Estonian Journal of Engineering, 2009, **15**, 1, 34–47 doi: 10.3176/eng.2009.1.04

Labour assignment and workload balance evaluation for a production line

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Received 26 August 2008

Abstract. The paper describes a study of a real production line located in North America. A method has been developed to help quick and yet efficient assignment of labour to a production line. The labour assignment tables show cycle time and labour efficiency in accordance with the assignment. Regression analysis of the data in the tables shows that the dependence of the cycle time and labour efficiency are negatively exponential to the number of assigned workers. The exponents in the models can be employed as a balance index to evaluate the workload balance of the production line.

Key words: cycle time, labour assignment, labour efficiency, workload balance.

1. INTRODUCTION

Make-to-order manufacturing has been challenging the manufacturing industry for decades. Different from traditional manufacturing, make-to-order manufacturing produces only items ordered by customers. The uncertainty of product ordering brings up many issues that production line managers have to face. For example, because the exact production order is not known beforehand due to the uncertainty, a line manager is always short of time to study the production order for efficient labour assignment and less-delay-time production scheduling. Therefore, practically useful tools are needed to iron out these issues.

Ever since the recognition of Toyota’s successful lean manufacturing practice, many methods have been tried to improve workload balance in production lines in order to achieve greater production flexibility and to increase labour efficiency. Such research has various focuses in areas such as theoretical analysis [1,2], optimization algorithms [3,4], production flexibility [5,6], workload balancing [7,8], cellular manufacturing design [9,10], etc. It surely provides theory, algorithms, production line design ideas, as well as workable concepts to the industry. The production line managers, however, may have more interest in a handier tool for their daily production administration.

In this paper, the actuality of a production line in a manufacturing firm located in North America has been studied in order to find tools to ease and yet optimize the workload assignment. In this regard, a workload assignment table was developed to give optimized labour assignments. With the table, a line manager is able to quickly and yet optimally assign labour to the production line in regard to the change of the production order. In the study, the workload balance index was found to serve as a measure to evaluate workload balance in the production line. This quantifies the workload balance so that the places where more improvement is needed become obvious. With these two tools, a line manager will be more capable in managing a production line.

2. CREATING THE LABOUR ASSIGNMENT TABLE

2.1. The production line

The studied production line had 52 work shares in the entire line as shown in Fig. 1. Time standards of these 52 work shares were well studied and established. As shown in Fig. 1, the entire line was composed by the main assembly line

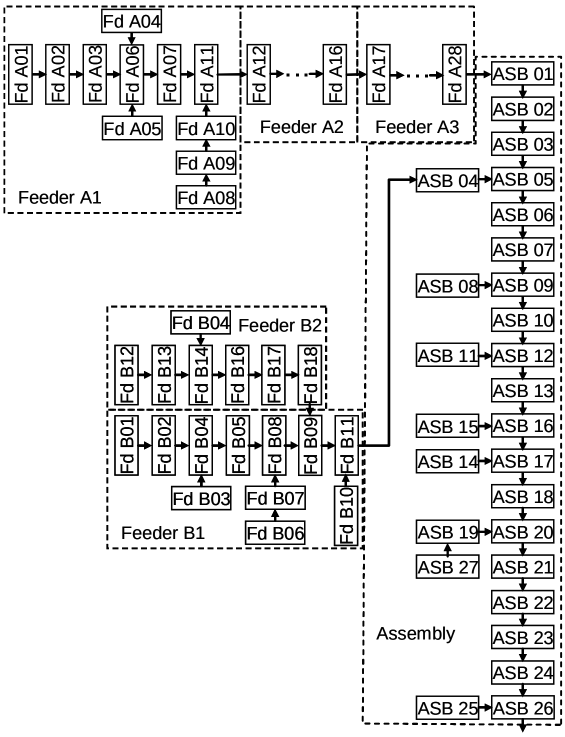

Fig. 1. Flow chart of the production line.

(ASB) and two feeder lines (FdA and FdB). The two feeder lines were divided into groups, in which workloads were not shared due to the line layout. Therefore there were six groups or sublines in the entire production line, counting the main assembly line as a subline. Depending on the number of workers, assigned to the line, the production rate (units/h), which could also be expressed as cycle time (min/unit), varied accordingly. In a make-to-order set-up, the number of workers, assigned to the line, depends on the demand from the market. When fewer workers were assigned, work shares were combined to a worker; in contrast, a work share can be taken care by more than one worker.

2.2. Labour assignment tables for sublines

At minimum, at least one worker was needed in a subline due to the physical set-up. Since the worker was supposed to handle all work shares in the subline, no delay was expected. The labour efficiency was 100% and the cycle time was the sum of time standards of all work shares.

Workers were assigned to the subline one by one afterwards. The workload was shared by the assigned workers. The sharing was attempted the best evenness possible wherever realistically feasible. The so designed labour assignment for the six sublines is shown in Tables 1–3.

No matter how many workers worked in a subline, there would be at least one bottleneck, in which the workload took the longest time. This workload time is apparently the time needed for a part to exit the subline and thus is the cycle time T_c of that subline with n workers

$$T_c = \max(t_i), \quad i = 1, 2, \ldots, n. \tag{1}$$

In Eq. (1), t_i is the ith work load. For each part, the value added time is the sum of time standards of all work shares Σt_i while the paid work time is nT_c. Therefore the labour efficiency E is

$$E = \frac{\sum t_i}{nT_c} \times 100. \quad \% \tag{2}$$

Since it was the bottleneck, where the cycle time was hold, it was the place that additional labour should be assigned to. If there were more than one bottlenecks, more than one worker had to be added simultaneously. In Table 2, for example, the number of workers jumps from 7 to 9, because there were two bottlenecks when seven workers worked in Feeder B1.

In this production line, the workload of some work shares allowed two workers to work on it simultaneously and therefore, the standard time of that work share was diminished twice. This was necessary when a single work share became a bottleneck as shown in Table 1 for Feeder A2. Because of this, adding more workers to the subline could become endless and thus this table developing process had to be ended as desired. If the work share otherwise did not allow more than one worker working on it, no more workers should be added.

Table 1. Workload balance table for feeder line A

Feeder A Group 1	Time Std, s	No of workers 1	2	3	4	5	6	7
Fd A01	1/8	274						26
Fd A02	26			99	68			
Fd A03	42		123				42	42
Fd A04	31						31	31
Fd A05	24					50	50	
Fd A06	22		151		53	64	45	45
Fd A07	23					54		
Fd A08	22			78	78	54	54	46
Fd A09	11							32
Fd A10	21							
Fd A11	52			97	75	52	52	52
Cycle time, s		274	151	99	78	64	54	52
Labour eff., %		100	91	92	88	86	85	75

Feeder A Group 2	Time Std, s	No of workers 1	2	3	4
Fd A12	29				
Fd A13	11		95	47	47
Fd A14	7	149			
Fd A15	48			48	48
Fd A16	54		54	54	54/2
Cycle time, s		149	95	54	48
Labour eff., %		100	78	92	49

Feeder A Group 3	Time Std, s	No of workers 1	2	3
Fd A17	15	128		
Fd A18	14			45
Fd A19	11			
Fd A20	5		59	
Fd A21	8			
Fd A22	6			34
Fd A23	12		69	
Fd A24	8			
Fd A25	16			
Fd A26	16			49
Fd A27	9			
Fd A28	8			
Cycle time, s		128	69	49
Labour eff., %		100	93	87

* Workloads with same shading are assigned to one worker.
** Arrows show the work flows.

Table 2. Workload balance table for feeder line B

Feeder B Group 1	Time Std, s	No of workers											
		1	2	3	4	5	6	7	9	10	11	12	13
Fd B01	56				116		56	56	56	56	75	75	75
Fd B02	9			155			60	60			2	2	2
Fd B03	51					107			51	51	51	51	51/2
Fd B04	50					104	95	95	59	59	50	50	50
Fd B05	45								45	45	45	45	45
Fd B06	55	483	214	154	98	98	98	55	55	55	55	55/2	55/2
Fd B07	43							43	43	43	43	43	43
Fd B08	38				133	79	79	79	79	38	38	38	38
Fd B09	41		269	174	136					41	41	41	41
Fd B10	50					95	95	95	50	50	50	50	50
Fd B11	45								45	45	45	45	45
Cycle time, s		483	269	174	136	107	98	95	79	59	55	51	50
Labour eff., %		100	90	93	89	90	82	73	68	82	69	59	74

Feeder B Group 2	Time Std, s	No of workers				
		1	2	3	4	5
Fd B12	18				43	43
Fd B13	25		79			
Fd B14	20				36	36
Fd B15	16	168		59		
Fd B16	35			55	35	35
Fd B17	19		89	54	54	19
Fd B18	35					35
Cycle time, s		168	89	59	54	43
Labour eff., %		100	94	95	78	78

* Workloads with same shading are assigned to one worker.
** Arrows show the work flows.

Table 3. Workload balance table for the assembly line

ASB	Time Std, s	No of workers											
		1	2	3	4	5	6	7	8	9	10	11	12
ASB 01	12								50	50	50	50	50
ASB 02	38						79	68					
ASB 03	18					99							
ASB 04	11				128				55	55	55	49	49
ASB 05	20			172									
ASB 06	6							71					
ASB 07	23		252				93					40	40
ASB 08	11					85			67				
ASB 09	33									56	56	45	45
ASB 10	12							65		43	43		
ASB 11	20				124		80		38			26	26
ASB 12	6									48	48		
ASB 13	42											42	42
ASB 14	6	462		139		91							
ASB 15	6							71	65				
ASB 16	5									59	32	32	32
ASB 17	6												
ASB 18	9												
ASB 19	27										39	39	39
ASB 20	12		210										
ASB 21	40						84	61	61	59	47	47	40
ASB 22	7												
ASB 23	7												21
ASB 24	7			151	99	99	59	59	59	52	52	52	
ASB 25	7												38
ASB 26	31												
ASB 27	40				111	88	67	67	67	40	40	40	40
Cycle time, s		462	252	172	128	99	93	71	67	59	56	52	50
Labour eff., %		100	92	90	90	93	83	93	86	87	83	81	77

* Workloads with same shading are assigned to one worker.
** Arrows show the work flows.

2.3. The labour assignment table for the entire line

Table 4 pools together the number of workers, the corresponding cycle time and labour efficiency from all sublines. It helped to develop a table for the entire production line (Table 5). Since no one could work in two sublines, there was at

Table 4. The labour assignment table for sublines

n	Cycle time, s						Labour efficiency, %					
	Fd A1	Fd A2	Fd A3	Fd B1	Fd B2	Asb	Fd A1	Fd A2	Fd A3	Fd B1	Fd B2	Asb
1	274	149	128	483	168	462	100	100	100	100	100	100
2	151	95	69	269	89	252	90.8	78.4	92.8	89.8	94.3	91.7
3	99	54	49	174	59	172	92.2	92.0	87.1	92.5	94.9	89.5
4	78	48		136	54	128	87.9	49.5		88.9	77.8	90.2
5	64			107	43	99	85.7			90.3	78.1	93.3
6	54			98		93	84.6			82.1		82.8
7	52			95		71	75.3			72.6		93.0
8				–		67				–		86.2
9				79		59				67.9		87.0
10				59		56				81.9		82.5
11				55		52				69.1		80.8
12				51		50				59.3		77.0
13				50						74.3		

Table 5. Labour assignment table of the entire production line (shadings show the bottlenecks)

No of workers in sublines						*n*	T_c	*E*
Fd A1	Fd A2	Fd A3	Fd B1	Fd B2	Asb			
1	1	1	1	1	1	6	483	57.4
1	1	1	2	1	1	7	462	51.5
1	1	1	2	1	2	8	274	75.9
2	1	1	2	1	2	9	269	68.7
2	1	1	3	1	2	10	252	66.0
2	1	1	3	1	3	11	174	86.9
2	1	1	4	1	3	12	172	80.6
2	1	1	4	1	4	13	168	76.2
2	1	1	4	2	4	14	151	78.7
3	1	1	4	2	4	15	149	74.5
3	2	1	4	2	4	16	136	76.5
3	2	1	5	2	4	17	128	76.5
3	2	2	5	2	5	19	107	81.8
3	2	2	6	2	5	20	99	84.0
4	2	2	6	2	6	22	98	77.2
4	2	2	7	2	6	23	95	76.2
4	3	2	9	2	6	26	93	68.8
4	3	2	9	2	7	27	89	69.2
4	3	2	9	3	7	28	79	75.2
4	3	2	10	3	7	29	78	73.6
5	3	2	10	3	7	30	71	78.1
5	3	2	10	3	8	31	69	77.8
5	3	3	10	3	8	32	67	77.6
5	3	3	10	3	9	33	64	78.8
6	3	3	10	3	9	34	59	83.0
6	3	3	11	4	10	37	56	80.3
6	3	3	11	4	11	6	483	57.4
6	3	3	12	4	11	7	462	51.5
7	4	3	12	5	11	8	274	75.9

least one worker in a subline. This started the development of Table 5. The bottleneck of the entire line laid in the subline, which had the longest cycle time. Additional labour was assigned to the bottleneck to reduce the cycle time. This repeated until it reached the desired number of workers. The cycle time in the table comes from the bottleneck sublines and the labour efficiency is calculated from Eq. (2) when applied to the entire line.

Table 5 was created to show how labour was best assigned and how cycle time and labour efficiency responded accordingly. When given a production task T_c, a line manager can quickly find how many workers are needed and what labour efficiency can be expected as the best by looking at this table. The manager can also know how to assign workers to the sublines by checking with the subline tables. Or, if a month production task is given, a line manager can use this table and subline tables to schedule the daily production for the best possible labour efficiency.

2.4. Plot of the cycle time and labour efficiency against the number of workers

The cycle time and labour efficiency were plotted against the number of workers as shown in Figs. 2 and 3 for sublines and in Fig. 4 for the entire

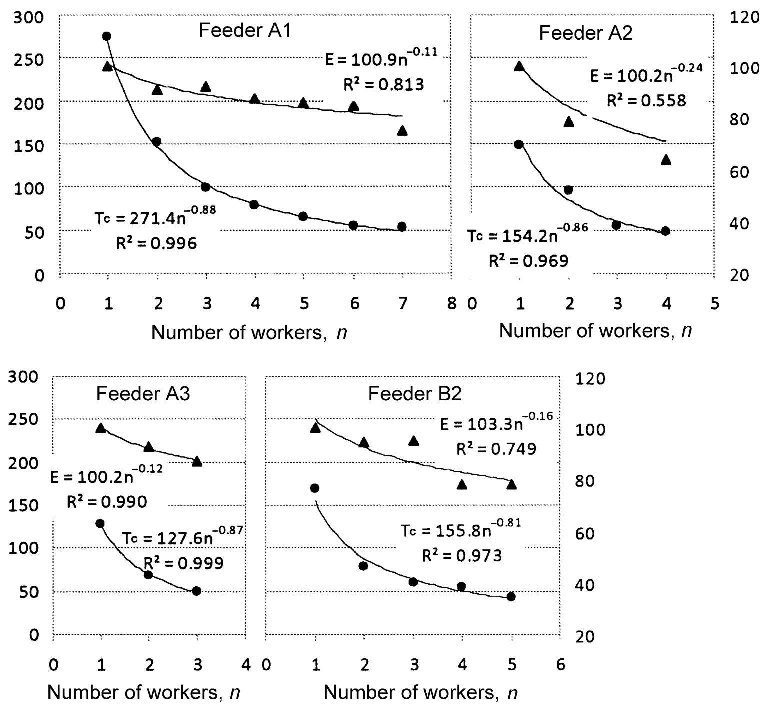

Fig. 2. Dependence of cycle time (left axis) and labour efficiency (right axis) on the number of workers for sublines A1, A2, A3 and B2.

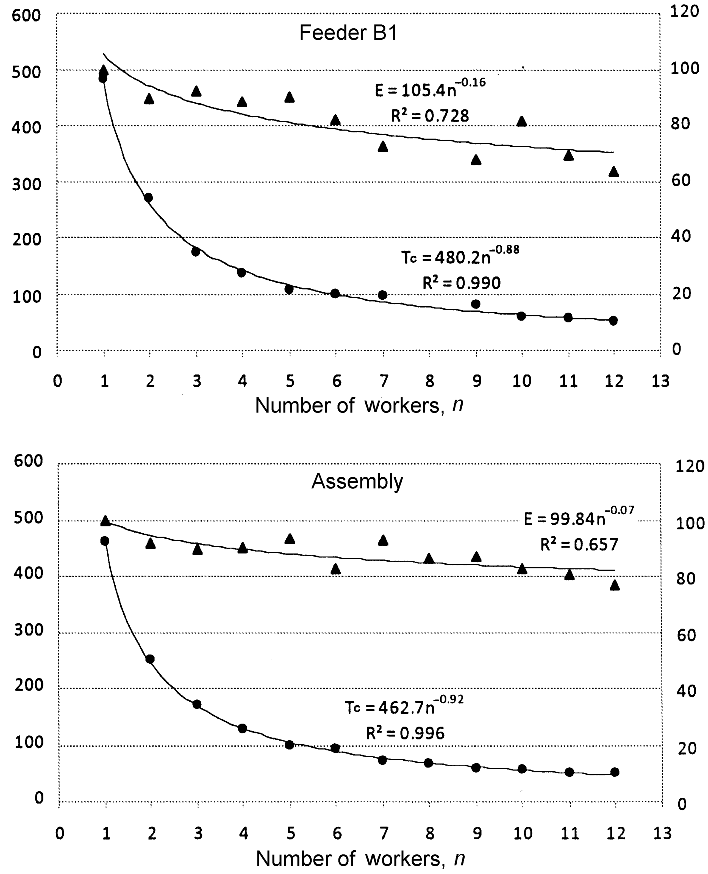

Fig. 3. Dependence of cycle time (left axis) and labour efficiency (right axis) on the number of workers for sublines B1 and Assembly.

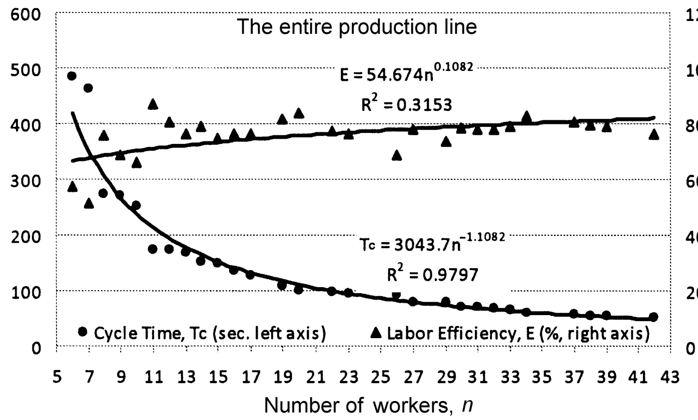

Fig. 4. Dependence of cycle time (left axis) and labour efficiency (right axis) on the number of workers for the entire production line.

production line. In these plots, the left vertical axis denotes cycle time and the right one denotes labour efficiency. Regression was applied to all plots. The resulted regression equations, along with the regression R-square values, were placed next to the regression lines from which they were derived. The cycle time regression models fitted very well to the plots. Though all labour efficiency regression models do not have the same high fitness as in the cycle time models, most of them show a good fit.

3. DISCUSSION

From Figs. 2 and 3, the regression models of the cycle time T_c on the number of workers n can be expressed as

$$T_c = \frac{T}{n^b}. \tag{3}$$

Values of T and b vary in different sublines. When $b = 1$, Eq. (3) is reduced to

$$T_c = \frac{T}{n}. \tag{4}$$

Equation (4) actually reflects such a labour assignment when the workload is absolutely evenly assigned (T is taken as the total workload of the line). Workloads of sublines are thus compared to the T values from the regression models. As shown in Table 6, T values from these two sources match each other. The small difference is reasonable and might be caused by the error of regression. Equation (3) hence can be considered as a theoretical model for the dependence of the cycle time on the number of workers with T denoting the total workload. Since $b = 1$ is for a perfect labour assignment, it can be reasonably assume that the closer to 1 is the value of b, the better is the subline balanced. Therefore the value of b can be taken as a balance index for measuring the workload balance of a production line.

When substituting T_c in Eq. (2) by Eq. (3), the labour efficiency becomes

$$E = \frac{100}{n^{(1-b)}}\%. \tag{5}$$

Table 6. Comparison of the real values of *T* with those from regression analysis

	Sublines					
	Fd A1	Fd A2	Fd A3	Fd B1	Fd B2	Asb
Regression	271.4	154.2	127.6	155.8	480.2	462.7
Reality	274	149	128	168	483	462

Table 7. Numerators and exponents in labour efficiency regression models

From regression	Sublines					
	Fd A1	Fd A2	Fd A3	Fd B1	Fd B2	Asb
Numerator	100.9	100.2	100.2	103.3	105.4	99.84
$1-b\ (E)$	0.11	0.24	0.12	0.16	0.16	0.07
$b(T_c)$	0.88	0.86	0.87	0.81	0.88	0.92
$(1-b)+(b)$	0.99	1.01	0.99	0.97	1.04	0.99

This model is in agreement with the regression results. As shown in Table 7 (see also Figs. 2 and 3), the numerators in the regressed labour efficiency equations are all close to 100. The exponents $(1-b)$ of n, when added with the exponents b of n in the regressed cycle time equations, are all close to 1, as can be expected in Eqs. (3) and (5). This adds trustfulness to the models expressed by Eqs. (4) and (5).

4. USAGE OF THE LABOUR ASSIGNMENT TABLE

In make-to-order manufacturing, daily production order varies both by the variety in the types of items and their number. In a various-product case, the Heijunka technique can be applied to have the ordered products grouped so that one single product is processed at a time [11]. Since a major change of the hardware configuration in a production line is neither affordable nor feasible, manipulating labour assignment to the line is likely the only option to accommodate the change. The labour assignment table developed in this study is a handy tool to help in such labour assignment. It can be used in a daily routine work to quickly assign labour to the line to start a day's work and the labour efficiency found in the table can be applied to evaluate the performance at the end of the day. For example, when asked to make 300 units of a product in a shift of seven working hours, the following can be quickly found. For there are 25 200 seconds in 7 hours, the required cycle time has to be no more than 25 200 seconds per 300 units or 84 s/unit. In Table 5 the closest capable cycle time is 79 s/unit with a total of 28 workers and 75.2% labour efficiency. The workload assignment of the 28 workers can then be quickly allocated (Table 8) as indicated in the workload assignment tables for sublines.

The labour efficiency provided in the table is a useful tool to pertinently measure the performance of the production line. Due to the fluctuation of labour efficiency, as shown in Fig. 4, the expected actual labour efficiency has to be changed accordingly. Therefore, instead of measuring labour efficiency against 100% as we normally do, the author of this study suggests to measure it against the expected value. In the above example, we know that the expected labour efficiency is only 75.2% for the entire production line. If the actual efficiency ends up at 74%, we may feel frustrated when comparing it to 100%. It, however, is actually 98.4% when compared to the expected 75.2%.

In the case when production can be planned for a certain period of time, say a week, the labour assignment table can be employed for scheduling to pursue the highest possible labour efficiency. When being assigned to produce 1300 units in a week of 5 working days, for instance, one can first find out that the required average cycle time is 96.9 s/unit, counting 7 working hours in a day. Table 5 shows that the closest capable cycle time is 95 s with 23 workers and 76.2% labour efficiency. The work order, however, does not have to be evenly spread out in five days. To achieve higher labour efficiency, the number of workers can be selected from those with higher labour efficiency, for instance, larger than 80%. Table 9 lists some options. All these combinations have labour efficiency over 80%, better than simply spreading out the workload into five days. A manager can decide to adapt one of them in accordance with other production tasks of the same production line as well as other production lines. Or, simply select combination 3 to achieve the highest possible labour efficiency. Because

Table 8. Labour assignment in sublines for producing 300 units in 7 working hours

	Fd A1	Fd A2	Fd A3	Fd B1	Fd B2	Asb
Workers	4	3	2	9	3	7
Cycle time, s	78	54	69	79	59	71
Labour efficiency, %	88	92	93	68	95	93

Table 9. Some scheduling options for manufacturing 1300 units in 5 days with high labour efficiency

	Number of workers	Cycle time, s	Labour efficiency, %	Production capability, unit/d	Needed days	No of units to be made	Average *E*, %
Comb 1	34	59	83	427	4	1708	83
Comb 2	37	56	80.3	450	3	1350	80.3
Comb 3	11	174	86.9	145	3	1335	84.26
	37	56	80.3	450	2		
Comb 4	19	107	81.8	236	2	1326	82.4
	34	59	83	427	2		
Comb 5	34	59	83	427	2	1304	82.1
	37	56	80.3	450	1		
Comb 6	34	59	83	427	1	1327	81.2
	37	56	80.3	450	2		
Comb 7	12	172	80.6	147	1	1302	81.3
	20	99	84	255	1		
	37	56	80.3	450	2		
Comb 8	19	107	81.8	236	1	1345	82.95
	20	99	84	255	1		
	34	59	83	427	2		

producing exactly 1300 units in a number of full days is not likely, the time left after making the 1300th unit on the last day can be scheduled for another production task.

5. CONCLUSIONS

The developed labour assignment tables can be used for the best possible workload balance. This predetermined workload assignment information is helpful to the administration in manipulating daily labour assignments against the make-to-order production tasks. Obviously, they can also be helpful in scheduling a long-term production plan.

Strongly supported by the experimental data, the suggested balance index *b* is able to quantify the perfection of workload balance in a production line. This is a powerful tool by managing workload balancing in production lines.

Both the cycle time and the labour efficiency models can be applied to predict cycle time and labour efficiency for a given number of workers. As the models indicate, cycle time and labour efficiency drop quicker when the number of workers is smaller and then slow down when the number of workers becomes bigger. When the number of workers increases to a certain level, both the cycle time and labour efficiency tend to stay almost constant. This indicates that increasing the number of workers over the optimum one can no longer significantly change neither the cycle time nor the labour efficiency.

This study was based on a specific production line. Although the results can be partly used in other similar cases, it is not necessarily applicable to other set-ups. The obtained models do not well match the regression model of the entire production line as shown in Fig. 4. This might be due to the difference between lines with and without feeders. Therefore, further research is needed to explore different production lines.

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Tööülesannete ning kvantitatiivse töökoormuse tasakaalu hindamine tootmisliinil

Luke H. Huang

On välja töötatud kiire ja efektiivne meetod tootmisliini tööjõuvajaduse planeerimiseks. Regressioonianalüüsi põhjal leiti, et tsükliaeg ja töö efektiivsus on liinitöötajate arvust negatiivses eksponentsiaalses sõltuvuses. Nii saadud mudelite järku saab kasutada tasakaaluindeksina, hindamaks tootmisliini koormuse tasakaalustatust. Metoodikat testiti praktikas Põhja-Ameerikas paikneval tootmisliinil. Katsetulemused näitasid tsükliaja ja tööefektiivsuse vastavust mudeli prognoosile.