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Optimization of assignment problems in production lines with different skilled labor levels

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ABSTRACT

In order to serve the purpose of the study, two different mathematical models which belong to production line to were developed to assign workforces to the jobs who have different skills. The assignment model had been examined on a product that produced in a specified welding line in the automotive industry. All labor levels related to the product were analyzed by time study firstly and then the collected data were analyzed. New skill levels of workers, skill matrix were determined according to skill requirements (min. and max.) of the jobs. All collected data which come from time studies and skill matrix were used as an input parameter in the mathematical model that aim to minimize the unit production cost. Reports of mathematical models showed that it is necessary to assign right skilled worker to the job to minimize the production cost and increase the efficiency online. In this case the implementation was made by selecting a product in the welding manufacturing line. In the line, there are 5 stations that have 14 jobs and 27 operators. A modeling has been carried out in which the operators can be assigned to jobs under optimum conditions, based on assignment criterias. Models of sensitivity analyzes and statistic report results obtained the importance of the differences in the level of competence and the effect on the duration of the job as well as the decrease in the labor costs by assigning the correct workforce to the right job and by assigning right conditions to the model.

1. Introduction

The first developments in Operations Research emerged during World War II regarding the need for defense. The studies that started in those years with the aim of optimization have progressed to the present day. In 1947, the Simplex Optimization method was found by George Dantzig and the simplex algorithm led to improvements in linear programming [1, 2]. Although assignment problems are seen as a special type of transportation problems, they are also encountered as the most common type in linear programming models in operations research. The assignment problem, which is the common type of transportation problems, was first brought forward by Frank L Hitchcock in 1941 [3]. As a result of finding of the Simplex algorithm by Dantzing, modeling of transportation and assignment problems by linear programming and solving them by simplex algorithm have been also realized [2]. In the assignment problems, there are (a-amount of) tasks and (b-amount of) resources; the assignment is made to the tasks (a) that will be realized by available resources (b) and a cost emerges during this assignment. It is aimed here to use each resource in a task, and to achieve a solution method including an algorithm that will ensure that the cost is minimized in a controlled manner while performing this. Alternative solution methods have been reached by developing the simplex algorithm logic and these approaches have been used in solving problems in many different areas. It has been seen that in some of these alternative methods, the duration of the operation is shortened and in also some of them, more advanced problems are dealt with. The fact that Tjalling C. Koopmans and Martin Beckmann used linear programming models to explain the role and importance of assignment problems in economic activities can be given as an example for using simplex algorithm logic in different areas and achieving alternative solutions. In this

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study, two problems involving economic activities were discussed, and it was observed that economic results could be obtained by assigning not only divisible resources but also non-divisible resources [5].

The most commonly used solution method for assignment problems is the Hungarian Method which tries to reach the solution with the method of obtaining reduced matrices at each step by transforming the problem information into 0-1 matrix. The Hungarian Method was introduced by Khun in 1955. In the light of the knowledge he obtained while reading Konig's book on the theory of graphics and after his research on the subject, Khun found the Hungarian Solution Method [4]. Although the assignment problems are a type of transportation problems, it is encountered as a method that is widely used in the field of production and that is especially used frequently in operator and machine assignments. In 2017, Aicha Ferjani and her colleagues studied on an assignment problem in which many changes in the production sector, particularly changes in customer demands, were made to keep the system dynamic. With systems sensitive to changes, operators and machine assignments should be performable. Changes that occur affect the time of the mainstream while the assignment is made; one of these changes that affect the time of the mainstream is also the fatigue that occurs in the operators. Operators can spend more time than expected in their assigned tasks due to fatigue. In the study, in which the effect of the fatigue on the task duration was investigated, an intuitive analysis method with multiple criteria was used and a more dynamic machine operator assignment was attempted to perform. The results of Ferjani et al. showed that fatigue had an effect on the mainstream time and that the intuitive approach gave better results [6]. In the study which was carried out by Stefanie Brilon in 2010 and which was about assigning of the tasks requiring different skills to the operators whose skill levels were unknown, it was focused primarily on the performance of the operators for the task assignments to be done. The mathematical model for assigned workers was established. In the first case, the employer may assign any worker to any task that he deems appropriate. In the second case, there are workers coming from outside to the company. According to the workers coming from outside and considering the performances of the existing workers, the assignment was made by the employer. Based on Peter's principle and taking into account the characteristics of the task, the model was created by assigning the certain workers to certain tasks [7]. In the study of Moreira and Costa conducted in 2009, it was observed that the assignment problem is an area in which meta-heuristic algorithms were developed based on linear programming and better solutions could be reached [8]. By using the tabu algorithm, which was developed using meta-heuristic algorithm, an assembly line balancing study was performed in the assignment problem. In the addressed problem, operators with disabilities were used due to the fact that social awareness of the welfare of people with disabilities was also effective, and the solution of the problem of the completion of the task at different times due to the operators assigned to the task was discussed. In the design of tabu search algorithm developed to solve these problems, it was aimed to develop an algorithm that would make assignments as simple, flexible, accurate and fast as possible. In the established mathematical model, assignments were made taking into account task priority order and takt times in business centers (aiming to minimize). It is argued that in the tabu algorithm, an established mathematical model should be simple and flexible as well as fast and providing the correct solution. The tabu algorithm was run on the problem a large number of times and it was observed that better results were obtained [8]. In their study, in a firm making cellular production, Li and colleagues [9] developed a mathematical model that took into account the variable and fixed labor cost and assigned the operators to cells by minimizing the total cost. They calculated the total production costs based on costs varying depending on different capabilities. The competencies of the operators were determined according to the 3-sigma rule by using Gaussian distribution method and by taking into account the production efficiency that the operators obtained during the time they used the machines that they could use. Then, a technical value of the competence of each operator was created according to this method. When the results were interpreted in terms of variable and fixed labor costs, it was observed that the total cost decreased as the competencies of the staff and the number of working staff with high competency increased [9]. There are many criteria for assignment problems in production systems. In the study conducted by Achraf Ammar and his colleagues in 2013 [10], first, important features of Assignment Problems in production systems were discussed. Then, analysis was carried out by taking into consideration the other characteristics which could be evaluated as criteria and which revealed the type of problem. These characteristics were flexibility of employees, number of station, movement of labor, nature of the problem (static or dynamic assignment), human thinking (e.g., learning and forgetting effects), system type (e.g., U-shaped systems and cellular organizations), and different methods used to solve the problems (e.g., mathematical approaches, simulation, multi-criteria decision making, fuzzy logic, and methods containing a combination of these approaches). There were significant findings in the analysis results. In relation to the approaches used for dynamic operator assignments, it was remarked that although neural network simulation metamodels had been widely used in some approaches such as multiple approaches and learning methods, studies had not yet become prevalent as widely as desired, but they had an important potential [10]. Another method that has recently started to be used in assignment problems is artificial-intelligence genetic-algorithm, which is well-known and become widespread today. The study of Shaikh Nizami et al. [11] can be shown as an example for this. In this study, it is generally mentioned that the assignment problems solved by Hungarian Method can be solved by the genetic algorithm and this method is a faster and more effective tool. While using the method, the algorithm/matrix is created by using some genetic terms (e.g., genotype, chromosome, crossbreeding, selection, multiplication, mutation, etc.). By coding the objective function and constraints according to this algorithm, sequential operations are performed, and the solution is achieved [11]. In another assignment problem in which the genetic algorithm was used, a problem in which an operator could be assigned to more than one task, task-scheduling and operator-placement constraints were available, and circumstances including operator capacity constraints changed daily costs to perform tasks were dealt with [12]. In another study, the topic was the assignment model developed by Cesani and Steudel in 2005 to demonstrate the labor flexibility (based on the principles of labor sharing and labor balancing) characterized by the mobility of the operator working within the cell in cellular production systems. In this study, the focus was to investigate the effect of different work distribution strategies (For example; when only one operator is responsible for one machine or group, or when more than one operator are responsible for one machine or a group of machines) on system performance. The results of the experiment showed that the balance of workload assigned to individual operators and the level of work load shared between operators were important factors in determining the performance of the system [13]. In the study of Heimerl and Kolisch [14], assigning of multi-faceted operators to the tasks according to the knowledge/skill, loss in value and company's ability level objectives was discussed and by the established model (limited nonlinear continuous optimization model), it was attempted to reach the strategy that could be. When the performed assignments and the learning curves based on these were examined, it was concluded that faster learning made the human resources more specialized and this also led the company to have a wider quality [14]. In the study carried out by Bryan and his colleagues, the model of assigning operators to production areas was established to take into account both human and technical characteristics and their effects on system performance. Test results showed that this model offered better task assignments than employees who only consider technical capabilities. Therefore, it supports the topic that companies allocate more space on human element in the design of production systems. [15].

In our study, the area to be examined among the assignment models is an assignment problem with different levels of labor force in production lines. A product (Damper Trailer) that came out of a welding line whose assignment model was determined in the Automotive Sector was studied. The model includes tasks done at different levels of labor force. The durations of the tasks vary according to the competence of the operators who do the tasks.

There are many important constraints that affect the objective function in assignment problems. A problem with important parameters or constraints for the automotive sector, such as the presence of different levels of labour force, the inability to assign each labor force to each task, presence of the minimum level of competence required for the operators to be employed in order to assign the operator (factors inherent in the resource process are also effective in determining competencies.), changing the time of the task done according to competence and turning this time into cost was addressed.

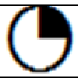
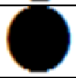
Two models were established using Linear Programming in order to complete the product as soon as possible and to minimize labor costs with the correct assignments when assigning labor force in production lines or products, which required different levels of labor force in the automotive sector. In the first mathematical model, it was aimed to ensure the cost minimization in the lines that had certain cycle time (takt) by assigning the operators at different levels of labour force taking in to account the level required by the task. On the other hand, in the second model, the cycle time (time) was unclear; while making cost minimization, making also line balancing was aimed by this second model in which operators at different labor force levels were assigned to the level required by the task and operators who minimized the time difference between assignments and had maximum time to do the task defined the cycle time (takt). The differences between these two models will be interpreted.

2. Data Analysis and Mathematical Modeling

2.1 Data Analysis

In the trailer welding line where the model will be installed for the damper trailer product, there are a total of 27 operators who could work throughout the factory. The competence of these operators are different from each other. For 8 different technical features to be sought in a person who would work on the trailer welding line where all trailer vehicle variants were produced, the competency table of the persons was formed. These technical features are: making manufacturing and welding by reading technical drawings, making MAG welding, making longitudinal girder spot and its welding, making longitudinal girder completion welding, making cold straightening, making positioner spot and its welding, making the final completion welding and making flame straightening. While these technical features were examined according to the operators, 4 level of competence was determined. The specified levels of competence are displayed visually in a circle and each quarter of the circle is described as a level of competence.

Table 1. Description of the Competency Levels Used in the Competency Table

1.Level (1L)		He has on-the-job training (can work with supervision).
2.Level (2L)		He can work alone only at that station.
3.Level (3L)		He can work alone at all stations.
4.Level (4L)		This level is the instructor level.

The operators whose competency levels were determined according to their technical features are shown in the competency table as follows.

Table 2. Trailer Welding Line Competency Table

Work Abilities / Operator	A1	A2	A3	A4	A5	A6	A7	A8
1.operator	4L	4L		4L	4L	4L	4L	3L
2.operator	4L	4L	4L	3L		2L	2L	2L
3.operator	4L	4L	2L	3L	4L	2L	4L	4L
4.operator	1L	2L	3L	2L		1L	2L	1L
5.operator	3L	4L	1L	4L	4L	2L	3L	4L
6.operator	1L	2L	1L	1L		2.L	1L	
7.operator	2L	4L	1L	3L	3L	1L	4L	4L
8.operator	2L	4L	1L	3L	3L	1L	4L	4L
9.operator	3L	4L	1L	3L	4L	4L	3L	3L
10.operator	1L	2L	1L	2L		3L	2L	
11.operator	1L	3L	1L	3L		2L	2L	2L
12.operator	1L	2L	3L	2L		1L	2L	
13.operator	1L	3L	1L	1L		2L	2L	
14.operator	1L	3L	1L	1L		2L	1L	
15.operator	1L	3L	1L	1L		3L	1L	
16.operator	1L	3L	1L	3L		1L	2L	
17.operator	2L	3L	3L	2L		1L	1L	
18.operator	2L	3L	1L	3L	2L	1L	1L	
19.operator	1L	2L	1L	1L		1L	2L	
20.operator		2L				1L		
21.operator		1L					1L	
22.operator	1L	2L	1L	1L		1L	1L	
23.operator		1L	1L	1L				
24.operator		1L		1L		1L		
25.operator		2L		1L			1L	
26.operator		2L		1L				
27.operator		2L		1L				

For the production of damper trailer, there are 5 stations on the Trailer Welding Line and 14 different tasks are being done in total; therefore, 14 labour force is needed. The levels of the needed labor force must be determined according to the needs of the task to be done. The following table provides information about which station and level of competency the 8 technical features in the competency table should be located at.

Table 3. Minimum Competency Requirements in the Stations According To the Technical Features in the Competency Table

Technical Necessaries	1.Sta.	2.Sta.	3.Sta.	4.Sta.	5.Sta.
A1	Min3L	Min3L	Min3L	Min3L	Min3L
A2	Min3L		Min3L	Min3L	Min3L
A3	Min2L				
A4		Min2L			
A5		Min3L			
A6			Min3L	Min3L	
A7					Min2L
A8					Min3L

When Table 3 and Table 2 are redesigned according to the requirements of the tasks assigned, the following table showing for which station and at which level operators have the labor force emerges. This is one of the tables that will be the basis for modeling the problem.

While time-study activities for Damper trailer product were carried out, for 14 different tasks at 5 stations, data sets were created by taking the time-study of the operator at each level.

Table 4. Competency Levels of Operators According to the Requirements of the Tasks of the Stations

Operator	1.Sta.	2.Sta.	3.Sta.	4.Sta.	5.Sta.
1.operator	4L	4L	4L	4L	4L
2.operator	4L	3L	3L	3L	3L
3.operator	4L	4L	3L	3L	4L
4.operator	2L	1L	1L	1L	2L
5.operator	3L	4L	3L	3L	4L
6.operator	1L	1L	2L	2L	1L
7.operator	2L	3L	2L	2L	4L
8.operator	2L	3L	2L	2L	4L
9.operator	3L	2L	4L	4L	3L
10.operator	1L	1L	3L	3L	1L
11.operator	1L	1L	2L	2L	2L
12.operator	2L	1L	1L	1L	1L
13.operator	1L	1L	2L	2L	2L
14.operator	1L	1L	2L	2L	2L
15.operator	1L	1L	3L	3L	1L
16.operator	1L	1L	2L	2L	2L
17.operator	3L	1L	2L	2L	1L
18.operator	2L	2L	2L	2L	1L
19.operator	1L	1L	2L	2L	1L
20.operator	1L	1L	1L	1L	1L
21.operator	1L	1L	1L	1L	1L
22.operator	1L	1L	1L	1L	1L
23.operator	1L	1L	1L	1L	1L
24.operator	1L	1L	1L	1L	1L
25.operator	1L	1L	1L	1L	1L
26.operator	1L	1L	1L	1L	1L
27.operator	1L	1L	1L	1L	1L

Table 5. Distribution of Tasks and Operators Assigned to Stations in the Model

Stations					Total Works-Operators
1.Sta	2.Sta	3.Sta	4.Sta	5.Sta	
2 work	4 work	3 work	2 work	3 work	14 works
2 op.	4 op.	3 op.	2 op.	3 op.	14 operators

The distribution of tasks and operators to be assigned at stations is as follows.

Table 4 shows the distribution of tasks to be assigned according to stations and the minimum level of competence required. All operators at different competency levels worked in 14 tasks, and a data set was created with the obtained time studies. The following table was created between the tasks and competency levels taking into account the averages obtained from this data set. The data in the table will be accepted as standard in mathematical modeling to be created.

When we match the information in Table 6 and Table 4, we can obtain the following dataset. The created data set will be used effectively in the modeling of the problem.

Table 6. The Maximum-Minimum Periods obtained for Each Task from the Operators with Different Competency

	Min-Max Time Studies (minute)				
Works	Max-Min	1L	2L	3L	4L
1.Sta 1.Work	Max	165	155	145	120
	Min	150	140	125	105
1.Sta 2.Work	Max	120	105	90	80
	Min	105	95	80	70
2.Sta 1.Work	Max	115	105	90	80
	Min	100	90	80	70
2.Sta 2.Work	Max	110	100	85	75
	Min	95	80	70	65
2.Sta 3.Work	Max	145	135	120	110
	Min	130	125	105	95
2.Sta 4.Work	Max	165	155	140	130
	Min	140	135	120	105
3.Sta 1.Work	Max	170	155	150	130
	Min	155	135	125	110
3.Sta 2.Work	Max	165	150	140	125
	Min	150	145	130	105
3.Sta 3.Work	Max	145	135	120	110
	Min	140	130	115	105
4.Sta 1.Work	Max	165	155	140	125
	Min	150	145	125	105
4.Sta 2.Work	Max	160	155	140	125
	Min	155	145	130	100
5.Sta 1.Work	Max	130	120	115	110
	Min	120	115	110	100
5.Sta 2.Work	Max	115	105	90	80
	Min	100	90	80	70
5.Sta 3.Work	Max	145	135	120	110
	Min	140	130	115	105

Table 7. The Maximum-Minimum Periods obtained for Stations, Tasks, and Operators from the Time-Study Dataset

	Time Studies (minutes)						
Operator	1.Sta 1.Work	1.Sta 2.Work	2.Sta 1.Work	...	5.Sta 1.Work	5.Sta 2.Work	5.Sta 3.Work
1.operator	max= 120 min= 105	max= 80 min= 70	max= 80 min= 70	.	max= 110 min= 100	max= 80 min= 70	max= 110 min= 105
2.operator	max= 120 min= 105	max= 80 min= 70	max= 90 min= 80	.	max= 115 min= 110	max= 90 min= 80	max= 120 min= 115
3.operator	max= 120 min= 105	max= 80 min= 70	max= 80 min= 70	.	max= 110 min= 100	max= 80 min= 70	max= 110 min= 105
4.operator	max= 155 min= 140	max= 105 min= 95	max= 115 min= 100	.	max= 120 min= 115	max= 105 min= 90	max= 135 min= 130
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
25.operator	max= 165 min= 150	max= 120 min= 105	max= 115 min= 100	...	max= 130 min= 120	max= 115 min= 100	max= 145 min= 140
26.operator	max= 165 min= 150	max= 120 min= 105	max= 115 min= 100	...	max= 130 min= 120	max= 115 min= 100	max= 145 min= 140
27.operator	max= 165 min= 150	max= 120 min= 105	max= 115 min= 100	...	max= 130 min= 120	max= 115 min= 100	max= 145 min= 140

The information in Table 6, which were created by determining according to competency level (1, 2, 3, 4th level) of the observations taken from each operators for each task without assignment criteria, consists of standardized durations according to the level at which the operator is located at the relevant station.

The writing of the model was realized by using the tables created as a result of the analyses carried out on the data collected. The following general information related to the factory was used in the model as data.

- 07:45-17:45 working hours (10 hours)
- 60 minutes lunch break
- 15 minutes of morning tea break
- 15 minutes of afternoon tea break
- Daily Net Working Time; 510 Minutes/Day
- Hourly Labor Fee; 7 Euro/Hour
- The Available Takt Time for Damper Trailer; 150 minutes/vehicle
- Number of Operators Who Can Work in the Production of Damper Trailer; 27 Operators
- Number of Stations Required for Damper Trailer Production; 5 Stations
- Number of Tasks to Be Assigned to the Stations in the Production of Damper Trailer; 14 Tasks

- Number of Operators with Appropriate Competency Required to Be Assigned to the Stations in the Production of Damper Trailer; 14 Operators

Since damper trailer is a vehicle produced in mass production, the company aims to minimize takt time by minimizing labor unit cost. However, there are some constraints in the production. Some of these constraints are that the requirements of the task are different, the competence levels of the operators are different, and there is the inability to appoint the right person to the right task. In addition, even if the person with the right competency is assigned to the task, the time to perform the task varies according to the capacity he/she has; this time period should not exceed the time of the takt. Time studies of operators at all levels were taken for the same task. When the time studies taken from the same person for the same task were examined, it was observed that the person did the task at different times in each cycle. Therefore, for the task realization duration, a standard minimum and maximum period of time was determined among the operators who were at the same task and at the same level. While mathematical models were established, the models were written by taking the highest of these durations. This is because operators always have the possibility of completing the task at the highest time. For this reason, in order to establish the model with the correct data, modeling was performed on GAMS 23.5 program by using the maximum task completion times.

2.2 Model 1: There is a Specific Cycle (Takt) Time

Notations used in the model;

Xijk: decision variable that takes 1 if k operator is assigned to j task at i station, otherwise takes 0

Tijk: task completion time of k operator at i station for j task

Cw: 1-minute labor fee

CSi: Cycle time of i station

Di: decision variable that takes 1 if i operator is assigned to the 1st station, otherwise takes 0

Ei: decision variable that takes 1 if i operator is assigned to the 2nd station, otherwise takes 0

Fi: decision variable that takes 1 if i operator is assigned to the 3rd station, otherwise takes 0

Gi: decision variable that takes 1 if i operator is assigned to the 4th station, otherwise takes 0

Hi: decision variable that takes 1 if i operator is assigned to the 5th station, otherwise takes 0

Objective function and constraints of the model;

It was aimed that the objective function would sum and minimize the multiplications of unit labor fee and task completion time of k operator when k operator was assigned to i station for j task.

$$z = \min \sum_{i=1}^{m}\sum_{j=1}^{u}\sum_{k=1}^{t} Xijk \times Tijk \times Cw$$

i=1,.....,m j=1,.....,u k=1,.....,t (1)

1st Constraint: it is added because it is required to assign one of the operators to j task at i station (if the assignment is not made, the task cannot be performed, even the product cannot be produced, and the missing operation is seen.)

$$\sum_{k=1}^{t} Xijk = 1 \qquad i= 1,.....,m \quad j=1,......,u \qquad (2)$$

2nd Constraint: It is added so that task completion time of k operator assigned to j task at i station does not pass the cycle time (takt)

$$\sum_{i=1}^{m}\sum_{j=i}^{u} Xijk \times Tijk \le CSi \qquad k= 1,.....,t \qquad (3)$$

3rd Constraint: Because k operator who has appropriate competency must be assigned to j task at i station, it is added so that assignments of the operators who have appropriate competencies are performed by established equations.

For example, if one of the 1, 2, 3, 5, 9 or 17th operators from the competency cluster must be assigned to the 1st task at the 1st station;

$$X111 + X112 + X113 + X115 + X119 + X1117 = 1 \quad (4)$$

The same formulization is also applied for other tasks.

4th Constraint: it is added because k operator must be assigned to one of the stations.

$$\sum_{k=1}^{t} Dik + Eik + Fik + Gik + Hik = 1$$

i= 1,.....,m (5)

5th Constraint: if k operator is assigned to i station, the other tasks in i station can be also assigned to him/her (In other words, each operator can take more than one task at the station assigned within the takt time.)

For example; in order to assign all the tasks in the 1st station to the 1st operator;

$$X111 \le D11$$
$$X121 \le D11$$
$$X131 \le D11 \qquad (6)$$
.
.
$$X1N1 \le D11$$

The formulization should be also repeated for other stations and operators.

According to the solution report (Appendix-1) for the mathematical model written in GAMS 23.5, the cycle time value was found as 145 minutes. Assignments made in the Gams program are transferred to the table as follows; task completion time of a operator who assigned that task (Tijk) and the cost value comprised of paid fee for that task (Tijk x Cw) are shown in the table.

Table 8.Summary Table of the Assignments Made According to the Model-1 Solution

Model-1 Summary Table of Assigns				
Sta (i)	Work (j)	Assinged Operators (k)	Times (Tijk)	costs (Tijk*Cw)
1. sta	1.work	17.op	145	17,40 €
1. sta	2.work	12.op	90	10,80 €
2.sta	1.work	2.op	90	10,80 €
2.sta	2.work	3.op	75	9,00 €
2.sta	3.work	18.op	135	16,20 €
2.sta	4.work	5.op	130	15,60 €
3.sta	1.work	1.op	130	15,60 €
3.sta	2.work	9.op	125	15,00 €
3.sta	3.work	6.op	135	16,20 €
4.sta	1.work	10.op	140	16,80 €
4.sta	2.work	15.op	140	16,80 €
5.sta	1.work	8.op	110	13,20 €
5.sta	2.work	4.op	105	12,60 €
5.sta	3.work	7.op	110	13,20 €

Because the task with the longest work time (1st station and 1st task) takes 145 min, although the duration of the other tasks are shorter, there will be waiting in other tasks until the end of the 145-minute task; in other words, it is the task that constitutes the bottleneck of the line. For this reason, even if all operators work under 145 min, their labor costs are paid as if they worked for 145 min and while the direct labor cost of the vehicle is loaded, 145-minute work time is taken into account.

Table 9. Results Regarding the Capacity and Financial Status of the Company When Assignments are Made According to the Model-1 Solution

Model-1Results of Capacity and Financial Rates							
Cost Unit (Euro/Takt)	Cycle Time (max Tijk)		Cost Unit(Cw)		Total Operators		
	145	X	0,12	X	14	=	243, 60 €
Capasity of Vehicle per Shift(Vehicle/Shift)	Shift Time		Cycle Time (max Tijk)				
	510	/	145			=	3,52
Daily Production Cost (Euro/Day)	Cost Unit		Capasity of Vehicle per Shift				
	243,60 €	X	3,52			=	857, 47 €
Annual Production Capacity (Vehicle/Year)	Capasity of Vehicle per Shift		Workday (All year)				
	3,52	X	250			=	880
Annual Production Cost (Euro/Year)	Cost Unit		Annual Production Capacity				
	243,60 €	X	880				214. 368, 00 €

2.3 Model 2: The cycle (Takt) Time is Uncertain

The notations used in the model;

Sij: sum of the duration of the tasks assigned to the j operator at i station

Ji: {cluster of the operators who will work at i station}

Ci: Max {Siji} cycle time of i station

Xijk: decision variable that takes 1 if k operator is assigned to j task at i station, otherwise takes 0

Tijk: task completion time of k operator at i station for j task

Cw: 1-minute labor fee

Di: decision variable that takes 1 if i operator is assigned to the 1st station, otherwise takes 0

Ei: decision variable that takes 1 if i operator is assigned to the 2nd station, otherwise takes 0

Fi: decision variable that takes 1 if i operator is assigned to the 3rd station, otherwise takes 0

Gi: decision variable that takes 1 if i operator is assigned to the 4th station, otherwise takes 0

Hi: decision variable that takes 1 if i operator is assigned to the 5th station, otherwise takes 0

Objective function and constraints of the model;

The objective function was added such a way to minimize the cycle time difference between the stations.

$$Z = \min \sum_{i=1}^{n} \left| Cn - Cn - 1 \right| \qquad i= 1,.....,n \qquad (7)$$

1st Constraint: it was added because it was required to assign one of the operators to j task at i station.

$$\sum_{k=1}^{t} Xijk = 1 \qquad i= 1,.....,m \quad j=1,......,u \qquad (8)$$

2nd Constraint: It was added because k operator whose competency level was appropriate must be assigned to j task at i station.

For example, if one of the 1, 2, 3, 5, 9 or 17th operators from the competency cluster must be assigned to the 1st task at the 1st station;

$$X111 + X112 + X113 + X115 + X119 + X1117 = 1 \quad (9)$$

The same formulization is also applied for other tasks.

3rd Constraint: Since the tasks are performed simultaneously, k operator should not be assigned to more than one task at the same time; therefore, it was added.

$$\sum_{i=1}^{m} \sum_{j=1}^{u} Xijk \leq 1 \qquad k= 1,.....,t \qquad (10)$$

4th Constraint: At i station, the sum of the durations of the tasks assigned to j operator constitutes Sij.

$$\sum_{i=1}^{m} \sum_{j=1}^{u} Xijk \times Tijk = Sij$$

i= 1,.....,m j=1,......,u (11)

5th Constraint: it was added so that (Sij)s in at i station constitute the maximum cycle time.

$$IfCi = \max(Sij); \tag{12}$$

$$Ci = \max \sum_{i=1}^{m} \left| Sij - Sij + 1 \right| \qquad j= 1,.....,u \tag{13}$$

According to the solution report (Apendix-2) for the mathematical model written in GAMS 23.5, the cycle time value was found as 140 minutes. Examining the model solution results, it is seen that Xijk, which is the 0-1 decision variable, takes approximate values. In the solution, operators' assignments whose approximate values are close to 1 should be accepted as 1 and operators should be assigned to the tasks in stations. The following assignments show operators assigned to the Xijk decision variable for the solution of the problem. Assignments made in the Gams program were transferred to the table as follows; the assignment values of the decision variables, the total task time assigned to the operator (Sij), and the station cycle time (Ci), which takes the maximum value of the (Sij)s assigned to the station are shown on the table.

Table 10. Summary Table of the Assignments Made According to the Model-2 Solution

Model-2 Summary Table of Assigns						
Sta (i)	Work (j)	Assing Value	Assinged Operators (k)	Times (Tijk)	Cycle Time (Ci)	
1.sta	1.work	0,7	2.op	120	C1	120
1.sta	2.work	1,0	12.op	90		
2.sta	1.work	0,8	7.op	90	C2	130
2.sta	2.work	0,5	5.op	75		
2.sta	3.work	0,5	18.op	135		
2.sta	4.work	0,7	3.op	130		
3.sta	1.work	0,6	1.op	130	C3	135
3.sta	2.work	1,0	9.op	125		
3.sta	3.work	0,9	6.op	135		
4.sta	1.work	0,6	10.op	140	C4	140
4.sta	2.work	0,7	15.op	140		
5.sta	1.work	1,0	8.op	110	C5	135
5.sta	2.work	1,0	11.op	105		
5.sta	3.work	1,0	4.op	135		

Because the task with the longest work time (4th station and 1st and 2nd tasks) takes 140 min, although the duration of the other tasks are shorter, there will be waiting in other tasks until the end of the 140-minute task; in other words, it is the task that constitutes the bottleneck of the line. For this reason, even if all operators work under 140 min, their labor costs are paid as if they worked for 140 min and while the direct labor cost of the vehicle is loaded, 140-minute work time is taken into account.

Table 11. Results Regarding the Capacity and Financial Status of the Company When Assignments are Made According to The Model-2 Solution

Model-2Results of Capacity and Financial Rates							
Cost Unit (Euro/Takt)	Cycle Time (max Tijk) 140	X	Cost Unit(Cw) 0,12	X	Total Operators 14	=	235,20 €
Capasity of Vehicle per Shift(Vehicle /Shift)	Shift Time 510	/	Cycle Time (max Tijk) 140			=	3,64
Daily Production Cost (Euro/Day)	Cost Unit 235,20 €	X	Capasity of Vehicle per Shift 3,64			=	856,13 €
Annual Production Capacity (Vehicle/Year)	Capasity of Vehicle per Shift 3,64	X	Workday (All year) 250			=	910
Annual Production Cost (Euro/Year)	Cost Unit 235,20 €	X	Annual Production Capacity 910				214.032,00 €

2.4 Comparison of the Model 1 and Model 2 Results

When the assignments carried out in the models are examined, it is seen that 8 of 14 tasks are assigned to the same operator in both models. In the other 6 assignments, since the models have different objective functions, it is seen that the assignments are also different.

When we compared Table 1 and Table 2 as the financial status and capacity status of the results of the assignments made within the reference range of Model-1 & Model-2;

- Considering the actual unit costs, it was seen that an 8.4 euro gain was ensured during a Takt period and Model 2 provided a 3.45% reduction in the cost per vehicle.
- It was observed that vehicle production capacity in Model 2 increased by 13% in shift.
- It was also determined that due to the 5-minute cycle time difference between Model 1 and Model 2, Model 2 made a profit of € 7392 in 2 years; this profit corresponds to the production cost of 31 vehicles per year.

3. Sensitivity Analysis

All results from Model-1 and model-2 comparisons show that model-2 achieves more efficient results. Therefore, the sensitivity analysis will be written through Model-2. The writing and solutions of the models will be done through the GAMS program and the results will be compared. Information about new models to be created for sensitivity analysis;

- In the new Model-2.1, the number of operators (human resource) will be increased from 27 operators to 35 operators, the number of stations will be increased from 5 stations to 6 stations, and due to the addition of the 6th station, the number of tasks will increase to 16. Therefore, the number of operators required to be assigned will also be 16.
- In the new Model-2.2, the number of operators (human resource) will be increased from 35 operators to 40 operators, the number of stations will be increased from 6 stations to 8 stations, and due to the addition of the 7th and 8th stations, the number of tasks will increase to 20. Therefore, the number of operators required to be assigned will also be 20.
- In the new Model-2.3, the number of operators (human resource) will be increased from 40 operators to 50 operators, the number of stations will be increased from 8 stations to 10 stations, and due to the addition of the 9th and 10th stations, the number of tasks will increase to 25. Therefore, the number of operators required to be assigned will also be 25.

3.1 Sensitivity Analysis 1 (New Model 2.1)

The new model (Model 2.1) constituting the 1st step of the sensitivity analysis will be established by being expended according to 6th station to which the objective function and constraints of Model 2 will be added, 2 tasks connected to this station and the new 8 operators added to 27 operators. A total of 16 operators will be required for 16 tasks. In addition to Table 3, technical requirement for manufacturing and welding by reading technical drawings at a minimum 2nd level and technical requirement for MAG welding at a minimum 2nd level are required at the 6th station. In addition to Table 6, Table 12 was obtained for 6th station. See also Apandix-3 for the competencies of new operators added.

Examining the model solution results, it is seen that Xijk, which is the 0-1 decision variable, takes approximate values. In the solution, operators' assignments whose approximate values are 0.5 and above should be accepted as 1 and operators should be assigned to the tasks in the stations. The following assignments show operators assigned to the Xijk decision variable for the solution of the problem. Assignments made in the Gams program were transferred to the table as follows; the assignment values of the decision variables, the total task time assigned to the operator (Sij), and the station cycle time (Ci), which takes the maximum value of the (Sij)s assigned to the station are shown on the table.

Table 12. Maximum-Minimum Period Table Obtained For Each Task from Time Surveys Taken From Operators of Different Abilities (6th Station-New)

Works	New Min-Max Time Studies (minute)				
	MinMax	1L	2L	3L	4L
6.Sta 1.Work	Max	145	135	130	110
	Min	140	130	120	100
6.Sta 2.Work	Max	145	135	130	90
	Min	140	130	120	80

Table 13. Summary Table of Assignments made according to the Sensitivity Analysis 1 Model-2.1 Solution

Model-2.1 Summary Table of Assigns						
Sta (i)	Work (j)	Assing Value	Assinged Operators (k)	Times (Tijk)	Cycle Time (Ci)	
1.sta	1.work	0,9	30.op	120	C1	120
1.sta	2.work	1	12.op	90		
2.sta	1.work	1	7.op	90	C2	130
2.sta	2.work	0,9	3.op	75		
2.sta	3.work	1	5.op	110		
2.sta	4.work	0,9	32.op	130		
3.sta	1.work	0,9	1.op	130	C3	130
3.sta	2.work	1	9.op	125		
3.sta	3.work	1	10.op	120		
4.sta	1.work	0,5	28.op	125	C4	140
4.sta	2.work	0,5	29.op	140		
5.sta	1.work	0,9	8.op	110	C5	110
5.sta	2.work	1	4.op	105		
5.sta	3.work	0,9	35.op	110		
6.sta	1.work	0,9	2.op	110	C6	135
6.sta	2.work	0,9	11.op	135		

Because the task with the longest work time (4th station 2nd task) takes 140 min, although the duration of the other tasks are shorter, there will be waiting in other tasks until the end of the 140-minute task; in other words, it is the task that constitutes the bottleneck of the line. For this reason, even if all operators work under 140 min, their labor costs are paid as if they worked for 140 min and while the direct labor cost of the vehicle is loaded, 140-minute work time is taken into account.

Despite the same cycle time as Model-2 (140 min), the Actual Unit Cost and the Annual Production Cost increased because 2 operators worked more. However, since the cycle time was not changed, the capacity also was not changed.

3.2 Sensitivity Analysis 2 (New Model 2.2)

The new model (Model 2.2) constituting the 2nd step of the sensitivity analysis will be established by being expended according to the 7th and 8th stations to which the objective function and constraints of Model 2.1 will be added, 4 tasks connected to these stations and the new 5 operators added to 35 operators. There will be a total of 20 tasks and 20 operators will be required. In addition to Table 3, technical requirement for making cold straightening at a minimum 2nd level at the 7th station and technical requirement for making the final completion welding at a minimum 2nd level at the 8th station are required. In addition to Table 6, Table 15 was obtained for the 7th and 8th stations. See also Apandix-4 for the competencies of new operators added.

Table 14. Results related to the Capacity and Financial Status of the Company When Assignments are Made According to the Sensitivity Analysis 1 Model-2.1 Solution

Model-2.1Results of Capacity and Financial Rates							
Cost Unit (Euro/Takt)	Cycle Time (max Tijk) 140	X	Cost Unit(Cw) 0,12	X	Total Operators 16	=	268,80 €
Capasity of Vehicle per Shift(Vehicle/Shift)	Shift Time 510	/	Cycle Time (max Tijk) 140			=	3,64
Daily Production Cost (Euro/Day)	Cost Unit 268,80 €	X	Capasity of Vehicle per Shift 3,64			=	978,43 €
Annual Production Capacity (Vehicle/Year)	Capasity of Vehicle per Shift 3,64	X	Workday (All year) 250			=	910
Annual Production Cost (Euro/Year)	Cost Unit 268,80 €	X	Annual Production Capacity 910				244.608,00 €

Table 15. Maximum-Minimum Period Table Obtained for Each Task from Time Surveys Taken from Operators of Different Abilities (7th and 8th Stations-New)

	New Min-Max Time Studies (minute)				
Works	Max-Min	1L	2L	3L	4L
7.Sta 1.Work	Max	130	120	100	90
	Min	125	110	95	70
7.Sta 2.Work	Max	130	120	100	90
	Min	125	110	95	70
8.Sta 1.Work	Max	120	110	100	90
	Min	115	105	95	70
8.Sta 2.Work	Max	120	110	100	90
	Min	115	105	95	70

According to the solution report belonging to the mathematical new model written in gams, the objective function value was found as 130 minutes. When the model solution results are examined, it is seen that contrary to Model-2 and Model-2.1, Xijk, which is the 0-1 decision variable, do not take approximate values, but takes exact values as desired. Operators added to the system in Model-2.2 were selected as fully competent for all stations and tasks (4th level). Therefore, looking at the model result, it is seen that since there were a sufficient number of operators suitable for the desired competencies of the tasks, a full-value assignment was done. Assignments made in the Gams program were transferred to the table as follows.

Since the task with the longest work time (the 4th task at the 2nd stations and the 1st task at the 3rd station) takes 130 min, although the duration of the other tasks are shorter, there will be waiting in other tasks until the end of the 130-minute task; in other words, it is the task that constitutes the bottleneck of the line. For this reason, even if all operators work under 130 min, their labor costs are paid as if they worked for 130 min and while the direct labor cost of the vehicle is loaded, 130-minute work time is taken into account.

Table 16. Summary Table of Assignments Made according to the Sensitivity Analysis 2 Model-2.2 Solution

Model-2.2 Summary Table of Assigns						
Sta (i)	Work (j)	Assing Value	Assinged Operators (k)	Times (Tijk)	Cycle Time (Ci)	
1. sta	1.work	1	39.op	120	C1	120
1. sta	2.work	1	12.op	90		
2.sta	1.work	1	34.op	90	C2	130
2.sta	2.work	1	8.op	85		
2.sta	3.work	1	5.op	110		
2.sta	4.work	1	36.op	130		
3.sta	1.work	1	1.op	130	C3	130
3.sta	2.work	1	9.op	125		
3.sta	3.work	1	10.op	120		
4.sta	1.work	1	38.op	125	C4	125
4.sta	2.work	1	37.op	125		
5.sta	1.work	1	3.op	110	C5	110
5.sta	2.work	1	35.op	80		
5.sta	3.work	1	40.op	110		
6.sta	1.work	1	28.op	110	C6	110
6.sta	2.work	1	29.op	90		
7.sta	1.work	1	32.op	90	C7	90
7.sta	2.work	1	30.op	90		
8.sta	1.work	1	7.op	90	C8	110
8.sta	2.work	1	2.op	110		

Table 17. Results related to the Capacity and Financial Status of the Company When Assignments are Made According to the Sensitivity Analysis 2 Model-2.2 Solution

Model-2.2Results of Capacity and Financial Rates							
Cost Unit (Euro/Takt)	Cycle Time (max Tijk) 130	X	Cost Unit(Cw) 0,12	X	Total Operators 20	=	312,00 €
Capasity of Vehicle per Shift(Vehicle/Shift)	Shift Time 510	/	Cycle Time (max Tijk) 130			=	3,92
Daily Production Cost (Euro/Day)	Cost Unit 312,00 €	X	Capasity of Vehicle per Shift 3,92			=	1223,04 €
Annual Production Capacity (Vehicle/Year)	Capasity of Vehicle per Shift 3,92	X	Workday (All year) 250			=	980
Annual Production Cost (Euro/Year)	Cost Unit 312,00 €	X	Annual Production Capacity 980				305.760,00 €

Though the cycle time decreased to 130 minutes compared to Model-2, the Actual Unit Cost and the Annual Production Cost showed a decreasing increase because 6 operators worked more. Moreover, since the cycle time decreased, the production capacity increased.

3.3 Sensitivity Analysis 3 (New Model 2.3)

The new model (Model 2.3) constituting the 3rd step of the sensitivity analysis will be established by being expended according to the 9th and 10th stations to which the objective function and constraints of Model 2.3 will be added, 5 tasks connected to these stations and the new 10 operators added to 40 operators. There will be a total of 25 tasks and 25 operators will be required. In addition to Table 3, technical requirement for making positioner spot and its welding at a minimum 3rd level at the 9th station and technical requirement for making MAG welding at a minimum 3rd level at the 10th station are required. In addition to Table 6, Table 18 was obtained for the 9th and 10th stations. See also Apandix-5 for the competencies of new operators added.

Table 18. Maximum-Minimum Period Table Obtained For Each Task from Time Surveys Taken From Operators of Different Abilities (9th and 10th Stations-New)

	New Min-Max Time Studies (minute)				
Works	Max-Min	1L	2L	3L	4L
9.Sta 1.Work	Max	130	120	100	90
	Min	125	110	95	70
9.Sta 2.Work	Max	130	120	100	90
	Min	125	110	95	70
9.Sta 3.Work	Max	130	120	100	90
	Min	125	110	95	70
10.Sta 1.Work	Max	120	110	100	90
	Min	115	105	95	70
10.Sta 2.Work	Max	120	110	100	90
	Min	115	105	95	70

According to the solution report belonging to the mathematical new model written in gams 23.5, the objective function value was found as 130 minutes. When the model solution results are examined, it is seen that contrary to Model-2 and Model-2.1, Xijk, which is the 0-1 decision variable, do not take approximate values, but takes exact values as desired and in a similar way with Model 2.2. Operators added to the system in Model-2.3 were selected as fully competent for all stations and tasks (4th level). Therefore, looking at the model result, it is seen that since there were a sufficient number of operators suitable for the desired competencies of the tasks, a full-value assignment was done. Assignments made in the Gams program were transferred to the table as follows; the assignment values of the decision variables, the total task time assigned to the operator (Sij), and the station cycle time (Ci), which takes the maximum value of the (Sij)s assigned to the station are shown on the table.

Table 19. Summary Table of Assignments Made according to the Sensitivity Analysis 3 Model-2.3 Solution

Model-2.3 Summary Table of Assigns						
Sta (i)	Work (j)	Assing Value	Assinged Operators (k)	Times (Tijk)	Cycle Time (Ci)	
1. sta	1.work	1	39.op	120	C1	120
1. sta	2.work	1	29.op	80		
2.sta	1.work	1	32.op	80	C2	130
2.sta	2.work	1	8.op	75		
2.sta	3.work	1	5.op	110		
2.sta	4.work	1	42.op	130		
3.sta	1.work	1	1.op	130	C3	130
3.sta	2.work	1	9.op	125		
3.sta	3.work	1	2.op	120		
4.sta	1.work	1	38.op	125	C4	125
4.sta	2.work	1	37.op	125		
5.sta	1.work	1	28.op	110	C5	110
5.sta	2.work	1	30.op	80		
5.sta	3.work	1	41.op	110		
6.sta	1.work	1	40.op	110	C6	110
6.sta	2.work	1	48.op	90		
7.sta	1.work	1	47.op	90	C7	90
7.sta	2.work	1	46.op	90		
8.sta	1.work	1	7.op	90	C8	90
8.sta	2.work	1	3.op	90		
9.sta	1.work	1	45.op	90	C9	90
9.sta	2.work	1	44.op	90		
9.sta	3.work	1	43.op	90		
10.sta	1.work	1	18.op	90	C10	100
10.sta	2.work	1	11.op	100		

Table 20. Results related to the Capacity and Financial Status of the Company When Assignments are Made According to the Sensitivity Analysis 3 Model-2.3 Solution

Model-2.3Results of Capacity and Financial Rates							
Cost Unit (Euro/Takt)	Cycle Time (max Tijk)		Cost Unit(Cw)		Total Operators		390,00 €
	130	X	0,12	X	25	=	
Capasity of Vehicle per Shift(Vehicle/Shift)	Shift Time		Cycle Time (max Tijk)				3,92
	510	/	130			=	
Daily Production Cost (Euro/Day)	Cost Unit		Capasity of Vehicle per Shift				1528, 80 €
	390,00 €	X	3,92			=	
Annual Production Capacity (Vehicle/Year)	Capasity of Vehicle per Shift		Workday (All year)				
	3,92	X	250			=	980
Annual Production Cost (Euro/Year)	Cost Unit		Annual Production Capacity				382.200,00 €
	390,00 €	X	980				

Since the task with the longest work time (the 4th task at the 2nd stations and the 1st task at the 3rd station) takes 130 min, although the duration of the other tasks are shorter, there will be waiting in other tasks until the end of the 130-minute task; in other words, it is the task that constitutes the bottleneck of the line. For this reason, even if all operators work under 130 min, their labor costs are paid as if they worked for 130 min and while the direct labor cost of the vehicle is loaded, 130-minute work time is taken into account.

Though the cycle time decreased to 130 minutes compared to Model-2, the Actual Unit Cost and the Annual Production Cost showed a decreasing increase because 11 more workers worked. Moreover, since the cycle time decreased, the production capacity increased.

4. Results and Discussions

4.1 Results and Recommendations Related to the Assignment of the Operator who has the Right Competency to the Right Task, Training Planning, Human Resource Planning and Productivity

It was seen that in Model-2 and Model-2.1, the Xijk decision variable received a decimal value between 0 and 1, but in Model-2.2 and model-2.3, it received value of 0 or 1 as desired. When the reason of this was examined, it was observed that there was no human resource (operator) who had appropriate competency in Model-2 and model-2.1. Therefore, in the model, the assignments were done by giving decimal values to some competent operators. In Model-2.2, it was intervened in this situation; the 35, 36, 37, 38, 39 and 40th operators with the highest level of competence in all tasks were included in the model and it was ensured that the assignments were converted into 0 or 1. The same situation was carried out by including the 41, 42, 43, 44, 45, 46, 47, 48, 49, 50th operators with full competence in the model. In an enterprise, this situation means that when the model is run, if there is an assignment other than the value of 0 or 1, there is a missing labor force in the station or task where this assignment is performed. This situation must be reported to the planning department and assignment of an operator with appropriate competence should be ensured. If there is no such operator, the subject should be communicated to the Human Resources Unit, the decision to make training planning for existing operators or the decision to seek new human resources should be made. In this way, training plans and human resource needs can be objectively revealed. From a different viewpoint, because increasing the competencies of operators will create a supply, increasing the competency will also trigger for individual competition. All of these effects will result in a win-win relationship while increasing the intangible assets (intellectual capital) in the medium-term from the growth-learning perspective for the firm. In the medium and long-term, there will be many productivity gains, such as the development of operations, the decrease in cycle time, and the increase in capacity. It will be possible to observe that intangible assets (intellectual capital) transform into tangible assets for the company along with their productivity outputs. The established model pointed out that the person with the correct competence should work in the correct operation; also, the gains that it would bring were evaluated in terms of the medium and long-term.

4.2 Results and Recommendations Related to Productivity Provided by the Cycle of Finding Bottlenecks and Continuous Recovery

It is observed that as a result of the assignments in Model-2 and model-2.1, the cycle time has remained at 140 minutes, and as a result of the assignments with the addition of competent staffs into the model-2.2, it has dropped to 130 minutes. In the model-2.3, it is seen that although it has been continued to add the competent staffs in the model, the cycle time has not improved, but remains in 130 minutes as a result of the assignments. When the reason of this is examined, for Model 2.2 and model 2.3, it is seen that the duration of the work is 130 minutes, even if the most competent operator (4th level) were assigned for “the 4th task at the 2nd Station” and “the 1st task at the 3rd Station”. In an enterprise, this should mean that when you run the model, if you want to perform productivity studies in tasks affecting the cycle time, such as improving cycle time, line balancing, and providing capacity increase, it is necessary to perform improvement in the task or tasks that affect cycle time. When the model is executed, it is pointed out to the points of the task or tasks (that is, operations) that create bottlenecks and that affect the cycle time. This indicates that an enterprise needs improvement in which product, which station, and which task of the relevant station. After the improvement, a model that provide the presentation of the data in an objective in which direct results can be obtained and comparison for before and after can be made was developed. At the same time, the necessity of using simple production techniques come into prominence. In the improvements to be made, it should be focused on the non-value added activities in the operation prior to Kaizen, improvements should be designed to eliminate them, team works should be carried out on how value added activities can be done more efficiently, measurements should be repeated after Kaizen, and the difference should be reflected to the model as a result of improvement. Simple production methods can be taken as a guide in the operation improvement studies to be carried out. In order to emphasize the necessity and importance of the improvement, it was assumed that in “Sensitivity Analysis Model-2.3”, an improvement was made on the 130-minute “4th task at the 2nd station” and “1st task at the 3rd station” which affected the cycle time. Assuming that this time was reduced from 130 minutes to 110 minutes, the same model was run again as “Sensitivity Analysis Model-2.3 Version 2”, and the following results was obtained. According to the solution report for the new mathematical model written in gams, the objective function value was found as 125 minutes.

Table 21. Summary Table of the Assignments Made According to the Solution of Sensitivity Analysis 3 Model-2.3 Version 2

Model-2.3 Version 2 Summary Table of Assigns						
Sta (i)	Work (j)	Assing Value	Assinged Operators (k)	Times (Tijk)	Cycle Time (Ci)	
1. sta	1.work	1	39.op	120		120
1. sta	2.work	1	29.op	80	C1	
2.sta	1.work	1	32.op	80		
2.sta	2.work	1	3.op	75		
2.sta	3.work	1	43.op	110	C2	110
2.sta	4.work	1	44.op	110		
3.sta	1.work	1	9.op	110		
3.sta	2.work	1	1.op	125	C3	125
3.sta	3.work	1	2.op	120		
4.sta	1.work	1	37.op	125	C4	125
4.sta	2.work	1	36.op	125		
5.sta	1.work	1	38.op	110		
5.sta	2.work	1	30.op	80	C5	110
5.sta	3.work	1	42.op	110		
6.sta	1.work	1	41.op	110		
6.sta	2.work	1	50.op	90	C6	110
7.sta	1.work	1	49.op	90		
7.sta	2.work	1	48.op	90	C7	90
8.sta	1.work	1	46.op	90		
8.sta	2.work	1	45.op	90	C8	90
9.sta	1.work	1	47.op	90		
9.sta	2.work	1	40.op	90	C9	90
9.sta	3.work	1	28.op	90		
10.sta	1.work	1	5.op	90	C10	
10.sta	2.work	1	1.op	100		100

As seen in the assignments of Sensitivity Analysis 3 Model -2.3 Version 2, when it was assumed that an improvement was made on the 130-minute "4th task at the 2nd station" and "1st task at the 3rd station" and when it was accepted that this time was reduced from 130 minutes to 110 minutes, as a result of the assignments, the model was able to be reduced only to 125 minute cycle time due to other works that had effects on cycle time. When the model was run, it was said that the task or tasks (that is, operations) that affect the cycle time pointed out to the points creating the bottleneck and this indicated that an enterprise needed to be improved in which product, which station, and which task of the relevant station. Looking at the assignments of the Sensitivity Analysis 3 Model-2.3 version 2, they indicate that the new improvement points are "the 2nd task at the 3rd stations", "the 1st task at the 4th station" and the "2nd task at the 4th Station". These operations also should be improved by making new kaizens, pre-post measurements should be done and continuous improvement cycle should be established by running the model according to new data at each time.

4.3 Results and Recommendations on Cycle Time, Number of Operators and Unit Cost

The following chart summarizes the cycle time of the established models, the number of operators needed to perform the production during this cycle, and the production cost per vehicle when the constraints of the models are ensured.

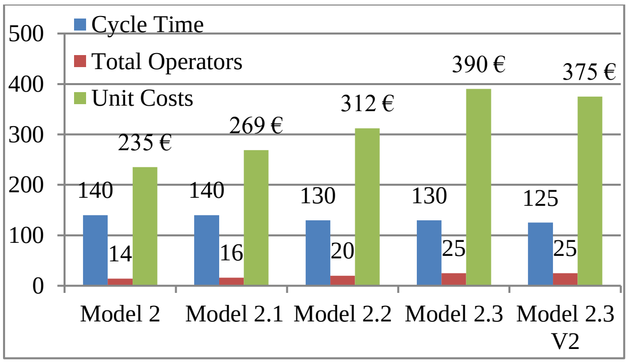


Figure 1. Results obtained on cycle time, number of operators (operators) and unit cost

- In the Sensitivity Analysis Model-2.1, with the addition of "the 6th Station 1st and 2nd tasks" to the Model-2, the number of operators increased from 14 operators to 16 operators and the cost per unit of the vehicle increased because the cycle time did not change.
- In the Sensitivity Analysis Model-2.2, with the addition of "the 7th Station 1st and 2nd tasks" and "the 8th station 1st and 2nd tasks" to the Model-2.1, the number of operators increased from 16 operators to 20 operators and the cost per unit of the vehicle increased although the cycle time changed. If the cycle time was the same, the unit cost would be 337 Euros, but it is currently 312 Euros. Reduction in cycle time provided an 8% cost recovery in cost per vehicle.
- In the Sensitivity Analysis Model-2.3, with the addition of "the 9th Station 1st, 2nd and 3rd tasks" and "the 10th station 1st and 2nd tasks" to the Model-2.2, the number of operators increased from 20 operators to 25 operators and the cost per unit of the vehicle increased because the cycle time did not change.
- In the Sensitivity Analysis Model-2.3 Version 2, with the assumed improvement in cycle time compared to the Model-2.3, it was observed that with the same sources and constraints, the unit cost became 390 euros instead of 375 euros. The decrease in cycle time provided a 4% cost recovery in cost per vehicle.

4.4 Results and Recommendations on Annual Production Capacity and Annual Production Cost

The annual production capacities and the annual production costs obtained in the established models are summarized in the charts below.

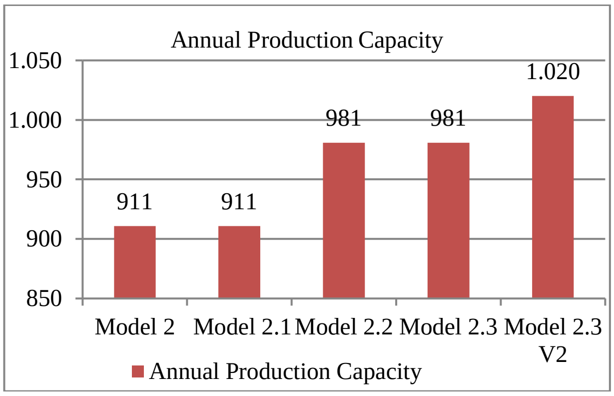


Figure 2. The obtained results on annual production capacity

- In Model-2 and Sensitivity Analysis Model 2.1, the company has the capacity to produce 911 vehicles per year since the cycle time is the same.
- In the Sensitivity Analysis Model 2.2 and Sensitivity Analysis Model 2.3, since the cycle time decreased from 140 minutes to 130 minutes, the capacity of the company increased to the capability of producing 981 vehicles per year. 8% capacity increase was observed here.

In the Sensitivity Analysis Model 2.3 Version 2, when the model was run according to the assumption that improvement was done in the operation, the capacity of the company increased to the capability of producing 1020 vehicles per year because the cycle time was reduced from 130 to 125 minutes. 4% capacity increase was observed here. A 5-minute improvement in the cycle time created an opportunity to produce 39 more vehicles in a year and 4% capacity improvement was achieved. Even if this result is based on the assumption, it reveals the ability of the model to determine the continuous improvement needs and also shows the consequences of this.

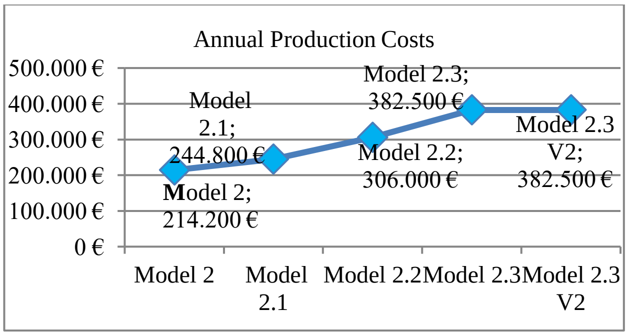


Figure 3. Results obtained on annual production cost

5. Conclusions

In the models, the annual production costs that the enterprise must bear in line with its annual production are as shown in the chart. By adding the fixed expenses and the vehicle sales figures in the annual budget to these analyses as data and by taking the variable costs from the annual production cost according to the data of the model, the break-even analysis of the enterprise can be achieved, and by combining it with the results of the model, it can be contributed to the strategic planning and projects of the enterprise.

References

1. Hillier, F.S., Lieberman, G.J., *Introduction to Operations Research*, 2010, New York:McGraw-Hill,Inc.
2. Nash, J., *The Dantzig simplex method for linear programming*. Computing in Science & Engineering, 2000. p.29-31.
3. Hitchcock, F., *The Distribution of a Product from Several Sources to Numerous Localities*. Studies in Applied Mathematics, 1941. p.224-230.
4. Kuhn, H. W., *The Hungarian Method for the Assignment Problem.*Naval Research Logistics Quarterly, 1955. (2): p.1-2.
5. Koopmans, C. and Beckmann, M., *Assignment Problems and the Location of Economic Activities*, Econometrica, 1957. 25(1): p. 53-76.
6. Ferjani, A., Ammar, A., Pierreval, H., Elkosantini, S., *A simulation-optimization based heuristic for the online assignment of multi-skilled workers subjected to fatigue in manufacturing systems*, Computers & Industrial Engineering, 2017. p. 663–674.
7. Brilon, S., *Job Assignment with Multivariate Skills*, Preprints of the Max Planck Institute for Research on Collective Goods, 2010.
8. Moreira, M., and Costa, A., *A minimalist yet efficient tabu search algorithm for balancing assembly lines with disabled workers*, XLI SBPO Pesquisa Operacional na Gestão do Conhecimento, 2009: p. 660-671.
9. Li,Q., Gong, J., Tang, J. and Song, J., *Simulation of The Model of Workers Assignment in Cellular Manufacturing based on the Multifunctional Workers*, Chinese Control and Decision Conference, 2008.
10. Ammar, A., Pierreval, H., Elkosentini, S., *Worker Assignment Problems in Manufacturing Systems: A Literature Analysis*, Rabat-Morocco IESM Conference, 2013.
11. Nizami, S., Khan, F., Khan, N., Inayatullah, S., Inayatullah,S., *A New Method for Finding the Cost of Assignment Problem Using Genetic Algorithm of Artificial Intelligence, International Journal of Latest Trends in Computing*, 2011. 2(1): p.135.
12. Kotwal, J. and Dhope, T. *Solving Task Allocation to the Worker Using Genetic Algorithm*, International Journal of Computer Science and Information Technologies, 2015. 6 (4): p.3736-3741
13. Cesanı, V. and Steudel, H., *A study of labor assignment flexibility in cellular manufacturing systems*, Computers & Industrial Engineering, 2005. 48: p.571-591.
14. Heimerl, C. and Kolisch, R., *Work assignment to and qualification of multiskilledhuman resources under knowledge depreciation and company skill level targets*, International Journal of Production Research, 2010. 48(13): p.3759-3781.
15. Norman, B., Tharmmaphornphilas, V., Needy, K., Bidanda, B. and Warner, R., *Worker assignment in cellular manufacturing considering technical and human skills*, International Journal of Production Research, 2002. 40(6): p. 1479-1492