AN ASSEMBLY LINE BALANCING PROBLEM WITH IDENTICAL PARALLEL STATIONS AND WORKER CAPABILITY

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AN ASSEMBLY LINE BALANCING PROBLEM WITH IDENTICAL PARALLEL STATIONS AND WORKER CAPABILITY

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To my family...

ABSTRACT

This study focuses on the balancing problem of the assembly lines in Vestel Electronics' TV production facility. TV production includes numerous tasks, and complex precedence relationships increase the problem's complexity. In assembly lines, the production is made in a given cycle time, and parallel stations can be opened to increase the line's efficiency. The tasks of the stations are performed by the workers. This study aims to assign the workers to the stations depending on their capabilities and not exceeding the cycle time of the line, and increasing the production rate by opening identical parallel stations. A mathematical model is formulated to solve the assembly line balancing problem type-1, which includes opening parallel stations and assigning the workers to the stations based on worker skills. Moreover, company-specific constraints are added to the model to satisfy the production conditions. Depending on the company's requirements, an alternative meta-heuristic algorithm is developed to receive more rapid solutions than the mathematical model. Computational experiments show that the developed algorithm can be used as a decision-support tool to satisfy the production metrics.

Keywords: Parallel Stations Assembly Line Balancing Problem, Worker Capability, Mixed Integer Linear Programming, Meta-Heuristic Algorithms

ÖZETÇE

Bu çalışma, Vestel Elektronik'in TV üretim tesisindeki montaj hatlarının dengeleme problemine odaklanmaktadır. TV üretiminde çok sayıda iş bulunmaktadır ve bu işlerin karmaşık öncelik ilişkileri problemin kompleksliğini arttırmaktadır. Üretim montaj hatlarında belirli bir çevrim süresinde gerçekleşmekte ve paralel istasyonlar açılarak hattın hattın verimliliğini arttırılabilmektedir. İstasyonlarda bulunan işler işçiler tarafından yapılmaktadır. Bu çalışmadaki amaç, işçileri kabiliyetlerine göre hattın çevrim süresini aşmayacak şekilde istasyonlara atamak ve paralel istasyonlar açarak hattın verimliliğini arttırmaktır. Paralel istasyonların açılması ve işçilerin yeteneklerine göre istasyonlara atanmasını içeren montaj hattı dengeleme problemi tip-1'i çözmek için bir matematiksel model formüle edilmiştir. Ayrıca, üretimin koşullarını sağlamak amacıyla şirkete özgü kısıtlar matematiksel modele dahil edilmiştir. Şirketin ihtiyaçlarına bağlı olarak, matematiksel modele göre daha hızlı çözümler elde etmek amacıyla alternatif bir meta-sezgisel algoritma geliştirilmiştir. Hesaplamalı deneyler, geliştirilen algoritmanın üretim metriklerini karşılamak için bir karar destek aracı olarak kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Paralel İstasyonlu Hat Dengeleme Problemi, İşçi Becerileri, Karma Doğrusal Tam Sayılı Programlama, Meta-Sezgisel Algoritmalar

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CHAPTER I

INTRODUCTION

Assembly lines are a common manufacturing technique where a product is produced through a series of sequential tasks, and separate stations carry each out. Assembly lines suitable for mass production are designed to increase efficiency by dividing tasks into simpler sub-tasks, with each worker specializing in a specific task. Assembly lines are widely used in automotive, electronics, and food processing industries, and humans, machines, or robots can be used at the stations.

Assembly Line Balancing Problems(ALBPs) focus on the decision of the task assignments of the assembly lines. Assembly Line Balancing Problems can be classified into two main groups; Simple Assembly Line Balancing Problems(SALBPs) and General Assembly Line Balancing Problems(GALBPs), based on their features. One of the versions of SALBP, Simple Assembly Line Balancing Problem - 1, aims to minimize the number of stations at a known cycle time. This study focuses on SALBP-1 with parallel stations.

Parallel Stations Assembly Line Balancing Problem(PSALBP) is an enhanced version of SALBP. In the Simple Assembly Line Balancing Problem, the tasks are assigned to the stations according to a defined cycle time, and the goal is to minimize the number of stations (SALBP-1). In Parallel Stations Assembly Line balancing problems, parallel stations are created by combining stations, and the goal is to reduce the total number of stations.

In the assembly lines, the tasks can be performed by the workers in the stations.

In mass-production assembly lines where the cycle time is short, the employee's performance can affect production. Therefore, the labor force difference between the workers has been discussed and included in the problem.

This study focuses on the line-balancing problem of Vestel Electronics' TV production assembly lines. This study aims to reduce the total number of stations in the line by grouping the stations in the assembly lines to increase the efficiency of the line and to assign workers to these stations who will not exceed the cycle time. However, the product includes various numbers of tasks, and the complex precedence relationships of the tasks increased the complexity of the problem. In addition, the upper limit of parallel stations that can be opened according to the structure of the facility and the time limit for the solution makes the problem even more difficult.

This study consists of the following sections. In Section 2, information about the company and details about the problem is described. The literature review of the problem is presented in Section 3. Section 4 explains the details of the mathematical model and solution methods, and section 5 gives the results of the developed algorithm. **In Section 6, the benefits of the study are stated, and the study is proposed to the company as a decision support system.**

CHAPTER II

PROBLEM DEFINITION

In this section, general information about the company and details about the problem will be explained.

2.1 Information About the Company

Vestel Electronics, which has over 7300 employees and produces 6 million televisions annually, is one of the biggest electronics companies in Europe. The main product range of Vestel Electronics is Television (TV), Electric Vehicle Chargers(EVC), Smart Board, Led Wall, etc. Furthermore, Vestel Electronics manufactures equipment and components for its products.

2.2 Details of Production

The annual TV production amount at Vestel Electronics is 6 million units. Moreover, Vestel Electronics is the leading component supplier for their TVs. Vestel Electronics has eight facilities for producing TVs, their other products, and also components of these products in the same location. One of these facilities, assembly lines, called "final-assembly" are used in TV production to reach this high output.

Cells are purchased from suppliers which are located in Asia. The electronic parts and the product components are made in-house or purchased from suppliers and brought to the assembly lines. The television is produced when these parts are combined. The material flow of the company in the assembly lines is given in Figure 1:

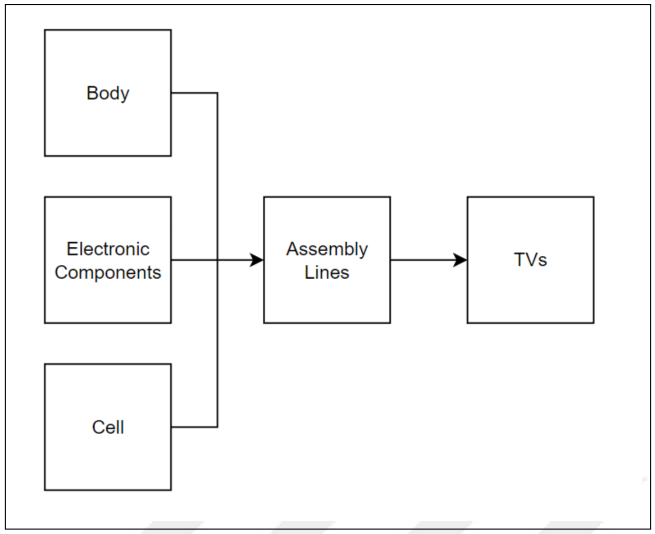

Figure 1: Metarial Flow

The assembled product is packed and delivered to the warehouses to be sent to the customer.

2.3 Assembly Lines in the Production

This study focuses on opening parallel stations to increase the production rate of TVs in the assembly lines. The assembly lines are a manufacturing method suitable for mass production, where the raw materials and semi-products of the product are assembled, and the final product is formed. The company has 15 assembly lines for TVs and 1 for Visual Solutions products in the final assembly facility.

Production starts at 08:00 a.m. in this facility, where approximately 1200 workers are employed. The facility works in 2 or 3 shifts depending on the forecast.

The assembly lines in the facility are grouped according to some characteristics. These features are:

- Size of the products (Small, Mid, Large Sizes),
- Type of the products (Thick, Thin TV),

- The technological and physical types of the line.

The layout of one of TVs assembly lines is given in Figure 2:

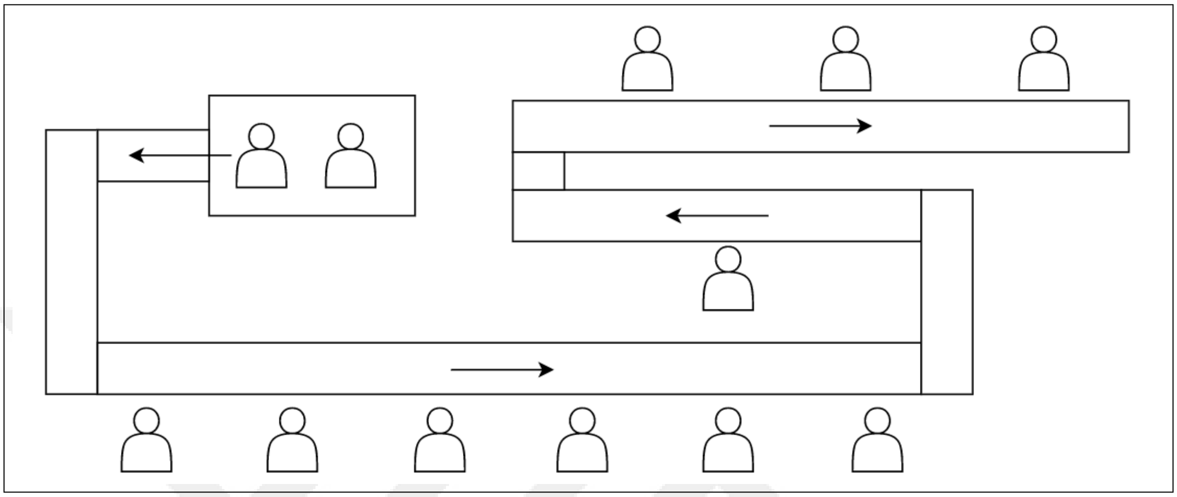

Figure 2: Line Layout

The physical structure of the assembly lines in the facility is straight assembly lines. On average, 50 stations are in these assembly lines. In these assembly lines, the robots can be used for production. However, mainly labor is used, and precisely one worker works on the stations.

Due to precedence relationships, it is difficult to assign tasks to stations effectively. The efficiency can be increased, and the total number of stations can be reduced by opening identical parallel stations. One or more simple stations are combined, and all tasks are performed on each station to open a parallel station. Thus, the parallel stations opened become identical.

A sample describing the identical parallel station structure is given in Figure 3:

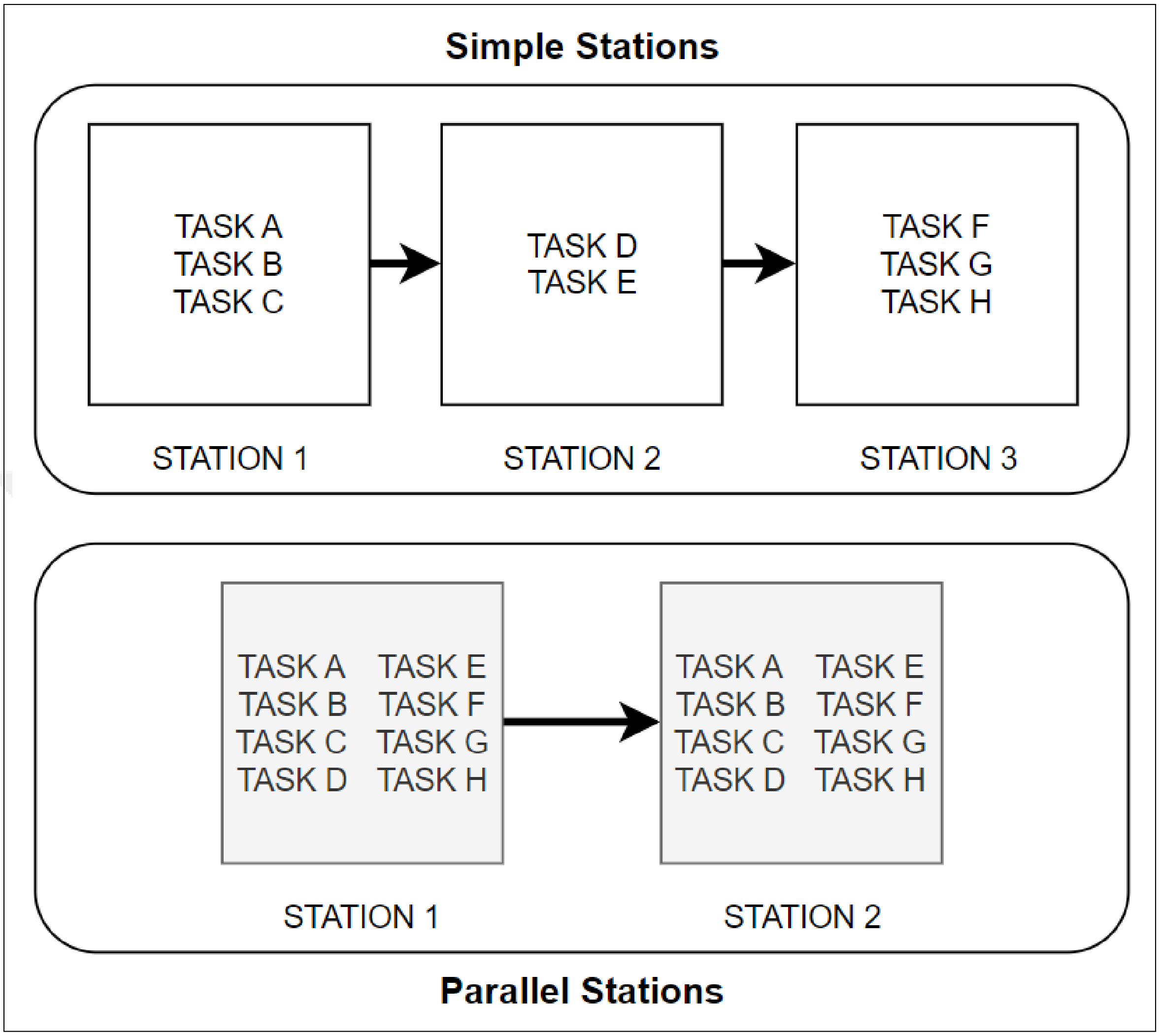

Figure 3: Structure of Simple and Parallel Stations

2.4 Product Variety of TVs

TV can be separated into two main groups in terms of physical structure. One of them is a thin-framed TV which is called Borderless TV, and the other is a thick-framed TV. These two main groups have a variety of sizes from 22" to 75". In this facility, where customer-based production is carried out, product models are formed according to the customer's demands, besides the size differences and the physical structure. There are hundreds of TV models in the lower breakdown.

The various number of different product models causes numerous combinations in product times and the number of jobs. Furthermore, these different product models can vary in task numbers and total task times into themselves. The sample graph of the number of jobs and total task times of orders defined on an assembly line in a shift is given in Figure 4:

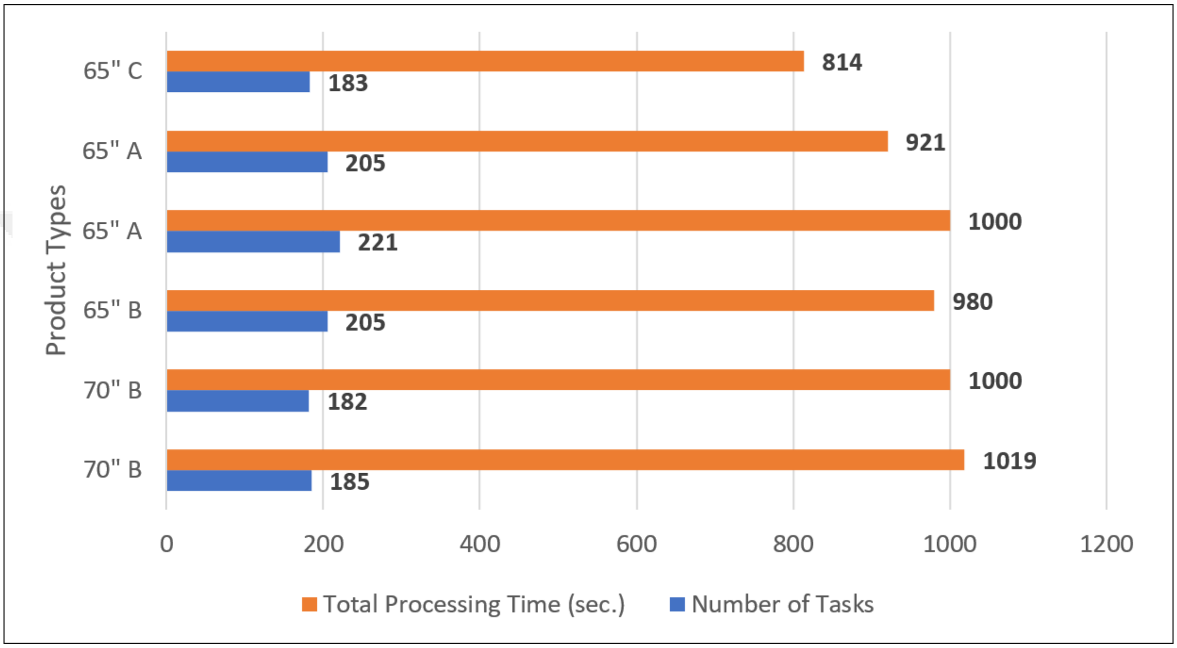

Figure 4: Produced Models in a Shift

The above chart shows the variety of products in one shift of a production line. The models in the graphic are produced sequentially. When the new model will produce, each time, the tasks and the workers are assigned to the stations by the team leader of the line during the setup.

2.5 The Effect of Labor Difference on Production

In the assembly lines, workers can work, and robots can be used for production. Although robots are used on the company's assembly lines, most of the tasks are completed by workers. Due to the management approach of the company, even the employee can be capable of performing any task. However, there are differences between workers in terms of task completion times. In production, where the cycle time is short, the performance and abilities of workers can directly affect production, which can lead to loss of production. For this reason, assigning tasks to workers with which they are competent is critical.

Figure 5 is given below, which shows an example of completion times for a task from 20 workers:

Figure 5: Observed Worker Times

As can be seen in Figure 5, some workers complete that job at a slower time than the standard time for the job. If one of the slow workers is assigned to the station where that job is performed, a bottleneck may occur in the production line, resulting in a loss of production. Therefore, it is vital to select workers who complete the jobs at the stations at a faster or equal pace than the standard duration of the tasks.

2.6 Current System in the Production

The production starts at 08:00 a.m. in Vestel Electronics. At the beginning of each shift, team leaders count the number of personnel at the line which they are responsible for. Before the start of production, a 15-minute daily management meeting, is held on each line. After the meeting, the team leader allocates the tasks to the stations and assigns workers.

The team leader considers the technological constraints of the tasks and the physical constraints of the station while allocating the tasks to the stations. After the employee's recruitment process is complete, the company provides the employee with general training about all tasks in production. Therefore, the workers in the Final Assembly facility can do all the tasks on the line. While the team leader assigns the workers to the stations, he evaluates the skills of the workers based on his own experience and makes appointments accordingly.

The number of tasks in orders in a shift and the total process times are given in Figure 4. Monthly unique order numbers are given in Figure 6:

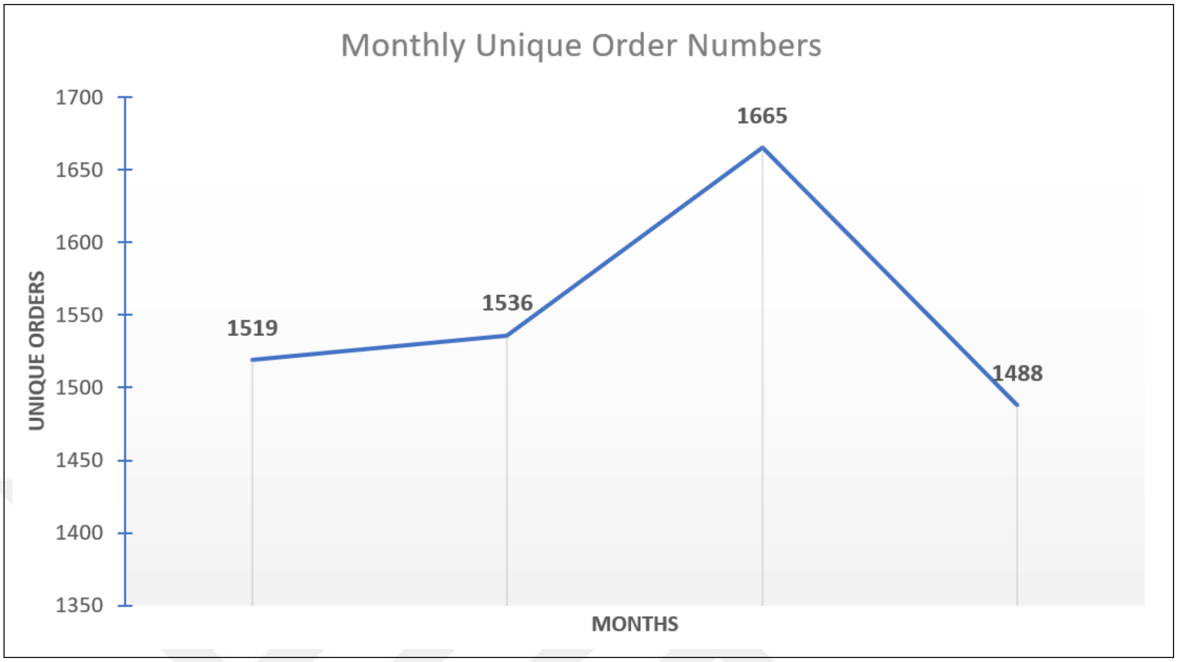

Figure 6: Unique Order Numbers

Each unique order code has a unique number of jobs and a unique total processing time. Many unique orders allocated by team leaders can cause management difficulties and a loss of efficiency. For this reason, another aim of this study is to find the optimum result according to the current production conditions by allocating the orders tasks by the computer instead of the human.

CHAPTER III

LITERATURE REVIEW

As part of this study's scope, a detailed literature search was conducted on assembly line balancing problems. When the literature is reviewed, assembly line balancing problems can be divided into two main groups, as indicated in Figure 7 [1] (C. Becker and A. Scholl, 2006):

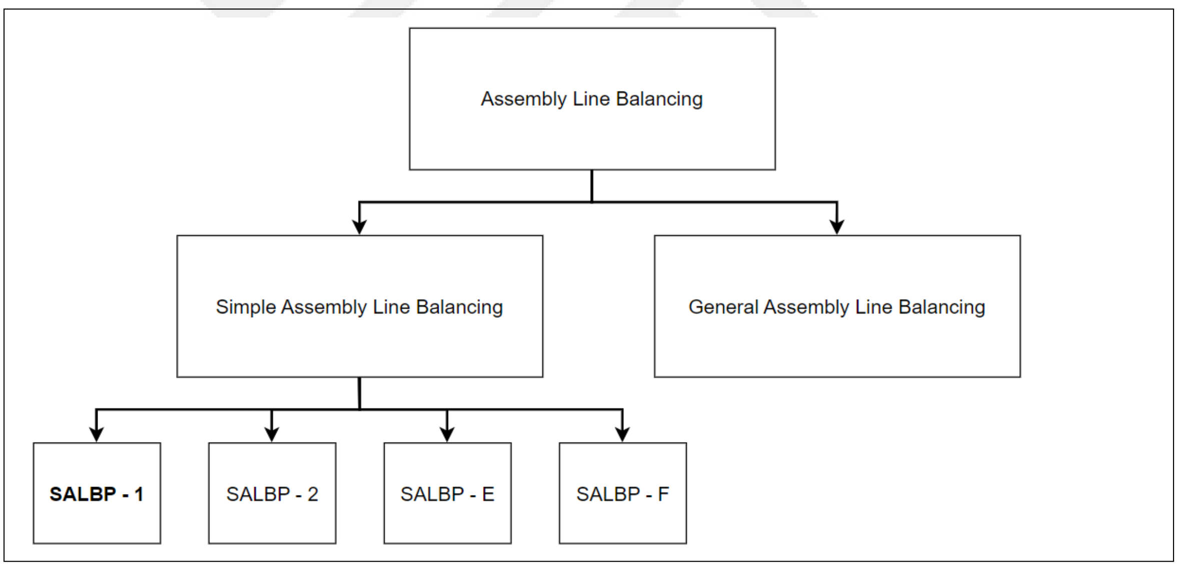

Figure 7: Classification of Assembly Line Balancing Problems

This study focuses on the SALBP-1, shown in Simple Assembly Line Balancing in Figure 7, where the number of stations is minimized with a given certain cycle time. Some of the articles reviewed in the literature within the scope of this study are summarized in Table 1 in historical chronicle order:

Table 1: Literature Review of Assembly Line Balancing Problems

Nu.	Problem Type	Year	Paper Name	Solution Method
1	SALBPs	1963	Hoffmann	Heuristic
2	PSALBP	1974	G. M. Buxey	Heuristic
3	PSALBP	1989	J. F. Bard	Dynamic Programming
4	MMALBP	1997	R. G. Askin et.al.	Mathematical Model, Heuristic
5	TSP	1997	N. Mladenović et.al.	Heuristic
6	PSALBP	1998	P. R. McMullen et.al.	Heuristic
7	PSALBP	2006	P. M. Vilarinho et.al.	Heuristic
8	PSALBP	2009	Ege et.al.	Branch and Bound, Heuristic
9	MMALBP	2011	S. Akpinar et.al.	Mathematical Model, Heuristic
10	PSALBP	2013	Topaloglu et.al.	Mathematical Model
11	moALB	2013	W. Zhang et.al.	MOEA
12	ALBHW	2015	B. Sungur et.al.	Mathematical Model
13	ALWABP	2016	O. Polat et.al.	Heuristic
14	ALBPs	2020	Aguilar et.al.	Mathematical Models
15	TALB	2020	Z. Li et.al.	Branch and Bound
16	ALWABP	2021	Katiraee et.al	Mathematical Model
17	PSALBP	2021	Miranda et.al	Mathematical Model Heuristic

[2] (T. R. Hoffmann, 1963) has created a matrix for the precedence relations between tasks and developed an enumeration algorithm that assigns the tasks with these precedence relations.

[3] (G. M. Buxey, 1974) has executed the positional weight heuristic method for the identical parallel stations(called multiple stations) assembly line balancing problem.

[4] (P. A. Pinto, D. G. Dannenbring and B. M. Khumawala, 1981) have presented Branch and Bound Algorithm and a heuristic method for the solution method to the assembly line balancing problem where parallel stations can be opened.

[5] (J. F. Bard, 1989) has developed a dynamic programming formulation to solve the line balancing problem with parallel stations opening parallel stations in order to increase the efficiency of the line.

[6] (R. G. Askin and M. Zhou, 1997) have developed a mathematical model and a heuristic algorithm to solve the mixed model assembly line balancing problem, the solution methods can also open parallel stations.

[7] Variable Neighborhood Search (VNS) algorithm was first proposed by (N. Mladenović and P. Hansen, 1997). The developed VNS algorithm was executed on a traveling salesman problem and compared results to the other algorithm.

[8] (R. P. McMullen and G. V. Frazier, 1998) have presented a multi-objective meta-heuristic algorithm to solve the simple assembly line balancing problem type 2 with parallel stations. In the multi-objective function, there are goals such as minimizing the total cost, smoothness index, and lateness.

[9] (A. S. Simaria and P. M. Vilarinho, 2001) have developed a meta-heuristic algorithm for the parallel station assembly line balancing problem and have analyzed

outputs of the algorithm.

[1] (C. Becker and A. Scholl, 2006) have examined the historical development of assembly line balancing problems, and have categorized the problems.

[10] (P. M. Vilarinho and A. S. Simaria, 2006) have created a meta-heuristic algorithm that solves simple assembly line balancing problems with parallel stations. The performance of the algorithm is compared to another meta-heuristic algorithm.

[11] (A. Corominas, R. Pastor and J. Plans, 2008) have developed a mathematical model that assigns skilled and unskilled workers and minimizes the number of temporary workers for a factory that hires temporary workers according to factory needs.

[12] (Y. Ege, M. Azizoglu and N. E. Ozdemirel, 2009) have discussed the assembly line balancing problem with parallel stations in their study. In this study, parallel station creation methods were divided into two main groups and were explained. A Branch and Bound algorithm and a Branch and Bound Heuristic were developed for solving parallel stations assembly line balancing problems. The results of the two algorithms were compared in this study.

[13] (A. Scholl, M. Fliedner and N. Boysen, 2010) have presented a mathematical model for the assignment constrained assembly line balancing problem, which is an improved version of SALBP and they have named ARALBP.

[14] (S. Akpinar and G. M. Bayhan, 2011) have presented a mathematical model and a meta-heuristic method to solve the mixed model assembly line balancing problem called MMALBP in their study.

[15] (G. Tuncel and S. Topaloglu, 2013) have generated an integer programming(IP) mathematical model for an assembly line balancing problem. The mathematical model in this study can open parallel stations.

[16] (W. Zhang, W. Xu and M. Gen, 2013) have developed a multi-objective function mathematical model to solve the assembly line balancing problem that includes worker capacities(moALB-wc). Moreover, they have developed a multiobjective evolutionary algorithm to solve moALB-wc.

[17] (B. Sungur and Y. Yasemin, 2015) have examined an improved version of the simple assembly line balancing problem that assigns the workers dependent on their costs and called ALBHW (Assembly Line Balancing with Hierarchical Worker Assignment).

[18] (O. Polat, Can B. Kalayci, O. Mutlu and S. M. Gupta, 2016) have called the worker-assigned improved version of assembly line balancing problem type 2, where the cycle time is minimized, ALWABP-2, and have presented a two-phase neighborhood search meta-heuristic algorithm to solve this problem.

[19] (H. Aguilar, A. García-Villoria, and R. Pastor, 2020) have presented the historical development of parallel assembly lines and have made groupings about parallel assembly lines.

[20] (Z. Li, I.Kucukkoc and Z. Zhang, 2020) have developed the branch and bound algorithm that was proposed as the exact solution method for the assembly line balancing problems, for two-sided assembly line balancing problems.

[21] (S. T. Yildiz, G. Yildiz and R. Okyay, 2020) have proposed a mathematical method and a meta-heuristic algorithm for the parallel station assembly line balancing problem that assigns workers according to assembly worker types.

[22] (E.Alvarez-Miranda, S. Chace, and J. Pereira, 2021) have created a mathematical model, a dynamic programming model, and a meta-heuristic algorithm for parallel station assembly line balancing. The results of these three algorithms were compared in this study.

[23] (N. Katiraee, M. Calzavara, S. Finco and D. Battini, 2021) have categorized the tasks according to their difficulties, have developed a mathematical model for ALWABP-2 and have analyzed its outputs in their study.

[24] (Boysen, P. Schulze, and A. Scholl,2022) have presented the historical development of assembly lines and have made groupings about assembly lines.

In this study, internet-sourced datasets, well-known in the literature were used. In the literature, there is information such as how these data sets were created and the outputs from the datasets. [25] (T. R. Hoffmann, 1990) [26] (A. School and C. Becker, 2006)

CHAPTER IV

METHODOLOGY

In this study, an exact method and a meta-heuristic algorithm are suggested for increasing the production rate by opening parallel stations. Parallel Stations Assembly Line Balancing Problem (PSALBP) method is suggested as the exact method. Parallel Stations Assembly Line Balancing Problem is the enhanced version of the Simple Assembly Line Balancing Problem. Simple Assembly Line Balancing Problems can be divided into four main classifications as given in Table 2 [1] (C. Becker and A. Scholl, 2006):

Table 2: Types of Simple Assembly Line Problems

		cycle time	
		given	minimise
no. of stations	given	SALBP-F	SALBP-2
	minimise	SALBP-1	SALBP-E

Parallel Stations Assembly Line Balancing Problem described in this study is an improved version of the Simple Assembly Line Balancing Problem type 1, which minimizes the total station number under the given cycle time.

The assumptions and constraints accepted because of the company's production system and the physical conditions are given below:

- Only one operator can work at a station,
- The task times are certain, deterministic, and equal to or lower than the cycle

time,

- All tasks can be assigned to only one station, and there are precedence relationships between tasks,
- The cycle time is certain, and maximum efficiency is aimed according to the number of theoretical station numbers by opening the parallel stations,
- An infinite number of parallel stations cannot be opened, and there is an upper limit to the number of parallel stations,
- Some of the tasks cannot perform together in the same station,
- The skills of the workers were found by the average of the observations taken, are independent of the stations, and rated according to the standard time of the task.

4.1 Solution Methods

The mathematical model and the meta-heuristic algorithm are explained in this section.

4.1.1 Mathematical Model

The notation of the mathematical model is given in Table 3:

Table 3: Notation of Mathematical Model

Indices	
N	Set of tasks–indexed by i, j
S	Set of stations–indexed by s
W	Set of workers–indexed by w
Parameters & Data	
P_i	The task time of task i
D_j	The set of the predecessor tasks of task i
CAP_{iw}	The capability of worker w in task i
U	The upper bound of the parallel stations
M	Big M
C	The cycle time
Decision Variables	
x_{is}	1, If task i is assigned to station s; 0, otherwise
y_s	1, If any task is assigned to station s ; 0, otherwise
l_{ws}	1, If worker w is assigned to station s; 0, otherwise
z_s	The parallel station numbers of stations s

$$\text{minimize} \quad \sum_{s}^{S} y_s + z_s \tag{1}$$

$$\text{subject to:} \quad \sum_{s}^{S} x_{is} = 1 \qquad \forall i \in N, \tag{2}$$

$$\sum_{s}^{S} l_{ws} \leq 1 \qquad \forall w \in W, \tag{3}$$

$$\sum_{w}^{W} l_{ws} = (y_s + z_s) \qquad \forall s \in S, \tag{4}$$

$$\sum_{i}^{N} P_i \; x_{is} \leq C \; (y_s + z_s) \qquad \forall s \in S, \tag{5}$$

$$\sum_{i}^{N} (P_i \; x_{is} \; l_{ws} \; CAP_{iw}) \leq C \; (y_s + z_s) \qquad \forall s \in S, \forall w \in W, \tag{6}$$

$$\sum_{s}^{S} s \; x_{is} \leq \sum_{s}^{S} s \; x_{js} \qquad \forall i \in N, \forall i \in D_j, \tag{7}$$

$$x_{is} + x_{js} \leq 1 \qquad \forall i \in N, \forall j \in NT_i, \forall s \in S, \tag{8}$$

$$z_s \leq U \qquad \forall s \in S, \tag{9}$$

$$z_s \leq M\ y_s \qquad \forall s \in S, \tag{10}$$

$$\sum_{s}^{S} z_s \leq (\sum_{s}^{S} y_s) - 1, \tag{11}$$

$$(x_{is}, y_s, l_{ws}) \in \{0, 1\}, z_s \in Z^{+} \qquad \forall i \in N, \forall s \in S, \forall w \in W \tag{12}$$

The objective function (1) minimizes the number of simple and parallel stations. Constraints (2) guarantee that each task is assigned to a station. Constraints (3) guarantee that workers are not assigned to more than a station. Constraints (4) guarantee that the total worker number equals the total station numbers. Constraints (5) guarantee that each station's time is less than or equal to the cycle time. Constraints (6) ensure that each worker's time is less than or equal to the cycle time with their capabilities. Constraints (7) ensure the precedence relationships between the tasks. Constraints (8) ensure that the tasks of i and j cannot be assigned to the same station. Constraints (9) ensure that the number of opened parallel stations is less than or equal to the upper bound of the parallel stations. Constraints (10) ensure that the parallel station "s" cannot be opened if the simple station "s" is not opened. Constraints (11) ensure that the total parallel station number is less than the total simple station number.

Company-specific constraints were added to the mathematical model depending on the company's requirements and satisfaction with production needs:

$$(z_s \leq U) \tag{13}$$

A limit is set on the number of parallel stations opened regarding the structure of the assembly lines and manageability.

$$(x_{is} + x_{js} \leq 1) \tag{14}$$

Some tasks cannot be assigned together at the same station due to ensuring quality requirements or technological reasons.

In addition to the data in the company, the mathematical model was also tested with sample data sets whose solutions are known. The purpose of the sample data is to test the mathematical model without the complex precedence relationships in the company's data. The number of variables formed by the sample and the company data are given in the tables below:

Table 4: Decision Variables of the Sample Data, GUNTHER

Decision Variables	Tasks (i)	Workers (w)	Stations (s)	Total
x[i,s]	35	-	35	3.150
l[w,s]	-	53	35	
y[s]	-	-	35	
z[s]	-	-	35	

Table 5: Decision Variables of the Company's Data, Large-Sized TV

Decision Variables	Tasks (i)	Workers (w)	Stations (s)	Total
x[i,s]	205	-	60	19.920
l[w,s]	-	125	60	
y[s]	-	-	60	
z[s]	-	-	60	

4.1.2 Meta-Heuristic Algorithm

In this study, a meta-heuristic algorithm has been developed to give a rapid solution as an alternative to the mathematical model. Variable Neighborhood Search

(VNS) algorithm is suggested as the meta-heuristic algorithm for this study. Variable Neighborhood Search algorithm is a meta-heuristic algorithm that researches local neighborhoods, was first proposed by [7] (N. Mladenović and P. Hansen, 1997). The general structure of the developed algorithm is given as a flow diagram in Figure 8:

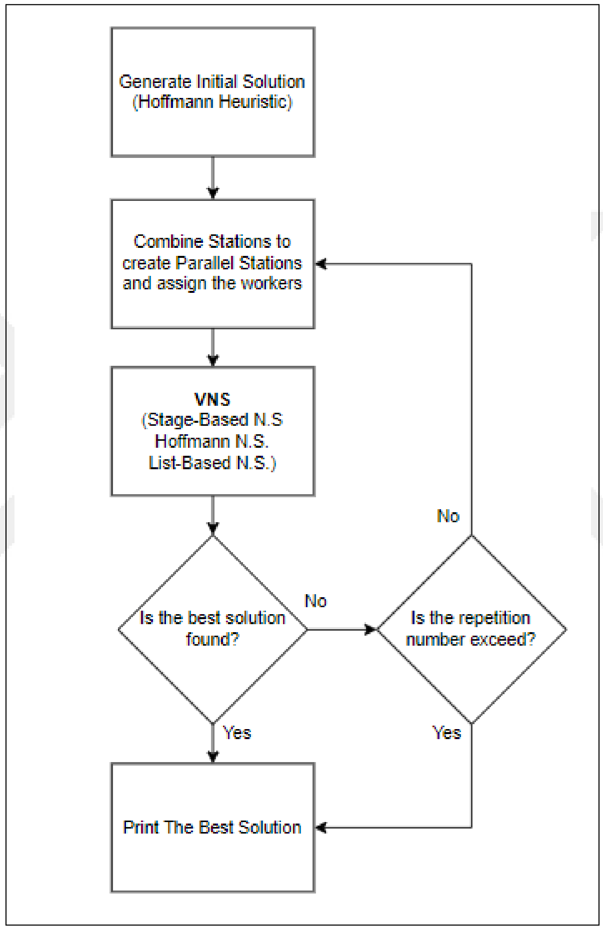

Figure 8: Flow Chart of The Algorithm

The developed VNS algorithm consists of five main parts. First, Hoffman Heuristic is applied to assign all jobs to stations by controlling their precedence relationship. After all the assigned tasks, parallel stations are created by grouping the stations. Workers are assigned to the created parallel stations depending on their task skills at the stations. Station-Based Neighborhood Search, Hoffmann Neighborhood Search, and List-based Neighborhood Search are applied to the current balancing solution, respectively, by checking the feasibility. These parts of the algorithm will be explained in the sections below:

4.1.2.1 Hoffmann Heuristic

Hoffman Heuristic is a heuristic algorithm for line balancing proposed by Thomas R. Hoffmann in 1963. In this algorithm, precedence relationships between tasks are saved as a binary code in a precedence relationships matrix. Then, the tasks to be assigned are assigned to the first possible station by checking the precedence relationships matrix. [2] (T.R.Hoffmann, 1963)

An example priority matrix of binary codes is given in Table 6:

Table 6: An Example Precedence Matrix

	1	2	3	4	5	6
1		1	1			
2				1		
3				1		
4					1	
5						1
6						

The priority relationship structure expressed by the priority matrix in the table is given in Figure 9:

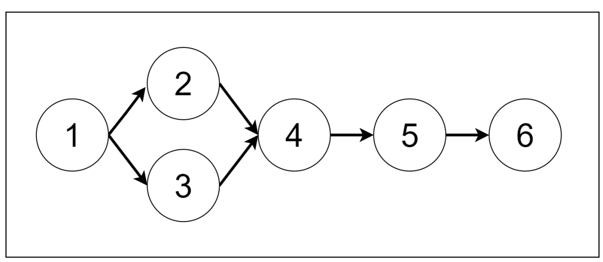

Figure 9: An Example Precedence Relationships Diagram

4.1.2.2 Creation of Parallel Stations

Parallel stations are a grouping station process to increase the efficiency of the line or to reduce the total number of stations. The parallel stations considered in this study are identical parallel stations. Therefore, the newly grouped stations formed by merging more than one station should all have the same tasks. Consequently, the cycle time of the parallel station formed by the grouping of two stations should be equal to the sum of the cycle times of the two stations forming it, equation(13) must be provided.If simple station k1 and simple station k2 combine to form parallel station k3 ($Simple_{k1} \cup Simple_{k2} = Parallel_{k3}$):

$$\sum_{s \in k1} t_i + \sum_{s \in k2} t_i = \sum_{s \in k3} t_i \tag{15}$$

There are three methods for station grouping. These are forward-stepping grouping, backward-stepping grouping, and mixed-stepping grouping. In forward-step grouping, a random station is first selected. Then, the selected station is grouped with the next station. The cycle times are recalculated according to the workers' skills at the two stations, and the feasibility is checked. If the solution is infeasible, the solution will not be accepted.

All steps of forward-stepping grouping are applied to back-stepping grouping. Unlike forward-stepping, in the back-stepping grouping, the randomly selected station is grouped with the previous station. Mixed-stepping grouping consists of the combination of these two groupings. The best solution is accepted from the best result within these algorithms.

4.1.2.3 Stage-Based Swap & Move

In Stage-Based Neighborhood Search algorithm, it is a search method in which a solution is obtained by assigning the tasks from the station where they were assigned to another station (move) or by swapping the stations of two tasks(swap) [22] (E.A. Miranda et.al., 2021).

The stations where the tasks are located are kept in a list. In this list, i-th position corresponds to the task, and the value of i-th position corresponds to the number of stations. The swap operation is the switching of the stations where the two tasks are allocated. For example, let Task A is at Station 1, and Task B is at Station 2. When Stage-Based swap operation is applied to Task A and Task B, Task A is assigned to Station 2, and Task B to Station 1. In the move operation, a job is assigned to another station instead of the current station. After both operations, the feasibility is checked. The solution is accepted, if it is feasible.

4.1.2.4 Hoffmann Neighborhood Search

Hoffmann Neighbor Search method is proposed by [22] (E.A. Miranda et.al., 2021). The main purpose of the algorithm is to split the parallel station into two simple stations. As in section 4.1.2.2, The sum of the cycle times of the stations consisting of the separation of the parallel station must be equal to the cycle time of the separated parallel station, and equation(13) must be provided.

4.1.2.5 List-Based Swap & Move

The swap and move operations in a List-Based Neighborhood Search are the same as those in a Stage-Based Neighborhood Search algorithm. The main difference between the two search methods comes from task-saved lists and representation. In List-Based Search, tasks are saved in a list in the order in which they are assigned. The solution representation is a permutation list of jobs. In the swap operation, two randomly selected tasks in the solution display are switched, and the whole list is reassigned to the stations in order. In the move operation, a randomly selected task is placed in a randomly selected position on the solution display. The tasks in the recently created list are assigned to the stations in order. In both operations, if the solution is infeasible, the algorithm continues on to the next step. In the created algorithm, the solution feasibility is checked after each neighborhood search.

The pseudocode of the generated VNS algorithm is given in Algorithm 1:

Algorithm 1 Variable Neighborhood Search Algorithm

1: Create an initial solution according to Hoffmann Heuristic due to details given in section 4.1.2.1
2: **while** the best solution is not found **do**
3:     Make the stations to parallel and assign workers to the stations due to information given in section 4.1.2.2
4:     Search Stage-Based Swap Neighborhood according to description given in section 4.1.2.3. Go to the line 3, if the current solution is improved.
5:     Search Stage-Based Move Neighborhood according to details given in section 4.1.2.3. Go to the line 3, if the current solution is improved.
6:     Search Hoffmann Heuristic Neighborhood due to description given in section 4.1.2.4. Go to the line 3, if the current solution improved.
7:     **function** (Convert the representation)
8:         Convert the representation of the current solution list-based to stage-based.
9:     **end function**
10:     Search List-Based Swap Neighborhood according to explanation given in section 4.1.2.5. Go to the line 3, if the current solution is improved.
11:     Search List-Based Move Neighborhood due to details given in section 4.1.2.5. Go to the line 3, if the current solution is improved.
12:     **function** (Convert the representation)
13:         Convert the representation of the current solution list-based to stage-based.
14:     **end function**
15:     **if** working time $>600 sec.$ **then**
16:         **return** current best solution
17:         **break**
18:     **end if**
19: **end while**
20: Iterate the number of repetitions of the algorithm.

CHAPTER V

COMPUTATIONAL STUDY AND RESULTS

In this chapter, the results of the mathematical model and meta-heuristic algorithm will be shared. Firstly, details about the data used in the study will be given afterward, information about the system used in the Computational Study section will be given, and the outputs will be analyzed.

5.1 Details of the Data

Two different data were used in this study. One of them is the data from [27] "https://assembly-line-balancing.de/salbp/", whose widely used and most known in the literature. We will call this data internet-sourced data. The other data is the data of the products in the company. The purpose of using two different data is to remove the complexity effect of the company data when comparing the mathematical model and VNS algorithm.

Task and cycle time details of internet-sourced data and company data are given in the Table 7:

Table 7: Details of Internet-Sourced Data

Nu.	Data Source	Data Name	Data Code	Tasks	Cycle
1	Literature, Internet-Sourced	MERTENS	MERTENS	7	6
2	Literature, Internet-Sourced	BUXEY	BUXEY	29	25
3	Literature, Internet-Sourced	GUNTHER	GUNTHER	35	40
4	Literature, Internet-Sourced	WARNECKE	WARNECKE	58	53
5	Literature, Internet-Sourced	LUTZ3	LUTZ3	89	74

In the internet-sourced data, only the processing times and precedence relations of the tasks are included. The number of stations and the worker capacity matrix needed to be used in the study were obtained by the following methods:

$$\text{Number of stations} = \text{Number of tasks} \tag{16}$$

$$\text{Number of workers} = \lceil \text{Number of tasks} * 1.5 \rceil \tag{17}$$

In the worst-case scenario, each task is assigned to individual stations. In this case, it is sufficient for the number of stations to be equal to the number of jobs. It is shown in equation (16). For the number of workers, we predicted that it would be sufficient to create 1.5 multiple the number of stations we created according to the number of tasks in the data we have. It is shown in equation (17). After the number of workers was obtained, worker capabilities were created to be compatible with company data. In the table below, the observed average working times of six workers for ten tasks in a sample company data are given in Table 8:

Table 8: Processing Times of 6 workers for 10 task samples in L1 data

Task	**Worker 1**	**Worker 2**	**Worker 3**	**Worker 4**	**Worker 5**	**Worker 6**
0	3.44	3.53	3.57	3.50	3.42	3.43
1	3.07	3.02	2.99	3.04	2.90	2.92
2	1.94	2.01	2.03	2.04	1.97	1.92
3	10.02	10.05	10.01	10.10	10.09	10.07
4	10.03	9.97	10.03	10.00	9.99	9.95
5	16.03	15.99	16.01	16.08	15.98	15.94
6	5.95	5.91	6.08	6.10	5.96	6.02
7	11.92	11.93	11.91	11.95	11.96	11.94
8	8.04	7.90	7.99	7.97	8.04	8.03
9	18.97	18.93	18.91	18.99	18.96	19.08

As a result of time studies and observations, it has been determined that there is a 10% time difference between the workers performing the tasks.

Table 9: Details of Company Data

Nu.	Data Source	Data Name	Data Code	Tasks	Cycle
1	Company	Small-Size TV	S1	125	14
2	Company	Small-Size TV	S2	125	13.8
3	Company	Mid-Size TV	M1	175	30
4	Company	Mid-Size TV	M2	181	25
5	Company	Large Size TV	L1	205	46
6	Company	Large-Size TV	L2	221	45

Table 9 shows that as the size of the product increases, the number of tasks included in the product increases. The assembly lines in the company are designed according to the sizes of the TVs or the physical structure of the TVs, and the products that can be produced in these assembly lines are certain. Therefore, TVs of different sizes can be produced at different stations. For this reason, the number of stations and workers used in the data varies according to the product type. The number of stations and workers in the assembly lines for which product types are suitable are given in Table 10:

Table 10: The Number of Stations and Workers on Assembly Lines

Nu.	Product Type	Stations	Workers
1	Small-Size TV	50	125
2	Mid-Size TV	55	125
3	Large-Size TV	65	125

5.2 Results

In this study, IBM CPLEX 20.1 are used as a solver for solving the mathematical model, and Python 3.8 is used to code the meta-heuristic algorithm. The solver and the algorithm were run on a PC with an i7-11800H CPU with 2.3 GHz 16 threads and 64 GB memory (RAM).

According to the production management approach of the company, an upper limit has been set for the number of parallel stations to be opened. In order to compare the mathematical model and VNS, data were input with and without this upper limit.

5.2.1 Scenario 1 - Results of the Sample Data

The number of decision variables of internet-sourced data is given in Table 11:

Table 11: Details of the Sample Data

Name	Tasks	Stations	Workers	Integer Variables	Binary Variables
MERTENS	7	7	11	7	133
BUXEY	29	29	44	29	2146
GUNTHER	35	35	53	35	3115
WARNECKE	58	58	87	58	8468
LUTZ3	89	89	134	89	19936

The results of the internet-sourced data, including the upper limit of parallel stations (U=1) and 600 sec time limits, are given in Table 12:

Table 12: Results of Internet-Sourced Data - 1

					Mathematical Model		***VNS***	
Data	**Total Task Times**	**Cycle**	**U**	**Best Integer**	**Solution**	**Gap**	**Solution**	**Gap**
MERTENS	29	6	1	5	5	0	5	0
BUXEY	324	25	1	13	14	1	14	1
GUNTHER	483	40	1	13	13	0	14	1
WARNECKE	1548	53	1	30	32	2	34	4
LUTZ3	1644	74	1	23	Infeasible	-	25	2

The results of the internet-sourced data, including 600 sec time limits without the upper limit of parallel stations, are given in Table 13:

Table 13: Results of Internet-Sourced Data - 2

Data	Total Task Times	Cycle	U	Best Integer	*Mathematical Model*		*VNS*	
					Solution	**Gap**	**Solution**	**Gap**
MERTENS	29	6	S-1	5	5	0	5	0
BUXEY	324	25	S-1	13	13	0	14	1
GUNTHER	483	40	S-1	13	13	0	14	1
WARNECKE	1548	53	S-1	30	32	2	34	4
LUTZ3	1644	74	S-1	23	Infeasible	-	24	1

When the results of the internet-sourced data are compared, there does not seem to be a big difference between the mathematical model and VNS. However, the critical point here is that under a given time limit, VNS can be given a solution when the mathematical model is infeasible. Furthermore, as it's supposed to be the performance of the algorithms increased when the upper limit on the number of parallel stations was removed.

5.2.2 Scenario 2 - Results of the Company's Data

The number of decision variables of internet-sourced data is given in Table 14:

Table 14: Details of Company Data

Name	**Tasks**	**Stations**	**Workers**	**Integer Variables**	**Binary Variables**
S1	125	50	125	50	12550
S2	125	50	125	50	12550
M1	175	55	125	55	16555
M2	181	55	125	55	16885
L1	205	60	125	60	19860
L2	221	60	125	60	20820

The results of company's data, including the upper limit of parallel stations (U=1) and 600 sec time limits, are given in Table 15:

Table 15: Results of Company Data - 1

Data	Total Task Times	Cycle	U	Best Integer	*Mathematical Model* Solution	*Mathematical Model* Gap	*VNS* Solution	*VNS* Gap
S1	454.70	14	1	33	Infeasible	-	37	4
S2	437.93	13,8	1	32	Infeasible	-	37	5
M1	750.71	30	1	26	Infeasible	-	26	0
M2	690.83	25	1	28	Infeasible	-	31	3
L1	1007.90	46	1	22	Infeasible	-	24	2
L2	999.90	45	1	23	Infeasible	-	25	2

The results of company's data, including 600 sec time limits without the upper limit of parallel stations, are given in Table 16:

Table 16: Results of Company Data - 2

Data	Total Task Times	Cycle	U	Best Integer	*Mathematical Model* Solution	*Mathematical Model* Gap	*VNS* Solution	*VNS* Gap
S1	454.70	14	S-1	33	Infeasible	-	36	3
S2	437.93	13,8	S-1	32	Infeasible	-	36	4
M1	750.71	30	S-1	26	Infeasible	-	26	0
M2	690.83	25	S-1	28	Infeasible	-	31	3
L1	1007.9	46	S-1	22	Infeasible	-	23	1
L2	999.90	45	S-1	23	Infeasible	-	24	1

The mathematical model and VNS were executed on internet-sourced data and company data. When the outputs are analyzed, it is seen that the mathematical model gives better results on GAP in small-instances data. The gap we use here is the absolute gap. However, when the data has big-instances data, the mathematical model cannot give a solution within the given running time limits.

The mathematical model and VNS were tested within a 5-minute time limit according to the company's needs. The performance of the mathematical model on the company data was tested by increasing the time limit from 5 minutes to 24 hours, but the mathematical model still could not give a solution.

The mathematical model and meta-heuristic algorithm developed in the study are compared with one of the line's current balancing in the company. The mathematical model was not compared to the current balancing because the mathematical model could not give a solution for the company's data. The meta-heuristic algorithm was run under conditions that would meet the company's needs (to be opened parallel station upper limit U = 1, runtime 600 seconds). For the comparison, the balancing of M1 data is given in Section 5.1 on an assembly line is used.

In the company, parallel stations are not opened in production. Therefore, the worker assignment performance of the company and the meta-heuristic algorithm were not compared. For this reason, a comparison has been made over the minimum number of stations that need to be opened to produce the M1 TV model and the line efficiencies. The efficiency was calculated with the formula in Equation 18.

$$\text{Line Efficiency} = \frac{\text{Sum of Task Times}}{\text{Cycle * Stations}} \tag{18}$$

The current line balancing of Product M1 is given in Figure 10:

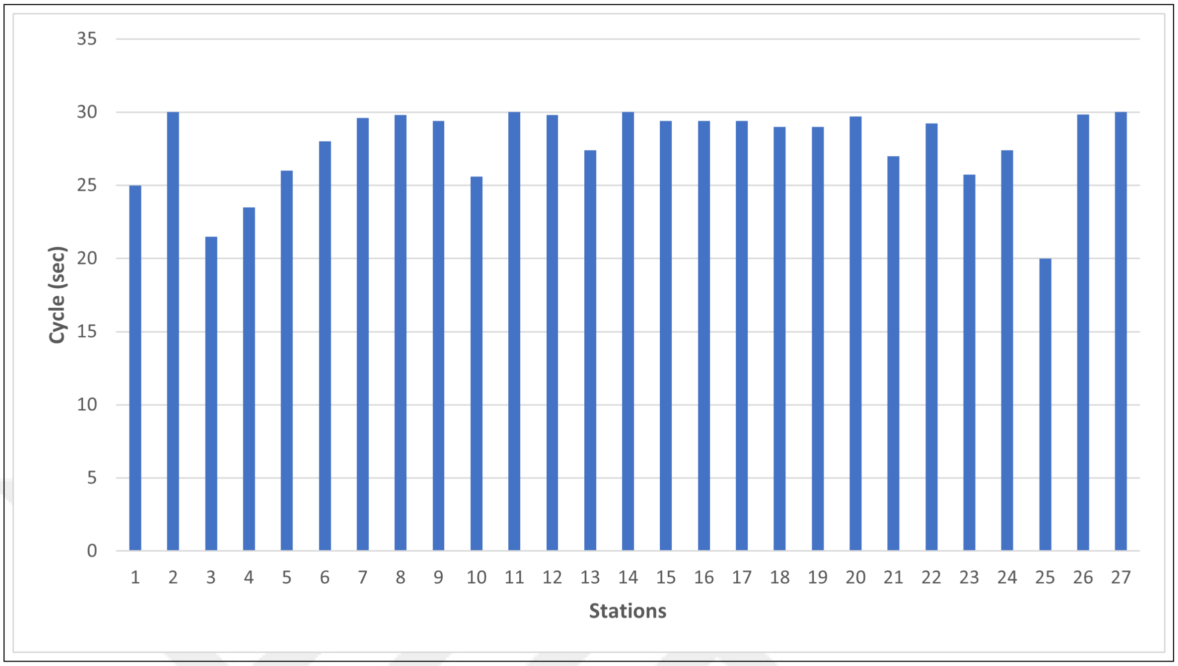

Figure 10: Current System

In order to produce Product M1 with a cycle time of 30 seconds, which is the longest work time, without opening parallel stations, a minimum of 27 stations must be opened. The efficiency of this line balancing is 92.6%.

The result of VNS for Product M1 is given in Figure 11:

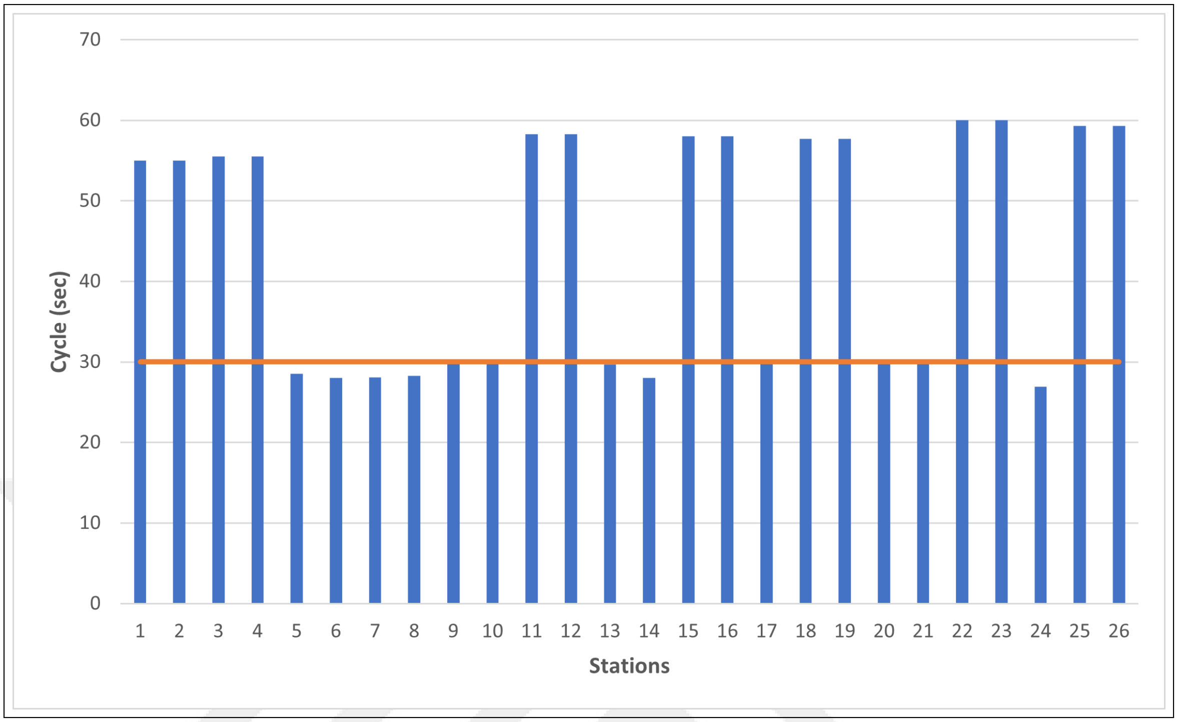

Figure 11: VNS Solution

In order to produce Product M1 with a cycle time of 30 seconds, which is the longest work time with opening parallel stations, a minimum of 26 stations must be opened. The efficiency of this line balancing is 96.2%.

In Figure 11, the stations that appear above the cycle time are parallel stations. The cycle time of parallel stations is twice the cycle time of the line, but it yields two products in one cycle. The tasks that cannot be assigned with no idle times in the stations due to priority relations can be assigned together by opening a parallel station. Figure 13 shows that the parallel station solution has fewer idle-time stations than the simple station solution:

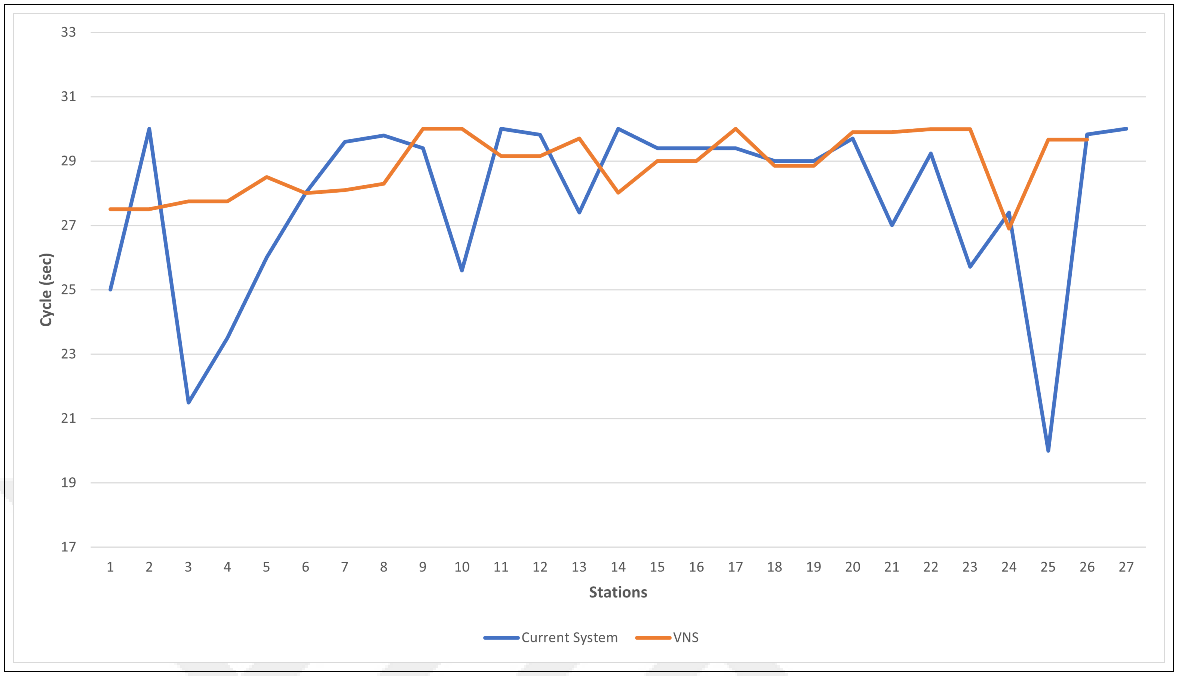

Figure 12: Comparing the Current System and VNS

In the VNS solution, idle times in simple stations were reduced by opening parallel stations, decreasing one station, and resulting in a 3.6% increase in efficiency.

CHAPTER VI

CONCLUSION

This study addresses a real-life problem related to production at Vestel Electronics' TV Final Assembly Facility. The manufacturing constraints, due to physical and technological factors, affect production efficiency and the overall balance of the production line for the assembly lines of TV. The objective of this study is to enhance the efficiency of the assembly line by grouping stations.

The production employs approximately 1200 employees. According to the company's management approach, employees receive training to perform all tasks. However, the performance of employees varies based on their skills. When a bottleneck occurs on the production line due to employee skill discrepancies, assigning employees to tasks they perform poorly can directly result in production losses. Therefore, it is necessary to assign operators to tasks at stations based on their skills by ensuring they do not exceed the cycle time of the tasks.

In the production process, many setups can be performed in one shift. According to the management decision, a solution that yields results in less than 5 minutes is required. Within this scope, a mathematical model has been developed to group stations effectively, assign workers to these stations, and incorporate production-specific constraints of the company while optimizing the objective function to achieve maximum output based on the number of existing stations. The mathematical model takes a long time to give a solution. Consequently, a meta-heuristic algorithm has been developed to provide faster outputs compared to the mathematical model. The mathematical model and algorithm were run on internet-sourced and company data, and the results were compared. In addition, the algorithm has been compared against an existing line balance in the company, and differences have been revealed. The results of the computation show that all heuristic methods offer satisfactory solutions for the real-life problem within the given time limit. The developed methods were presented to Vestel Electronics as a decision support system to improve production.

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