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Workforce Assignment with a Different Skill Level for Automotive Parts Assembly Lines

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Abstract. One of the most important operational issues in an assembly line is to allocate workers to tasks (or workstations) so that their workloads can be well-balanced. We address a new workforce assignment problem in an assembly line where workers can perform all tasks but have a different skill level, which affects not only the throughput but also the number of defective products. We derive two mathematical programming models that can be used in various production environments. One is with the objective of the throughput maximization while keeping the defect rate under a given criteria and the other is for the minimization of the total rework time while achieving a given throughput. Several experiments are performed with the proposed two models by changing the number of workers and a proportion of skilled workers. We also compare the two models and provide managerial insights.

Keywords: Workforce assignment problem, different skill level, defect rate, rework time

1 Introduction

Allocating tasks to assembly lines in order to optimize a certain objective is called an assembly line balancing problem (ALBP), which was introduced in 1955 [1]. The problem has been known to be NP-hard due to its high complexity [2]. A basic problem of ALBP is called a ‘simple ALBP’, which does not consider the skill difference of workers and only assigns one worker to each workstation [3]. Most previous studies on worker assignment problems have assumed homogeneous worker skills, and less attention has been paid to the quality problem caused from heterogeneous performance levels of workers [4]. There have been a few approaches on assigning workers with different skill levels to tasks, which was known as an assembly line worker assignment and balancing problem (ALWABP) [5][6]. They typically consider two objectives, which are the minimization of the number of workers while achieving a given cycle time (ALWABP-1) and the minimization of the cycle time with a given number of workers (ALWABP-2) [4][6]. These studies have assumed that only one worker is assigned to

each task, and there have recently been some studies that consider tasks requiring multiple workers [7][8].

We address a workforce assignment problem for multiple assembly lines for automotive parts where products are assembled while moving on a paced conveyor belt. The assembly process consists of multiple operations, each of which is composed of several tasks. Workers can perform all the tasks but have a different skill level. Multiple workers, at most M_{max} workers, can be assigned to a task. The number of assigned workers and their skill levels affect the throughput and defect rate of the task. After a product is assembled, its quality is checked, and rework is done if any defect exists. Hence, we need to assign workers to tasks efficiently in order to maximize the throughput or minimize the total rework time.

2 Problem Definition

This assignment problem takes place in multiple wiring harness assembly lines. The wiring harnesses are the organized sets of wires, terminals, and connectors that run throughout the entire vehicle. Each assembly line consists of three operations, cable grapping, clipping, and taping, which are performed sequentially, and each operation consists of multiple tasks. The task time and the number of defects in each task depends on the number of assigned workers, their skill levels, and characteristics of vehicles assembled.

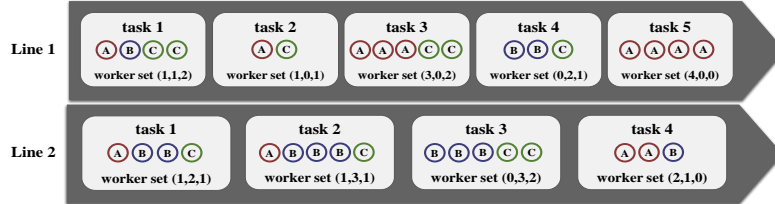


Fig. 1. Example of assigning workers to tasks

Fig. 1 shows an example of two assembly lines that have five and four heterogeneous tasks, respectively. The skill levels are divided into three, A, B, and C, and the number of assigned workers in each level, called a worker set, is represented as well. The workload of these tasks is all different depending on product types assigned to each line. If we assign more highly skilled workers to a task, the task time can be reduced significantly, which increases the throughput, and the defect rate of the task can also be reduced. In this problem, we assume that workers in the same skill level have the same performance. We also assume that the throughput and defect rate of a task are deterministic functions of a worker set, which will be discussed in Section 3.1.

After a product is assembled in a line, its quality is checked, and the rework is performed if a defect is observed. This procedure is done by some specified workers who are not considered in the problem. Rework of defective products is an inefficient process which lowers the productivity, thus it is reasonable to consider the minimization

of the total rework time as the objective in our problem. We also consider the throughput as another objective. The assembly lines we assume have many workers who are often absent without notice and leave the workplace during working hours. Hence, an efficient assignment of workers needs to be made frequently, several times a day, while considering various skill levels of workers and the remaining number of workers.

3 Approach

3.1 Problem Formulation

Table 1 shows the parameters and decision variables we use.

Table 1. Notations for problem formulation

Indices & Sets	
$i \in I$	Index of lines
$j \in J$	Index of tasks
$k \in K$	Index of worker sets
$l \in L$	Index of skill levels
Parameters	
M_{kl}	Number of workers with skill level l in worker set k
N_l	Number of workers with skill level l
TH_{ijk}	Throughput of task j in line i when performed by worker set k
f_{ijk}	Defect rate of task j in line i when performed by worker set k
A	Upper limit of the defect rate
r_{ij}	Rework time for task j in line i
D_i	Daily demand assigned to line i
t	Daily operating hour of factory
Decision Variable	
x_{ijk}	1 if task j in line i is performed by worker set k , and 0 otherwise

<p>Model 1 (throughput maximization)</p> $\text{maximize } \min_{i,j} \left(\sum_k TH_{ijk} x_{ijk} \right)$ <p>s.t. $\sum_k x_{ijk} = 1, \quad \forall i \in I, j \in J \quad (1)$</p> $\sum_{i,j,k} x_{ijk} M_{kl} = N_l, \quad \forall l \in L \quad (2)$ $\sum_k f_{ijk} x_{ijk} \leq \alpha, \quad \forall i \in I, j \in J \quad (3)$	<p>Model 2 (rework time minimization)</p> $\text{minimize } \sum_{i,j,k} r_{ij} D_i f_{ijk} x_{ijk}$ <p>s.t. $\sum_k x_{ijk} = 1, \quad \forall i \in I, j \in J \quad (4)$</p> $\sum_{i,j,k} x_{ijk} M_{kl} = N_l, \quad \forall l \in L \quad (5)$ $\sum_k TH_{ijk} x_{ijk} t \geq D_i, \forall i \in I, j \in J \quad (6)$
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The proposed two models have the following objectives; one is to maximize the minimum throughput of assembly lines and another is to minimize the total daily rework time. Two models share some constraints; Constraints (1) and (4) and Constraints (2) and (5) are the same. Constraint (1) indicates that one worker set must be assigned to each task in a line, and Constraint (2) is used to ensure that the number of workers assigned to each task is equal to the total number of workers we have. Constraint (3) restricts the maximum defect rate that needs to be achieved in Model 1, and Constraint (6) controls the minimum throughput to meet the daily demand.

A worker set indicates the number of workers in each skill level, and one worker set is assigned to a task. For example, a worker set (2,0,1) for a task means that 2 workers in level A, 0 worker in level B, and 1 worker in level C are assigned to the task. The workers who are absent or leave the workplace are considered when counting the number of workers and creating worker sets in the models.

3.2 Estimation of throughput and defect rate

The throughput and defect rate of each worker set are calculated by considering the fact that as more workers are assigned, the task time is reduced and less mistake is made. We assume that a worker with level A is 15% faster than a level B worker, and 29% faster than a level C worker, based on the data we have and interviews with production managers. We then designed a simple linear model to express the throughput $TH_{ij(n_A, n_B, n_C)}$ of worker set (n_A, n_B, n_C) where $n_A, n_B,$ and n_C are the numbers of workers in levels A, B and C, respectively.

$$\begin{aligned} TH_{ij(n_A, n_B, n_C)} &= n_A TH_{ij(1,0,0)} + n_B TH_{ij(0,1,0)} + n_C TH_{ij(0,0,1)} \\ &= \left(n_A + \frac{1}{1.15} n_B + \frac{1}{1.29} n_C \right) TH_{ij(1,0,0)} \end{aligned} \quad (7)$$

However, the throughput does not increase infinitely and tops out at a certain point in practice. Hence, we use a square root transformation with ϵ for considering randomness in the model.

$$TH_{ij(n_A, n_B, n_C)} = \sqrt{n_A + \frac{1}{1.15} n_B + \frac{1}{1.29} n_C} \times TH_{ij(1,0,0)} + \epsilon \quad (8)$$

We can now calculate the throughput of all tasks for each worker set if $TH_{ij(1,0,0)}$ is given. In a similar way, we assume that a defect rate of a level A worker is reduced by 20 and 43% compared to a level B and C worker, respectively. For the defect rate $f_{ij(n_A, n_B, n_C)}$ of a worker set (n_A, n_B, n_C) , we have the following.

$$f_{ij(n_A, n_B, n_C)} = \frac{f_{ij(1,0,0)}}{\sqrt{n_A + 0.8n_B + 0.57n_C}} + \epsilon \quad (9)$$

4 Result

The proposed models were solved by using ILOG CPLEX 12.10. We assume that the factory runs 8 hours a day, with 8 assembly lines each of which has 9 different tasks. There are 55 possible worker sets when the maximum number of workers (M_{max}) is 5.

Table 2. Experimental results (TH in unit/hour, Rework in hour)

WCR	Distribution of worker skill levels (A : B : C)														
	Distribution 1 (4.5 : 1 : 4.5)					Distribution 2 (3 : 4 : 3)					Distributon 3 (2 : 6 : 2)				
	Model 1		Model 2		TH/Rework	Model 1		Model 2		TH/Rework	Model 1		Model 2		TH/Rework
	TH	Rework	TH	Rework		TH	Rework	TH	Rework		TH	Rework	TH	Rework	
100%	74.25	13.68	68.36	13.18	11.83	74.25	13.51	68.06	13.15	16.96	74.25	13.44	68.84	13.13	16.93
95%	74.25	14.06	68.36	13.52	10.93	74.25	14.00	68.36	13.49	11.44	74.25	13.82	62.96	13.46	31.40
90%	74.25	14.48	67.26	13.90	11.88	74.25	14.36	66.36	13.86	15.73	74.25	14.26	66.51	13.83	17.93
85%	74.25	14.75	62.08	14.30	27.25	74.25	14.70	61.67	14.26	28.35	74.25	14.65	61.67	14.23	30.17
80%	74.25	15.17	60.64	14.74	31.50	74.25	15.17	60.64	14.70	28.92	74.25	15.13	60.64	14.67	29.26
75%	74.25	15.68	56.23	15.22	39.39	74.25	15.61	56.23	15.18	42.06	73.81	15.54	55.87	15.15	46.08
70%	71.89	16.22	54.90	15.76	36.86	71.78	16.16	54.52	15.71	38.56	71.44	16.08	54.52	15.68	42.87
65%	68.78	16.82	52.70	16.35	34.39	68.78	16.73	52.70	16.30	37.68	68.56	16.68	52.70	16.27	38.68
60%	65.60	17.46	47.74	17.02	40.64	65.60	17.38	47.74	16.97	43.65	64.78	17.32	47.74	16.94	44.57
55%	62.02	18.16	46.16	17.78	41.27	62.02	18.13	46.16	17.73	38.86	61.67	18.06	46.16	17.69	42.52
50%	58.07	18.95	46.96	18.65	36.42	58.07	18.93	46.96	18.59	33.25	56.75	18.85	46.94	18.56	33.60
45%	50.93	19.90	44.98	19.66	24.98	53.05	19.84	44.98	19.60	33.31	50.97	19.79	44.52	19.56	28.42
40%	inf.	inf.	43.29	20.86	-	inf.	inf.	43.29	20.79	-	inf.	inf.	41.44	20.75	-
35%	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-
30%	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-
25%	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-
20%	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-	inf.	inf.	inf.	inf.	-

*inf. : infeasible

The defect rate, α , is set to 0.04, and the rework time for each task, which is independent from the worker assignment of the assembly line, is randomly generated from $N(80, 16)$ where $N(\mu, \sigma)$ is a normal distribution with the mean of μ and standard deviation of σ . The daily demand of each line D_i is 320 for all lines, and $TH_{ij(1,0,0)}$ and $f_{ij(1,0,0)}$ for all i and j are randomly generated from $N(100, 10)$ and $N(5, 0.005)$, respectively.

Since we consider absenteeism of workers, the total number of workers at assembly lines varies every day. There are 72 tasks (8 lines * 9 tasks) where each task may contain up to 5 workers, so at most 360 workers can be hired in the whole assembly line. We denote the ratio of the total number of workers we have to 360 as a worker capacity ratio (WCR). The experiments are performed by changing WCR from 20 to 100%, and the results are shown in Table 2. When WCR is small (i.e., less than 40%), the problem becomes infeasible because the demand and defect rate constraints cannot be satisfied. When WCR is larger than or equal to 80%, the throughput is the same with Model 1 regardless of the worker skill ratios. We can also observe that as the number of level C workers becomes smaller, the throughput and rework time are enhanced.

The ratio of the throughput difference to the rework time difference from the two models, denoted as TH/Rework in Table 2, is computed by (throughput from Model 1 – throughput from Model 2)/(rework time from Model 1 – rework time from Model 2).

This value means a tradeoff between objective values of Models 1 and 2, and Model 1 becomes more favorable in a high TH/Rework condition. As WCR is smaller, TH/Rework becomes larger, which means that the rework time reduction from using Model 2 becomes much smaller than the throughput improvement from Model 1 when the number of workers we have is small. Hence, when WCR is large, it is more reasonable to use Model 2, and Model 1 is appropriate when WCR is relatively small.

5 Conclusion

In this study, the two optimization models were presented to address the workforce assignment problem. Worker sets are assigned to each task in a line to maximize the throughput or minimize the total rework time. The throughput and defect rate of each worker set have been computed by analyzing product data and used in the formulation. We then compared the two models and provided some managerial insights. In the future, an efficient algorithm needs to be developed to handle a large-sized problem.

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