Practical Assembly-Line Balancing in a Monitor Manufacturing Company

Parames Chutima and Haruetai Suphapruksapongse
Department of Industrial Engineering, Chulalongkorn University,
Bangkok 10330, Thailand

Abstract

The objective of this research is to demonstrate a practical approach to balance and synchronize a monitor assembly line which is characterized by several manufacturing constraints. The constraints as such could lower production rates of the line if they are not considered as integrated parts of the whole system. The research begins with manufacturing constraint analysis to identify which one has the most impact and governs the productivity of the line. The output of the analysis is then used for comparing the efficiency between single-model assembly line balancing and multi-model assembly line balancing approaches. In addition, the algorithms to balance the line, i.e. COMSOAL and the current factory method, are compared. The research enquiry is investigated by computer simulation. An experimental design with 3 factors, namely line balancing methods, line balancing algorithms, and conveyor speeds, are conducted to evaluate the significance of the factors measured by the number of stations, line efficiency, output, and throughput time. It is found that the number of stations used in the multi-model assembly line balancing is less than the single-model one. In addition, the line balancing methods and line balancing algorithms provide significant enhancements to line efficiency, output, and throughput time. The multi-model assembly line balancing combined with COMSOAL method contributes to higher line efficiency, higher output, and less throughput time. Moreover, the conveyor speeds only influence the throughput time, without any impact on line efficiency and output.

Key words: Multi-model line-balancing, Computer simulation.

1. Introduction

An assembly line comprises a finite set of work elements sometimes called tasks. Each task is characterized by an operation processing time and a set of precedence relationships, which specify the allowable orderings of the tasks. Assembly line balancing (ALB) is the process of allocating a group of tasks to be performed on an ordered sequence of workstations in such a manner that all workstations have approximately an equal amount of assigned workload to optimize some measures of performance, e.g. minimize the number of workstations, minimize cycle time, minimize the balance delay, or optimize the combination of the aforementioned objectives, without violating precedence relationships.

Typical constraints that must be considered while attempting to group tasks and allocate them to each workstation when designing the assembly line include: (1) Precedence relationships; (2) The number of workstations cannot be less than the number of tasks and the minimum number of workstations is one; (3) The cycle time must be greater than or equal to the maximum of any workstation time and the time of any task. In other words, the workstation time must not exceed the cycle time.

The ALB problems can be broadly classified into 2 categories: single model line balancing (SMLB) and multi/mixed model line balancing (MMLB). The SMLB is the classical and simplest form of the ALB problems. This version assumes dedicated, single-model assembly lines where task times can be deterministically or stochastically obtained, and a performance measure is to be optimized. In contrast, the MMLB version assumes deterministic or stochastic task times, but the assembly line is allowed to produce multiple products. In multi-model lines, two or more products are assembled separately in batches, whereas in mixed-model lines, single units of different models can be produced in any order or mix to the line. However, when batch size is one, the two definitions are overlapped. As a result, it is appropriate to consider both types within a single broad category, i.e. multi-model lines.

Thomopoulos [10] develops the adaptation of single model line balancing techniques to solve the multi/mixed model line balancing problem. They modify the Kilbridge and Wester's heuristic [6] to consider the total schedule for a whole shift and assign tasks to operators on a shift basis instead of cycle-time. For sequencing, the procedure is based on the penalty costs of inefficiency resulting from model sequencing.

COMSOAL (Computer Method of Sequencing Operations for Assembly Lines) is a computer heuristic originally being a solution approach for the ALB problem [1]. It can be used to generate a feasible solution to resource allocation problems for each iteration. After repeatedly running COMSOAL, it results in many feasible solutions from which the best is chosen. Many researchers indicate that COMSOAL is a viable method to solve resource allocation problems when compared to the results from several well-known resource allocation algorithms. In some cases, optimal solutions can also be found [3, 8]. A more comprehensive review can be seen in [5].

It is easy to notice that organizing the assembly line based solely on the results of COMSOAL may cause negative impacts to the line performances, especially where automated material handling systems with limited buffer spaces are used. As a result, there is a need for a tool that can verify whether or not the designed line is appropriate. Computer simulation is one of the tools that can be employed to identify any possible operations problem of complex systems before conducting actual implementation [9]. Hence, this approach is adapted in the research.

In this paper, the multi-model line balancing and COMSOAL are used to improve the efficiency of assembly line balancing of a monitor manufacturing company. Simulation and experimental designs are conducted to identify significant factors affecting the performances of the system. Suitable parameters setting is the outcome of response surface analysis [4].

2. Company Profile

In recent years, changes in technology and customer's need has resulted in the demand of new products with high variety in terms of appearance, functionality, price, etc. To survive, manufacturers have to develop production lines that can support the production of various products simultaneously. The company in this case study has a similar problem of this kind. Its products are various models of monitors, typed thin film transistor liquid crystal display (TFT LCD). Each model of monitor has different sets of tasks and precedence relationships.

The current approach of ALB exercised by the company is as follows. Whenever a new product is introduced, a process engineer attempts to balance the line by his own experience. The information used to allocate tasks to workstations includes precedence relationship and cycle time. The efficiency of the assembly line is evaluated and adjusted by trial and error through manufacturing pilot lots. It is clear that interruption of the line is inevitable and the solution tends to be far from optimum.

In addition, the company applies the single-model assembly line concept. Hence, whenever there is a change in the model, the whole line has to stop to adjust the number of workers and change some equipment. The foreman has to prepare assembly work instructions and discuss then with the workers. During model changing, if a shortage of manpower occurs, the foreman will be put in the positions of those needed. On the other hand, if the number of workers is too many and the foreman cannot find any job for them, they will be idle for such period. While adding in or pulling out workers and some equipment from the line, line stoppage is unavoidable.

The LCD monitor has to be produced through 3 main sub-assembly lines, i.e. functions keyboard, interface board, and panel assembly lines. The study is focused on 3 models, namely L1, L2, and L3, since they cover more than 80% of the company's sales revenue.

3. Methodology

The research starts from the comparison between single-model and multi-model ALB techniques by using the current factory method and COMSOAL. For single-model assembly lines, after completion of each model, major machine and operator setups are required. Precedence diagram, task time, and desired output rate are basic information needed for conducting ALB.

In multi-model assembly lines, two or more products are separately assembled in batches without changes in the number of operators and equipments during model changing. Multi-model ALB is the modification of single-model one with the following assumptions: (1) Planning horizon is a shift and task-to-operator assignment is performed on a shift basis rather than on cycle-time; (2) Task time is replaced by the total time needed for the tasks to complete all models; and (3) Overall precedence diagram is the combination of each model's precedence diagram. Real data is collected from the factory's floor and used as inputs for both single-model and multi-model ALB by applying the current factory method COMSOAL. After obtaining preliminary results, line balancing efficiency is improved by employing the trade and transfer method [7].

As mentioned earlier, line balancing can be used to analyze the assembly line subject to the number of stations and idle time. However, the status of the handling system, e.g. conveyor speeds or buffer space, cannot be analyzed by ALB. Simulation is the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments to give a better understanding of the behavior of the system for a given set of conditions. Therefore, simulation is introduced to study the impact of the handling system and analyze the efficiency of the assembly line after solving ALB problems.

To simulate the system, input data has to be identified and collected. For this problem, it is clear that the operations of the workers are the main input of the LCD monitor assembly lines that cause variability in task time. Therefore, Input Analyzer of ARENA is used to fit a number of distributions to the real data and select the most appropriate one, measured by Chi-square and Kolmogorov-Smirnov goodness-of-fit tests. After that the simulation model of the real assembly line is developed based on such inputs. The next step is to verify that the model behaves in the way that it is intended according to the modeling assumptions made for raising an acceptable level of user's confidence. Many features of ARENA are utilized to verify the models, e.g. graphical animation and many commands in Run Controller such as TRACE and STEP. Finally, validation which is the process of ensuring that the model behaves similar to the real system, is employed. Statistics (pair-t test) is used to test whether or not the outcomes from the model and the real system are identical at the acceptable level.

The LCD monitor assembly line is a non-terminating system since any incomplete operation will be carried over to the production in the next day. As a result, data regarding the warm-up period is required from pilot runs to identify the steady state of the system to reduce initial condition bias. Also, suitable simulation run length and batch size have to be identified by using the Output Analyzer of ARENA. It divides data into groups approximately independent of each other and is suitable for calculating a confidence interval of the mean. Having done all these, the developed model is good enough to answer any inquiry related to ALB problems.

4. Assembly Line Analysis

Assembly line analysis is the process of identifying factors and their levels that have significant impacts to the efficiency of the assembly line by considering both hard and soft constraints of the line incorporating the design of experiments. The first two factors of interest include (1) types of ALB (single- or multi-model ALB) and (2) methods of ALB (factory method or COMSOAL). These factors are important since the management expects that appropriate types and methods of ALB can improve the efficiency of the line.

After ALB is solved, another factor which needed much consideration is conveyor speed. This can be considered as a soft or hard constraint of the assembly line since it is adjustable (soft) but within a predefined limit (hard). In function keyboard, interface board, and panel assembly lines, there are several sections of conveyors. Although each section is independent of one another, unsuitable conveyor speed settings will result in problems in the assembly line, e.g. too slow conveyor speed may cause operators to wait for a new work piece; whereas too fast conveyor speed may cause printed circuit boards (PCB) jam and damage from bumping of carriers (pallets). Therefore, adjusting conveyor speeds to synchronize with one another without violating any constraint in the assembly line is crucial.

Technically, conveyor speed is very important for PCB when moving past the solder wave machine. Too fast conveyor speed will cause difficulty for liquid solder to attach on PCB; whereas, too slow may burn PCB. This limitation is considered as a hard constraint. Two to three seconds is the most suitable time for PCB to be in the solder wave machine as recommended by the machine manufacturer. Another hard constraint of conveyor speed is in the panel assembly line. Conveyor speed also affects the time in the burn-in process (the last process before functional test and white balance checking process) which requires at least 90 minutes to warm the panel.

To analyze 3 assembly lines of LCD monitor production, the level of conveyor speed is assigned by analyzing each conveyor section, and then the results of initial simulation outcomes plus reasonable conveyor speeds given by the process engineer are considered as follows:

1. Function keyboard assembly line and interface board assembly line consist of a 5 sub assembly conveyor as shown in Figure 1:

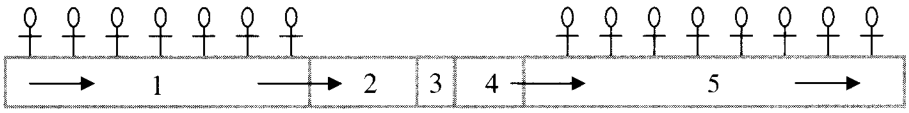

Figure 1. Function keyboard assembly line and interface board assembly line

- 1st conveyor section: Section of material insertion, e.g. diode, resister, and capacitor, which is performed by workers as shown in Figure 2. The conveyor speed recommended by process engineer can be used in the real production.

Figure 2. 1st conveyor section (material insertion process)

- 2nd conveyor section: Pre-solder wave section, a buffer conveyor before soldering process in the solder wave machine, allows a maximum of 6 PCBs on the conveyor as shown in Figure 3. The speed of this conveyor is calculated so that it can synchronize with the 1st and 3rd conveyor sections. Required information includes 1st and 3rd conveyor speeds, length of 2nd conveyor, and size of PCB buffer. In addition, it has to consider the PCB pre-heat time before starting the soldering process in the solder wave machine. This time is required to improve the quality of soldering.

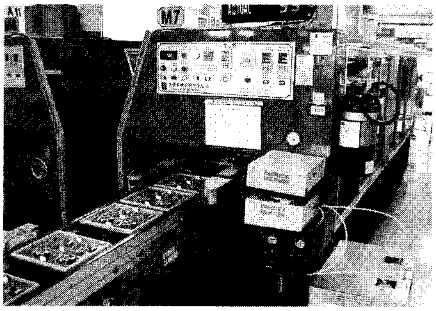

Figure 3. 2^{nd} conveyor section (Pre-solder wave section)

- 3^{rd} conveyor section: This conveyor section is in the solder wave machine. The manufacturer recommends that 2 – 3 seconds (not more or less) is needed for liquid solder to attach to a PCB firmly. As a result, the conveyor speed is set by dividing the length of conveyor by the time in the solder wave machine (2-3 seconds).
- 4^{th} conveyor section: Post-solder wave section, which is another buffer of the line located at the end of the solder wave machine. It allows a maximum of 3 PCBs. This section of the conveyor is examined in the same way as the 2^{nd} conveyor's section. In addition, the constraint of this section is that the conveyor speed must not be too fast in order to cool down the temperature of the PCBs after passing the soldering process.
- 5^{th} conveyor section: This section consists of solder inspection, function test, and final assembly, which is performed by workers as shown in Figure 4. The conveyor speed recommended by the process engineer can be used in the real production system.

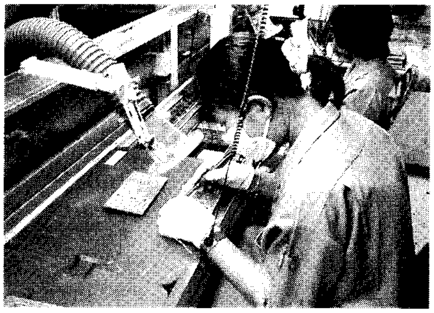

Figure 4. 5^{th} conveyor section (solder inspection process)

2. Panel assembly line consists of 3 sub-assembly conveyors as shown in Figure 5:

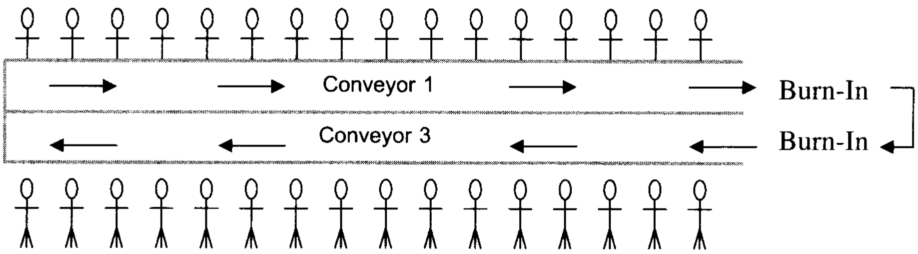

Figure 5. Panel assembly line

- 1st conveyor section: Section of pre-panel assembly and panel assembly which is performed by workers as shown in Figure 6. The conveyor speed recommended by the process engineer can be used in the real production.

Figure 6. 1st conveyor section (panel assembly process)

- 2nd conveyor section: This conveyor section is the burn-in process which requires burn-in times of 5,400 seconds at minimum as shown in Figure 7.

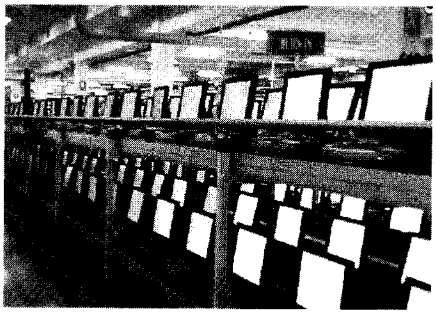

Figure 7. 2nd conveyor section (burn-in process)

- 3rd conveyor section: Section of panel function test and visual inspection which is performed by workers as shown in Figure 8. The conveyor speed recommended by the process engineer can be used in the real production.

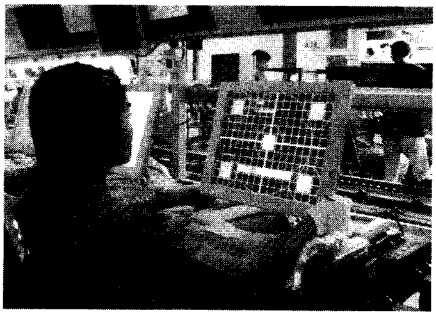

Figure 8. 3rd conveyor section (panel function test process)

From the above physical and technical constraints, the factors and their levels used to conduct the design of experiments are summarized in Table 1.

Table 1. Factors and levels of factor considered for the experimental designs

Factor	Factor Level		
	Function Keyboard	Interface Board	Panel
Line balancing type (A)	multi-model (m) and single-model (s)	multi-model (m) and single-model (s)	multi-model (m) and single-model (s)
Line balancing method (B)	COMSOAL (c) and factory method (p)	COMSOAL (c) and factory method (p)	COMSOAL (c) and factory method (p)
Conveyor speed section 1 (C)	15, 16, 17, 18	15, 16, 17, 18	13, 14, 15, 16
Conveyor speed section 2 (D)	5, 6, 7, 8	5, 6, 7, 8	5, 6, 7
Conveyor speed section 3 (E)	14, 15, 16, 17, 18	14, 15, 16, 17, 18	13, 14, 15, 16
Conveyor speed section 4 (F)	6, 7, 8, 9	6, 7, 8, 9	-
Conveyor speed section 5 (G)	15, 16, 17, 18	15, 16, 17, 18	-

Note: Conveyor speed is measured in centimeter per second

5. Results

The result can be shown in 2 different scenarios which are the results from ALB and the results from the experimental designs.

- **ALB Results**

In LCD monitor production, it is given that one workstation is occupied by one worker. The number of workstations resulting from ALB is shown in Table 2.

Table 2. The number of workstations from ALB

Assembly Line	Number of Workstations							
	COMSOAL				Factory method			
	Single-model			Multi-model	Single-model			Multi-model
	L1	L2	L3		L1	L2	L3	
Function Keyboard	21	**23**	**23**	21	19	**23**	**23**	21
Interface Board	18	20	**22**	20	18	21	**22**	20
Panel	22	25	**26**	25	22	25	**26**	25
Total	23 + 22 + 26 = 71			66	23 + 22 + 26 = 71			66

By applying COMSOAL to single-model ALB, the function keyboard assembly line of model L1 requires 21 workstations. This means that 21 workers are required to complete the assembly process. Similarly, model L2 requires 23 workstations (23 workers) and model L3 requires 23 workstations (23 workers) respectively. Therefore the supervisor has to provide enough manpower at the maximum quantity, i.e. 23 workers. Likewise, for the interface board assembly line, the supervisor has to provide 22 workers (max [18, 20, 22]). Finally, the panel assembly line requires 26 workers (max [22, 25, 26]). Therefore, the total number of workers required in LCD monitor assembly for all product models is 71 workers (23+22+26) for single-model ALB. It is found that the current factory line balancing method gives the same number of required manpower (71 workers).

For multi-model ALB, it is found that only 66 workers are required to produce LCD monitors for all product models for both COMSOAL and the current factory ALB method. Although COMSOAL and factory ALB method gives the same result, the company is recommended to use COMSOAL since it is a systematic approach and not dependent on knowledge of the planner. In addition, when other tested cases are investigated by the company, it is found that COMSOAL is often correct. In comparison, it is clear that multi-model ALB gives a better result than the single-model one in terms of number of work stations and manpower requirement. The difference of 5 workstations (5 workers) causes substantially decreased labor cost. Moreover, setup time is reduced according to no major change in manpower and equipment which increases the efficiency of the assembly line.

- **Experimental Design Results**

The results from the design of experiments are analyzed through 3 factors, i.e. line balancing methods, line balancing types, and conveyor speeds. The significance of the factors is evaluated by considering line efficiency, output, and throughput time. From pilot simulation conducted during the analysis of assembly line, conveyor speeds show no significance to line efficiency and output. As a result, conveyor speeds are not taken into consideration further for these measures of performances. Only line balancing types and methods are considered in the design of experiments in order to find suitable levels of factors that can improve line efficiency and output. The results from the study show that multi-model assembly line balancing with COMSOAL gives the best solutions in terms of line efficiency and output compared with the other methods for all assembly lines (Table 3).

Table 3. Line efficiency and output

Assembly Line	Multi-model with COMSOAL		Multi-model with factory method		Single-model with COMSOAL		Single-model with factory method	
	Line Efficiency	Output	Line Efficiency	Output	Line Efficiency	Output	Line Efficiency	Output
Function Keyboard	0.8169	1,334	0.7353	1,307	0.7747	1,288	0.7036	1,240
Interface Board	0.8414	1,333	0.8168	1,293	0.7497	1,290	0.7160	1,253
Panel	0.8654	1,314	0.8423	1,298	0.8343	1,271	0.8216	1,192

For throughput time, the factor in enquiry of function keyboard assembly line and interface board assembly line contain 7 factors and for panel assembly line contains 5 factors as shown in Table 1. Since the number of factors is high, the investigation of throughput time is conducted through 2^k factorial design, which is the most efficient method when the number of factors is high. In 2^k factorial design, each factor has only two levels (maximum and minimum values of the factor are selected) that provide the smallest number of runs of k factors to evaluate a complete factorial design. This kind of design is widely used in factor screening experiments [4]. After initial factor screening, the significant factors are further processed to identify their suitable levels in combination to minimize throughput time. The results are quite similar to those of line efficiency and output in that multi-model ALB in combination with COMSOAL outperforms the others. To minimize throughput time, conveyor speed for each section of the assembly line has to be set as follows (some sections that are not mentioned can be set arbitrarily since they are not significant).

- Function key board assembly line: multi-model ALB with COMSOAL; conveyor speed for 1st section, 2nd section, and 5th section are 18 cm/sec, 8 cm/sec, and 18 cm/sec respectively.
- Interface board assembly line: multi-model ALB with COMSOAL; conveyor speed for 1st section, 2nd section, 4th section and 5th section are 18 cm/sec, 8 cm/sec, 9 cm/sec, and 18 cm/sec respectively.
- Panel assembly line: multi-model ALB with COMSOAL; conveyor speed for 2nd section and 3rd section are 7 cm/sec, and 16 cm/sec respectively.

6. Conclusion

From the study of different line balancing methodologies, it is found that the number of workstations used in the multi-model ALB is less than in the single-model one. This gives substantial reduction in labor cost that the company has to pay. However, when implementing this result to the real assembly line, some other constraints have to be considered, e.g. material handling system. It is found from pilot experiments that if material handling speeds are not synchronized with the cycle time of the assembly line, the output rate dropped substantially. As a result, there is a need to consider which resource is the bottleneck of the assembly system as a whole, i.e. worker, conveyor, equipment, etc., and bottleneck management must be done properly. In addition, all recommended conveyor speeds must give acceptable processing time in the solder wave machine and burn-in time. One of the potential tools that can be used to investigate this issue is computer simulation. The results from factorial designs indicate that line balancing method and type improve impact line efficiency, output, and throughput time significantly. The multi-model ALB and COMSOAL contribute to higher line efficiency, higher output, and lower throughput time. Moreover, in this system, conveyor speed only influences the throughput time. Although multi-model ALB prevails in this study, several factors have to be considered in practice, e.g. operator skill, quality of the products, etc. Other important factors that need further investigation are batch size and sequencing of each product model. In addition, investment cost incurred in modifying the current single-model assembly line to the multi-model one is another issue that needs consideration from the production manager. In order to be more responsive to smaller batch size, the mixed-model assembly line requires further investigation.

7. References

[1] Aucus, A. L., COMSOAL: A Computer Method of Sequencing Operations for Assembly Lines, Int. J. Prod.Res., 4, 4: 1966.

[2] Dennis, P. C., Introduction to Simulation Using SIMAN (2nd Ed.), Singapore: McGraw-Hill, 1995.

[3] DePuy, G. W. and Whitehouse, G. E., Applying the COMSOAL Computer Heuristic to the Constrained Resource Allocation Problem, Computers & Industrial Engineering. 38: pp. 413-422, 2000.

[4] Douglas, C. M., Design and Analysis of Experiments. Fifth Edition, John Wiley & Sons, Inc, 2000.

[5] Gosh, S. and Gagnon, R., A Comprehensive Literature Review and Analysis of the Design, Balancing and Scheduling of Assembly System, Int. J. Prod. Res. 27, 4: pp. 637-670, 1989.

[6] Kilbridge, M. D. and Wester, L., A Heuristic Method of Assembly Line Balancing. Journal of Industrial Engineering, 12, 4: pp. 292-298, 1961.

[7] Moodie, C. L. and Young, H. H., A Heuristic Method of Assembly Line Balancing for Assumptions of Constant or Variable Work Element Times, Journal of Industrial Engineering. 16, 1: pp. 23-29, 1965.

[8] Nkasu, M. M. and Leung, K. H., Computer Integrated Manufacturing Assembly System Design, Integrated Manufacturing Systems. 6, 6: pp. 4-14, 1995.

[9] Sameh, M. S. and Mike, D. B., Comprehensive Simulation Analysis of a Flexible Hybrid Assembly System, Integrated Manufacturing Systems. 9, 3: pp. 156-167, 1998.

[10] Thomopolos, N. T., Line Balancing-Sequencing for Mixed-Model Assembly, Management Science. 14, pp. 59-75, 1967.