ASSEMBLY LINE BALANCING IMPLEMENTATION IN MINOR AND SUB ASSEMBLY WORK SHOP AT SHIPYARDS

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SUMMARY

Recently, the competitive environment is very tough in shipbuilding industry and under these circumstances, manufacturing a ship in a shorter time becomes significantly important in order to meet the customer demands. Therefore, it is hard to do that by using traditional manufacturing techniques. The shipyards located in Turkey usually have functional locations for the machines and this situation often causes longer production times. Instead of this, assembly lines should be redesigned as workshops in the shipyard. Prefabrication work unit is a good example in which an assembly line is needed to be designed. In this study, an assembly line design for prefabrication work unit was performed. For this, assignments of work operations to work shops were carried out by using Largest Set Rule Algorithm and some alternatives were created according to compare the different values of cycle time. These alternatives were simulated by using a production simulation program and the most appropriate assembly line design was presented.

1. INTRODUCTION

In recent applications, shorter cycle times are demanded for meeting of customer requests and traditional production systems are replaced with assembly lines. Furthermore, many shipyards have made great efforts to improve their productivity [1]. Assembly lines comprise the base of the production system in mounting operation. Assembly lines include various workshops which align one after the other along a line and each of them performs specific work activities. Raw materials enter into the system from one end and products or interim products exit from the other end of the line. An assembly line is a flow-oriented production system where the productive units performing the operations, referred to as stations, are aligned in a serial manner [2]. The assembly line balancing problem consists of assigning tasks to an ordered sequence of stations such that the precedence relations among the tasks are satisfied and some performance measure is optimized [3].

In the traditional production system, the machines are located according to their functions in the plant. In this case, the production time of the final product becomes higher. Whereas, if the machines are aligned in an ordered line and the operations are performed in a parallel manner, the production time of the final product becomes less. In particular, in shipbuilding sector in Turkey, the machines and equipment are placed in accordance with their functions rather than the assembly line logic. This situation causes higher fabrication time.

In this study, prefabrication work unit in a ship production system was illustrated as an example and it is aimed to design an appropriate assembly line at this station in order to reduce the production time of the sub-assembly structures. At the first stage of the work, the work activities and their durations were determined with comprehensive work research. At the second stage of the work, the assignments of the work activities to work stations were carried out by using Largest Set Rule Algorithm method, which is a technique used in assembly line balancing problem. SIMIO simulation software was employed to create the simulation model of the work units in the third stage. At the final stage (Stage 4), the simulation results were evaluated and the most appropriate assembly line system for prefabrication plant was presented. In many industries, assembly line balancing applications are performed. Mercedes in automotive sector [4], Beko in white goods sector [5], and Arena in textile sector [6] employ assembly line balancing implementations. In literature, there are quite a few works concerning the assembly line balancing applications in shipbuilding. In their study, Storch and Lim [7], a shipyard production system was considered and some production cells were built and finally a model of assembly line balancing was presented. The works are mainly concerned with scheduling problems in ship production system. Kajiwara et al [8] made a mathematical model of dynamics of assembly lines and stockyard. Lee et al [9] developed a project namely DAS (DAewoo Shipbuilding Scheduling) to solve the scheduling and planning problem of Daewoo Shipyard. Qu et al [10] worked on the assembly sequence of blocks. Therefore, this study is one of the several works in assembly line balancing application for prefabrication plant.

1.1 PREFABRICATION WORK UNIT IN SHIPBUILDING

There are many workshops in a shipyard and each of them has a function to realize the specific activities. Prefabrication is one of the most important work plants in shipyard production system. In this station, minor and sub-assemblies products are fabricated. The single parts including sections and plates are transferred to this station and the parts are mounted each other. As a result of this mounting operation, minor assembly structures are fabricated at first. Then, these minor assembly structures are mounted each other and finally, sub assembly products are manufactured. Parts are firstly fixed with tack welding. Then, the grinding operation is performed on spot welds. After tack welding, the TIG welding is carried out in order to combine the parts each other. In the same way, after TIG welding, the welded-surfaces are grinded with grinding machine. In this way, the mounting operation is completed.

1.2 LARGEST SET RULE ALGORITHM

This method was developed by Agrawal in 1985 [11]. This decision rule allots a set of related operations to a worker as against the usual operation-by-operation allotment, thereby giving much more flexibility in sequencing the workers. Figure 1 depicts the steps of Largest Set Rule Algorithm [12].

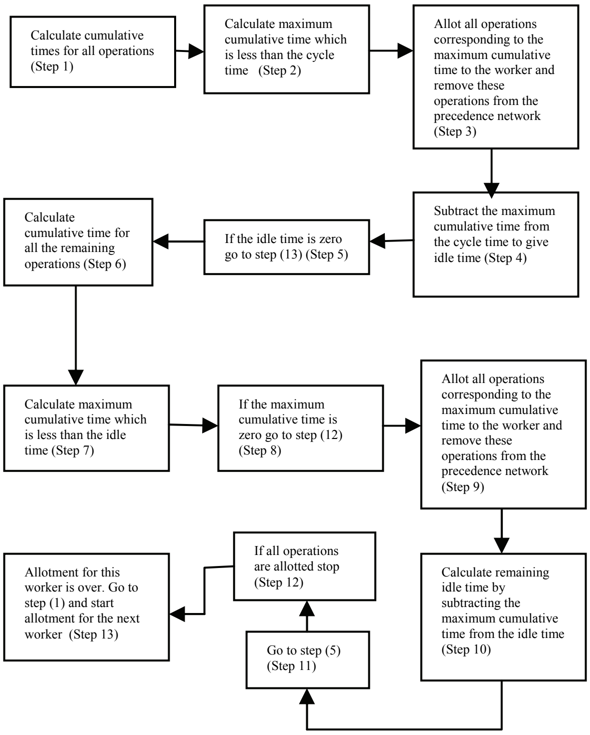


Figure 1. The flow chart of Largest Set Rule Algorithm

2. METHODOLOGY

This study consists of four stages. In the first stage, work operations with their durations being performed in pre-fabrication work unit have been determined. While doing this, the comprehensive investigation of the whole operations have been performed. After that stage, the assembly line balancing process was carried out by using the balancing method namely the largest set rule algorithm (Stage 2). At this stage, the assignments of the work operations to the work units were carried out by using this balancing technique and the number of work stations and the processing times of each work shop were achieved. Then, simulation of the work units was performed by SIMIO environment (Stage 3) and the simulation results were obtained such as number in system (work in process) and number of the fabricated parts. At the final stage (Stage 4), the evaluation of the results was carried out. Figure 2 depicts the stages of the methodology of the study.

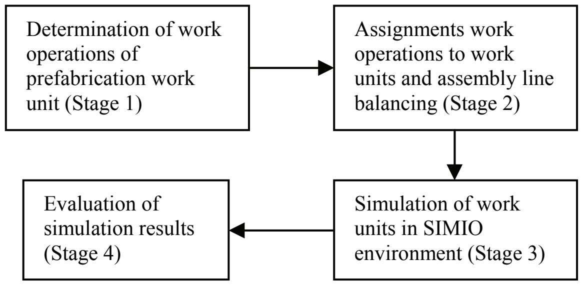


Figure 2. Stages of the work

3. ASSEMBLY LINE BALANCING IMPLEMENTATION

3.1 DETERMINATION OF WORK ACTIVITIES OF PREFABRICATION WORK UNIT (STAGE 1)

Here, the prefabrication work unit, which is one of the most significant work stations in shipbuilding, was investigated and the work activities were determined. Table 1 shows the work activities and their durations in prefabrication plant. Table 1 also presents the precedence of the activities.

3.2 ASSIGNMENTS OPERATIONS TO WORK UNITS AND ASSEMBLY LINE BALANCING (STAGE 2)

In this section, an assembly line in prefabrication plant is going to be created by using Largest Set Rule Algorithm. There are number of four cases including cycle times of 30, 40, 50, and 60 minutes, respectively. For instance, Case 1 represents cycle time of 30 minutes.

3.2 (a) Assignment of operations for cycle time of 30 min. (Case 1)

Since the assignment process of work activities to work stations takes a long calculation, only assignment process to work station 1 will be shown here. The cumulative durations of each work activity is represented in Table 2. Accordingly, the cumulative duration of work activity-4 is the nearest to cycle time of 30 min. Therefore, work activity-4 and the previous activities of work activity-4 will be assigned to work station 1.

Therefore, work operations 1, 2, 3, and 4 are assigned to Station 1 and total idle time for Station 1 is 0,008 minutes. In the same way, when the same method was applied for the other work stations, the following situation shown in Tab.3 was created. As can be seen from Tab.3, there are number of 22 work stations in assembly line. And the duration of each work station is presented in Table 3.

3.2 (b) Assignment of work operations for cycle time of 40 min. (Case 2)

In this section, the assignment process for cycle time of 40 minutes was carried out and the results presented in Table 4 were achieved. There are number of 18 work stations in the assembly line. For instance, the processing time of work station 9 is 37,132 minutes and the work activities 23-s01-c, 24-s01, 25-s01, 26-s01, and 27-s01 will be performed in this station.

3.2 (c) Assignment of work operations for cycle time of 50 min. (Case 3)

Here, the assignment process for cycle time of 50 minutes was carried out and the results presented in Table 5 were obtained. In this assembly line, 15 work stations are available. For instance, the processing time of work station 14 is 30,71 minutes and the work activities 49, 50, 51, 52, 53, 54, 55, and 56-a will be performed in this station.

3.2 (d) Assignment of work operations for cycle time of 60 min. (Case 4)

The assignment process for cycle time of 50 minutes was carried out in this section and the data presented in Table 6 were found. In this assembly line, numbers of 11 work stations are available.

3.3 SIMULATION OF WORK UNITS IN SIMIO ENVIRONMENTS (STAGE 3)

3.3 (a) Simulation model of Case 1

Figure 4 depicts the simulation model of Case 1. As can be seen from Figure 4, there are number of 22 work stations in the assembly line and they are ordered along the line. For each work station, the processing times of the work stations are written in modules. For instance, the processing time of the station 4 is 29,5 minutes as shown in Figure 5. The production system is scheduled to operate according to a work schedule as shown in Figure 6. The system is operated along 8 hours a day and starts to work at 8 a.m. and finishes working at 17 p.m. The system does not also operate between 12 and 13 p.m. for the lunch time. The work stations are linked up each other by paths and the distance of each path is considered as 3 meters. Figure 7 represents the SIMIO representation of path 7. After building the SIMIO model of the system, it is run along 30 days between September 12 and October 12. Figure 8 illustrates the interface of run setup.

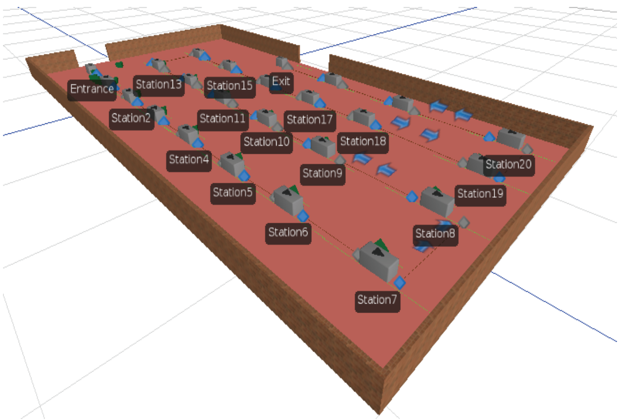


Figure 4. Simulation model of Case 1

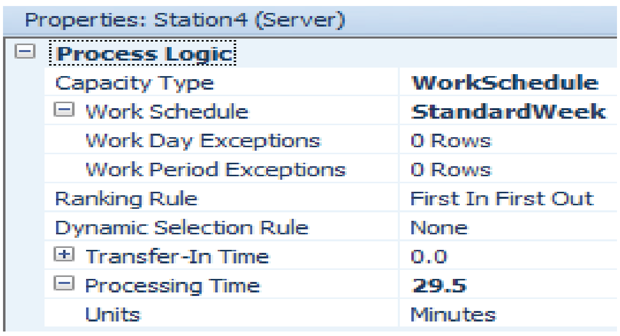


Figure 5. SIMIO presentation of Station 4

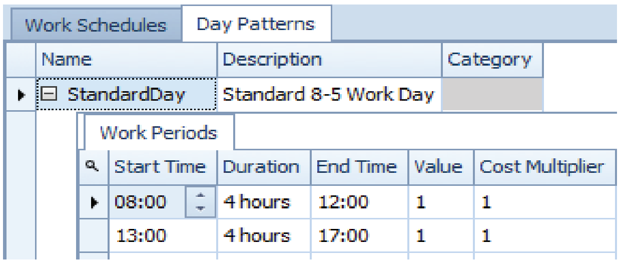


Figure 6. SIMIO presentation of work schedule

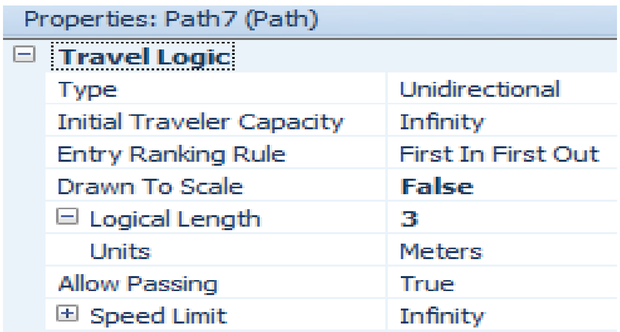


Figure 7. SIMIO presentation of Path 7

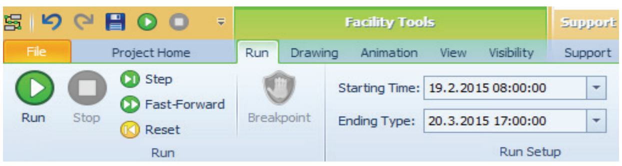


Figure 8. SIMIO presentation of Run setup

Figure 9 shows the simulation results of the system. As can be seen from Figure 9, the system created 2917 parts in a span of 30 days but only 348 parts exited the system. That means the maximum number of work in process in the system is 2569 parts. Therefore, we can say that numbers of 348 parts are fabricated in this system in 30 days.

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average Total
ModelEntity	Parts	[Population]	Content	NumberInSystem	Average	1.290,0573
					Maximum	2.569,0000
			FlowTime	TimeInSystem	Average (Ho...	332,7667
					Maximum (Ho...	642,0152
					Minimum (Ho...	26,2652
			Throughput	NumberCreated	Total	2.917,0000
				NumberDestroyed	Total	348,0000

Figure 9. SIMIO presentation of Case 1 results

3.3 (b) Simulation model of Case 2

Figure 10 shows the simulation model of Case 2 in SIMIO environment. There are 18 work stations in the system. The model was built by creating the modules and entering the processing times which were presented before. In the same way, the system was run along 30 days and some data were achieved as shown in Figure 11. While, number of 2917 parts entered into the system and number of 261 parts were fabricated at the end of operation of 30 days, work in process quantity in the system is 2656.

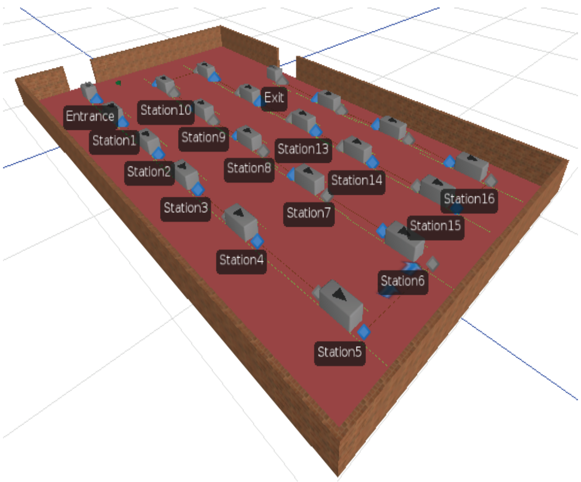


Figure 10. Simulation model of Case 2

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average Total
ModelEntity	Parts	[Population]	Content	NumberInSystem	Average	1.332,1825
					Maximum	2.656,0000
			FlowTime	TimeInSystem	Average (Ho...	343,6822
					Maximum (Ho...	663,6812
					Minimum (Ho...	26,4302
			Throughput	NumberCreated	Total	2.917,0000
				NumberDestroyed	Total	261,0000

Figure 11. SIMIO presentation of Case 2 results

3.3 (c) Simulation model of Case 3

Figure 12 depicts the simulation model of Case 3 in SIMIO environment. The system has number of 15 work stations was run along 30 days. In Figure 13, number of parts arriving to system and number of the parts exited were presented. According to this, 2917 parts arrived into the system and numbers of 209 parts were fabricated at the end of operation of 30 days. Besides, number of work in process in the system is 2708.

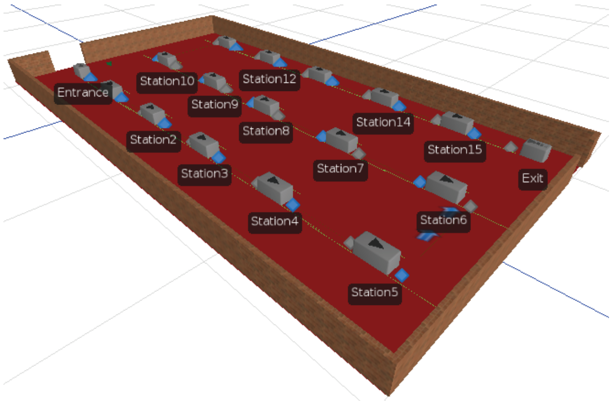


Figure 12. Simulation model of Case 3

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average Total
ModelEntity	Parts	[Population]	Content	NumberInSystem	Average	1.357,3024
					Maximum	2.708,0000
			FlowTime	TimeInSystem	Average (Ho...	350,0188
					Maximum (Ho...	676,5993
					Minimum (Ho...	26,2660
			Throughput	NumberCreated	Total	2.917,0000
				NumberDestroyed	Total	209,0000

Figure 13. SIMIO presentation of Case 3 results

3.3 (d) Simulation model of Case 4

In the last situation (in case 4), number of 11 work units are available in the system as can be seen from Figure 14. As a result of running the system along 30 days, the data were obtained as illustrated in Figure 15. Accordingly, number of 2917 parts arrived into the system and only 174 parts were fabricated. Therefore, number of work in process in the system is 2743.

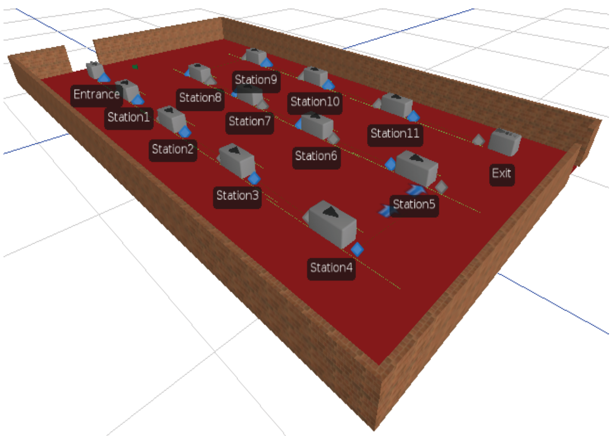
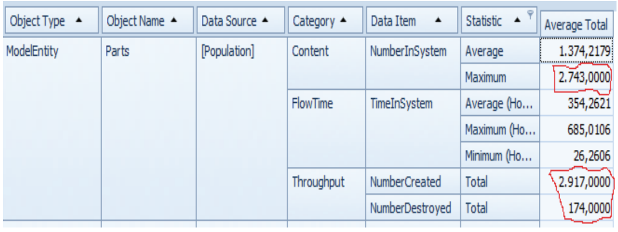


Figure 14. Simulation model of Case 4



Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average Total
ModelEntity	Parts	[Population]	Content	NumberInSystem	Average	1.374,2179
					Maximum	2.743,0000
			FlowTime	TimeInSystem	Average (Ho...	354,2621
					Maximum (Ho...	685,0106
					Minimum (Ho...	26,2606
			Throughput	NumberCreated	Total	2.917,0000
				NumberDestroyed	Total	174,0000

Figure 15. SIMIO presentation of Case 4 results

3.4 EVALUATION OF SIMULATION RESULTS (STAGE 4)

In this section, the simulation results achieved from SIMIO will be commentated. The most significance criteria in a production system are the number of the fabricated units and the rank of number in system (work in process). In Figure 16, these values obtained from simulation results were presented. Accordingly, the higher value of minor and sub assembly section number fabricated and the least value of section number in system belong to the cycle time of 30 minutes. On the other hand, in the cycle time of 60 minutes, the system manufactures the least number of products and the quantity of work in process is higher. As can be understood, as the cycle time is increasing, work in process is also increasing while the number of fabricated parts is decreasing.

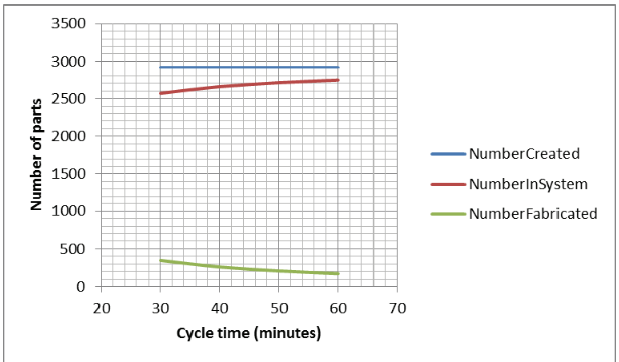


Figure 16. Cycle time- number of parts relations

4. CONCLUSIONS

In this study, numbers of four alternatives in assembly line design were created for pre-fabrication work unit in the shipbuilding process. Here, the most significance criteria are the number of the fabricated units and the rank of number in system (work in process). According to the findings of this work, the assembly line, which has higher number of fabricated units and lower work in process, should be preferred. This study demonstrates that the cycle time should be of little value in order to achieve higher number of fabricated units and lower work in process. Whereas, higher value of cycle time causes less production amount and more work in process in the system which is an undesirable thing. When an assembly line design for prefabrication work unit is contemplated to be built by the shipyard, cycle time is needed to be selected in lower values to meet the criteria. By doing this, the pre-fabrication work unit is able to produce more products in a certain time and also less work in process can be obtained.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. LEE, D.K., KIM, Y., HWANG, I.H., OH, D.K. and SHIN, J.G., Study on a process-centric modelling methodology for virtual manufacturing of ships and offshore structures in shipyards, *International Journal of Advanced Manufacturing Technology,* Volume 71, No. pp 621-633, 2014.
2. BOYSEN, N., FLIEDNER, M. and SCHOLL, A., A classification of assembly line balancing problems, *European Journal of Operational Research*, Volume 183, pp. 674-693, 2007.
3. EREL, E. and SARIN, S.C., A survey of the assembly line balancing procedures, *Production Planning and Control,* Volume 9, No. 5, pp. 414-434, 1998.
4. TURGAY, E., Line balancing and application in automotive industry (in Turkish), *MSc Thesis,* Faculty of Management, Istanbul Technical University, Istanbul, Turkey, 1996.
5. AKER, A. and AYAR, T., Theory of line balancing (in Turkish), *Undergraduate dissertation*, Engineering Faculty, Kocaeli University, Kocaeli, Turkey, 2003.
6. GUNER, M.G. and UNAL, C. S., Line balancing in the apparel industry using simulation techniques, *Fibres & Textiles*, Volume 16, No.2, pp. 75-78, 2008.
7. STORCH, R.L. and LIM, S., Improving flow to achieve lean manufacturing in shipbuilding, *Production Planning and Control*, Volume 10, No. 2, pp. 127-137, 1999.
8. KAJIWARA, H., HITOI, Y, and HASSAN, K., Max-plus approach to scheduling problems of block assembly lines, *Proceedings of MARTEC 2010 The International Conference on Marine Technology 11-12 December*, BUET, Dhaka, Bangladesh, pp.189-194, 2010.
9. LEE, J.K., LEE, K.J., PARK, H.K., HONG, J.S., and LEE, J.S., Developing Scheduling Systems for Daewoo Shipbuilding: DAS Project, *European Journal of Operational Research*, Volume 97, No.2, pp.380-395, 1997.

10. QU,S., JIANG, Z., and TAO, N., An integrated method for block assembly sequence planning in shipbuilding, *International Journal of Advanced Manufacturing Technology*, Volume 69, No. 5-8, pp. 1123-1135, 2013.

11. AGRAWAL, P.K., The Related Activity Concept in Assembly Line Balancing, *International Journal of Production Research*, Volume 23 (2), pp. 403-421, 1985.

12. ERYURUK, S.H., Clothing Assembly Line Design Using Simulation And Heuristic Line Balancing Techniques, *Tekstil ve Konfeksiyon*, Volume 22, No. 4, pp. 360-368, 2012.

Table 1. Operations and durations in prefabrication station

No.	Operations	Duration (min.)	Precedence
1	Spreading out parts on the floor	4,9	-
2	Finding corresponding parts	1	1
3	Finding corresponding parts and taking them to other parts	23	2
4	Overhead crane goes down the batch	1	3
5	Overhead crane holds the batch	2	4
6	Overhead crane lifts the batch	1	5
7	Overhead crane transports the batch to the corresponding location	0,3	6
8	Overhead crane puts down the batch on the floor	1	7
9	Overhead crane leaves the batch	1	8
10	Overhead crane goes up from batch	1	9
11	Overhead crane returns to plate stock area	0,3	10
12-s01	Preparing grinding machine (1)	1,6	11
12-b01	Preparing grinding machine (2)	0,5	11
12-b04	Preparing grinding machine (3)	0,5	11
12-b02	Preparing grinding machine (4)	0,5	11
12-b05	Preparing grinding machine (5)	0,5	11
13-s01	Grinding parts (1)	5,7	12-s01
13-b01	Grinding parts (2)	4,3	12-b01
13-b04	Grinding parts (3)	4,3	12-b04
13-b02	Grinding parts (4)	4,3	12-b02
13-b05	Grinding parts (5)	4,3	12-b05
14-s01	Finding parts and taking them to the welding parts (1)	12	13-s01
14-b01	Finding parts and taking them to the welding parts (2)	2	13-b01
14-b04	Finding parts and taking them to the welding parts (3)	2	13-b04
14-b02	Finding parts and taking them to the welding parts (4)	2	13-b02
14-b05	Finding parts and taking them to the welding parts (5)	2	13-b05
15-s01	Alignment parts on the marks (1)	6	14-s01
15-b01	Alignment parts on the marks (2)	0,25	14-b01
15-b04	Alignment parts on the marks (3)	0,25	14-b04
15-b02	Alignment parts on the marks (4)	0,25	14-b02
15-b05	Alignment parts on the marks (5)	0,25	14-b05
16-s01	Fixing the parts on marks and welding corner piece (1)	6	15-s01
16-b01	Fixing the parts on marks and welding corner piece (2)	0,25	15-b01
16-b04	Fixing the parts on marks and welding corner piece (3)	0,25	15-b04
16-b02	Fixing the parts on marks and welding corner piece (4)	0,25	15-b02
16-b05	Fixing the parts on marks and welding corner piece (5)	0,25	15-b05
17-s01	Preparing tack welding machine(1)	1,5	16-s01
17-b01	Preparing tack welding machine (2)	0,25	16-b01
17-b04	Preparing tack welding machine (3)	0,25	16-b04
17-b02	Preparing tack welding machine (4)	0,25	16-b02
17-b05	Preparing tack welding machine (5)	0,25	16-b05
18-s01	Mounting parts with tack welding (1)	3,9	17-s01
18-b01	Mounting parts with tack welding (2)	1,5	17-b01
18-b04	Mounting parts with tack welding (3)	1,5	17-b04
18-b02	Mounting parts with tack welding (4)	1,5	17-b02
18-b05	Mounting parts with tack welding (5)	1,5	17-b05
19-s01	Preparing grinding machine (1)	1,5	18-s01
19-b01	Preparing grinding machine (2)	0,25	18-b01
19-b04	Preparing grinding machine (3)	0,25	18-b04
19-b02	Preparing grinding machine (4)	0,25	18-b02
19-b05	Preparing grinding machine (5)	0,25	18-b05
20-s01	Grinding after tack welding (1)	2,2	19-s01
20-b01	Grinding after tack welding (2)	0,8	19-b01
20-b04	Grinding after tack welding (3)	0,8	19-b04
20-b02	Grinding after tack welding (4)	0,8	19-b02
20-b05	Grinding after tack welding (5)	0,8	19-b05
21-s01	Preparing tig welding machine (1)	6	20-s01
21-b01	Preparing tig welding machine (2)	1	20-b01
21-b04	Preparing tig welding machine (3)	1	20-b04
21-b02	Preparing tig welding machine (4)	1	20-b02
21-b05	Preparing tig welding machine (5)	1	20-b05
22-s01	Welding electrode goes down welding area and starts welding operation (1)	4,5	21-s01
22-b01	Welding electrode goes down welding area and starts welding operation (2)	0,75	21-b01

22-b04	Welding electrode goes down welding area and starts welding operation (3)	0,75	21-b04
22-b02	Welding electrode goes down welding area and starts welding operation (4)	0,75	21-b02
22-b05	Welding electrode goes down welding area and starts welding operation (5)	0,75	21-b05
23-s01-a	Tig welding of the parts (1)	25	22-s01
23-s01-b	Tig welding of the parts (2)	25	22-s01
23-s01-c	Tig welding of the parts (3)	25	22-s01
23-b01	Tig welding of the parts (4)	28,2	22-b01
23-b04	Tig welding of the parts (5)	28,2	22-b04
23-b02	Tig welding of the parts (6)	28,2	22-b02
23-b05	Tig welding of the parts (7)	28,2	22-b05
24-s01	Preparing grinding machine (1)	1,75	23-s01-c
24-b01	Preparing grinding machine (2)	0,25	23-b01
24-b04	Preparing grinding machine (3)	0,25	23-b04
24-b02	Preparing grinding machine (4)	0,25	23-b02
24-b05	Preparing grinding machine (5)	0,25	23-b05
25-s01	Grinding after tig welding (1)	4,2	24-s01
25-b01	Grinding after tig welding (2)	1,6	24-b01
25-b04	Grinding after tig welding (3)	1,6	24-b04
25-b02	Grinding after tig welding (4)	1,6	24-b02
25-b05	Grinding after tig welding (5)	1,6	24-b05
26-s01	Preparing grinding machine	0,75	25-s01
27-s01	Grinding plate parts	5,4	26-s01
28-s01	Overhead crane goes down plate parts	6	27-s01
29-s01	Overhead crane holds plate parts	3	28-s01
30-s01	Overhead crane lifts plate parts	6	29-s01
31-s01	Overhead crane transports plate parts to the corresponding location	1,8	30-s01
32-s01	Overhead crane puts down plate parts	6	31-s01
33-s01	Fixing plate parts to corresponding place and welding cornerpiece	24	32-s01
34-s01	Overhead crane leaves plate parts	3	33-s01
35-s01	Overhead crane goes up from plate parts	6	34-s01
36-s01	Tack welding of plate parts	4,7	35-s01
37-s01	Preparing grinding machine	0,75	36-s01
38-s01	Grinding plate parts after tack welding	2,7	37-s01
39-s01	Preparing tig welding machine	3	38-s01
40-s01	Welding electrode goes down welding area and starts welding operation (1)	2,2	39-s01
40-s01-a	Welding electrode goes down welding area and starts welding operation (2)	2,2	39-s01
40-s01-b	Welding electrode goes down welding area and starts welding operation (3)	2,2	39-s01
40-s01-c	Welding electrode goes down welding area and starts welding operation (4)	2,2	39-s01
41-s01-a	Tig welding of plate parts (1)	30	40-s01
41-s01-b	Tig welding of plate parts (1)	30	40-s01-a
41-s01-c	Tig welding of plate parts (1)	30	40-s01-b
41-s01-d	Tig welding of plate parts (1)	30	40-s01-c
42-s01	Preparing grinding machine	0,75	41-s01-d
43-s01	Grinding plate parts after tig welding (1)	5,1	42-s01
43-b01	Grinding plate parts after tig welding (2)	5,1	42-s01
43-b04	Grinding plate parts after tig welding (3)	5,1	42-s01
43-b02	Grinding plate parts after tig welding (4)	5,1	42-s01
43-b05	Grinding plate parts after tig welding (5)	5,1	42-s01
44	Overhead crane holds the minor assembly structure	1	43
45	Overhead crane lifst the minor assembly structure	2	44
46	Overhead crane transports minor assembly structure to corresponding location	0,6	45
47	Overhead crane puts down the minor assembly structure to the location	2	46
48	Minor assembly structure is fixed and corner piece is welded	8	47
49	Overhead crane leaves minor assembly structure	1	48
50	Overhead crane goes up from minor assembly structure	2	49
51	Minor assembly structure is welded with tack	1,3	50
52	Preparing grinding machine	0,16	51
53	Grinding minor assembly structure after tack welding	0,61	52
54	Preparing tig welding machine	0,66	53
55	Welding electrode goes down welding area and starts welding operation	0,5	54
56-a	Tig welding operation of minor assembly structure (1)	24,4	55
56-b	Tig welding operation of minor assembly structure (2)	24,4	56-a
57	Preparing grinding machine	0,16	56-b
58	Grinding minor assembly structure after tig welding	1,14	57
59	Overhead crane goes down sub assembly structure	0,5	58
60	Overhead crane holds sub assembly structure	2	59
61	Overhead crane lifts sub assembly structure	0,5	60
62	Overhead crane transports sub assembly structure to the buffer area	0,75	61
63	Overhead crane puts down sub assembly structure on the buffer area	0,5	62
64	Overhead crane leaves sub assembly structure	2	63
65	Overhead crane goes up from sub assembly structure	0,5	64
66	Overhead crane returns to pre-fabrication area	0,75	65

Table 2**.** Cumulative durations of work operations for work station 1

Work operation	Total duration (minutes)
1	4,992
2	5,992
3	28,992
4	29,992 (M)
5	31,992
6	32,992

Table 3. Work stations and operations for cycle time of 30 min

Station no.	Work operations	Station time (min.)
1	1, 2, 3, 4	29,992
2	5, 6, 7, 8, 9, 10, 11,12-s01,13-s01,14-s01,12-b01,12-b04,12-b02,12-b05	27,903
3	15-s01,16-s01,17-s01,18-s01,19-s01,20-s01,21-s01	27,168
4	22-s01,23-s01-a	29,5
5	23-s01-b,13-b05	29,449
6	23-s01-c,24-s01,14-b05,15-b05,16-b05,17-b05	29,5
7	25-s01,26-s01,27-s01,28-s01,29-s01,30-s01,31-s01, 18-b05, 19-b05, 20-b05	29,764
8	32-s01, 33-s01	30
9	21-b05, 22-b05, 23-b05	29,95
10	34-s01, 35-s01, 36-s01, 37-s01, 38-s01, 39-s01, 40-s01, 13-b04, 14-b04, 15-b04, 16-b04, 17-b04, 24-b05	29,86
11	41-s01-a	30
12	41-s01-b	30
13	41-s01-c	30
14	41-s01-d	30
15	13-b02, 14-b02, 15-b02, 16-b02, 17-b02, 18-b02, 19-b02, 20-b02, 21-b02, 22-b02, 13-b01, 14-b01, 15-b01, 16-b01, 17-b01, 18-b01, 19-b01, 20-b01, 21-b01, 22-b01, 42-s01, 43-s01	28,618
16	23-b01, 24-b01, 18-b04	29,927
17	23-b02, 24-b02, 19-b04, 20-b04	29,555
18	21-b04, 22-b04, 23-b04	29,95
19	24-b04, 25-b01, 25-b04, 25-b02, 25-b05, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55	26,527
20	56-a	24,433
21	56-b, 57, 58, 59, 60, 61, 62, 63	29,992
22	64, 65, 66	3,25

Table 4. Work stations and operations for cycle time of 40 min

Station no.	Work operations	Station time (min.)
1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12-s01, 12-b01, 12-b04, 12-b02	39,654
2	13-b04, 14-b04, 15-b04, 16-b04, 17-b04, 18-b04, 19-b04, 20-b04, 21-b04, 22-b04, 23-b04, 24-b04	39,895
3	13-b02, 14-b02, 15-b02, 16-b02, 17-b02, 18-b02, 19-b02, 20-b02, 21-b02, 22-b02, 23-b02, 24-b02	39,856
4	13-b01, 14-b01, 15-b01, 16-b01, 17-b01, 18-b01, 19-b01, 20-b01, 21-b01, 22-b01, 23-b01, 24-b01	39,77
5	13-s01, 14-s01, 15-s01, 16-s01, 17-s01, 18-s01, 19-s01, 20-s01, 12-b05	39,409
6	13-b05, 14-b05, 15-b05, 16-b05, 17-b05, 18-b05, 19-b05, 20-b05, 21-b05, 22-b05, 23-b05, 24-b05	39,981
7	21-s01, 22-s01, 23-s01-a, 25-b01, 25-b04	38,7
8	23-s01-b, 25-b02, 25-b05	28,2
9	23-s01-c, 24-s01, 25-s01, 26-s01, 27-s01	37,132
10	28-s01, 29-s01, 30-s01, 31-s01, 32-s01	22,8
11	33-s01, 34-s01, 35-s01, 36-s01, 37-s01	38,499
12	38-s01, 39-s01, 40-s01, 41-s01-a	37,998
13	41-s01-b	30
14	41-s01-c	30
15	41-s01-d, 42-s01, 43-s01, 44, 45, 46	39,492
16	47, 48, 49, 50, 51, 52, 53, 54, 55	16,277
17	56-a	34,433
18	56-b, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66	33,242

Table 5. Work stations and operations for cycle time of 50 min

Station no.	Work operations	Station time (min.)
1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12-b05, 13-b05, 14-b05, 15-b05, 16-b05, 17-b05, 18-b05, 19-b05, 20-b05, 21-b05, 22-b05, 12-b01, 12-b04	49,663
2	12-s01, 13-s01, 14-s01, 15-s01, 16-s01, 17-s01, 18-s01, 19-s01, 20-s01, 21-s01, 12-b02	46,971
3	13-b04, 14-b04, 15-b04, 16-b04, 17-b04, 18-b04, 19-b04, 20-b04, 21-b04, 22-b04, 23-b04, 24-b04, , 25-b04, 13-b01, 14-b01, 15-b01, 16-b01, 17-b01, 18-b01	49,96
4	13-b02, 14-b02, 15-b02, 16-b02, 17-b02, 18-b02, 19-b02, 20-b02, 21-b02, 22-b02, 23-b02, 24-b02, 25-b02, 22-s01, 19-b01, 20-b01, 21-b01, 22-b01	48,811
5	23-s01-a, 23-s01-b	50
6	23-s01-c, 24-s01, 25-s01, 26-s01, 27-s01, 28-s01, 29-s01	46,314
7	30-s01-c, 31-s01, 32-s01, 33-s01, 34-s01, 35-s01	46,8
8	36-s01, 37-s01, 38-s01, 39-s01, 40-s01, 41-s01-a	43,497
9	23-b01, 24-b01, 25-b01	30,05
10	23-b05, 24-b05, 25-b05	30,05
11	41-s01-b	30
12	41-s01-c	30
13	41-s01-d, 42-s01, 43-s01, 43, 44, 45, 46, 47, 48	49,492
14	49, 50, 51, 52, 53, 54, 55, 56-a	30,71
15	56-b, 57, 58, 59, 60, 61, 62 ,63, 64, 65, 66	33,242

Table 6**.** Work stations and operations for cycle time of 60 min

Station no.	Work operations	Station time (min.)
1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12-s01, 13-s01, 14-s01, 12-b01, 12-b02, 12-b04, 12-b05	57,895
2	15-s01, 16-s01, 17-s01, 18-s01, 19-s01, 20-s01, 21-s01, 22-s01, 23-s01-a	56,668
3	23-s01-b, 23-s01-c, 24-s01, 25-s01, 26-s01	56,732
4	27-s01, 28-s01, 29-s01, 30-s01, 31-s01, 32-s01, 33-s01, 34-s01, 13-b05	59,649
5	35-s01, 36-s01, 37-s01, 38-s01, 39-s01, 40-s01, 41-s01-a, 13-b04, 14-b04, 15-b04, 16-b04, 17-b04, 18-b04, 19-b04, 20-b04	59,192
6	41-s01-b, 41-s01-c	60
7	14-b05, 15-b05, 16-b05, 17-b05, 18-b05, 19-b05, 20-b05, 21-b05, 22-b05	59,858
8	41-s01-d, 42-s01, 43-s01, 21-b04, 22-b04	37,642
9	23-b05, 24-b05, 25-b05, 23-b01, 24-b01	58,5
10	23-b04, 24-b04, 25-b01, 25-b04, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55	51,527
11	56-a, 56-b, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66	57,675