CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Implementation of Takt Time and Model for Optimal Resource Allocation for Production Optimization

by

Muhammad Ibtisam Arshad

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Mechanical Engineering

2024

Dedicated to my support system. . .

"My Family, My Professors and Friends"

CERTIFICATE OF APPROVAL

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Acknowledgement

"In the name of The Omniscient, The Omnipotent, The Omnipresent and The Omnibenevolent for the blessing of choosing me for this endeavor."

First and foremost, to my creator, my life coach, the most gracious, the most beneficent, ALLAH S.W.T., I owe it all to you, Thank you!

I would like to thanks my supervisor Dr. Ghulam Asghar for his utmost effort and precious time in the completion of my thesis. Under his guidance, I successfully overcame many difficulties throughout my thesis.

At this stage, I think of my loving parents whose selfless sacrificial life and their great efforts and never-ending prayers have enabled me to do my MS Thesis.

Finally yet importantly, I am grateful to all my friends and other supportive teachers who helped me in every path of life.

(Muhammad Ibtisam Arshad)

Abstract

Assembly line operations have evolved with the passage of time and become an evident part of operations in nearly all manufacturing industries. These processes of manufacturing goods are used to achieve delivery targets and customer satisfaction in a rapid and safe way. Generally, there are some draw backs of these manufacturing operations, which need to be tackled to obtain better performance. The disadvantages are the generation of bottlenecks, which can limit the resource utilization and reduce equipment efficiency. To overcome this problem, various assembly line balancing techniques have been developed worldwide and these studies managed to combine few techniques into a single efficient model for optimal resource allocation.

The study aims to implement Takt time & Model for Optimal Resource Allocation (MORA) in two individual electronics manufacturing companies, which are taken as case study sources. An imbalanced assembly line is chosen for elimination of bottleneck and minimization of high cycle time in order to achieve smooth operation. Takt time is calculated for both industries and MORA is designed and implemented through linear programming mathematical model. Model nomenclature is based on excel solver solution, where solver method is based on simplex linear programming (LP) model.

The research work analyzes the relationship between takt time & MORA (Model for Optimal Resource Allocation), which combines the traditional approaches of type-I & type-II assembly line balancing. This study also manages to explain and improve the pace of the assembly line through takt time calculation and MORA implementation. The results of the current study are applicable in other discrete parts manufacturing industries as well where assembly line operations are being performed.

Key Words: Takt Time, MORA, Cycle Time, Linear Programming, Solver solution

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Abbreviations

ALB	Assembly Line Balancing
CP	Constraint Programming
CT	Cycle Time
CS_1	Case Study 1
CS_2	Case Study 2
CUST	Capital University of Science & Technology
DV	Decision Variable
KPI	Key Performance Indicators
MORA	Model for Optimal Resource Allocation
NVA	Non-Value Added
OEE	Overall Equipment Efficiency
OEM	Original Equipment Manufacturer
PAM	Parallel Assignment Method
REBA	Rapid Entire Body Assessment
SALBP	Simple Assembly Line Balancing
SOP	Steps of Procedure
TT	Takt Time

Symbols

TT	Takt Time
CT	Cycle Time
S	Shift Time
T_A	Actual Time
N	Number of Equipment & Operators
T_{Op}	Cycle Time of Operation

Chapter 1

Introduction

1.1 Background

Generally, the production assembly lines exist in almost all types of industrial setups, this way of production is highly efficient in order to overcome the bottlenecks and optimize the workloads. Lean production techniques have greatly affected the way manufacturing setups are made and one critical aspect of lean production is the takt time that gives a relation between available production time and customer demand. This tool combined with the type-I & type-II techniques of assembly line balancing can be utilized to improvise the way assembly lines are operating.

Assembly line production is considered one of the biggest revolutions in the 20th century. During this period, the industries were revolutionizing rapidly and the race of faster pace of production was the key for all industries in order to cope for higher customer demands. To overcome these problems, industries started to adopt a production technique in which parts were moved through a belt or conveyor system. On this line/conveyor, several stations were installed and specific activities were carried out at each station. This allowed for the higher pace of production, the parts were being manufactured and assembled faster in order to meet customer demands and got an additional advantage over other industries.

Long before this revolution, workers having expertise in their fields' mostly crafted parts with hands, each craftsman had to use his skills to prepare separate parts and the individual parts were combined together at the end to complete the product. The power to run conveyor systems were not available and sometimes streams of water had been used to move products downstream and carry out specific activity on different stops. This process was technically a bit fast but still not feasible due to variation in stream flows and parts being rusted and damaged during the process.

As the industry revolutionized, new machines were developed, power to run these machines was now readily available. This prompted industries to install workstations and machinery at intervals along with the conveyor systems to produce an assembly line that would result in nonstop and discrete production setups.

In 1901, Ransom Olds [1] built an assembly line for his automobile production system. He patented his setup and this new process of production allowed his production system to manufacture and assemble large quantities of vehicles in shorter span of time. The output of the company was increased five times in just one year. This assembly line setup produced vehicles at cheaper rate as well and became famous for faster deliveries. His model of assembly line production laid a foundation for the assembly line systems that were built in the coming decades.

FIGURE 1.1: *Ransom Olds First Assembly Line in 1901*

Assembly lines were widely adopted through mid-1900s, engineers began to adopt this process and installed more workstations and machinery to minimize labor load, increase efficiency, and reduce delivery periods. Although the process was widely adopted for automobile industries, but it gained popularity in other industrial setups as well like manufacturing industries of commercial and strategic projects.

In modern world, robotic arms and highly sophisticated equipment are installed on assembly lines. The use of artificial intelligence (AI) technology is increased in recent years that reduces the need of manual labor and increases production pace keeping the quality of goods up to the mark. Although this method of assembly line production is fast but it has major problems of the bottleneck creation and lag generation in between working stations of assembly line, which need to be addressed in the current era. To overcome these problems, this research work aims to apply takt time technique and MORA (Model for Optimal Resource Allocation) by combining type-I & type-II assembly line methods in electrical parts manufacturing industries to understand the impact and overall benefits attained by using this method.

1.2 Problem Statement

In recent extremely better global production situation, the products are required to be delivered at a faster pace and at lesser consumer price. The market level of products has widely increased and the manufacturing companies require understanding and forecasting of customer demand well ahead of time. This can be achieved through the implementation of takt time technique in industrial setups. This method itself is not sufficient enough as the assembly lines encounter various problems like bottlenecks and lag during the production that can result in delayed delivery and customer dissatisfaction. This can be minimized by the implementation of some sort of assembly line balancing model to overcome operation issues of production. Hence, this work focuses on the calculation of takt time based on the case study [2, 3] and applies MORA (Model for Optimal Resource Allocation) to reduce bottlenecks and optimize production of the industries.

1.3 Research Questions

This study will response to the questions mentioned below

1.3.1 Question 1

Does calculation of Takt time help in setting of production line pace?

1.3.2 Question 2

Does MORA model remove bottleneck in assembly line?

1.3.3 Question 3

Does optimization of assembly line result in increased output?

1.3.4 Question 4

Does Takt time calculation & MORA hold a relationship in optimization of assembly line?

1.3.5 Question 5

Does this research apply to all discrete parts manufacturing industries?

1.4 Objectives of the Study

Development of MORA (Model for Optimal Resource Allocation) and linking of the subject model with the takt time tool is the primary purpose of this study to optimize production. The final model is supposed to remove bottlenecks and idle times between workstations in subject case studies by streamlining the operations and making smooth flow of parts that would help to meet customer demand by increasing the production.

The study has following specific objectives that are considered in this research work:

1.4.1 Research Objective 1

To set the pace of assembly line by calculating takt time in current assembly lines.

1.4.2 Research Objective 2

Implementation of MORA model to remove bottleneck in assembly lines for smooth operation.

1.4.3 Research Objective 3

Increase the output of subject case studies in order to meet required customer demand.

1.4.4 Research Objective 4

To inspect and understand the relationship of Takt time & MORA model for optimization in assembly lines.

1.5 Importance of Study

The study aims to optimize the assembly lines by the implementation of Takt time and MORA (Model for Optimal Resource Allocation) model. Once the model is designed and the operation is optimized, the methodology is expected to serve in other industries as well that are operating assembly lines and facing bottlenecks in their operations. The model is quick to adopt and provides efficient results to optimize the pace of assembly line during production.

Following benefits are expected to be achieved by the implementation of designed methodology:

1.5.1 Continuous flow

The bottleneck in one station, causing reduced output is expected to be streamlined, resulting in nonstop and continuous flow of operation.

1.5.2 Reduced idle times

Due to high cycle time of particular workstation, other stations receive increased idle times, that are expected to be minimized.

1.5.3 Minimization of conjunction

Line balancing is supposed to reduce the chances of any conjunction possibility in operation.

1.5.4 Resource utilization

Each equipment is expected to be utilized at maximum possible efficiency due to reduce idle times.

1.5.5 Reduced processing times

The total processing time of each item will be minimized due to smooth sequential flow.

1.5.6 Cost reduction

Increased output in same amount of time resulting in higher sales and less inventory is expected to reduce overall cost

1.5.7 Waste minimization

Balancing of assembly line would result in minimized waste at each station, as less scrap would be made.

1.5.8 Safe operation

The work in process inventory piled up due to imbalance assembly line, which can act as a tripping or fire hazard; whereas, a balanced operation would minimize this risk.

1.5.9 Minimized labor

To overcome the customer demand and to reduce shortfall per day, manual labor and additional equipments are required. Implementation of designed model is expected to create smooth sequential flow and minimize the need of manual labor to resolve workstation shortages.

1.6 Supporting Theories

Traditionally several theoretical perspectives are presented around the globe by various researchers to balance the assembly lines. Two main forms of the assembly line balancing techniques are; type-I and type-II balancing.
The type-I balancing includes the assignment of equipment to workstations for balancing of assembly line and the type-II balancing includes the reduction of cycle time by mathematical or digital models.

Common techniques between these two types of balancing include the following methodologies:

- Value Stream Mapping (VSM)
- Identification of Non-Value-Added Activities (NVA)
- Linear programming models
- Re Sequencing of processes
- Consideration of workforce skill
- Maximization of utilization
- Addition of safety stocks
- Revision of assembly line layout

- Implementation of 5s technique (Lean methodology)

The implementation of Takt Time tool and MORA (Model for Optimal Resource Allocation) is designed to include both Type-I and Type-II of traditional balancing approaches along with linkage of Takt time to balance the assembly line operation of subject case studies. Hence, this methodology covers features from all aspects of traditional approaches.

1.7 Report Organization

This research work contains five chapters; the first chapter emphases on contextual, statement of case problem, objectives, significance of the study, and supporting theories related to assembly line balancing. The second chapter is based on explanation of traditional balancing approaches and current literature along with the research gap. In third chapter, the research methodology and calculation of operational parameters are demonstrated. The fourth chapter describes the calculations and results. Finally, the fifth chapter concludes the research work and provides future recommendations for other researchers along with the boundaries and limitations of the current research work.

Chapter 2

Literature Review

2.1 Assembly Line Balancing through Equipment / Operators Addition (Type-I)

Productivity improvement in assembly operations is critical in order to meet customer deadlines. One way of achieving this goal is through the addition of equipment and operators in the assembly line of production system. In assembly line system various workstations collectively work together to assemble a product, each workstation consists of one or more than one machines that perform various operations on a part before passing it to next workstation. During the operation, bottlenecks may be generated between workstations due to imbalance assembly line. This can result in generation of work in process inventory (WIP) building up at that station. To overcome this situation one way to balance the assembly line is by assigning machines from one workstation to another where load is high.

Similarly, number of operators assigned on one workstation can be shifted to another station with high workload to balance the assembly line. Fansuri et al. [3] explained this in his case study of line balancing at an electronic company that manufactures electrical goods. The study implemented the line balancing by identifying the bottleneck workstations through takt time calculation, station number two is found to be the bottleneck resulting in the generation of work in process (WIP) inventory before station number one. To balance the assembly line, two operators and one machine from station six is transferred to station two. This swapping of operators and equipment resulted in reduced load at station number two as shown in figure 2.1. The bottleneck of the assembly line operation is removed and inventory piled up at station number two is minimized.

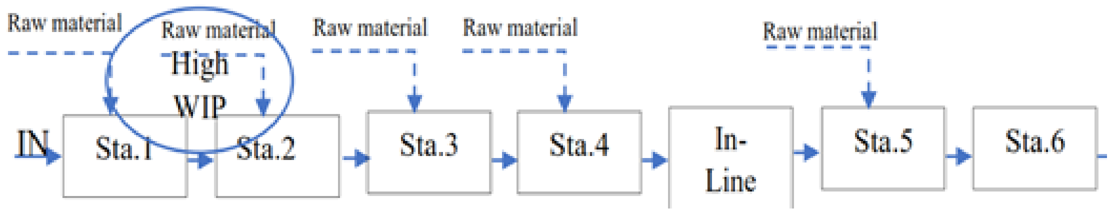

FIGURE 2.1: *Assembly Line Resources Swapping*

The operation of the assembly line is bottleneck free and inventory pile up at station number two is minimized. Assignment of equipment and operators can become a complicated task if the assembly process is wide spread across the setup. In such cases, before assigning the operators across workstation best practice is to analyze the skills of each operator as well. Martignago, et al. [4] suggested the use of mathematical model for managing the workforce in assembly line operations for high output industry. A large number of tasks are performed parallel, takt times are calculated for these systems which are then compared with the operation or cycle times of workstations.

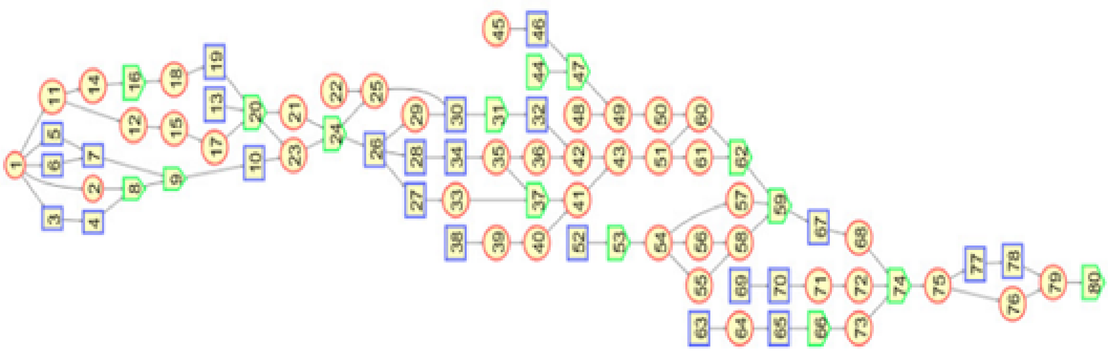

FIGURE 2.2: *Assembly Line Management in High Output (Parallel Tasks) Industries*

The operators are assigned in such wide spread operations by considering the skills of the operators instead of considering only the number of operators as traditionally done by previous researchers. The model limitation is that due to high number of parallel operations, the computation time is increased greatly and the activities tree is very wide spread. Thus, only high skilled operators are shifted to workstations where load is high. Consideration of overall equipment efficiency (O.E.E) [5] is one way of finding out the performance of machines installed at workstations.
This is calculated as:

TABLE 2.1: *Overall Equipment Efficiency*

Parameter	Ideal (%)	Normal (%)
Performance	95	85
Quality	99.9	90
Availability	95	80
O.E.E	90	61

This is used to indicate the efficiency of the running machines. By using overall equipment efficiency (O.E.E), the machines are rated against each other and equipment that is underutilized is swapped with newer equipment. The machines with greater efficiency may be transferred to workstation with high loads. A mathematical model of linear programming can also be designed for assignment of equipment to various workstations as shown in table 2.2

TABLE 2.2: *Workstations Assignment*

j					***k***				
	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0
6	0	1	0	0	0	0	0	0	0
7	0	0	1	1	0	0	0	0	0
8	0	0	0	0	0	1	0	0	0
9	0	0	0	0	1	0	1	1	0

For this purpose, an objective function is defined for minimizing the total time or cost while various machines are entered as subject in model. Constraints are defined in the model, which help in optimizing the system. Kamarudin and Rashid [6] designed a mathematical model for assignment of equipment (j) on workstations (k) through linear programming in their research study. The results optimized and balanced the assembly line operations. Navas-Barrios et al. [7] applied mixed model linear programming method on lead acid batteries factory, different workstations having multiple activities to be processed are considered. Solver is used to discover the best allotment of stations. The cycle times are calculated and ideal workstations are found as shown in table 2.3.

TABLE 2.3: *Cycle Times per Station*

Work station	**1**				**2**		**3**	**4**				
Tasks	A	B	C	E	D	F	H	G	I	J	K	L
Time / Task (s)	0.6	0.1	0.6	3	4	0.3	4	1	2	0.1	0.1	0.2
Time / station (s)	4.4				4.2		4	3.6				

Values are entered in solver and total workstations required are reduced from ten to four, which resulted in overall lead time reduction. An objective function is defined and the goal is to minimize the total number of workstations, which the program did effectively. The final improvement achieved through subject linear programming model is summarized in table 2.4. a 59.11% increase in efficiency and -93.28% reduction in idle time is achieved using the designed programming model. This programming tool utilizes the simplex linear programming model available in excel solver solution. Constraints are defined by the user and objective function is set for optimization of the workstations assignment. It can be observed from table 2.4 this study has saved idle duration by -28 seconds which can be considered as significant change in order to optmize the assembly line operation.

Table 2.4: *KPI's Marking*

KPI	Cycle Time	Total Time	Workstation	Efficiency	Idle duration
Earlier	4	17	10	34	30
Later	4	17	5	88	2
Difference	-	-	-5	54	-28
Change (%)	-	-	-50	159	-93

Buxey, G, [8] suggested two balancing approaches; the first approach is centered on positional weight method and the second approach is the random generation method. A comparison is made between the two methods to withdraw differences that help in assigning the equipment and operators to workstations. Rubinovitz and Levitin [9] expressed that the traditional algorithms provide single solution of the problems; whereas, in actual assembly line, multiple problems can arise, which need multiple solutions. Thus, the priorities for workstations allocation are considered. This priority allocation allows flexibility and multiple solutions to balance the assembly line.

Hackman et al. [10] proposed a quick and active heuristic for simple assembly line balancing problem. The goal is to reduce the number of workstations, for this purpose a branch and bound algorithm is proposed. This algorithm provides a technique that decreases the magnitude of bound and branch tree. Similarly, for increasing production rate, the assembly line balancing solution are also dealt with same algorithm in order to reduce cycle times.

Hoffmann [11] emphasized on successful balancing of assembly line using work elements. In order to successfully balance an assembly operation, the work essentials are to be assigned subject to constraints of the assembly line to optimize the flow. The procedure used in this study results in optimal solution of line balancing by using a matrix consisting of ones and zeros, which also called as precedence matrix. Total elements used are nine and the FORTRAN programming language is used to steady the operation and compare the solutions to reduce cycle times and production line delays.

Arik et al. [12] presented a mixed integer programming method for a simple assembly line balancing problem of type-I. The unknown task and demand are represented with grey numbers; these numbers are used to show the uncertainty of various parameters in this assembly line balancing problem. The aim is to lessen the number of total stations. A precedence matrix is generated and minimum numbers of workstations are calculated. Results from this mathematical model provide an assignment that does not disturb the precedence relations among the various activities and the workstations. The sum of the task times is less than the cycle times.

Kilincci [13] used a Petri-net heuristic to balance a simple assembly line of type-II (SALBP-2). This mathematical tool uses graphical aid in order to model a system and analyze it. SALBP-2 is for balancing the assembly line by minimizing the total cycle times for specific number of given workstations. The available tasks are assigned to different workstations by reachability analysis, which is the actual way of using Petri-nets. The results of SALBP-2 are considered by trial method for different cycle times. If the results are not feasible, the heuristics adds the cycle time until there is a reasonable answer. MATLAB coding is used for all directions. In the end, good results are achieved for the proposed technique that improves the overall performance of assembly line.

Pinarbasi et al. [14] and Zohali et al. [15] carried out assembly line balancing using order reliant on setup times. Different sets of jobs are performed at different workstations; each activity has its own setup and cycle times, which depend on the sequence of the stations. The aim is to minimize the cycle times (type-II) by assigning tasks to workstations in an optimal manner and sequencing these activities at each workstation. In order to balance this, mix-integer programming model technique is utilized. To further balance the line a logic-based bender decomposition algorithm (LBB) is presented, which provides more feasible solution by reducing the times and optimally balancing the assembly line.

Akagi et al. [16] focused on reduction of cycle times using operators' assignments. In a typical assembly line, mostly no parallel workstations are permissible. In this condition, the workstation with least cycle time becomes the work element with maximum time and this limits the rate of production. In this work, a secondary method to increase the rate of production by reducing the cycle times is proposed. This is done by assignment of more than one (multiple) workers on a single workstation also called parallel assignment method (PAM) and this resulted in the production improvement. The process is carried out in two phases; during first stage of PAM, the workstations and work features are allocated. This resulted the prolonged operation times of workers as compared to the amount of workers on workstation. In the next stage of parallel assignment method (PAM), assignment of workers and work elements is carried out and this resulted in the reduced work elements.

2.2 Assembly Line Balancing through Idle Time Reduction (Type-II)

Optimization of production in assembly lines is necessary for smooth operation, another traditional method of assembly line balancing is through the identification of idle times between workstations and minimization of these highlighted idle times. This is considered as type-II approach of assembly line balancing, the goal is to reduce cycle times of workstations by identification and minimization of idle times in operations. This reduction of cycle times helps to achieve the takt time target and maintain smooth flow of parts through all stations resulting in bottle-neck elimination.

Mishan and Tap [17] presented a methodology to increase the efficiency and productivity of a food-processing assembly line. Idle times were calculated for the activities and the packaging process and dough divider tasks were the two activities that faced most loads (less idle time). For packaging process, a new design is implemented by adding packaging bags, which resulted a less processing time than cycle time. Similarly, for dough dividing task, a new machine is installed to reduce cycle time of the process. After making the modifications, the results showed that the effectiveness of the operations on assembly line is improved up to 46% as represented in figure 2.3.

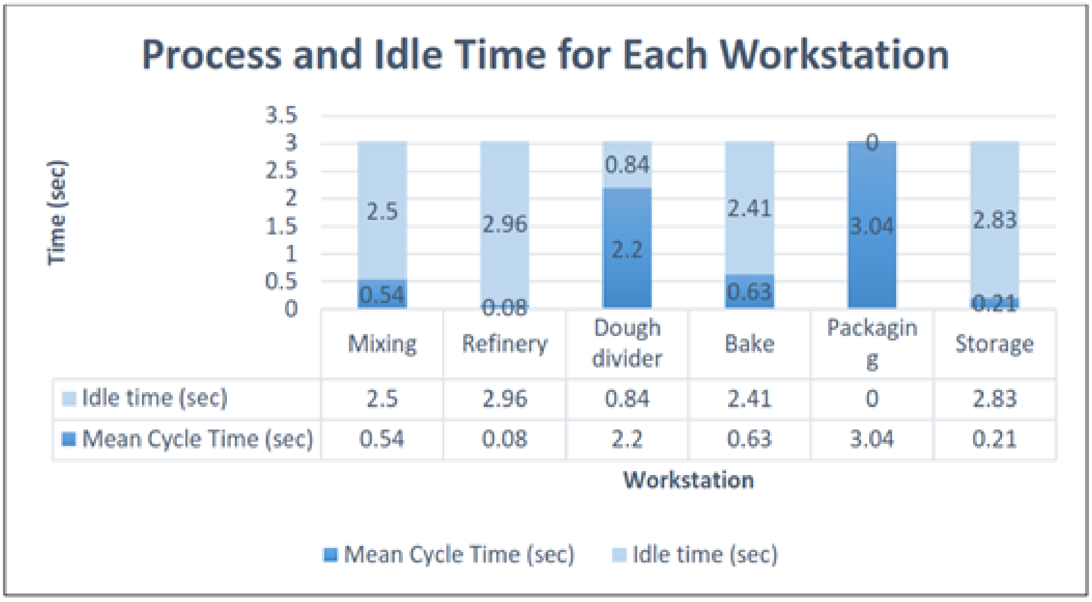

FIGURE 2.3: *Idle Time Management in High Load Processes*

Pinto et al. [18] described an approach to simultaneously process different choices of manufacturing alternatives and tasks assignments with stations to decrease the cost and times of operations. An integer-programming model is applied with different activities of cost and cycle times. The applied model minimizes the cycle times using solver and provides an optimal solution to balance the assembly line.

Tang et al. [19] used a bee-colony-algorithm with sluggish time decrease methods; the study described a method to balance the two-sided assembly line, which is widely used for large production setups. In order to solve this complex line, the researchers introduced a discrete artificial bee colony technique. The goal was to compress the actual cycle times by reducing the idle times of operations. Tasks were assigned according to operations times to minimize over all times, thus reducing the idle times of the operations and system.

Kilbridge and Wester [20] used a heuristic approach to balance the assembly line. The cycle times of all activities were listed and the stations were assigned according to cycle times in order to minimize the delay as much as possible. This method was more appropriate as compared to the trial method in which solution was not optimized and the chances of errors were high. The heuristic method is most suitable for industries with high production rates and parallel process as shown in complex figure 2.4 below. Multiple process are being performed simultaneously which can result in bottleneck generation easily.

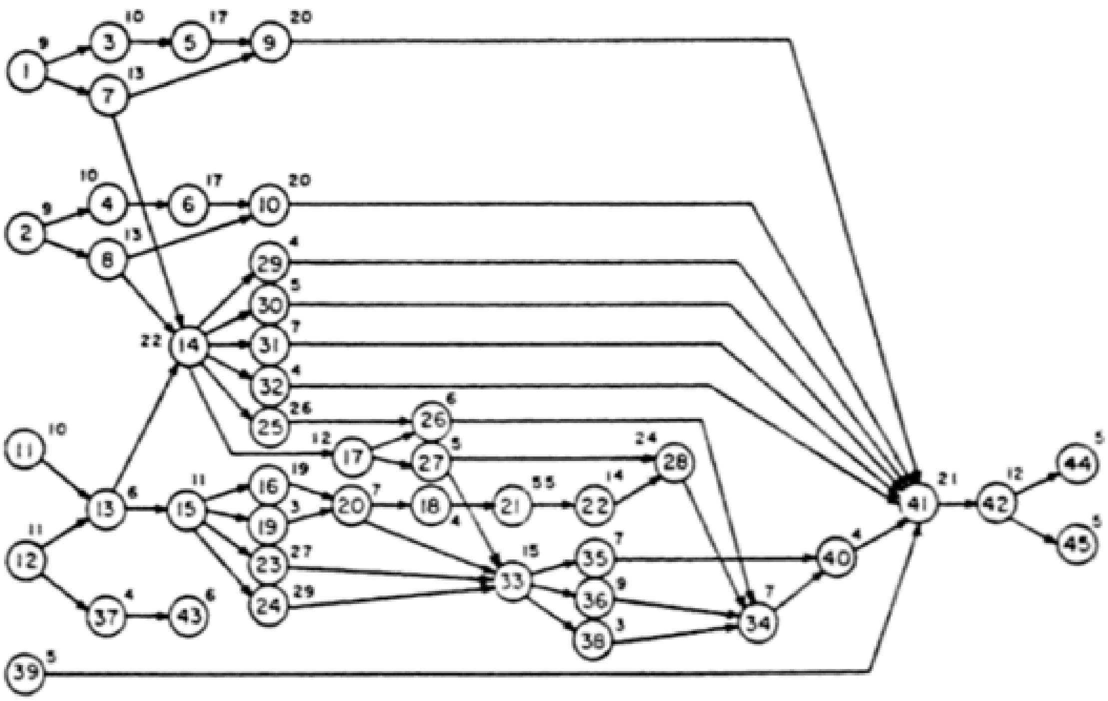

FIGURE 2.4: *Heuristic Method to Balance Assembly Line*

Reduction of cycle times through type-I and type-II approaches is utilized with the aim of minimizing the idle times in the system. Scholl and Vob [21] analyzed these two types in their case study through implementation of Tabu search algorithm. The type-I methodology is to assign the tasks with the given stations in such a method that total number of workstations are minimized. In type-II, the goal is to maximize the rate of production or minimize the total cycle times of all workstations. In both types, the constraints of the precedence relations are to be considered for balancing of assembly lines. For type-I, the heuristic priority rules are considered for balancing; whereas for type-II, the repetitive application are considered. The Tabu search is also utilized to analyze the effectiveness of these approaches in order to balance the assembly lines.

Arikan, M. [22] further analyzed the tabu algorithm and implemented a reactive tabu method to solve the problem. The aim is to decrease the cycle times or capitalize on the rate of assembling of line. An algorithm based on reactive tabu search is suggested to find the optimal solution. Since tabu search is well known method, there is very little research on a reactive tabu algorithm to explain the issue. The reactive tabu method applies inserting along with swapping moves to neighboring solutions as shown in figure 2.5 and also applies a population heuristic like a genetic algorithm.

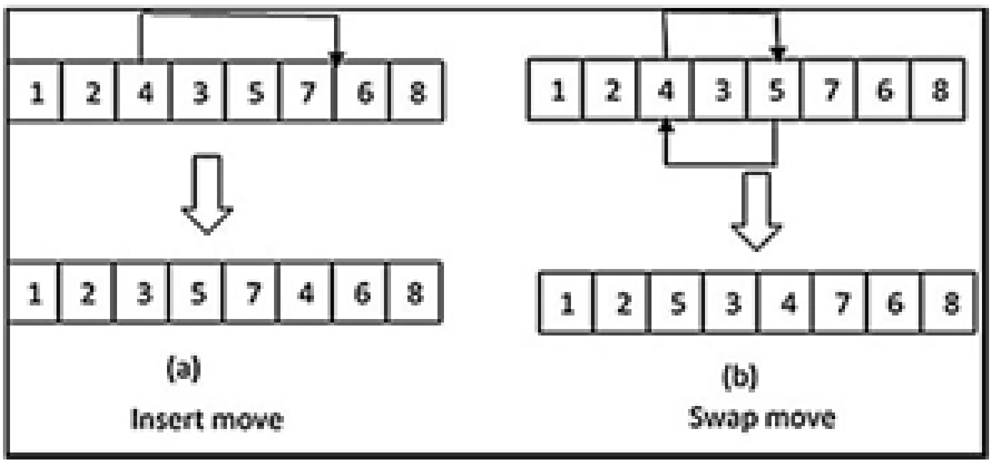

FIGURE 2.5: *Reactive Tabu Method by Swapping Moves to Neighboring Solutions*

The results are verified on different benchmarks problems chosen from literature such as the particle swarm optimization (PSO) algorithm and other multi-objective algorithms. The results show that this suggested reactive Tabu search presents an improved assembly line balancing solution as compared to other existing models.

Azizoglu and Imat [23] focused on a simple assembly line balancing problem, which has static given number of stations. Each station has a pre-described cycle time. The aim of the authors is to decrease the sum of squared deviations of all stations cycle times. This method increases the smoothness of workload and maintains a balance. In order to minimize the objective, few optimal bounding mechanisms and optimal properties are established, which are then used in the branch and bound model. The results show that this algorithm is suitable to solve mid-level problems in a reasonable time; thus, balancing the overall assembly lines by reducing workstations' cycle times.

Grzechca, W. [24] focused on the reduction of number of workstations in an assembly line in order to balance the assembly line and reduce the idle times of the workstations. The author evaluated two main types of assembly line layouts; the parallel single lines (serial) and the U-type assembly line layouts. Calculations were carried out and parameters like line efficiency (LE), smoothness index (SI), and line times (LT) are calculated for both (serial and U-shaped) types of layouts. The aim was to minimize the idle times between workstations through layout adjustment of assembly lines. The data found from the calculations of line efficiency, smoothness index, and line times showed a significant change in idle times for both layouts, figure 2.6 shows the data values of idle times for serial type layout; whereas, figure 2.7 represents the idle time values for U-shaped layout. The comparison of results of both layouts illustrates that the U-type assembly line layout significantly reduces the idle times of workstations and minimizes the numbers of workstations, resulting in a balanced assembly line operation and increased productivity of the system. This comparison of two different types of layouts are necessary to highlight the differences of process flows in each layout.

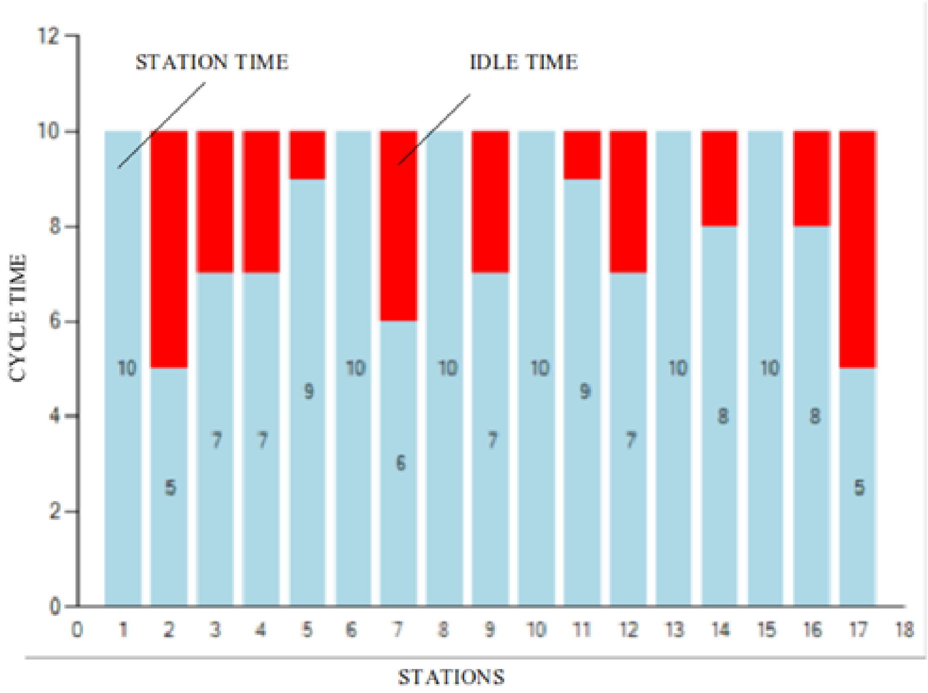

FIGURE 2.6: *Idle Times for Serial Shaped Assembly Layout*

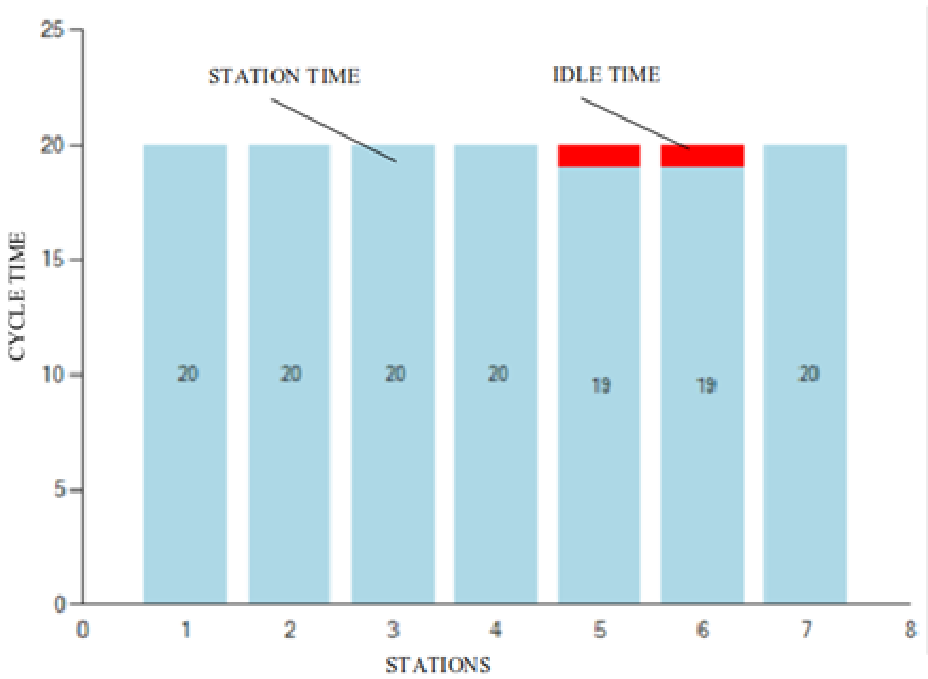

FIGURE 2.7: *Idle Times for U-Shaped Assembly Layout*

Lam et al. [25] presented a case for an electronics company assembly line balancing; the main concern is the bottleneck that arises due to imbalance flow of the assembly line. The goal of the author was to focus on the lean management activities in order to minimize waste. Analysis of the line was carried out to find the wastes and non-value-added activities. The main parameter was the line balancing indexes, which were found by calculations. Several benefits were deducted by implementing this lean line balancing technique, which could be applied in other industries as well. The quality of production was increased and bottlenecks were minimized in the assembly line.

Ongkunaruk and Wongsatit [26] aimed to increase the output in a mega size frozen chicken manufacturing company in Thailand. The work study method was used to analyze the production process and examined the bottleneck in assembly operation. Three main processes were design, methodology, and approach. First, the cycle times of all processes were calculated in the assembly process and then the complex assembly was designed and identified the bottleneck in the operation. After this, line balancing (LB) along with the theory of constraint approach was applied. A special approach of ECRS (eliminate-combine-rearrange-simplify) was suggested and applied for the assembly operations. Through this new approach of ECRS, grouping was done by combining two workstations into a single station and simplification was done by transporting the chicken instead of walking. Cycle time and number of workers were reduced in this way, thus increasing the line efficiency significantly and reducing idle times in operations.

Zupan and Herakovic [27] presented a case study for the optimization of the production line using a discrete simulation method. During the first phase, the basic theory and processes for the balancing of production line were presented, in the real case study there were two production lines and one assembly line. The simulation model was built on discrete simulation approach. Initial results were obtained from this approach, after balancing of assembly processes; for improvement in performance, some additional measures were taken for optimization by using the improved the discrete simulation method. Production rate was also increased; thus, the utilization of machines was increased as shown in below figure 2.8.

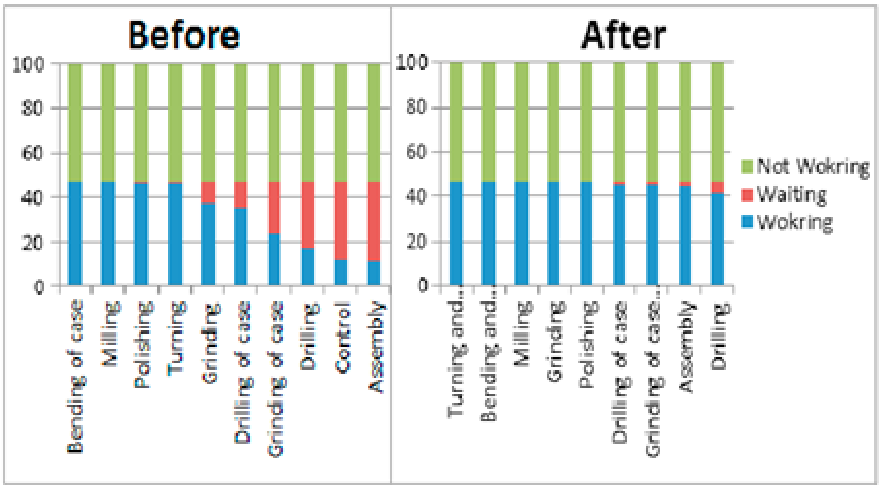

FIGURE 2.8: *Idle Times Minimization Through Discrete Simulation Method*

2.3 Assembly Line Balancing through Takt Time Calculation (Type-II)

Takt time is an aspect of lean production, which links the customer requirement with the accessible assembly time and is utilized to increase pace of assembly. It explains the time available to prepare one item. Thus, it is the general vacant assembly time divided by the total predicted requirement of the client for that time period. Calculation of takt time provides a baseline for production pace, if accurately followed, the assembly line can provide continuous operation without any bottlenecks and the customer demand could also be met.

Luciano et al. [28] implemented takt time with a flow mapping tool in a coffee powder workshop. This work contains the examination of coffee powder assembly arrangement using the value flow mapping method in a workshop. The preparation of the method was recognized in the Toyota-Production-System (TPS), where the formation of value maps was recognized as steady work. The tool classifies likely faults in the production line. It weighs on measuring supply chain management and thus suggesting a map of the assembly process by means of the takt time calculation. Other techniques that are linked to value flow mapping and can be utilized with takt time are PDCA cycle [29–32] and variable and/or fixed takt times [33–35].

Some other studies [36, 37] utilized takt time in automobile plant with the goal of increasing the output by finding base production rates. The paint shop of the case plant was measured as the bottleneck of the factory by measuring the takt time of the assembly line. Thus, it was chosen as the point to increase productivity and achieve the market requirement. Takt times of the recognized procedures were logged on the sheets. The main causes of little productivity are analyzed by the cause and effect analysis. The other actions to improve the productivity were examined. Different mix model assembly line balancing techniques were applied on a production line where multiple parallel operations were taking place. The goal was to reduce the cycle times of all activities. The numbers of elements used were more than one; therefore, one single technique could not be adopted and the results were combined to choose the most optimal outcomes for reducing overall lead time.

Kumar et al. [38] targeted to increase the efficiency of a production line in a hemming unit using three separate line balancing methods. A hemming unit having twelve unique workstations consisting of manual work labor execution is considered. For each workstation, the average cycle times were obtained through historical data and the takt times for every workstation were analyzed using the Yamazumi chart. Few rules of line balancing that were implemented in this study are Kilbridge, the largest candidate and ranked positional weight rule. These rules implementation significantly increased the line efficiency and made it possible to decrease the workstations as well the balancing of assembly line in subject hemming unit.

Firake and Inamdar [39] tried to improve the productivity in an automotive industry assembly line by improving the line efficiencies. Assembly lines are the main concern in automotive industries; any bottleneck workstation in these lines can result in overall reduction in efficiency and productivity of the plant. The bottleneck station was identified in the layout and the non-value-added activities (NVA) along with those non-value-added events, which are necessary to perform, were studied. The unnecessary non-value-added actions in the production were eliminated by computing the takt times and cycle times of each workstation. The activities, which took additional times, were reduced and processing times were also made equal. This decreased the cycle times and made possible to remove the bottleneck in workstation and resulted in the balancing of automotive assembly line and increased the production output.

Eswaramoorthi et al [40] utilized an improvised method for balancing of assembly line operations with the goal to meet the takt time by implementing a new terminology known as flow index. This proposed a method consisting of two steps based on COMSOAL (computerized method of sequencing operations of assembly lines), which is an algorithm that attempts to reduce or minimize the total workstations quantity and smoothen the work-load against the mentioned workstations. The smooth flow was obtained by reducing the flow index figure. The results were compared with other famous balancing methods and values showed that the design algorithm performed well for most data sets.

Sihombing et al. [41] carried out work on the significance of number of operators and non value added activities in an assembly line of a manufacturing unit. A tuner production line case was considered for implementation and three key elements were identified for balancing. These elements were; total number of operators working on the equipment, the tools and equipment for production, and the process for production. The study carried out the line balancing by using fact-model; a simulation technique to eliminate the bottlenecks. It improved the productivity and assigned the workforce (operators) where required optimally. The model used CPM (critical path method), takt times, and non-value added activities techniques to balance the assembly line. The critical path method identified those activities that were most important for the completion of the project and such activities were vital because the successful completion was dependent on these tasks. This path highlighted the longest path in a network diagram. By using CPM, scheduled tasks were prioritized and offsets were measured. Along with CPM implementation, the takt times and NVA (non-value-added activities) identification and analysis also helped in balancing the assembly line operation in this case. The process of simulation is shown in figure 2.9.

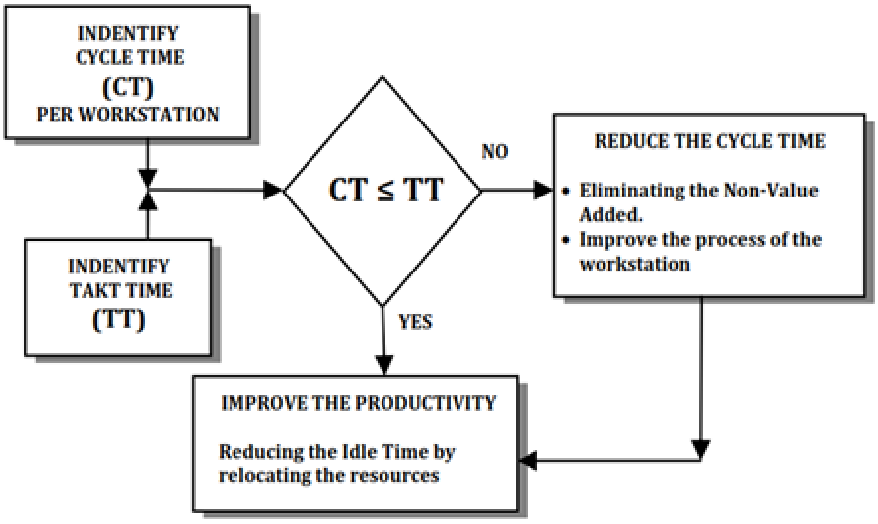

FIGURE 2.9: *Simulation Hierarchy Using Logic Gates*

Nallusamy and Saravanan [42] utilized takt times in a small scale industry. Lean manufacturing techniques were emphasized along with their significance in manufacturing companies in order to meet the difficulties of contemporary global market. This technique could significantly increase the productivity and decrease the lead times, which may result in meeting the customer expectations. The aim was on the lean aspects in a small automotive component producing factory. Standard operating procedures (SOP) were utilized to add standardization in production along with Kanban implementation by indicating the part numbers and their description for every workstation. Value stream mapping and ranked positional weights were performed in order to steady the line loads effectively and reduce transportation time of items between stations. By implementing these methodologies, the cycle and setup times were decreased, which resulted in the removal of bottlenecks as all process times were under takt times.

Wilhelm et al [43] presented a new Ergo takt concept, although there is a wide increase in automated assembly line, but manual assembly work stations are still vastly required and used in industries. Currently manual assembly lines are balanced using the takt times of workstations which doesn't incorporate the human centered balancing. In this study a human centered balancing method for line balancing using an indicator that is ErgoTakt is utilized which improves the old takt times and helps to optimize the assembly line cycle times. An ergo sentinel software is used with online monitoring of activities to find the best solution by minimizing the objective function of cycle time of workstations. The results show that this new approach is feasible and optimizes the entire assembly line.

2.4 Assembly Line Balancing through Capacity / Efficiency Improvement (Type-I)

In process industry, multiple operations are being carried out simultaneously on various workstations; in order to avoid bottlenecks, the work is done on capacity enhancement of the system. Multiple techniques are utilized for efficiency improvement of ongoing operations. These techniques and capacity enhancement planning help to avoid bottlenecks and maintain a smooth flow of assembly line for continuous production and customer satisfaction.

The study reported by Kumar [44] enhanced the capacity of an assembly line in a truck body assembly workshop using lean principles. The primary work is done on the use of value stream mapping for ideal and current state of operations and they are compared for an optimal solution. Authors applied tree diagram and prioritization of jobs in order to reduce cycle times. By using this tree diagram, the cycle times of various jobs are reduced resulting in the removal of bottlenecks. Work standardization and waste elimination methods are adopted to raise the effectiveness of the method. The capacity is increased by adding new equipment, shift, and manpower. This way of improvement in assembly line balancing is expensive to adopt but results in better optimization, since the changes adopted are physical and traditionally more renowned. The type of design is shown in figure 2.10; where, it can be observed that the subject activities are the desired tasks to meet the required takt time of 42 seconds. Also, the priorities to achieve the desired tasks are considered as well.

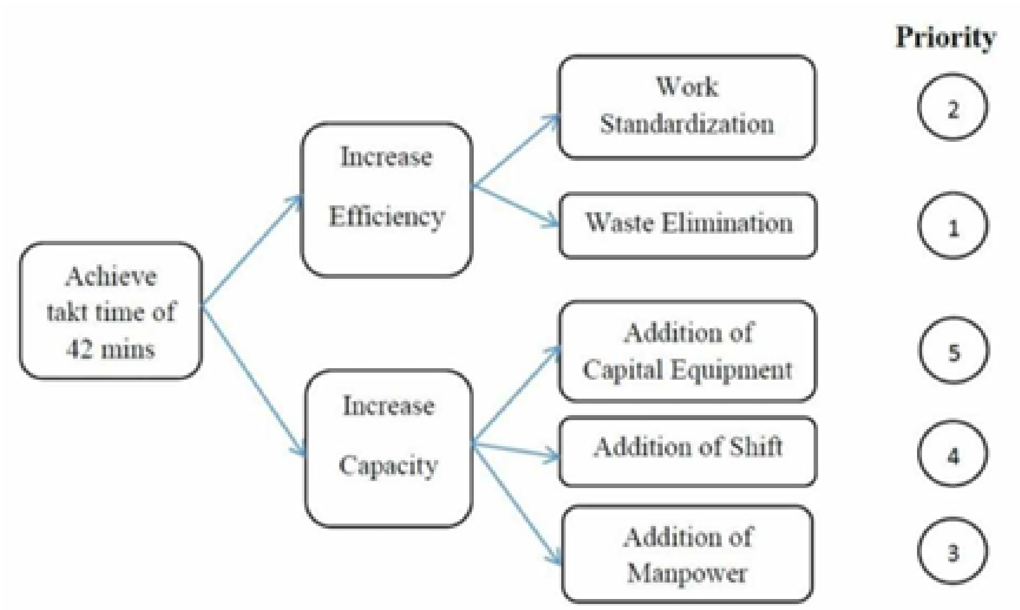

FIGURE 2.10: *Physical Activities for Enhancing Capacity*

Becker and Scholl [45] attempted to increase capacity and efficiency of the assembly line using line balancing methods varying from simple to generalized techniques. Various perspectives of line balancing are focused on return and price goals, the procedure requirement, variety, similar workstations and jobs, line layout of U-shape, task limitations, stochastic job times, and mixed-model lines. By considering these perspectives, one can choose among simple or generalized assembly line balancing technique desired.

Adnan et al. [46] presented a method for overall efficiency improvement of production line through line balancing. They showed two approaches to balance the assembly lines; one by reducing the cycle times of workstations and second by assigning tasks to workstations. Japanese KAIZEN technique was implemented to reduce waste by minimize non-value added activities for reducing cycle times. Other steps that reduced cycle times include arrangement of parts and management of manpower. This reduced the cycle times of workers and operations.

Sivasankaran and Shahabudeen [47] examined various problems faced during assembly line balancing. In modern times, mass production has become a key for industries, where high production rate is desired. This technique of mass production is categorized into machining and assembling on production lines. The balancing of assembly processes for desired volume of goods produced per shift is taken into account. The actual purpose is to decrease the total number of stations for a pre-arranged assembly line to reduce the cycle times. An attempt is made to develop a mathematical model. Numerous models are considered, some of them are based on either a single model or a multi-model assembly lines. Whereas, others are based on type of line like a U-type to carry out the assembly line balancing and some are based on task times. Final goal is to reduce the total cycle times of an assembly line.

Boysen et al. [48] attempted to increase the capacity of the assembly line through line configuration. The planning of line configuration is very important for higher paced production. It helps the researchers to plan their assembly lines in a way to support high production and output in facilities. In real world, the assembly line setups require a great amount of planning in order to configure their production for paced results. The practical settings and relevant models are presented to overcome the challenges of production lines.

Bowman [49] tried to enhance the efficiency of assembly line through linear programming model. Two types of assembly line balancing problems are examined. The feasible solution is generated by solving the integers of linear programming model and the production output is considered small. However, the application of this method on larger industries would result in large computations. The feasible solution is used to assign workstations for jobs.

Masood and Zhang [50, 51] presented software implementation and U-shaped assembly line structure for increased capacity and efficiency of the plant. The operations, which were critical and consumed high cycle times were first identified and then chosen for study. Simul-8 software is used to re-sequence the activities and balancing of assembly line. The utilization of machines is also enhanced, this results in reduced cycle times and through put rates. A U-shaped formulation is made based on worker tasks assignments and cycle times of operations on equipment. Scheduling is carried out and Pareto greedy approach is applied to optimize the objectives. In the end, a restart mechanism is suggested to reduce the cycle times of operation.

Esmaeilian and Gao [52, 53] utilized MATLAB models and computerized robotic programs to improve capacity and efficiency. In recent times, the use of robots for assembly lines and production companies have increased vastly, which are commonly named as robotic assembly lines. During production, some changes might occur and to overcome these variations, the assembly line robots must be re configured so that productivity can be increased. The tasks of assembly are assigned to the specific workstations for balancing of type-2 robotic assembly lines. Every workstation chooses a specific robot to carry out the tasks with an aim to minimize the total cycle time. A genetic algorithm is used in this study along with a heuristic method. In the end, the technique proposed a balanced workload solution at all stations.

Tsujimura et al. [54] presented a fuzzy set theory and real world data is taken into account while a fuzzy number is used to show the cycle times along with the implementation of the genetic algorithm. Khan et al. [55] developed a model that is multi-objective and addresses the total time (TT), customer satisfaction index (CSI) and the line efficiency index (LEI). The two cases are considered; one with the presence of precedence constraints and other without the presence of precedence constraints. The outcomes showed that the location of stations and their formations impacted the line efficiencies. Also, the efficiency is high when the case is considered without precedence constraints as shown in table 2.5 below.

TABLE 2.5: *Direct Relationship Between Number of Stations and Issues Frequency*

Parameter	**Little**					**Moderate**					**Huge**				
Issue freq.	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Processes	5	6	6	7	8	11	14	16	18	21	26	33	38	44	49
Configs.	3	3	4	5	5	6	7	8	9	11	13	15	18	20	22
Stations	3	3	3	3	3	4	4	4	5	6	8	10	11	11	12

Bard [56] evaluated costs along with the problem of assembly line balancing as an efficiency improvement. A dynamic programming (DP) formulation is devised, which an algorithm to resolve an assembly line balancing problem that has multiple parallel workstations. The generated solutions are tradeoff between the cost of facilities that are additionally installed and the minimum quantity of workstations, which are required to attain a balance. Both the costs of activities and the costs of equipment are considered, another feature is that this algorithm considers the unproductive time in a cycle as well. Industrial based tests are performed to analyze the computations. The algorithm has a limitation of not performing well when graph values are near zero.

Kursun and Kalaoglu [57] sselected a sweat shirt sewing company as a case study to focus on the high labor-intensive work of apparel manufacturing. The aim is to reduce the labor work intensity by balancing the line work load using the simulation method. At the start, time studies and detail work is carried out on the line. Secondly, in order to setup a simulation model for the line, real time data is chosen from case study on a factory floor. The gathered information is then converted into a simulation model and then it is compared with actual system. Bottlenecks are identified and removed through what-if analysis. Different decision alternatives are suggested by using simulation to the manufacturers resulting in an optimal line balancing.

Polat et al. [58] focused on an efficiency improvement through manpower productivity analysis. Due to the heavier physical workload, the operators are dealing with less performance output and other disorder reducing the production output and quality of life. This problem can be dealt by balancing the assembly lines and reducing the workloads on stations. The study not only considers the precedence constraints and cycle times but also the physical workload on each workstation. The aim is to minimize the cycle times of workstations along with the workload on every station. Thus, a rapid entire body assessment (REBA) technique is implemented to overcome this problem. Randomly generated workload values are considered and a goal programming model is applied in order to balance the assembly line by considering the workloads on stations.

TABLE 2.6: *Rapid Entire Body Assessment Considering Risk Level and its Response*

R.E.B.A Score	Risk Level	Response
1.0	Insignificant	None
2.0 ˜ 3.0	Small	Maybe Obligatory
4.0 ˜ 7.0	Intermediate	Obligatory
8.0 ˜ 10.0	Great	Vital Soon
11.0 ˜ 15.0	Excessive	Essential Now

Kim et al. [59] conducted a study on two-sided assembly line operations, where jobs are performed in parallel on each side of assembly line. These kinds of two-sided lines are often installed in the high out production plants. This work implements a genetic algorithm and a mathematical model for two-sided assembly line balancing. In designing, the algorithm features of two-sided assembly line balancing are considered. The results of the suggested genetic algorithm (GA) are linked with the current literature work and concluded that this algorithm yields better results as compared to the traditional work.

Jamil and Razali [60] prepared a simulation for balancing of assembly line in a vendor manufacturing company for automotive components. A mixed model assembly line for engines fuel vapor filter canisters production is evaluated. It is found that the production rate in the current process does not meet the demand of the customers even with the presence of safety stocks for multiple days. Detailed time studies and process flow analyses are carried out in order to setup a simulation model of assembly line. Real time information is gathered from the shop floor of the factory and then tested for distribution fit. The gathered information is converted into simulation model and compared with the actual system. After comparison, it is observed that the efficiency of line is not optimum due to different idle times. What-if analysis is then applied to overcome the bottlenecks and idle times to balance the line and enhancement of production efficiency. Man power is increased to reduce idle times and the simulation is performed by Pro-Model software.

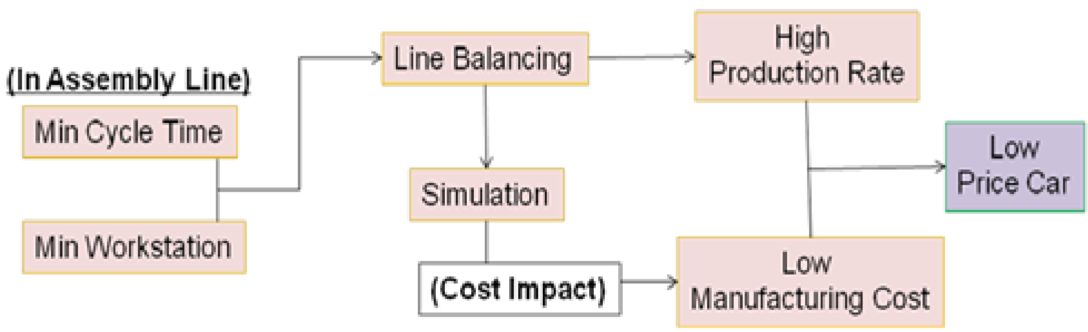

Figure 2.11: *Simulation Model and Real Time Data Comparison*

Hamta et al [61] performed work on flexible task times to improve the line efficiency. The machines considered for the study have flexible operations times between upper and lower bounds. The machines are capable of compressing the processing time of activities with the expense of high cost of operation due to wear and tear of equipment. Linear programming function is described and a bi-criteria integer programming solution (non-linear) is presented with two objective functions for reduction of cycle time and the total costs of the machinery. Design of experiments (DOE) terminology is applied to multiple parameters of this suggested algorithm. The obtained results show the effectiveness of this implemented procedure.

Another study [62] attempted to increase the efficiency of the line by reducing non-value added activities to optimize the production of assembly line. Line balancing is used to equally distribute the work tasks among workstation of the assembly line. The removal of non-value added activities helped in saving costly time and contributed in the efficiency enhancement. A case study of wire Harness company is studied and output of assembly line is increased by implementing line balancing and removal of NVA (Non value added) activities. The cycle times at different workstations are balanced in order to get the required results and increased the efficiency of the production system.

2.5 Research Gap

Electrical items are manufactured in mass quantity as discrete parts for nearly all global products; thus, it is difficult to accommodate the production process in a budget friendly and efficient manner due to multiple types of operations being performed simultaneously causing the generation of bottlenecks and idle times in assembly line operations.

For this purpose, more than sixty two previous studies were taken into account and it is found that traditional practices apply either type-I or type-II of assembly line balancing techniques and insufficient work is present that combines both methods along with implementation of takt time tool for production optimization.

Therefore, the purpose of this research work would be to address the bottleneck problem in two individual electronics parts manufacturing industries by means of takt time tool along with MORA (Model for Optimal Resource Allocation) model, in which type-I and type-II traditional balancing approaches are merged to carry out effective optimization and resource allocation of assembly line operations in both subject case studies.

Chapter 3

Research Methodology

3.1 Introduction

The method of research will be devised in this section, Model for Optimal Resource Allocation (MORA) and takt time implementation for smoothing of assembly operations is designed and evaluated that includes type-I and type-II balancing methods collectively implemented. Also, the relationship is examined between takt time and MORA (Model for Optimal Resource Allocation) for optimization of assembly line. The research methodology is further elaborated by explanation of technical terminologies utilized in this research work.

3.2 Research Design

The path through which a series of steps are followed to reach a designated goal is defined through research design. It explains who will be the stake holders of this research, which technique will be used to evaluate the data and also the methods to conclude the findings of the research. This research is based on case study, which will focus on the optimization of an imbalanced assembly line operation and analyze the relationship between takt time and MORA model. The takt time calculation and MORA (Model for Optimal Resource Allocation) model are designed to include both type-I and type-II of traditional balancing approaches along with the linkage of takt time to balance the assembly line operation of the subject case studies. Hence, this methodology covers features from all aspects of traditional approaches.

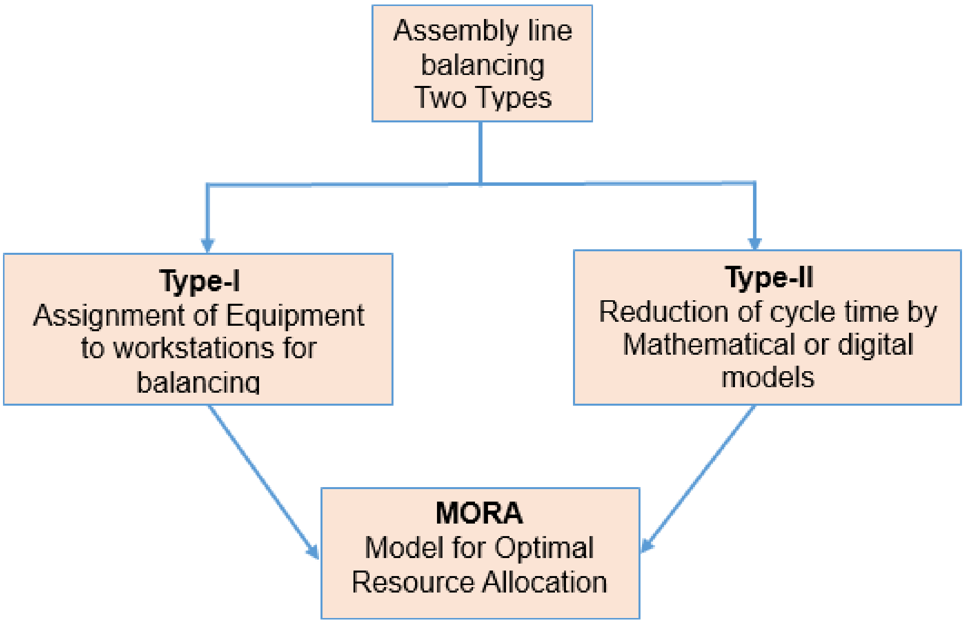

FIGURE 3.1: *Research Model*

3.2.1 Type of Study

This study is based on the optimization of assembly line process of two electrical parts manufacturing companies [2, 3], which is referred as "The cases". In these case studies, the research is done on an imbalanced assembly line that is chosen as target for minimization of bottlenecks and smooth operation. Takt time is calculated for the cases and MORA model is designed and implemented in order to minimize idle processes. The case research analyzes the relationship between takt time and MORA model, which combines traditional balancing approaches of type-I and type-II assembly line balancing. The case studies chosen in this research also attempts to explain and improve the pace of the assembly line through takt time calculation successfully. This study type (case study) is believed to be applicable in other processing industries as well; where assembly line operations are continuously being performed, through the implementation of newly designed MORA (Model for Optimal Resource Allocation) model. Thus, the research work is considered as a unique study first of its kind.

3.2.2 Units of Analysis

The case study implements various technical terminologies for optimization of assembly lines. These terminologies are calculated using available data from case study 1 and 2. Following parameters are calculated in these cases.

3.2.2.1 Takt time [TT]

Takt time is an aspect of lean production, which links the customer requirement with the accessible (Total available) assembly time and is utilized to increase pace of assembly line. It explains the time vacant or available to prepare one unit or item. Thus, it is the general vacant assembly time divided by the total predicted requirement (demand) of the client for that time period in order to maintain smooth flow of assembly line.

$$TT = [t \;/\; q] \ldots\ldots \text{ Eq (i)}$$

Where TT denotes Takt time, t is total vacant/available operational time and q symbolize requirement.

3.2.2.2 Theoretical time [T_{Th}]

This is the theoretical process time of one operation as per ideal working conditions suggested in SOP's / OEM manuals of factory which are recommended by default during operation.

3.2.2.3 Actual time [T_A]

Actual time consumed in process for each single operation as measured by factory operators.

3.2.2.4 Number of equipment and operators [N]

The total number of resources / equipment / manpower available against each process or the individual operators for each equipment is denoted by N. This parameter is inversely proportional to the cycle times of the processes, as the resources on one operation increases the total cycle time for that process decreases due to additional resources on that operation.

3.2.2.5 Cycle time of operation [CT]

The time consumed to complete single process, it is the time after which the item is finished at one station and ready to move for next operation in assembly line. The cycle time for one single operation on an assembly line is found by using the equation shown below:

$$CT = [T_A \ / \ N] \ \ldots\ldots \ \text{Eq (ii)}$$

3.2.2.6 Efficiency [E]

Effectiveness of separate assembly processes, this is found by calculating the ratio of theoretical and actual process times.

$$E = [T_{Th} \ / \ T_A] \ \ldots\ldots \ \text{Eq (iii)}$$

3.2.2.7 Cycle time of operation after efficiency impact [CT_E]

The time consumed to complete single process after considering efficiency loss, it is the time after which the item is finished and ready to move for next operation in assembly line.

$$CT_E = [\ CT \ / \ E]. \ \ldots\ldots \ \text{Eq (iv)}$$

3.2.2.8 Available time & parts

Following are the calculations for production time and required parts per shift for both case studies.

Case Study 1

- 1 operation shift = 480min
- Exclude time for breaks = 30min
- 480min – 30min = 450min
- Total time available (Case Study 1) = 450 min = 27,000 sec = t_{C1}
- Total parts processed (Case Study 1) = 1905 parts = q_{C1}

Case Study 2

- 1 operation shift = 710min
- Exclude time for breaks = 60min
- 710min – 60min = 650min
- Total time available (Case Study 2) = 650 min = 39,000 sec = t_{C2}
- Total parts processed (Case Study 2) = 1000 parts = q_{C2}

3.2.2.9 Takt time calculation

TT = [t / q], From Eq (i)
TT_{C1} = [27,000 / 1905] = **14.2 sec**
TT_{C2} = [39,000 / 1000] = **39.0 sec**
Where TT is Maximum time allowed for one process to avoid bottleneck

3.2.3 Techniques for Optimization

After using the equations described in previous section 3.2.2, various operational parameters are computed. These terminologies are used to calculate the cycle times, operation times and decision variables subject to constraints as explained in the later part of this work. The following steps are applied to optimize the process of assembly line in these case studies;

1. Takt time is calculated for the system.

2. Excel table is generated using above equations to obtain required operational parameters.

3. Cycle times are compared for each process with takt time.

4. In phase one, linear programming model is generated and applied as type-I and type-II solution to improve the process of assembly line and minimize the cycle time of the bottleneck process.

5. In phase two, additional steps for further minimization of cycle time are carried out on the bottleneck process.

6. Assembly lines are optimized and bottleneck process is smoothed through MORA model and takt time implementation.

3.2.4 Research Philosophy & Quantitative Research

The practice of assembly line balancing is widely adopted across the globe in various production industries, the traditional balancing methods are mainly categorized into two main types, that is the either through the assignment of resources (type-I) or using mathematical models (type-II). Thus, the current research work focuses on two case studies [2, 3] for implementation of newly designed MORA model (Model for Optimal Resource Allocation) that can be suited to various production organizations, which carry out operations in assembly lines.

This model combines traditional balancing approaches to generate a single and efficient solution for optimal results using the units of analysis explained in the previous section. The research is based on a quantitative approach that utilizes statistical tools to compute numbers and then measures new cycle times and analyzes the results for optimal solution. The primary decision variables in this quantitative research are the number of resources allocated to the various processes operating in the assembly lines and the desired cycle times of all the processes that are entered by the user to remove idle times of the system. This work is carried out using the MORA model as a linear programming method on excel solver solution. The end goal is to get the optimal cycle times, which must be below the takt time calculated for all processes of the assembly lines.

Chapter 4

Calculations & Results

4.1 Available Parameters in Case Studies 1 and 2

Cycle times, shift duration, number of operators and all other parameters required in the formulation of MORA against case study 1 source [2] is summarized in below table 4.1.

TABLE 4.1: *Case Study 1 Parameters for MORA validation*

	Assembly Stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
S	Total Shifts	1	1	1	1	1	1	1	1	1	1	1
$\mathbf{T_{(Op)}}$	Process Time (s)	13.0	10.0	9.3	8.1	14.3	14.3	15.4	10.5	11.1	12.4	15.1
N	Total Resources	1	3	1	0	1	1	3	1	0	1	1
CT	Cycle Time (s)	6.3	5.3	3.3	12.0	12.2	14.3	7.7	8.5	10.6	13.4	11.4
TT	Takt Time (s)	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2

It is observed that the cycle time for process station number 6 (14.3 sec) is higher than the takt time (14.2 sec); thus, resulting in delay per part production for the whole shift. This is causing bottleneck in assembly operation and work in process inventory is generated at process station 6 due to its highest cycle time on assembly line. Comparison of the cycle time with the takt time has revealed the root cause of the delayed operation in this selected case study 1 source and also identified the reason for not meeting demand of 1905 parts per shift.

Similarly, cycle times, shift duration, number of operators and all other parameters required in the formulation of MORA against case study 2 source [3] is summarized in below table 4.2.

TABLE 4.2: *Case Study 2 Parameters for MORA validation*

	Assembly Stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**
S	Total Shifts	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$\mathbf{T_{(Op)}}$	Operation Time - Sec	42	92	42	40	23	36	34
N	Total Resources (1spare)	1	1	1	1	1	1	1
CT	Cycle Time (s)	42.0	46.0	42.0	40.0	23.0	36.0	34.0
TT	Takt Time (s)	39.6	39.6	39.6	39.6	39.6	39.6	39.6

It is observed that the cycle times for assembly station 1, 2 and 3 are higher than the takt time (39.6 sec); thus, resulting in delay per part production for the whole shift. This is causing bottleneck in assembly operation and work in process inventory is generated at assembly station 2 due to its highest cycle time on assembly line. Comparison of the cycle time with the takt time has revealed the root cause of the delayed operation in the selected case study 2 source and also identified the reason for not meeting demand of 1000 parts per cell.

4.2 Cycle Time vs Takt Time Visually

The cycle times available in both case studies 1 and 2 are compared with the allowed takt times of both assembly lines in order to visually examine the differences as shown in figures 4.1 and 4.2 below. The stations with cycle times above takt times are mentioned in red color and each station cycle time limit is the takt time of the assembly line shown by yellow highlighted text on both case studies graphs. This helps in visual examination before MORA implementation.

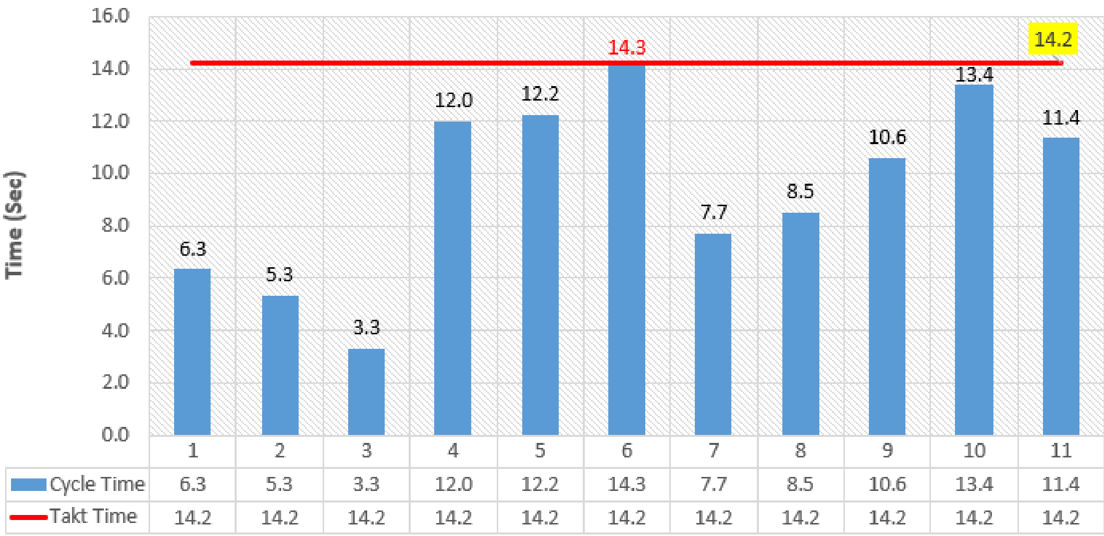

FIGURE 4.1: *Cycle Time vs Takt Time Case Study 1*

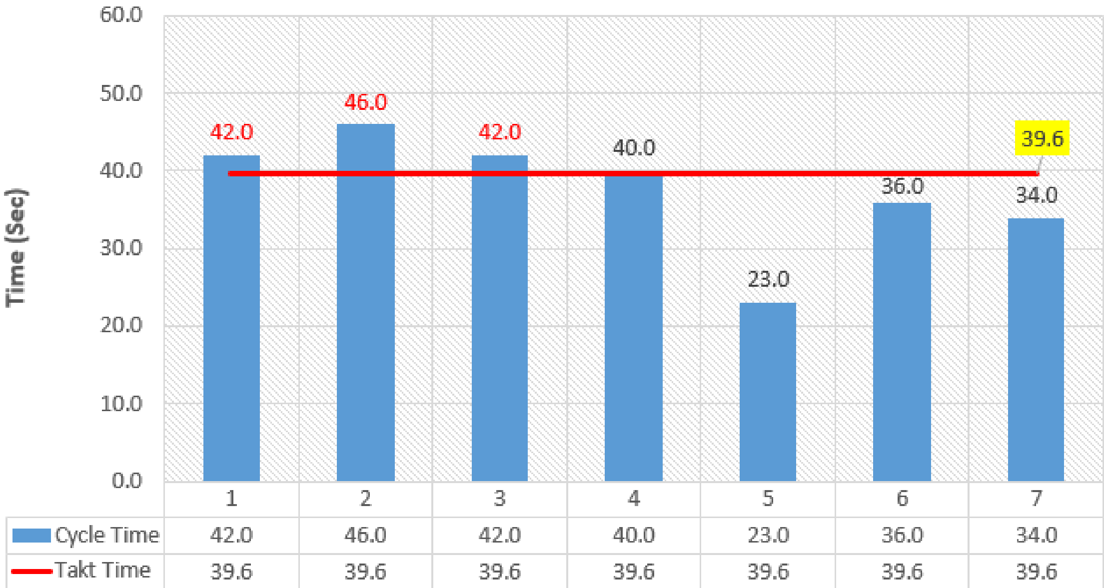

FIGURE 4.2: *Cycle Time vs Takt Time Case Study 2*

For smooth operation of the assembly lines, it is necessary to minimize the cycle times of all those processes whose values are greater then takt time of assembly line. In figure 4.1 the bottleneck process is at station number 6 and in figure 4.2 the bottleneck is in first 3 stations 1 to 3. As these processes are exceeding calculated takt times they are resulting in delayed operation as well as the work in process inventory pile up resulting in not meeting the production demand/target.

4.3 Optimization through MORA Model

It can be observed in figure 4.1 the bottleneck process is at station number 6 and in figure 4.2 the bottleneck is in first 3 stations 1 to 3. In order to minimize/eliminate these bottlenecks, MORA (Model for Optimal Resource Allocation) is implemented, which reduces the cycle times of the these mentioned stations using both type-I and type-II methods of line balancing.

4.3.1 Assignment of Resources through Mathematical Model

The MORA model involves the assignment of optimal quantity of resources to other stations of higher work load in order to balance the assembly line. From table 4.1 and 4.2, it can be observed that various resources are assigned to multiple operations. During the process, all equipments collectively work together to finish the part. In this way, the cycle time of a single process is reduced; resources from stations of lower work load are shifted to higher work load stations. This assignment is done through linear programming model designed and implemented specifically for these cases and maybe utilized in other industrial assembly lines as well. The linear model optimally assigns the ideal amount of resources to the stations of higher cycle times. Linear model decision variables, objective function, and constraints are defined below.

4.3.1.1 Decision Variables CS_1 (Case Study 1)

1^{st} DV = $\mathbf{X_i}$ = Total number of resources for process i, Where i = 1 to 11

2^{nd} DV = $\mathbf{D_i}$ = Desired cycle time for process i, Where i = 1 to 11

and "i" are the processes as mentioned below.

1) Number of resources in process MDS (Machine Dispenser Solder)

2) Number of resources in process H/M (Hand Mount)

3) Number of resources in process Clinching

4) Number of resources in process Re-flow oven

5) Number of resources in process Separator

6) Number of resources in process Cover Installation

7) Number of resources in process UV Jig (Ultra violet)

8) Number of resources in process AGC (Auto Gain Control)

9) Number of resources in process Auto Picture Test

10) Number of resources in process Picture Test

11) Number of resources in packing Packing

4.3.1.2 Decision Variables CS_2 (Case Study 2)

1^{st} DV = $\mathbf{X_i}$ = Total number of resources at assembly station i, Where i = 1 to 7
2^{nd} DV = $\mathbf{D_i}$ = Desired cycle time for assembly station i, Where i = 1 to 7
and "i" are the assembly stations 1 to 7.

The values for X_i are calculated through MORA model for optimal results and values for desired cycle times D_i are entered by user in model to ensure that there is no left-over time at any operation. In this way, the idle time will be minimized.

4.3.1.3 Objective Function CS_1 (Case Study 1)

Minimize = Z = $X_1D_1 + X_2D_2 + X_3D_3 + X_4D_4 + X_5D_5 + X_6D_6 + X_7D_7 + X_8D_8 + X_9D_9 + X_{10}D_{10} + X_{11}D_{11}$
Where Z = Total time consumed by all processes.
also Z = 1 to 11 stations

4.3.1.4 Objective Function CS_2 (Case Study 2)

Minimize = Z = $X_1D_1 + X_2D_2 + X_3D_3 + X_4D_4 + X_5D_5 + X_6D_6 + X_7D_7$
Where Z = Total time consumed by all processes on 1 to 7 stations.

4.3.1.5 Constraints CS_1 (Case Study 1)

C1 = $X_1+X_2+X_3+X_4+X_5+X_6+X_7+X_8+X_9+X_{10}+X_{11}<=13$ (Available resources)

C2 = $1X_1D_1 >= 10.0$ (Required process 1 time)

C3 = $1X_2D_2 >= 9.3$ (Required process 2 time)

C4 = $1X_3D_3 >= 8.1$ (Required process 3 time)

C5 = $1X_4D_4 >= 14.3$ (Required process 4 time)

C6 = $1X_5D_5 >= 14.3$ (Required process 5 time)

C7 = $1X_6D_6 >= 15.4$ (Required process 6 time)

C8 = $1X_7D_7 >= 10.5$ (Required process 7 time)

C9 = $1X_8D_8 >= 11.1$ (Required process 8 time)

C10 = $1X_9D_9 >= 12.4$ (Required process 9 time)

C11 = $1X_{10}D_{10} >= 15.1$ (Required process 10 time)

C12 = $1X_{11}D_{11} >= 14.0$ (Required process 11 time)

4.3.1.6 Constraints CS_2 (Case Study 2)

C1 = $X_1+X_2+X_3+X_4+X_5+X_6+X_7 <=8$ (Available resources)

C2 = $1X_1D_1 >= 42$ (Required process 1 time)

C3 = $1X_2D_2 >= 92$ (Required process 2 time)

C4 = $1X_3D_3 >= 42$ (Required process 3 time)

C5 = $1X_4D_4 >= 40$ (Required process 4 time)

C6 = $1X_5D_5 >= 23$ (Required process 5 time)

C7 = $1X_6D_6 >= 36$ (Required process 6 time)

C8 = $1X_7D_7 >= 34$ (Required process 7 time)

Now, a linear programming mathematical model (MORA) will be designed on excel solver solution using simplex linear programming (LP) method.

4.3.1.7 Linear Programming Model for Case Study 1 (Un-operated Form)

Initially a blank MORA model is presented in figure 4.3 below, horizontal parameters are total 11 installed workstations and vertical parameters show decision and desired variables, constraints, current cycle times and takt times. Left over values on extreme right must be zero after operating the model for maximum utilization of all stations. Since the 6th workstation (Covering) process has cycle time of 14.3 sec which is higher than the assembly line takt time of 14.2 sec, this process is the bottleneck station in this case study. It can be observed that the workstations 1 to 3 (Machine dispenser solder, Hand-mount station and clinching) have greater idle times along with some other stations (7 and 8), therefore, we enter higher desired cycle time values for these stations in order to allocate optimal resources against all workstations through MORA model. The linear programming mathematical model in an "empty" form is shown in figure 4.3 before operating.

MORA (Model for Optimal Resource Utilization) - Case Study 1 (CS 1)

Workstations	1	2	3	4	5	6	7	8	9	10	11	Usage (s)	Constraints	Total Req. (s)	Left Over (s)
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11				
No of Operators in each process															
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11				
Desired Cycle times per oper (Sec)												0			
Total Operators Available (No's)	1	1	1	1	1	1	1	1	1	1	1	0.0	<=	13.0	13
Process time 1	1	0	0	0	0	0	0	0	0	0	0	0.0	>=	10.0	10.0
Process time 2	0	1	0	0	0	0	0	0	0	0	0	0.0	>=	9.3	9.3
Process time 3	0	0	1	0	0	0	0	0	0	0	0	0.0	>=	8.1	8.1
Process time 4	0	0	0	1	0	0	0	0	0	0	0	0.0	>=	14.3	14.3
Process time 5	0	0	0	0	1	0	0	0	0	0	0	0.0	>=	14.3	14.3
Process time 6	0	0	0	0	0	1	0	0	0	0	0	0.0	>=	15.4	15.4
Process time 7	0	0	0	0	0	0	1	0	0	0	0	0.0	>=	10.5	10.5
Process time 8	0	0	0	0	0	0	0	1	0	0	0	0.0	>=	11.1	11.1
Process time 9	0	0	0	0	0	0	0	0	1	0	0	0.0	>=	12.4	12.4
Process time 10	0	0	0	0	0	0	0	0	0	1	0	0.0	>=	15.1	15.1
Process time 11	0	0	0	0	0	0	0	0	0	0	1	0.0	>=	14.0	14.0
Takt Time per operation (Sec)	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2				
Old Cycle Time per operation (Sec)	6.3	5.3	3.3	12.0	12.2	14.3	7.7	8.5	10.6	13.4	11.4				
Optimized Cycle Time per operation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				

FIGURE 4.3: *Empty Model Before Operation for Case Study 1*

4.3.1.8 Linear Programming Model for Case Study 1 (Operated Form)

Now the desired cycle times are entered and the excel solver solution is operated to find the optimal numbers of resources for all workstations as shown in figure 4.4 below

MORA (Model for Optimal Resource Utilization) - Case Study 1 (CS 1)															
Workstations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Usage (s)**	Constraints	**Total Req. (s)**	**Left Over (s)**
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11				
No of Operators in each process	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**1**	**1**	**2**	**1**				
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11				
Desired Cycle times per oper (Sec)	11.3	11.1	10.5	13.2	12.1	8.8	11.3	11.2	10.1	7.7	10.1	**134**			
Total Operators Available (No's)	1	1	1	1	1	1	1	1	1	1	1	13.0	<=	13.0	0
Process time 1	1	0	0	0	0	0	0	0	0	0	0	10.0	>=	10.0	0.0
Process time 2	0	1	0	0	0	0	0	0	0	0	0	9.3	>=	9.3	0.0
Process time 3	0	0	1	0	0	0	0	0	0	0	0	8.1	>=	8.1	0.0
Process time 4	0	0	0	1	0	0	0	0	0	0	0	14.3	>=	14.3	0.0
Process time 5	0	0	0	0	1	0	0	0	0	0	0	14.3	>=	14.3	0.0
Process time 6	0	0	0	0	0	1	0	0	0	0	0	15.4	>=	15.4	0.0
Process time 7	0	0	0	0	0	0	1	0	0	0	0	10.5	>=	10.5	0.0
Process time 8	0	0	0	0	0	0	0	1	0	0	0	11.1	>=	11.1	0.0
Process time 9	0	0	0	0	0	0	0	0	1	0	0	12.4	>=	12.4	0.0
Process time 10	0	0	0	0	0	0	0	0	0	1	0	15.1	>=	15.1	0.0
Process time 11	0	0	0	0	0	0	0	0	0	0	1	14.0	>=	14.0	0.0
Takt Time per operation (Sec)	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2				
Old Cycle Time per operation (Sec)	6.3	5.3	3.3	12.0	12.2	14.3	7.7	8.5	10.6	13.4	11.4				
Optimized Cycle Time per operation	**11.3**	**11.1**	**10.5**	**13.2**	**12.1**	**8.8**	**11.3**	**11.2**	**10.1**	**7.7**	**10.1**				

FIGURE 4.4: *After Operating Model (Optimal Assignment X_i Found) Case Study 1*

The figure above represents that the left-over values for all process times are now zero, which means that the processes have no idle times and the model has allotted optimal values to the variables X_i.

For the system to operate smoothly the resources must be assigned to the eleven workstations as shown in below table 4.3 below.

TABLE 4.3: *Changes in Resources Case Study 1*

Process #	**Process**	**Resources Old (N)**	**Resources New (N_{new})**	**Difference (N_{new} − N)**
1	Machine Dispenser Solder (MDS)	1	1	0
2	Hand mount station (H/M)	3	1	**-2**
3	Clinching	1	1	0
4	Reflow oven	0	1	**+1**
5	Separator	1	1	0
6	Cover Installation	1	2	**+1**
7	UV (Ultra Violet) Jig	3	1	**-2**
8	AGC (Auto Gain Control)	1	1	0
9	Auto Picture Test	0	1	**+1**
10	Picture Test	1	2	**+1**
11	Packing	1	1	0
	Total Resources	**13**	**13**	**0**

The mathematical model utilized the idle times of stations with less cycle times and optimally assigned resources from other workstations to bottleneck workstation 6 (Cover) in order to bring its new cycle time (8.8 sec) under takt time (14.3 sec). Model also ensured resource utilization does not exceed total available resources (13) on assembly line and all other left over values also remain zero for maximum utilization.

4.3.1.9 Solver Parameters (CS_1)

The solver parameters used in this model are shown in figure 4.5. The objective function is defined at cell N8 and decision variables are placed in cells C6 to M6. Similarly, the constraints are formed in cells N9 to N20 and P9 to P20. The solving solution method is chosen as simplex linear programming model instead of generalized reduced gradient (GRG) method. Results obtained are rounded to whole numbers instead of fraction decimals, since the resource assignments can be done with whole numbers only, which are approximated to the nearest significant figure.

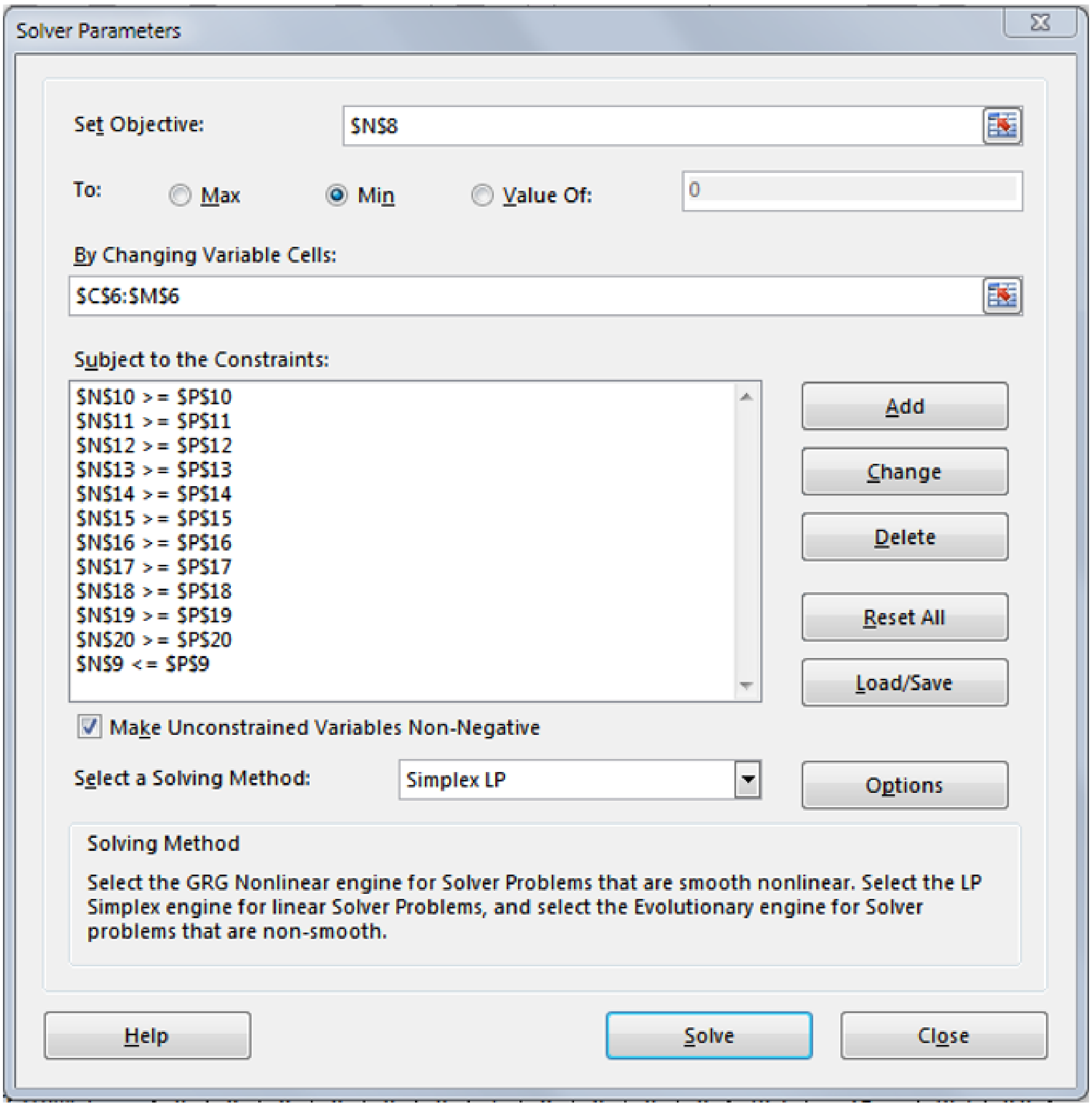

FIGURE 4.5: *Solver Parameters Used in the Model for Case Study 1*

4.3.1.10 Answer Report (CS_1)

The answer report created after operating the model is a system generated report by solver solution using the simplex linear programming model method as shown in figure 4.6 below. This is helpful in analyzing the binding values of all constraints along with the addresses of their cells and slack values for accurate readings of model as demonstrated in answer report above.

Microsoft Excel 15.0 Answer Report
Worksheet: [47. Optimization model.xlsx]Algorithim
Report Created: 27-Dec-23 11:51:31 AM
Result: Solver found a solution. All Constraints and optimality conditions are satisfied.
Solver Engine
Engine: Simplex LP
Solution Time: 0.015 Seconds.
Iterations: 11 Subproblems: 0
Solver Options
Max Time Unlimited, Iterations Unlimited, Precision 0.0001
Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$N$8	Desired Cycle times per oper (Sec) Usage (Sec)	134	134

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$C$6	No of Operators in each process X1	1	1	Contin
$D$6	No of Operators in each process X2	1	1	Contin
$E$6	No of Operators in each process X3	1	1	Contin
$F$6	No of Operators in each process X4	1	1	Contin
$G$6	No of Operators in each process X5	1	1	Contin
$H$6	No of Operators in each process X6	2	2	Contin
$I$6	No of Operators in each process X7	1	1	Contin
$J$6	No of Operators in each process X8	1	1	Contin
$K$6	No of Operators in each process X9	1	1	Contin
$L$6	No of Operators in each process X10	2	2	Contin
$M$6	No of Operators in each process X11	1	1	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$N$10	Process time 1 Usage (Sec)	10.0	$N$10>=$P$10	Binding	0.0
$N$11	Process time 2 Usage (Sec)	9.3	$N$11>=$P$11	Binding	0.0
$N$12	Process time 3 Usage (Sec)	8.1	$N$12>=$P$12	Binding	0.0
$N$13	Process time 4 Usage (Sec)	14.3	$N$13>=$P$13	Binding	0.0
$N$14	Process time 5 Usage (Sec)	14.3	$N$14>=$P$14	Binding	0.0
$N$15	Process time 6 Usage (Sec)	15.4	$N$15>=$P$15	Binding	0.0
$N$16	Process time 7 Usage (Sec)	10.5	$N$16>=$P$16	Binding	0.0
$N$17	Process time 8 Usage (Sec)	11.1	$N$17>=$P$17	Binding	0.0
$N$18	Process time 9 Usage (Sec)	12.4	$N$18>=$P$18	Binding	0.0
$N$19	Process time 10 Usage (Sec)	15.1	$N$19>=$P$19	Binding	0.0
$N$20	Process time 11 Usage (Sec)	14.0	$N$20>=$P$20	Binding	0.0
$N$9	Total Operators Available (No's) Usage (Sec)	13.0	$N$9<=$P$9	Binding	0

FIGURE 4.6: *Constraints Results and Resource Allocation Case Study 1*

The answer report depicts the feasibility of constraints defined in cells from N9 to N20 and P9 to P20. As shown in report, all the constraints are optimally linked with the formula.

The cycle times of all processes accompanied with the takt times are graphically displayed in figure 4.7. It can be noticed that the system is bottleneck free after the implementation of MORA model; however, it is at the edge of becoming bottleneck again as the station 4 reflow oven process cycle time is still close to takt time of system. This risk will be further minimized through phase-II optimization in next section so that assembly line operates at safe cycle times.

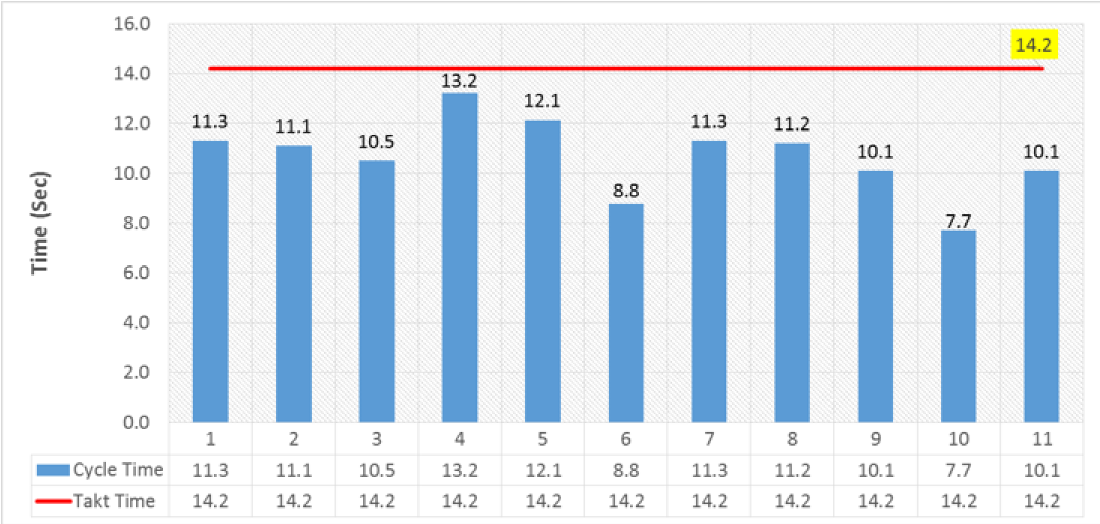

FIGURE 4.7: *First Phase Results for Case Study 1*

4.3.1.11 Linear Programming Model for Case Study 2 (Un-operated Form)

Initially a blank MORA model is presented in figure below, horizontal parameters are total 07 installed assembly workstations and vertical parameters show decision and desired variables, constraints, current cycle times and takt times. Left over values on extreme right must be zero after operating the model for maximum utilization of all stations. Assembly stations 1, 2, 3 and 4 have cycle times higher than takt time and the 2nd assembly workstation has cycle time of 46 sec which is highest, therefore, this process is the bottleneck station in this case study. It can be observed that the assembly workstations 5 to 7 have greater idle times, hence, we enter higher desired cycle time values for these stations in order to allocate optimal resources against all workstations through MORA model. The total available resources in this case study are 8 which can be seen as 0 usage when model is in empty form. min The linear programming mathematical model in an "empty" form is shown in figure 4.8 below before operation. Optimal cycle times are calculated in the last row of this model.

MORA (Model for Optimal Resource Allocation) - Case Study 2 (CS 2)											
Assembly Processes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Usage (s)**	**Constraints**	**Total Req. (s)**	**Left Over (s)**
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7				
No of Operators in each process											
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7				
Desired Cycle times per oper (Sec)								0			
Total Operators Available (No's)	1	1	1	1	1	1	1	0	<=	8	8
Process time 1	1	0	0	0	0	0	0	0	>=	42	42
Process time 2	0	1	0	0	0	0	0	0	>=	92	92
Process time 3	0	0	1	0	0	0	0	0	>=	42	42
Process time 4	0	0	0	1	0	0	0	0	>=	40	40
Process time 5	0	0	0	0	1	0	0	0	>=	23	23
Process time 6	0	0	0	0	0	1	0	0	>=	36	36
Process time 7	0	0	0	0	0	0	1	0	>=	34	34
Takt Time per operation (Sec)	39.6	39.6	39.6	39.6	39.6	39.6	39.6				
Old Cycle Time per operation (Sec)	42.0	46.0	42.0	40.0	23.0	36.0	34.0				
Optimized Cycle Time per operation	0.0	0.0	0.0	0.0	0.0	0.0	0.0				

FIGURE 4.8: *Empty Model Before Operation for Case Study 2*

4.3.1.12 Linear Programming Model for Case Study 2 (Operated Form)

Now the desired cycle times are entered and the excel solver solution is operated to find the optimal numbers of resources for all workstations as shown in figure 4.9 below. The model may perform several iterations before computing the final results, generally this process is fast.

The left-over values shown in figure below represents process times for all processes which are now zero, this means that the processes have no idle times and the model has allotted optimal values to the variables X_i in such a way that maximum utilization is carried out. Station number 2 is allotted 1 additional operator from reserve (spare) by model in order to bring station cycle time under assembly line takt time. This change in resource allocation results in removal of bottleneck from complete assembly line.

MORA (Model for Optimal Resource Allocation) - Case Study 2 (CS 2)											
Assembly Processes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Usage (s)**	**Constraints**	**Total Req. (s)**	**Left Over (s)**
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7				
No of Operators in each process	**1**	**2**	**1**	**1**	**1**	**1**	**1**				
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7				
Desired Cycle times per oper (Sec)	38.7	38.8	37.9	38.9	37.9	38.8	39.0	309			
Total Operators Available (No's)	1	1	1	1	1	1	1	8	<=	8	0
Process time 1	1	0	0	0	0	0	0	42	>=	42	0
Process time 2	0	1	0	0	0	0	0	92	>=	92	0
Process time 3	0	0	1	0	0	0	0	42	>=	42	0
Process time 4	0	0	0	1	0	0	0	40	>=	40	0
Process time 5	0	0	0	0	1	0	0	23	>=	23	0
Process time 6	0	0	0	0	0	1	0	36	>=	36	0
Process time 7	0	0	0	0	0	0	1	34	>=	34	0
Takt Time per operation (Sec)	39.6	39.6	39.6	39.6	39.6	39.6	39.6				
Old Cycle Time per operation (Sec)	42.0	46.0	42.0	40.0	23.0	36.0	34.0				
Optimized Cycle Time per operation	**38.7**	**38.8**	**37.9**	**38.9**	**37.9**	**38.8**	**39.0**				

FIGURE 4.9: *After Operating Model (Optimal Assignment X_i) Found Case Study 2*

For the system to operate smoothly the resources must be assigned to the seven assembly workstations as shown in below table 4.4.

TABLE 4.4: *Changes in Resources Case Study 2*

Process #	**Process**	**Resources Old (N)**	**Resources New (N_{new})**	**Difference (N_{new} − N)**
1	Assembly Station 1	1	1	0
2	Assembly Station 2	1	2	**+1**
3	Assembly Station 3	1	1	0
4	Assembly Station 4	1	1	0
5	Assembly Station 5	1	1	0
6	Assembly Station 6	1	1	0
7	Assembly Station 7	1	1	0
	Spare Operator	1	0	**-1**
	Total Resources	**08**	**08**	**0**

The mathematical model utilized the idle times of stations with less cycle times and optimally assigned resources to bottleneck assembly workstation 2 in order to bring its new cycle time (38.8 sec) under takt time (39.6 sec). Model also ensured resource utilization does not exceed total available resources (08) on assembly line and all other left over values also remain zero for maximum utilization.

4.3.1.13 Solver Parameters (CS_2)

The solver parameters used in this model are shown in figure 4.10 below. The objective function is defined at cell J8 and decision variables are placed in cells C6 to I6. Similarly, the constraints are formed in cells J9 to J16 and L9 to L16. The solving solution method is chosen as simplex linear programming model and results obtained are rounded to whole numbers instead of fraction decimals.

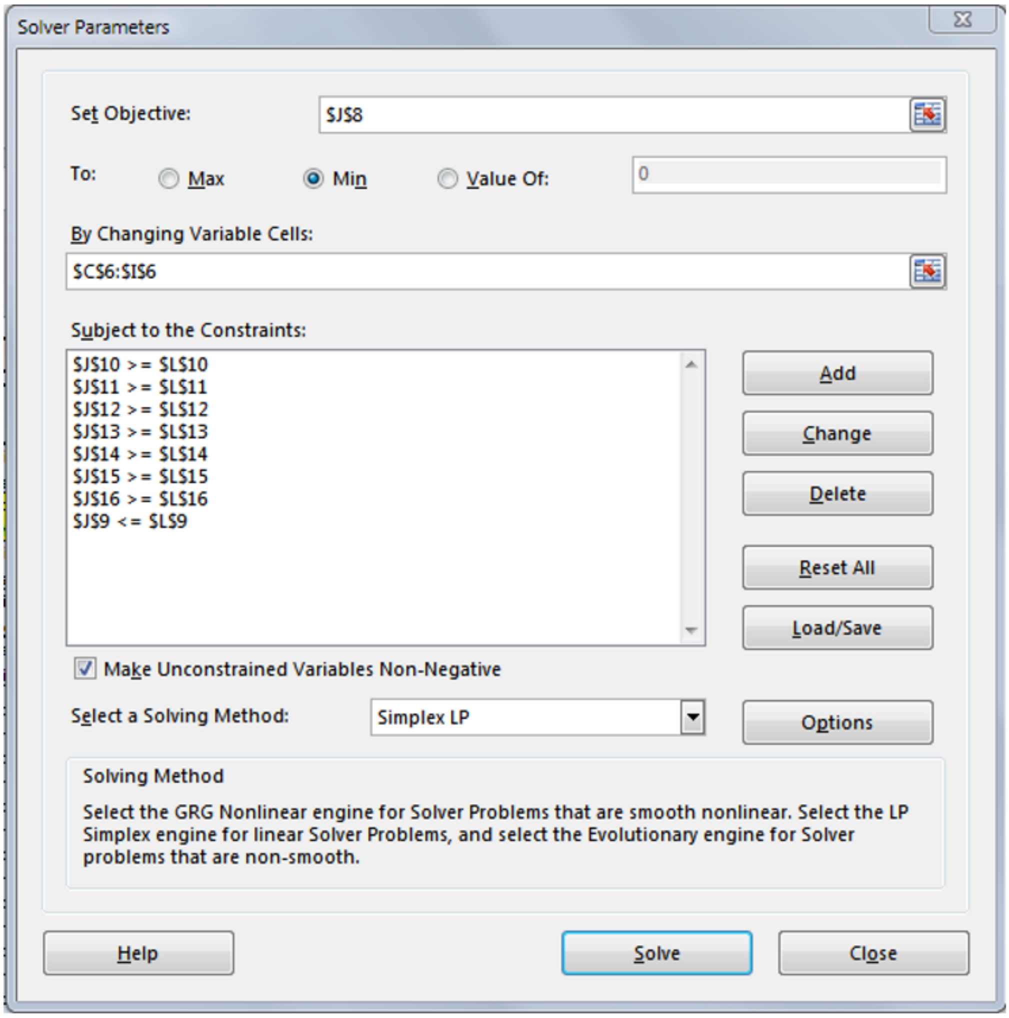

FIGURE 4.10: *Solver Parameters Used in the Model for Case Study 2*

4.3.1.14 Answer Report (CS_2)

The answer report created after operating the model is a system generated report by solver solution using the simplex linear programming model method as shown in figure 4.11 below.

Microsoft Excel 15.0 Answer Report
Worksheet: [42. Optimization model.xlsx]Algorithim
Report Created: 27-Dec-23 12:36:59 PM
Result: Solver found a solution. All Constraints and optimality conditions are satisfied.
Solver Engine
Engine: Simplex LP
Solution Time: 0.015 Seconds.
Iterations: 7 Subproblems: 0
Solver Options
Max Time Unlimited, Iterations Unlimited, Precision 0.00001
Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$J$8	Desired Cycle times per oper (Sec) Usage (s)	309	309

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$C$6	No of Operators in each process X1	1	1	Contin
$D$6	No of Operators in each process X2	2	2	Contin
$E$6	No of Operators in each process X3	1	1	Contin
$F$6	No of Operators in each process X4	1	1	Contin
$G$6	No of Operators in each process X5	1	1	Contin
$H$6	No of Operators in each process X6	1	1	Contin
$I$6	No of Operators in each process X7	1	1	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$J$10	Process time 1 Usage (s)	42	$J$10>=$L$10	Binding	0
$J$11	Process time 2 Usage (s)	92	$J$11>=$L$11	Binding	0
$J$12	Process time 3 Usage (s)	42	$J$12>=$L$12	Binding	0
$J$13	Process time 4 Usage (s)	40	$J$13>=$L$13	Binding	0
$J$14	Process time 5 Usage (s)	23	$J$14>=$L$14	Binding	0
$J$15	Process time 6 Usage (s)	36	$J$15>=$L$15	Binding	0
$J$16	Process time 7 Usage (s)	34	$J$16>=$L$16	Binding	0
$J$9	Total Operators Available (No's) Usage (s)	8	$J$9<=$L$9	Binding	0

FIGURE 4.11: *Constraints Results and Resource Allocation Case Study 2*

The answer report depicts the feasibility of constraints defined in cells from J9 to J16 and L9 to L16. As shown in report, all the constraints are binding in model and optimally linked with the formula. Thus, optimal results are achieved.

The cycle times of all processes accompanied with the takt times are graphically displayed in figure 4.12 below. It can be noticed that the system is bottleneck free after the implementation of MORA model; however, it is at the edge of becoming bottleneck again as the station 7 cycle time is still close to takt time of system. This risk will be further minimized through phase-II optimization in next section so that assembly line operates at safe cycle times.

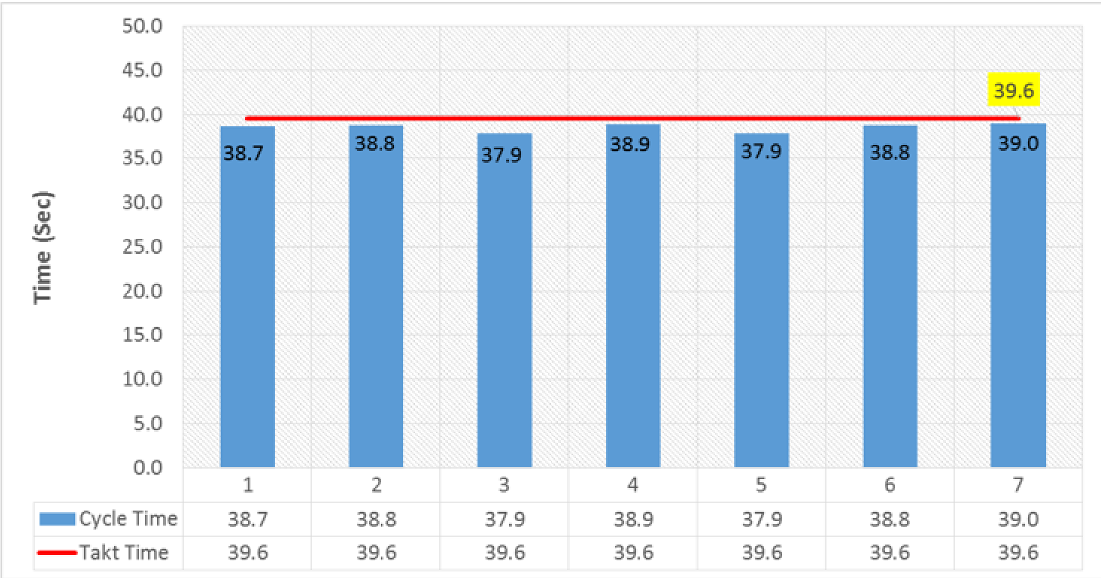

FIGURE 4.12: *First Phase Results Case Study 2*

4.3.2 Additional Steps for Cycle Time Reduction

During first phase, the resources are allotted in an optimal manner by using linear programming mathematical model on a solver solution, which significantly reduced the cycle times of the bottleneck workstations and brought it under the takt time of the assembly lines. These new cycle times are close to takt time and may result in another bottleneck in the assembly line. Therefore, non-statistical techniques are applied in phase two optimization in order to further reduce the cycle times of the workstations that have minimal idle times for maintaining the smooth and safe operation of the assembly lines in both case studies. These steps are carried out in three stages and their impacts are found from available literature.

Following improvement steps are carried out to reduce the workstations cycle times.

4.3.2.1 Step – 1: Addition of safety stocks – (1.3 % Impact)

The 4th workstation in case study 1 and 7th workstation in case study 2 hold the highest cycle times that are within takt time. Work in process inventory (WIP) can be generated at these stations due to high cycle times, one of the reasons for these high cycle times is the unavailability of production material on stations. The assembly station waits for production material to reach these stations and adds to total idle time of setup. To overcome this issue, addition of safety stock should be provided to reduce actual process times measured for operation. The measured time saved from this buffer storage activity is approximately 1.3% which is derived from the literature research. [60]

4.3.2.2 Step – 2: Consideration of workforce skill – (1.2 % Impact)

The key performance indicators (KPI's) must be defined for all operators working in shifts for both case studies. Once their benchmarking is done, highly skilled personnel can be chosen from low cycle time workstations and shifted to workstations having higher cycle times. The measured time saved from this skill utilization action is approximately 1.2% as communicated in literature study. [4]

4.3.2.3 Step – 3: Waste management – (1.8 % Impact)

Workstations with higher cycle times generally generate maximum amount and type of waste as leftover once the material moves for dispatching. To minimize this waste, lean management technique of 5S can be applied in the following sequence.

1. Sort
2. Set in order
3. Shine

4. Standardize

5. Sustain

FIGURE 4.13: *Lean Management Technique of 5S*

Non-value added (NVA) activities are identified through monitoring of various tasks in live sessions. Some activities like end product inspection are converted into sub-parts inspection to save time for final inspection. Other identified NVA's are obtaining approvals of processes, frequencies of machine's oil changing, greasing activities and production reports generation frequencies. These activities can be over performing tasks and minimized to only need base when required. The 5S implementation and NVA's elimination results in 1.8% reduction in cycle time as derived from literature study. [42].

4.3.2.4 New Cycle Times from Phase Two Activities in Case Study 1 and 2

Calculation for new cycle times for both case studies is now carried out to further reduce idle times in operation as shown in tables 4.5 and 4.6.

TABLE 4.5: *Phase-II Activities Saved Time in Case Study 1*

Case Study 1 - Workstation 4	Step–1	Step–2	Step–3
Cycle Time after Phase-I (s)	13.2	13.2	13.2
Percentage Impact (%)	1.30	1.20	1.80
Saved Time (s)	0.17	0.15	0.23

- Total time saved = 0.17 + 0.15 + 0.23 = 0.5 sec
- New cycle time for workstation 4 in CS_1 = 13.2 – 0.5 = 12.6 sec
- CT_{New} for CS_1 (station 4) = **12.6 sec**

TABLE 4.6: *Phase-II Activities Saved Time in Case Study 2*

Case Study 2 - Workstation 7	Step–1	Step–2	Step–3
Cycle Time after Phase-I (s)	39.0	39.0	39.0
Percentage Impact (%)	1.30	1.20	1.80
Saved Time (s)	0.50	0.46	0.70

- Total time saved = 0.50 + 0.46 + 0.70 = 1.6 sec
- New cycle time for workstation 7 in CS_2 = 39.0 – 1.6 = 37.4 sec
- CT_{New} for CS_2 (station 7) = **37.4 sec**

4.3.3 Elimination of Bottleneck in Case Study 1 and 2

The phase-I MORA model solution eliminated the bottlenecks in both case studies as shown in figure 4.7 and 4.12 after which the station with highest cycle time is identified in both case studies and non-statistical minimization methods are applied on respective stations. For case study 1, station number 4 now hold the highest cycle time (12.6 sec) and thus it has become the pace of assembly of line. At this pace assembly line output is expected to increase as calculated below.

- Shift time = 27,000 sec
- Assembly line pace = 12.6 sec / product
- Shift Output = 27,000 / 12.6 = **2142 Units** (Old Output 1888 Units)

MORA model implementation improved **output by 254 units /shift** that is **13.5% production increase** and bottleneck elimination in case study 1.

Similarly, for case study 2, station number 4 now hold the highest cycle time (38.9 sec) and thus it has become the pace of assembly of line. At this pace assembly line output is expected to increase as calculated below.

- Shift time = 39,600 sec
- Assembly line pace = 38.9 sec / product
- Shift Output = 39,600 / 38.9 = **1018 Units** (Old Output 860 Units)

MORA model implementation improved **output by 158 units /shift** that is **18.4% production increase** and bottleneck elimination in case study 2.

Now table 4.1 and 4.2 are updated with newer cycle time values after optimization in two phases for both case studies as shown in table 4.7 and 4.8 below.

TABLE 4.7: *Removal of Bottleneck in Case Study 1*

Assembly Stations		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
$\mathbf{N_{Old}}$	Resources (Old)	1	3	1	0	1	1	3	1	0	1	1
$\mathbf{N_{New}}$	Optimal Allocation	1	1	1	1	1	2	1	1	1	2	1
$\mathbf{CT_{Old}}$	Cycle Times (Old) sec	6.3	5.3	3.3	12.0	12.2	14.3	7.7	8.5	10.6	13.4	11.4
$\mathbf{CT_{New}}$	Cycle Times (New) sec	11.3	11.1	10.5	12.6	12.1	8.8	11.3	11.2	10.1	7.7	10.1
TT	Takt Time sec	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2

Similarly, for case study 2, the new parameters calculated after phase-I and phase-II optimization from MORA (Model for Optimal Resource Allocation) model are shown in table 4.8 below.

TABLE 4.8: *Removal of Bottleneck in Case Study 2*

	Assembly Stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**
$\mathbf{N_{Old}}$	Total Resources (Old) 1spare	1	1	1	1	1	1	1
$\mathbf{N_{New}}$	Optimal Allocation	1	2	1	1	1	1	1
$\mathbf{CT_{Old}}$	Cycle Times (Old) sec	42.0	46.0	42.0	40.0	23.0	30.0	34.0
$\mathbf{CT_{New}}$	Cycle Times (New) sec	38.7	38.8	37.9	38.9	37.9	38.8	37.4
TT	Takt Time sec	39.6	39.6	39.6	39.6	39.6	39.6	39.6

It can be observed that all cycle times are within takt time of both assembly lines, therefore, MORA model implementation in two phases resulted in optimal allocation of resources.

In phase one, the optimization through MORA model using linear programming mathematical model is carried out that optimally assigned resources to specific processes with high loads. Similarly, during phase two; the steps for cycle time reduction are suggested for further decrement of cycle times of bottleneck stations in both assembly lines. The difference is better understood through summarized comparison figures 4.14 and 4.15 provided below.

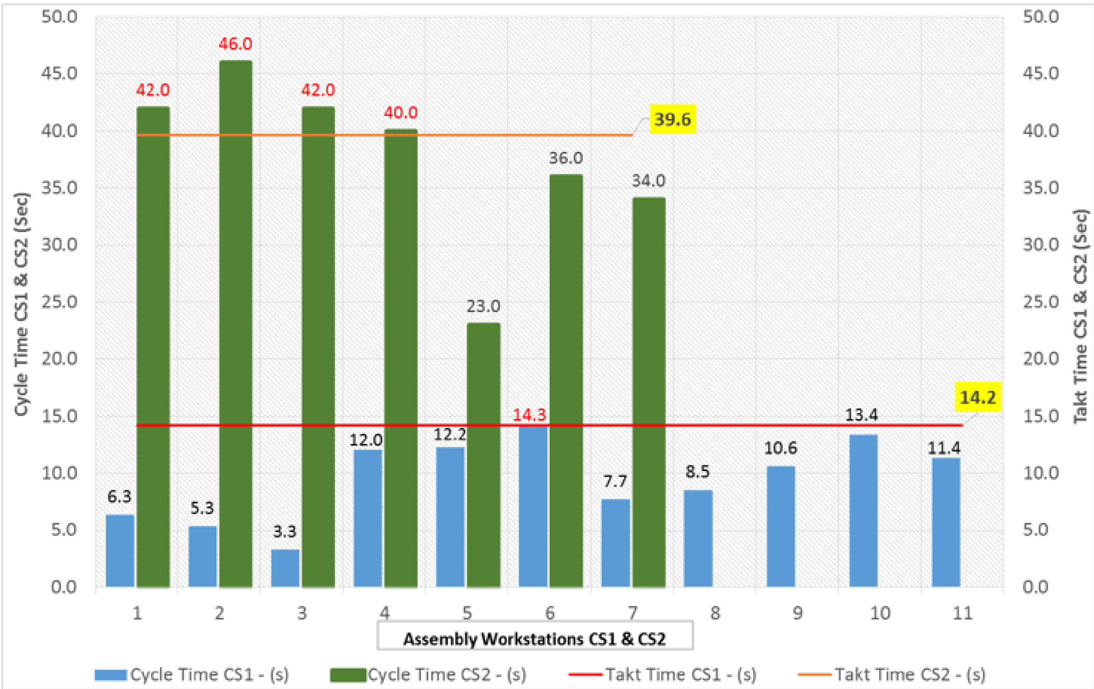

FIGURE 4.14: *Before Implementation of MORA Model in Both Case Studies*

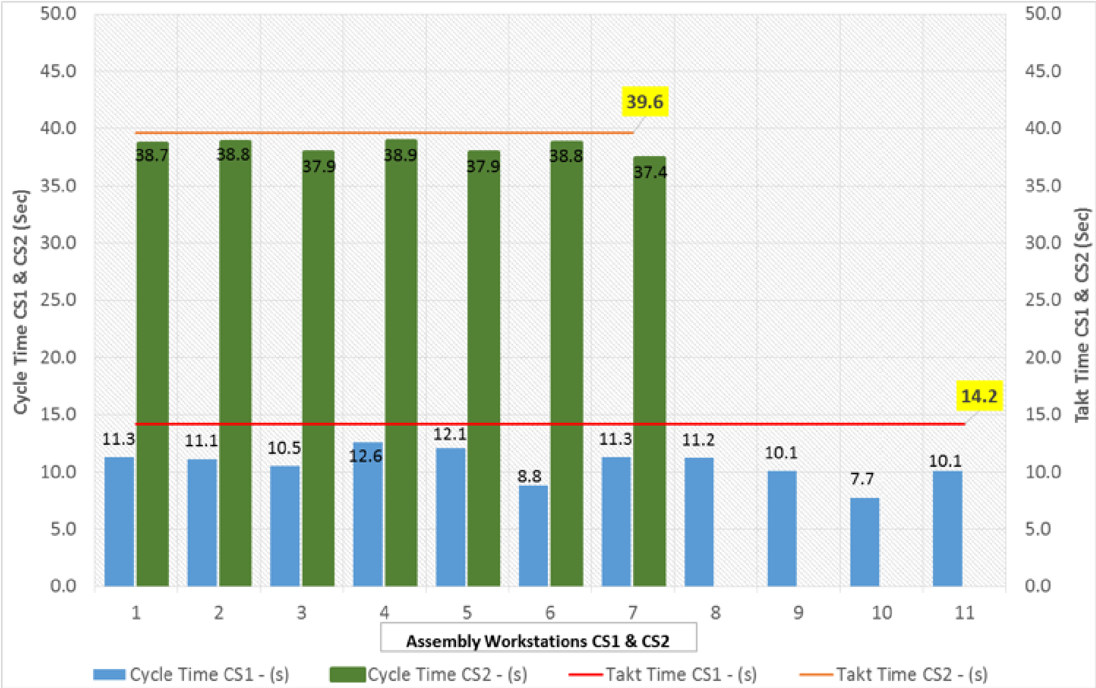

FIGURE 4.15: *After Implementation of MORA Model in Both Case Studies*

4.4 Validation of MORA Model for Case Study 1 and 2

In order to test the validity of MORA (Model for Optimal Resource Allocation) model results, random high and low values are entered in different workstations for both case studies and results are analyzed. Ideally on high random values the model should spare available resources as sufficient time is available for operation. Similarly, for low random values ideally the model should assign maximum available resources to that specific station.

4.4.1 High Desired Values in Case Study 1

The desired cycle times for random stations (6 and 10) are doubled and excel solver solution is operated to validate the behavior of model, since the desired values are very high from processes takt times, the model utilizes only **11 out of 13** available resources and spares 1 operator from both stations as shown in highlighted boxes in figure 4.16 below.

MORA (Model for Optimal Resource Utilization) - Case Study 1 (CS 1)

Workstations	1	2	3	4	5	6	7	8	9	10	11	Usage (s)	Constraints	Total Req. (s)	Left Over (s)
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11				
No of Operators in each process	1	1	1	1	1	1	1	1	1	1	1				
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11				
Desired Cycle times per oper (Sec)	11.3	11.1	10.5	13.2	12.1	20.0	11.3	11.2	10.1	20.0	10.1	134			
Total Operators Available (No's)	1	1	1	1	1	1	1	1	1	1	1	10.8	<=	13.0	2
Process time 1	1	0	0	0	0	0	0	0	0	0	0	10.0	>=	10.0	0.0
Process time 2	0	1	0	0	0	0	0	0	0	0	0	9.3	>=	9.3	0.0
Process time 3	0	0	1	0	0	0	0	0	0	0	0	8.1	>=	8.1	0.0
Process time 4	0	0	0	1	0	0	0	0	0	0	0	14.3	>=	14.3	0.0
Process time 5	0	0	0	0	1	0	0	0	0	0	0	14.3	>=	14.3	0.0
Process time 6	0	0	0	0	0	1	0	0	0	0	0	15.4	>=	15.4	0.0
Process time 7	0	0	0	0	0	0	1	0	0	0	0	10.5	>=	10.5	0.0
Process time 8	0	0	0	0	0	0	0	1	0	0	0	11.1	>=	11.1	0.0
Process time 9	0	0	0	0	0	0	0	0	1	0	0	12.4	>=	12.4	0.0
Process time 10	0	0	0	0	0	0	0	0	0	1	0	15.1	>=	15.1	0.0
Process time 11	0	0	0	0	0	0	0	0	0	0	1	14.0	>=	14.0	0.0
Takt Time per operation (Sec)	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2				
Old Cycle Time per operation (Sec)	6.3	5.3	3.3	12.0	12.2	14.3	7.7	8.5	10.6	13.4	11.4				
Optimized Cycle Time per operation	11.3	11.1	10.5	13.2	12.1	20.0	11.3	11.2	10.1	20.0	10.1				

FIGURE 4.16: *High Desired Values Validation Case Study 1*

4.4.2 Low Desired Values in Case Study 1

The desired cycle times for random stations (9 to 11) are now lowered to validate the behavior of model, since it is impossible to perform all these processes in such low cycle times, the model assigned **maximum resources to 9th station** and dropped 80% operation of 10th station. The 11th station operation could not be initiated at all, also, the utilization of resources remained 100% that is 13/13 as shown in figure 4.17 below.

MORA (Model for Optimal Resource Utilization) - Case Study 1 (CS 1)															
Workstations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Usage (s)**	**Constraints**	**Total Req. (s)**	**Left Over (s)**
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11				
No of Operators in each process	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**4**	**1**	**0**				
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11				
Desired Cycle times per oper (Sec)	11.3	11.1	10.5	13.2	12.1	12.5	11.3	11.2	**3.0**	**3.0**	**3.0**	**108**			
Total Operators Available (No's)	1	1	1	1	1	1	1	1	1	1	1	13.0	<=	13.0	0
Process time 1	1	0	0	0	0	0	0	0	0	0	0	10.0	>=	10.0	0.0
Process time 2	0	1	0	0	0	0	0	0	0	0	0	9.3	>=	9.3	0.0
Process time 3	0	0	1	0	0	0	0	0	0	0	0	8.1	>=	8.1	0.0
Process time 4	0	0	0	1	0	0	0	0	0	0	0	14.3	>=	14.3	0.0
Process time 5	0	0	0	0	1	0	0	0	0	0	0	14.3	>=	14.3	0.0
Process time 6	0	0	0	0	0	1	0	0	0	0	0	15.4	>=	15.4	0.0
Process time 7	0	0	0	0	0	0	1	0	0	0	0	10.5	>=	10.5	0.0
Process time 8	0	0	0	0	0	0	0	1	0	0	0	11.1	>=	11.1	0.0
Process time 9	0	0	0	0	0	0	0	0	1	0	0	12.4	>=	12.4	0.0
Process time 10	0	0	0	0	0	0	0	0	0	1	0	2.9	>=	15.1	**12.2**
Process time 11	0	0	0	0	0	0	0	0	0	0	1	0.0	>=	14.0	**14.0**
Takt Time per operation (Sec)	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2				
Old Cycle Time per operation (Sec)	6.3	5.3	3.3	12.0	12.2	14.3	7.7	8.5	10.6	13.4	11.4				
Optimized Cycle Time per operation	**11.3**	**11.1**	**10.5**	**13.2**	**12.1**	**12.5**	**11.3**	**11.2**	**3.0**	**3.0**	**3.0**				

FIGURE 4.17: *Low Desired Values Validation Case Study 1*

4.4.3 High Desired Values in Case Study 2

The desired cycle time for random station (2nd) is doubled to validate the behavior of model, since the desired value is very high from process takt time, the model utilizes only **7 out of 8** available resources and spares 1 operator from 2nd station as shown in highlighted boxes in figure 4.18 below.

MORA (Model for Optimal Resource Allocation) - Case Study 2 (CS 2)											
Assembly Processes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Usage (s)**	**Constraints**	**Total Req. (s)**	**Left Over (s)**
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7				
No of Operators in each process	**1**	**1**	**1**	**1**	**1**	**1**	**1**				
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7				
Desired Cycle times per oper (Sec)	38.7	80.0	37.9	38.9	37.9	38.8	39.0	**309**			
Total Operators Available (No's)	1	1	1	1	1	1	1	7	<=	8	1
Process time 1	1	0	0	0	0	0	0	42	>=	42	0
Process time 2	0	1	0	0	0	0	0	92	>=	92	0
Process time 3	0	0	1	0	0	0	0	42	>=	42	0
Process time 4	0	0	0	1	0	0	0	40	>=	40	0
Process time 5	0	0	0	0	1	0	0	23	>=	23	0
Process time 6	0	0	0	0	0	1	0	36	>=	36	0
Process time 7	0	0	0	0	0	0	1	34	>=	34	0
Takt Time per operation (Sec)	39.6	39.6	39.6	39.6	39.6	39.6	39.6				
Old Cycle Time per operation (Sec)	42.0	46.0	42.0	40.0	23.0	36.0	34.0				
Optimized Cycle Time per operation	**38.7**	**80.0**	**37.9**	**38.9**	**37.9**	**38.8**	**39.0**				

FIGURE 4.18: *High Desired Values Validation Case Study 2*

4.4.4 Low Desired Values in Case Study 2

In order to validate the MORA (Model for Optimal Resource Allocation) model on low cycle times, the desired cycle times for random stations (6 and 7) are now lowered and excel solver solution is operated to validate the behavior of model, since it is impossible to perform both processes in such low cycle times, the model assigned **maximum resources to 6th station** and the zero resources to the last station as its priority is to carry out the preceding operation first. The 7th station operation could not be initiated at all due to less available resources overall, also, the utilization of resources remained 100% that is 8 out of 8 available resources consumed as shown in figure 4.19 below.

MORA (Model for Optimal Resource Allocation) - Case Study 2 (CS 2)

Assembly Processes	1	2	3	4	5	6	7	Usage (s)	Constraints	Total Req. (s)	Left Over (s)
Decision Variables (Operators / Eqp)	X1	X2	X3	X4	X5	X6	X7				
No of Operators in each process	**1**	**1**	**1**	**1**	**1**	**3**	**0**				
Decision Variables (Desired Cycle Time)	D1	D2	D3	D4	D5	D6	D7				
Desired Cycle times per oper (Sec)	38.7	65.0	37.9	38.9	37.9	13.0	13.0	**275**			
Total Operators Available (No's)	1	1	1	1	1	1	1	8	<=	8	0
Process time 1	1	0	0	0	0	0	0	42	>=	42	0
Process time 2	0	1	0	0	0	0	0	92	>=	92	0
Process time 3	0	0	1	0	0	0	0	42	>=	42	0
Process time 4	0	0	0	1	0	0	0	40	>=	40	0
Process time 5	0	0	0	0	1	0	0	23	>=	23	0
Process time 6	0	0	0	0	0	1	0	36	>=	36	0
Process time 7	0	0	0	0	0	0	1	0	>=	34	34
Takt Time per operation (Sec)	39.6	39.6	39.6	39.6	39.6	39.6	39.6				
Old Cycle Time per operation (Sec)	42.0	46.0	42.0	40.0	23.0	36.0	34.0				
Optimized Cycle Time per operation	**38.7**	**65.0**	**37.9**	**38.9**	**37.9**	**13.0**	**13.0**				

Figure 4.19: *Low Desired Values Validation Case Study 2*

Chapter 5

Discussion and Conclusions

5.1 Research Discussion

The last section of this research includes the detailed discussion of the relationships among decision variables of subject case study, their calculations, results, analysis and significance for adoption in assembly line processes. Discussion is also carried out on practical implementations, theoretical implications, strengths and limitations of the study along with recommendations for the future work.

5.1.1 Practical & Theoretical Implications

This study serves to improve the unbalanced assembly line operations in the production industries. The MORA (Model for Optimal Resource Allocation) model based on mathematical function using linear programming model can optimally decide number of resources to be deployed to achieve desired cycle times of processing stations. It can aid in balancing of bottleneck processes during assembly line operations theoretically as well as practically. This model is formulated by combining typical balancing (type-I and type-II) approaches based on the literature and designed as a new model for optimal allocation of resources in assembly line operations.

5.1.2 Strengths of Research Outcome

This research work aims to provide the following derived benefits for assembly operations:

1. Continuous and smooth flow of operation by elimination of bottlenecks in high load stations.

2. The idle times are reduced for high load workstations.

3. Utilization of each equipment at maximum possible efficiency to achieve best results.

4. Reduced processing times of workstations.

5. Increased output in same amount of time resulting in higher production rate.

6. Minimization of waste and less scrap generation.

7. Safety enhancement of operations as there would be less work in process inventory, tripping and fire hazard would be minimized.

5.2 Conclusions

The calculation of takt time and cycle times of all processes indicates the bottleneck operation, which is the station 2 process in case study 1 and station 6 process in case study 2. In order to eliminate the identified bottlenecks in these case studies, a newly designed MORA model (Model for Optimal Resource Allocation) is applied on these assembly lines; this model optimally assigned resources and improved the operation's efficiency by reducing the cycle time of the bottleneck processes in both case studies. The new cycle times are within the calculated takt time and represents a continuous and streamline flow of the production lines. Thus, the model proved to be a significant method in this research work for optimizing the production flow and eliminating the bottleneck in the assembly lines of both case studies. Following table 5.1 summarizes the results of the subject case studies before and after the implementation of MORA model.

TABLE 5.1: *Summary of Results for Case Study 1 and 2*

Parameters for CS_1 & CS_2	**Case Study 1 (CS_1) Before & After MORA Optimization**			**Case Study 2 (CS_2) Before & After MORA Optimization**		
	Before	After	**Diff**	Before	After	**Diff**
Highest Cycle Time (s)	46.0	38.9	**-7.1 sec**	14.3	12.6	**-1.7 sec**
Production in Shift (Units)	1888	2142	**254 units**	860	1018	**158 units**
Improvement (%)	-	-	**13.5 %**	-	-	**18.4 %**

5.3 Limitations of Research

The research work is not applicable to all manufacturing or production industries, it specifically covers the production setups where assembly operations are being performed, but this is not a major concern as most of the manufacturing facilities in current times occupy an assembly line setup for finishing their production. Another limitation is the data values in both case studies that are based on a electrical items processing industries with high parts production per day, if the assembly setup is based on low number of output parts like vehicles assembly plants, the model may not suit very well as the cycle times maybe very large and different from each operation. The actual purpose of the study is to design a model for optimal assignment of resources and minimization of cycle time which is carried out significantly well as desired.

5.4 Future Recommendations

The future research can focus on making this model further applicable for production industries with less volume and high cycle time production processes. The model can be upgraded to provide desired cycle times through some systematic approach instead of users desired values that can further result in optimal assignment of resources. The cost of production when allocating resources and eliminating bottleneck through minimization of the cycle times can also be incorporated into this model in order to further optimize the assembly line operations.

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