stocks at the beginning of the period. A JIT processing plan will usually have violent workload swings and high capacity costs that may be alleviated by phasing the processing of the different parts. Phasing may be conducted by a simple row-rotation procedure as presented by Houghton and Portugal (1995a). The JIT plan that minimizes capacity costs will be referred to as the optimum JIT plan. Two-stage JIT optimization is easier to perform, as the difficulty of the row-rotation procedure increases exponentially with the growth of the number of products. When the number of products is large, then simultaneous scheduling might be even not an option, whereas partial optimum JIT schedules still can be developed.

We suggested the following heuristic for merger of partial schedules in a unified schedule and refer to it as the MPS heuristic.

All partial schedules are cyclical in the sense that when processing for period  $t = T$  is complete, the next processing period is  $t = 1$ . From this point of view in a partial schedule  $S_i$ , any processing period can be numbered as  $t = 1$  (indicating the beginning of the cycle of  $T$  periods), and for a cycle  $T$ ,  $R_i$  and  $CC_i$  will be the same. This defines  $T$  schedules produced by such cyclical shift. Cyclical shift is important because it preserves the JIT property of schedules.

The Master Production Scheduler receives partial schedules from line schedulers for pooling them together. If the number of WCs is not too large, then she can try all possible combination of the cyclical schedules. There will be  $N = T^m$  combinations. In practice  $T$  rarely exceeds 10 and  $m$  for pooling multi-skilled workers usually varies from two to four. Thus, the pooling can be done quickly using an ordinary PC.

Simultaneous scheduling has certain advantages for the *level* strategy. If the scheduling is performed with the use of the stones heuristic, then WRD of the common schedule almost sure will be smaller than WRD for the unified schedule. However, the same reason as in JIT scheduling provides here an important motivation to use the two-stage scheduling: line managers, who know well the peculiarities of the process can pack the jobs daily in the most efficient way (minimizing changeover time losses).

The heuristic for merger of partial schedules in a unified schedule (the MPS heuristic) here will be different, because there is no necessity to preserve the part cycles.

The MPS heuristic here will work as follows.

- Step 1     The initial order of partial schedules is arbitrary. Consider the first schedule.
  
- Step 2     The schedule developed during the previous step will be the *basic schedule*. Re-arrange this schedule in ascending order of workloads  $Q_t$  by period (the least loaded period will become  $\tau = 1$ , the next  $\tau = 2$  and so on).
  
- Step 3     Re-arrange the next partial schedule in descending order of workloads  $Q_t$  by period (the most loaded period will become  $\tau = 1$ , the next  $\tau = 2$  and so on).
  
- Step 4     Merge the schedule developed on the previous step with the basic schedule. Calculate combined workloads  $Q_t$ . If it was not the last partial schedule, go to step 2.

If it was the last partial schedule, then

- Step 5     Exit

The use of these heuristics we illustrate by the example of Ernest Adams Ltd.

## 6. Returning to the Case

The following series of calculations will demonstrate the implementation of our ideas at Ernest Adam Ltd. First, using the frozen meals line, we shall show how the planning was done and what had it costed before pooling the labour. Then we shall demonstrate the savings from implementation of a multi-skilled labour pool and scheduling heuristics developed in Section V for three similar lines.

The following data (table 1) reflects planning parameters of the frozen meals line after scaling and aggregating of similar products for downsizing the example.

**Table 1: Processing Shop Data**

Part, $i$	Processing		Assembly	Store
	batch size	batch proc. time, h	demand rate	opening stock
1	12	21	6	6
2	16	65	8	16
3	36	33	12	24
4	21	79	7	14
5	39	91	13	26
6	60	78	10	30

Average workload (equation(4)) = 123.7

In developing the following plans (tables 2-3) we use the heuristics presented in Houghton and Portugal (1995a). In order to understand further results we include a brief description of the methodology.

We shall start with the straightforward JIT planning (table 2). We would like to repeat once more that JIT planning gives good results when the inventory costs are more significant than capacity costs, that was in some industries till 1970s. Now the planning environment has changed. Expensive machinery and high cost of labour dramatically increased capacity costs, so the business environments with inventory costs higher or even comparable with capacity costs progressively become more and more rare. Still, if they exist, JIT planning is a preferred option.

From the cyclical property of JIT solutions, the set of part cycles is {2,2,3,3,3,6}. The shop cycle is therefore,  $T = LCM(2,3,6) = 6$  periods. Considering the opening stock in table 1, and the JIT property of the plan, the parts, which must be produced in period 1 to avoid assembly shop shortages, are parts 1, 3, and 4 (they are denoted by 1 in the first column). Going on, solution plan matrix is derived where each row represents a part and each column represents a time period. The model solution given in Table 2 shows the **Y** matrix and the corresponding load profile. The load profile shows workloads in the interval (17%, 217%) of the average capacity.

**Table 2. Regular JIT-Processing Plan**

Processing Period	1	2	3	4	5	6
Part 1	1		1		1	
Part 2		1		1		1
Part 3		1			1	
Part 4		1			1	
Part 5		1			1	
Part 6			1			
Load profile	21	268	99	65	224	65

**Table 3. Optimum JIT-Processing Plan**

Processing Period	1	2	3	4	5	6
Part 1	1		1		1	
Part 2		1		1		1
Part 3	1			1		
Part 4		1			1	
Part 5			1			1
Part 6	1					
Load profile	132	144	112	98	100	156

Phasing the processing of different parts to minimize capacity costs gives the solution shown in table 3, with workloads in the interval (79%, 126%) of average capacity. Production will be under average capacity for periods 3, 4 and 5, when managerial restraint is required to preserve the JIT system.

The optimum phased solution above is generated by a heuristic from Houghton and Portougal (1995b) that consists of two procedures:

### 6.1 The common part cycle procedure

1. For those parts with a common part cycle consider the rows in random order.
2. Rotate the current row to locate its unit element in the period with the minimum workload. Calculate the load profile range; if it shows no improvement, cancel the rotation.
3. Stop when further iterations do not give improved solutions.

### 6.2 The general part cycle procedure

Combine the smoothed groups with common part cycle arbitrarily over a shop cycle, as minor improvements only can be achieved by further rotations. A performance bound for this heuristic shows the solution is asymptotically optimum (Houghton and Portougal 1995b).

In table 4, we add a third processing plan in which the capacity requirement is levelled as far as possible with workloads in the interval (91%, 116%) of average capacity. Such plans are often far from being JIT, and they are used in environments when the holding costs are not significant as compared to capacity costs. This small-scale problem was solved exactly by complete enumeration.

**Table 4. Level Processing Plan**

Processing Period	1	2	3	4	5	6
Part 1	1		1	1		
Part 2		1		1		1
Part 3				1	1	
Part 4		1			1	
Part 5	1		1			
Part 6						1
Load profile	112	144	112	119	112	143

The common practice is to set regular capacity to cover average production requirements. Then above capacity production must be met through overtime. The workload of the “blind JIT” solution swings violently around regular capacity, an outcome that is expensive in labour and not uncommon for JIT systems. Also, the periods where production is under regular capacity for the optimum JIT solution will require managerial restraint to re-enforce the JIT principle that in these periods it is cheaper to pay labour to do nothing than to produce extra stock. The level plan will, of course minimize workload swings around the regular capacity.

Now we shall define the cost of different solutions.

To continue the above example, we shall assume that the cost per hour of daily capacity provided by regular staff is \$600 per 6 day week, whether it be used in production or

not; and that the cost per hour of overtime capacity is \$150, but only if we use it. Total capacity cost is the sum of regular and overtime capacity costs and this is to be minimized across the regular capacity level. The results of cost calculations are given in table 5.

*Table 5. Total Cost for Different Plans*

Regular Capacity, P (hrs/week)	Total Capacity Cost for Schedule (\$)		
	Regular JIT	Optimum JIT	Level Processing
10	108,300	108,300	108,300
20	105,300	105,300	105,300
30	103,650	102,300	102,300
40	102,150	99,300	99,300
50	100,650	96,300	96,300
60	<b>99,150</b>	93,300	93,300
70	<b>99,150</b>	90,300	90,300
80	100,650	87,300	87,300
90	102,150	84,300	84,300
100	103,800	82,500	81,300
110	106,800	<b>81,600</b>	<b>78,300</b>
120	109,800	82,800	79,050
<b>124</b>	111,000	83,400	80,250
130	112,800	84,300	82,050
140	115,800	87,000	85,050

Clearly, the traditional method of calculating regular capacity as the average workload given by formula (4), which defines a regular capacity of 123.7 hours per day, is not optimum for the level plan or for any other practical plan. If the regular capacity were set conventionally as the average workload (in our example 124 hours per week), then every week it would cost the company about \$2,000 more both for optimum JIT and level plans, and \$11,000 more for the regular JIT plan. Another pitfall: the capacity was set at 124 hours per week and was budgeted at nominal cost \$74,400 per week. Then we have a weekly deficit in labour budget of \$9,000 for optimum JIT and \$5,850 per week for level plans.

Now, suppose that we have made a pool of multi-skilled workers for two and for three similar working centres (for simplicity the same data is used for each WC). The case for comparison is taken from table 5. The results of the calculations are given in table 6. All the pool schedules were developed using heuristics for two-stage scheduling described above. Simultaneous scheduling would produce better pooling effects, however we think it is impractical. “Traditional idealistic” represents the imaginable cost of an absolutely level schedule, if it exists. As shown above it exists extremely rarely, but the cost of it indicates the lower bound of labour costs.

The interpretation of results is as follows:

- Pooling gives a significant improvement of labour costs for both strategies,
- Level strategy is still cheaper than JIT strategy, and workload variations (WRD) when using this strategy quickly converge to zero.



- If the workforce is calculated in a traditional way, it is still dramatically misleading, however the level pooled plan for 3 WC already is rather close to the traditional idealistic average schedule (it is just a coincidence that the level plan for 3 WC in this example practically has no workload variations, other examples show more considerable WRD).
- The labour cost savings from pooling are significant both for JIT and level plans, and they provide the proof of the viability of this type of labour organization.

**Table 6. Cost for Different Plans with or without Pooling**

Plan	Pool of 2 WC			Pool of 3 WC		
	WRD	Reg. Labour, $h$	Total cost, \$	WRD	Reg. Labour, $h$	Total cost, \$
Optimum JIT pooled	0.15	240	153,600	0.28	368	231,300
Optimum JIT not pooled	0.15	224	163,200	0.28	336	244,800
Level pooled	0.1	247	153,300	0.03	368	223,650
Level not pooled	0.1	224	156,600	0.03	336	234,900
Traditional idealistic	0	247	148,440	0	371	222,660

It is worth to discuss the JIT plans. It was shown before that even the optimum JIT plans are much more expensive in labour than level plans, so the use of JIT plans were restricted to the rare in batch manufacturing case of extremely high inventory holding costs. However, recently we see a new interest in JIT. The pool of workers may be seen as a mini profit-centre as presented by Monden (2002). Then, using JIT schedules for 2 WC we have huge savings from the pool-mini-profit-centre (table 6). However it is helpful to remember that unlike in level plans, the WRD in JIT plans does not converge with the pool increase. The result for 3 WC by absolute value is better, but it is relatively worse (per WC) than the result for 2 WC. At the same time for level schedules, the more labour is pooled, the better.

These results have been implemented at Ernest Adams Ltd. Changing the company's approach to production planning and introducing a pool of regular and overtime workers able to service several lines has significantly reduced the company's production costs.

## 6. Conclusion

This paper presents a formal definition and a practical solution for optimizing the size and cost of the pool of multi-skilled workers for production units operated under batch manufacturing. Cross-training workers to perform multi-skilled jobs is one of the modern trends in job design. As companies engage in downsizing, the remaining workforce is expected to do more and different tasks. Labour pooling may be

considered as a kind of a mini profit-centre. Methods suggested in this paper allow not only efficient pool scheduling, but also direct calculation of the cost savings from labour pooling. Although the results were implemented only at Ernest Adams Ltd, they may be useful for any batch manufacturing company.

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