Analysis of a Worker Assignment Model in a Lean Manufacturing Environment

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Abstract

This paper describes an expansion of a multi-period worker assignment model for a lean production cell that produces a single product family. The hypothetical cell operates eight hours per day, twenty days per month and has six workers performing ten tasks. The model assigns the workers to tasks and determines the levels of additional training that may be necessary to meet customer demand, quality requirements, and cross-training provisions. The two main factors analyzed are the number of workers trained beyond two tasks and frequency of job rotation. Four levels of worker training and three levels of job rotation frequency are evaluated. To be considered cross-trained, workers must be trained on at least two tasks. The four levels of worker training are zero, two, four, and six workers trained on more than two tasks. The zero level indicates that all workers are trained on only two tasks, while the other three levels indicate that that number of workers are trained on more than two tasks. The three levels of job rotation are eight, four, and two hour rotations per day. The solutions from the model are analyzed to determine the impact the two factors have on net present costs, quality costs, and training within the work month. The model expands upon the research of McDonald *et. al.*, [1] by allowing workers to increase their training by more than a single skill level during the 20-day planning period and by removing the budgetary constraints for training. The results of this model are expected to provide insight on the impact worker training and job rotation frequencies have on production line performance and provide guidance on training policies.

1. Introduction

In today's economy, companies need to control costs to remain profitable. Lean manufacturing focuses on continuously identifying and removing sources of waste or costs [2]. Lean manufacturing prescribes the use of cross-trained workers who are capable of performing all tasks in a manufacturing cell. Cross-training is a tool in which team members are trained on the tasks, duties, and responsibilities of multiple tasks in a specific cell or area. Cross-training provides workers with a clearer understanding of the cell [3], develops flexibility [4], [5], [6], and increases worker satisfaction [7]. Cross-training can be improved and reinforced through job rotation [8]. Job rotation also improves worker flexibility, worker satisfaction, and the worker's understanding of how their job impacts the rest of the cell.

Multiple worker assignment models exist that assign workers to tasks in a production cell [1], [9], [10], [11], [12], [13], [14], [15]. Lean manufacturing prescribes producing only enough product to exactly meet customer demand [4], [5], [8]. The referenced models, with the exception of McDonald *et. al.* [1], do not address the fact that cells may be able to produce more than customer demand. The models include constraints for cross-training and skill level for each task to be performed, but they do not include a penalty for overproduction, nor do they provide a worker assignment and job rotation schedule.

2. Description of the Worker Assignment Model

The proposed model for this paper is a variation of the model used by McDonald *et. al.* [1]. The model assigns workers to tasks during an assignment period while minimizing the net present cost of production. The net present cost of production is comprised of the cost to attain the initial cross-training level of workers, the incremental cost of training within the planning horizon in order to meet demand, the cost of work-in-process, and the cost of poor quality. The cost of the initial cross-training level of workers is not influenced by the model, but the cost is included to compare across scenarios. The cost of work-in-process and the cost of quality are both recurring costs for the planning horizon and the incremental cost of training is a one-time cost. The worker assignment model generates a schedule assigning workers to tasks for the planning period and identifies the training requirements for workers needing additional training in order to meet demand during the planning horizon. Table 1 defines the assumptions of the model and the following paragraphs define the model notation and provide the mathematical programming formulation of the worker assignment model.

Table 1. Assumptions for Worker Assignment Model

	Assumption
1.	Decisions are made for a single manufacturing cell with a specified set of machines.
2.	The manufacturing cell is dedicated to a single product family.
3.	The capabilities and capacity of each machine type are known and are considered constant.
4.	The processing times for all part types on different machine types are known for each operator.
5.	Set-up times are included in the processing times.
6.	Machine breakdowns are not considered.
7.	Absenteeism is not considered.
8.	A worker can only train up one skill level per task per planning horizon.
9.	All supplied parts have 100% on-time delivery and incoming quality.
10.	Production is maintained when a worker is in training. That is, when a worker is in training, the workstations where that worker would be assigned maintain the required productivity levels to meet customer demand by using workers from other areas, temporary workers who are currently at the skill level for which the worker is training, or by a supervising worker monitoring on-the-job training.

3. Model Notation, Definition, and Formulation

The following parameters are used in the worker assignment model.

i	Index of workers	$i = 1, 2, ..., I$
j	Index of tasks	$j = 1, 2, ..., J$
l	Index of skill levels	$l = 1, 2, ..., L$
t	Index of assignment periods	$t = 1, 2, \ldots, T$
$C_{Initial\ Training}$	The training cost incurred to reach the initial level of training;	
$C_{Training}$	Maximum permissible training costs during the planning horizon T;	
C_{ijl}	Cost to train worker i from the current skill level to skill level of l for task j;	
CH	Cost of holding inventory;	
CI_j	Per unit cost of inventory at task j;	
CQ_j	Per unit cost of poor quality at task j;	
D	Customer demand;	
MSL_i	Cross-training level for worker i (the number of tasks for which worker i is trained);	
NS_j	Necessary skill level for task j. That is, in order to perform task j it is necessary for the worker to have at least this skill level;	
P_{jl}	Productivity rate if task j is performed with skill level l (units per time);	
pr_j	Processing time required to perform task j;	

q_{ijl}	Quality level associated with worker *i* performing task *j* with skill level *l*;
s_{jl}	Skill level for task *j* at level *l* to represent skill depth (e.g., if task *j* has four levels (1, 2, 3, 4), then $s_{j1} = 1$; $s_{j2} = 2$; $s_{j3} = 3$; $s_{j4} = 4$);
Takt	The required *takt time*;
tr_{ijl}	Time required to train worker *i* from the current skill level to skill level *l* for task *j*;
T_{Total}	Total available training time for all of the workers in the cell;
w_{ij}	Initial skill level that worker *i* has for task *j*; and
u_{ij}	$\begin{cases} 1 \text{ If worker } i \text{ has the required skill depth for task } j\,(w_{ij} > NS_j) \\ 0 \text{ Otherwise} \end{cases}$

The primary decision for the model is to determine the assignment of each worker *i* to a task *j* at a skill level *l* for each assignment period *t*. Based on this, the schedule of the worker assignments to tasks during planning period *T* is determined. In addition, the level of required training can be determined since the initial skill level is known for each worker on each task. The following decision variables are used in the worker assignment model:

$$z_{ijlt} = \begin{Bmatrix} 1 & \text{If worker } i \text{ does task } j \text{ at skill level } l \text{ during assignment period } t, \\ 0 & \text{Otherwise} \end{Bmatrix}$$

$$y_{ijt} = \begin{Bmatrix} 1 & \text{If worker } i \text{ does task } j \text{ during assignment period } t \text{ at any skill level,} \\ 0 & \text{Otherwise} \end{Bmatrix}$$

$$v_{ijl} = \begin{Bmatrix} 1 & \text{If worker } i \text{ does task } j \text{ at skill level } l \text{ during any assignment period,} \\ 0 & \text{Otherwise} \end{Bmatrix}$$

The primary decision variable, z_{ijlt}, assigns workers to tasks at a given skill level for a given assignment period. The other two decision variables are based on the primary decision variable.

The objective function and constraints of the model are shown in Figure 1. The objective function minimizes the net present cost of production and is comprised of four terms. The first term represents the present cost for work-in-process - units that are produced at work stations in excess of customer demand. A cost of holding inventory is then applied to the value of the inventory. The second term represents the cost of poor quality. The third term is the initial cost of training all workers to their current skill level on all tasks. Lastly, the fourth term represents the incremental cost of training associated with the training needed determined by the model within the planning horizon *T* to best meet customer demand. The first two terms are recurring costs, while the last two terms are one-time costs.

Constraint (2) ensures that each task is assigned to an individual worker during each time period. Constraint (3) ensures that each worker is assigned to at least one task during each time period. Constraint (4) limits the number of tasks a worker can be assigned during each time period to be no greater than the cross-training level. For example, if MSL = 2, then the worker can do at most two tasks. Constraint (5) ensures that the workers are not assigned to more than *takt time* during each time period. Constraint (6) ensures that if a worker is assigned to a task during a time period, then the assignment only occurs at one skill level. Constraint (7) ensures that the worker assigned to a task during a time period meets the minimum skill level requirement for that task, NS_j. The skill index (*l)* for (s_{jl}) is determined by the maximum of either the initial skill level the worker has for a task (w_{ij}) or the current skill index (*l*). Constraint (8) ensures that customer demand for total shipments is met. Constraint (9) ensures that each upstream workstation makes enough good product to allow for the poor quality associated with the next downstream task. Constraint (10) ensures that a worker cannot be assigned to a task at any skill level for more than the total number of assignment periods in the planning horizon *T*. Constraint **(**11**)** ensures that a worker cannot be assigned to a task at at any skill level if the worker has not been assigned to that task during some assignment period. Constraint (12) ensures that the total time spent on training by all workers does not exceed the total number of training days permitted. Constraint (13) ensures that if a worker is trained on a task, that worker must perform that task at least once during the planning horizon *T*.

Objective Function:

$$\left[\sum_j\left(\sum_i\sum_l\sum_t P_{jl}z_{ijlt}q_{ijl}-D\right)CI_j(CH)\right](P/A,i\%,n)+$$

$$\left[\sum_i\sum_j\sum_l\sum_t\left(P_{jl}z_{ijlt}q_{ijl}CQ_j\right)\right](P/A,i\%,n)+ \qquad (1)$$

$$C_{Initial\ Training}+\left(\sum_i\sum_j\sum_l v_{ijl}C_{ijl}\right)(P/A,i\%,1)$$

Subject to:

$$\sum_i y_{ijt}=1 \qquad \forall j\in J,\forall t\in T \qquad (2)$$

$$\sum_j y_{ijt}\ge 1 \qquad \forall i\in I,\forall t\in T \qquad (3)$$

$$\sum_j y_{ijt}\le MSL_i \qquad \forall i\in I,\forall t\in T \qquad (4)$$

$$\sum_j pr_j y_{ijt}\le Takt \qquad \forall i\in I,\forall t\in T \qquad (5)$$

$$\sum_l z_{ijlt}\le y_{ijt} \qquad \forall i\in I,\forall j\in J,\forall t\in T \qquad (6)$$

$$\sum_i\sum_l z_{ijlt}s_{jl}\ge NS_j \qquad \forall j\in J,\forall t\in T \qquad (7)$$

$$\left(\sum_i\sum_l\sum_t P_{jl}z_{ijlt}q_{ijl}\right)\ge D \qquad j=J \qquad (8)$$

$$\left(\sum_i\sum_l\sum_t P_{jl}z_{ijlt}q_{ijl}\right)-\left(\sum_i\sum_l\sum_t P_{j+1l}z_{ij+1lt}q_{ij+1l}\right)\ge 0 \qquad j=1\ldots J-1 \qquad (9)$$

$$\sum_t z_{ijlt}\le v_{ijl}*T \qquad \forall i\in I,\forall j\in J,\forall l\in L \qquad (10)$$

$$\sum_t z_{ijlt}\ge v_{ijl} \qquad \forall i\in I,\forall j\in J,\forall l\in L \qquad (11)$$

$$\sum_i\sum_j\sum_l tr_{ijl}v_{ijl}\le T_{Total} \qquad (12)$$

$$u_{ij}-\sum_t y_{ijt}\le 0 \qquad \forall i\in I,\forall j\in J \qquad (13)$$

Figure 1. Worker Assignment Model.

4. Experimental Design and Current Results

The purpose of the experimental design is to determine the impact of cross-training and job rotation on the performance of a cellular manufacturing system. The two factors used for this research are: 1) the number of workers trained on additional tasks and 2) the frequency of job rotation. The frequency of job rotation is how often within an eight-hour time period workers are rotated between jobs they are trained to perform. This research uses a full factorial design with five levels of cross-training and three levels of job rotation frequency as seen in Table 2. The worker assignment model investigates the impact different levels of multi-skilling and job rotation have on overproduction, cost of poor quality, and cost of training.

Table 2. Experimental Design

Experiment	Cross-Training Level	Description	Job Rotation Frequency	Description
1	1	All six workers trained on two tasks	1	8-hour rotation
2	1		2	4-hour rotation
3	1		3	2-hour rotation
4	2	33% (2) of all workers trained on 4 tasks	1	8-hour rotation
5	2		2	4-hour rotation
6	2		3	2-hour rotation
7	2	33% (2) of all workers trained on 6 tasks	1	8-hour rotation
8	2		2	4-hour rotation
9	2		3	2-hour rotation
10	2	33% (2) of all workers trained on 8 tasks	1	8-hour rotation
11	2		2	4-hour rotation
12	2		3	2-hour rotation
13	2	33% (2) of all workers trained on all 10 tasks	1	8-hour rotation
14	2		2	4-hour rotation
15	2		3	2-hour rotation
16	3	67% (4) of all workers trained on 4 tasks	1	8-hour rotation
17	3		2	4-hour rotation
18	3		3	2-hour rotation
19	3	67% (4) of all workers trained on 6 tasks	1	8-hour rotation
20	3		2	4-hour rotation
21	3		3	2-hour rotation
22	3	67% (4) of all workers trained on 8 tasks	1	8-hour rotation
23	3		2	4-hour rotation
24	3		3	2-hour rotation
25	3	67% (4) of all workers trained on all 10 tasks	1	8-hour rotation
26	3		2	4-hour rotation
27	3		3	2-hour rotation
28	3	100% (6) of all workers trained on 4 tasks	1	8-hour rotation
29	3		2	4-hour rotation
30	3		3	2-hour rotation
31	3	100% (6) of all workers trained on 6 tasks	1	8-hour rotation
32	3		2	4-hour rotation
33	3		3	2-hour rotation
34	3	100% (6) of all workers trained on 8 tasks	1	8-hour rotation
35	3		2	4-hour rotation
36	3		3	2-hour rotation
37	3	100% (6) of all workers trained on all 10 tasks	1	8-hour rotation
38	3		2	4-hour rotation
39	3		3	2-hour rotation

The first 15 experiments have been run, and the authors are in the process of completing the other experiments. The results to date are shown in Table 3. From the analysis of the current results with $\alpha = 0.05$, it was found that training level is significant (p-value = 0.046), while job rotation frequency is not significant (p-value = 0.314). The next steps will be to compelete the experiments and re-run the factor analysis to determine the effects of training level and job rotation frequency when all of the experiments have been completed.

Table 3. Current Results

Experiment	Training Level	Rotation	NPC
1	1	1	$1,892,326.56
2	1	2	$1,867,990.27
3	1	3	$1,855,322.11
4	2	1	$1,881,239.73
5	2	2	$1,915,083.22
6	2	3	$1,868,364.48
7	2	1	$1,887,830.36
8	2	2	$1,894,092.98
9	2	3	$1,897,056.37
10	2	1	$1,940,338.38
11	2	2	$1,919,295.79
12	2	3	$1,894,532.75
13	2	1	$1,962,329.13
14	2	2	$1,922,834.00
15	2	3	$1,910,259.65

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