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# Improvement of Assembly Line Efficiency by Using Lean Manufacturing Tools and Line Balancing Techniques

Anass Mortada[1*], Aziz Soulhi[2]

[1] Mohammedia School of Engineers, University Mohammed V-Agdal, Av. Ibn Sina, Rabat, Morocco
[2] Higher National School of Mines, Rabat, Morocco
* Corresponding author's e-mail: anass.mortada@gmail.com

## ABSTRACT

This paper presents a solid methodology for improving the efficiency and productivity of assembly lines using Lean Manufacturing tools, in particular the Define, Measure, Analyze, Improve, and Control approach (DMAIC) and line balancing techniques, followed by a concrete application in a case study of a wiring industry assembly line. The first phase of the approach ensured a clear definition of the problem using the who, what, where, when, why, and how tool (5W1H) and a description of the manufacturing process. The measurement phase allowed the calculation of the Takt time (TT) and the timing of the cycle times of the 17 stations of the line with the use of data collected on the standardized work combination table (SWCT) documents. This facilitated the analysis phase by first establishing a Yamazumi chart showing the distribution of the load between the line's stations and allowing the identification of bottleneck stations, and then analyzing the situation through the 5-Why tools and the Ishikawa diagram. Thanks to the innovation phase and the ideal balancing conditions developed in this paper, it was possible to balance the line's stations using an action plan whose effectiveness was monitored during the control phase, improving efficiency from 78% to 95% with a saving in manpower by reducing the number of operators from 17 to 14.

**Keywords:** efficiency, line balancing, lean manufacturing, DMAIC, standardized work, Yamazumi chart.

## INTRODUCTION

The industrial sector is currently experiencing great competition, which is pushing companies to improve their performance indicators and make better use of their resources [1]. Efficiency is one of the indicators that needs to be focused on, which is directly linked to the automotive industry's strategy to improve productivity with minimum resources [2], especially in the automotive wiring industry. An assembly line is where the semi-finished product is transferred from one station to the other, where components are added by the operators in a sequence [3]. In order to maximize productivity on the assembly line, several Lean Manufacturing tools are recommended, in particular the DMAIC approach and workstation balancing techniques, which are mainly aimed at reducing cycle times and balancing the workstation load [4].

Cycle time is defined as the time required to complete a process at one station, meaning the time from the start of processing by the operator or machine until the product is ready to move to the next station [4]. In order to satisfy the customer's demand in terms of quantity and delivery time, it is necessary that the cycle time of the assembly line, which is determined by the workstation with the highest cycle time [5], also named the bottleneck, be the busiest station on the line [6], be less than the Takt time, which is the production rate imposed by the customer [4]. The objective of line balancing is to reduce waiting and idle times on the production line [1]. This requires the balanced distribution of tasks between operators. The process of each workstation can be clearly described using the standardized work combination table documents, and the workload of the workstations can be visually compared using the Yamazumi chart or operator balance chart [7], which is a bar chart where the cycle times of the line stations are represented as a histogram and compared to the Takt time represented by a horizontal axis on the time axis [4]. The Yamazumi diagram should be made both in the initial state and also after the improvements have been implemented, and the measurement of improvement is done by comparing the efficiency values of the two states [4].

However, the organization and design of manufacturing processes are often complex due to the interaction of many factors that can significantly influence the decisions that need to be made [8].

Indeed, companies often find it difficult to balance the load ideally between workstations, which limits their ability to achieve maximum assembly line efficiency due to the lack of methodologies for accurately calculating the optimum values of the parameters related to the line's operating mode.

The goal of this paper is to define a method that consists of the use of these lean tools in addition to developing five conditions for ideal line balancing, the respect of which, accurately and in the right order, makes it possible to calculate the minimum number of resources necessary to ensure both customer satisfaction and maximum efficiency by ensuring the elimination of waste and line balancing. This article also presents an application of the proposed methodology in a case study of a wiring assembly line, demonstrating the effectiveness of the approach and its role in improving efficiency.

## BACKGROUND

Many researchers have introduced methodologies aimed at improving the efficiency of production lines by acting on the balancing of workstations, based mainly on line balancing techniques.

Emrul Kays et al. (2019) proposed a 3-step method: the elaboration of the current state map, then the creation of the Yamazumi chart for the balancing of the workstations, and finally the creation of the future state map [9].

Nguyen Thi Lam et al. (2016) proposed an approach based on: drawing up a line balancing diagram to identify bottlenecks and prioritizing them in the analyses using tools such as the Ishikawa diagram; identifying value-added and non-value-added operations; collecting information and comments from operators; and finally determining actions to improve and reduce waste [10].

Dzulkarnain and Rahaman (2017) have defined a method based on time study to detect the idle time of each workstation through the Yamazumi diagram, then a calculation of Takt time allows to calculate the minimum number of workstations needed before balancing the line, and then a calculation of the new efficiency value [11]:

Balaji Rathod et al. (2016) have adopted a methodology starting with the definition of the problem by calculating the Takt time and the current cycle times, then a study of the movements in order to optimize the cycle times by reducing the non-value added operations, then the creation

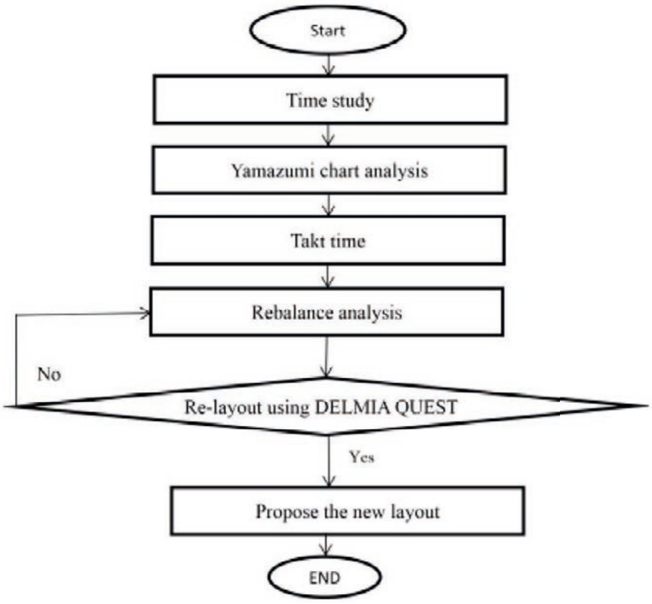


**Fig. 1.** Efficiency improvement method [11]

**Fig. 2.** Line balancing methodology [12]

of the Yamazumi chart, before moving on to the line balancing stage, which can be repeated if the expected results are not obtained until the ideal balancing state is reached in order to implement and standardize it [12].

Hasta and Harwati (2019) proposed the following steps to improve productivity: calculation of the current value of efficiency; identification and reduction of non-value-added work; reallocation of tasks; then reduction of manpower; and finally calculation of the new value of line efficiency and comparison with the initial state [6].

All these methodologies include steps to reduce waste and non-value-added operations and to distribute tasks in a more balanced way, bringing cycle times into line with Takt time. However, they do not provide a clear approach to line balancing, which means that the distribution of the load between workstations is carried out in the form of trials with the possibility of rebalancing in the case of errors, resulting in a loss of time and effort with each balancing attempt.

On the other hand, these methodologies do not take into account the variability of cycle times due to human factors or machine perturbations, which generate risks related to exceeding the Takt time and thus not satisfying the customer's demand.

## MATERIALS AND METHODS

Many previous studies of the improvement of industrial indicators have been based on Lean manufacturing tools. Lean management, derived from the Toyota production system, is now one of the most dominant management philosophies in both the industrial and service sectors [13]. Lean is a culture whose aim is to identify and eliminate waste using a number of tools and techniques [14]. Each of the lean production tools is designed to support the organization in eliminating manufacturing waste and meeting production improvement targets [15]. Implementing lean manufacturing in different types of organizations and processes can bring considerable financial gains through the reduction of waste and thus a major improvement in operational efficiency [16], by minimizing the resources required in the production process [17]. There are generally eight types of waste: overproduction, transport, waiting times, defects, overprocessing, excess inventory, unnecessary movements, and the non-use of employees' skills [18].

The most common Lean approaches include the DMAIC approach (Define, Measure, Analyze, Improve, and Control), which is a structured

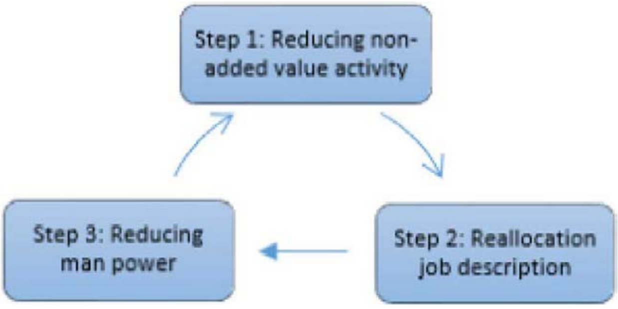


**Fig. 3.** Cycle of man powers' reduction [6]

approach to continuous improvement and problem solving that consists of five basic phases [19], this approach has been reinforced in the improvement phase by conditions developed to ensure ideal balancing of the assembly lines:

## Define phase

This first phase of the DMAIC approach enables the project team to draw up a project charter containing the problem to be dealt with and the critical points on which to concentrate efforts [20]. The 5W1H is one of the most effective tools to use during this phase. It is a questioning method that aims to unravel the issues; the acronym for which each letter corresponds to one of the following questions is: who, what, where, when, why, and how. These questions are open-ended and allow for a clear description of the problem and identification of the elements to be measured and analyzed, which then facilitates the resolution of the problem [21].

## Measure phase

The measurement phase is essential in this process, as it consists of a data collection carried out by the project team, which allows both to better detail the definition of the problem made during the first phase based on measurements describing the current state and also to facilitate the task of analysis during the next phase thanks to the significant values and indicators measured, which allow the root causes of the problem to be effectively identified later on [20]. Several tools and methods can be used in this phase, and among the most important are the standardized work (SW), which is the set of precise procedures containing all the tasks and actions to be done and the best methods to be followed by each operator in each manufacturing process [22].

Before any improvement action can be taken, the working standards must be developed and the process stabilized, which means that the SW are the starting point on which any continuous improvement activity is based. As Taiichi Ohno write, “Without standards, there can be no improvement” [23]. The SW is based on three main key elements:
- Takt time: is the production rate aligned with customer orders [23].
- Sequence: means the manual process steps in the order in which the operator must perform them [22]. In order to distribute the work properly, line balancing makes it possible to determine the necessary number of operators in the production line while ensuring that the cycle times of each workstation do not exceed the Takt time and that the workload is well balanced between the operators [23].
- Work in process: presents the minimum amount of stock at the manufacturing line that will allow production to continue efficiently and without constraints [22].

The implementation of standardized work is based on the elaboration of several basic documents, such as the standardized work combination table, which allows to deconstruct the global time and show the relation between the times of manual operations, walk time, the time of automatic processing by machine, and also the Takt time for each post in a sequence [22]. This table indicates to the operator the method of execution

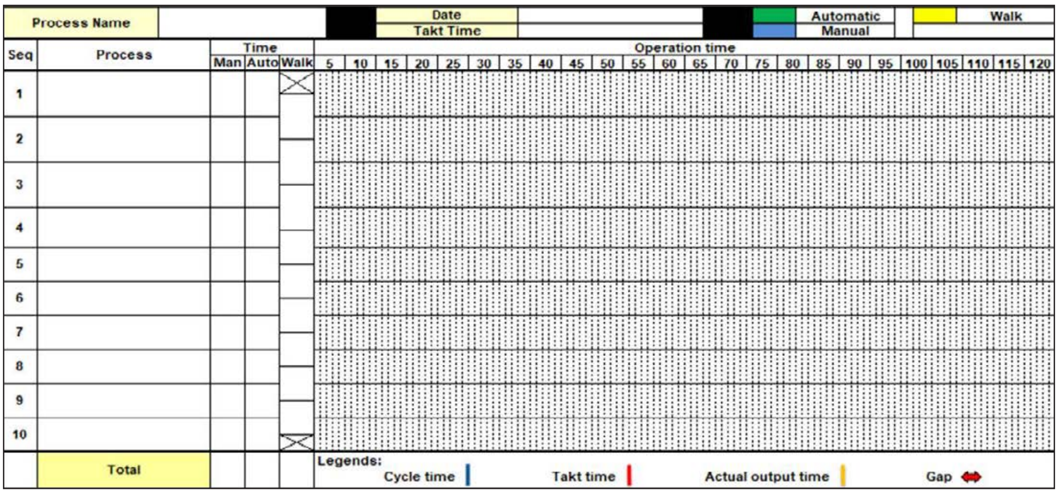


**Fig. 4.** Standardized work combination table

of the operations in order to respect the production rhythm imposed by the schedule [24], as shown in Figure 4.

## Analyze phase

As mentioned in the definition of the previous phase, the analysis stage is closely linked to the measurement stage, as this latter provides the indicators and data needed to describe the problem and the state of play. Then the project team organizes the collected data in order to clearly visualize and analyze the current situation. In a balancing project and following the use of SWCTs in the measurement phase, it is important to analyze them using one of the basic SW documents, which is the Yamazumi balancing chart or operator balance chart, which is used to visualize all the workloads at the workstations of an assembly line and compare them with the Takt time. It is based on the time required to execute each element of the process, so this chart facilitates the balancing of workstations. The ideal situation for a production line is when the distribution of workloads among the workstations is made in such a way that they are almost equal and very close to the Takt time without exceeding it [24].

In parallel, and in order to have a clear idea of the sources and origin of the problem, it is recommended to use the root cause analysis tools: the Ishikawa diagram and the 5 Whys [25].

The 5 Whys is an iterative questioning tool developed by Sakichi Toyoda at the Toyota Motor Corporation. It allows the determination of a chain of causes and effects that are at the origin of a certain problem and constitutes an essential element in the problem solving process. It is based on the question "Why?" which must be asked over and over again until the root cause of the anomaly is known. The identification of this root cause is the main objective of the 5 Whys, which then facilitates the proposal and determination of solutions. Each answer to the "Why?" question gives rise to other questions [26].

The Ishikawa diagram is a Lean tool that is represented in the form of a graphical diagram resembling the skeleton of a fish, showing the relationship between effects and their causes in such a way that the "head of the fish" placed on a horizontal axis represents the studied effect and the other segments, located on the horizontal axis of the "fishbone", contain its potential causes and sub-causes [27]. There are generally five segments reserved for five types of causes: machine, manpower, method, material, and environment [28], so their representation is as shown in Figure 5.

The distribution of causes by category makes the Ishikawa diagram more powerful and facilitates the identification of root causes, in particular by integrating the 5 Whys tool, and therefore the determination of different solutions capable of eradicating all the sources of the fault or anomaly studied [27].

## Improve phase

After a good analysis of the problem and the identification of all its root causes, the team moves on to the identification of ideas for improvement and the development of solutions capable of eradicating the root causes previously determined, and then implements these improvements [20].

The previous research works and methodologies present balancing steps that are valid only for specific assembly lines, and the method of calculating the required resources does not take into account the complexity of the process operations,

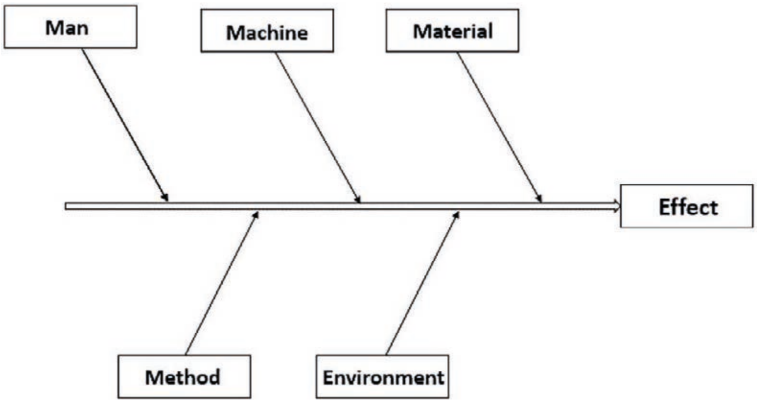


**Fig. 5.** Ishikawa diagram

which can lead to difficulties in redistributing the workload and thus to a low balancing of the stations and a low improvement in efficiency, as well as a risk that the line cycle time exceeds the Takt time, especially if the operations are poorly standardized, which increases the risk of variability.

In order to balance the workstations on an assembly line correctly and directly, we have developed five conditions that must be met precisely and in the order indicated. These make it possible to take into account all possible constraints, theoretically achieve the ideal state of line balancing, and then practically adapt the process to these requirements.

The five conditions developed in this paper can be expressed as follows:

- Condition 1 – before any calculation aimed at balancing the workstations, the process time (PT) or total cycle time of the workstations must first be reduced by eliminating waste within the process, especially unnecessary movements and overprocessing [6].
- Condition 2 – ideally, the cycle times of the line's workstations should all be equal to the average cycle time of the line, but in practice and given the complexity of some operations, this is unrealistic, hence the need to define a small interval around the ideal cycle time (ICT), which is the average of the cycle times of the line's workstations, and this interval [ICT-a, ICT+b] must contain all the values of the cycle times, with "a" and "b" values to be defined.
- Condition 3 – all the cycle times of the line must obviously be less than or equal to the Takt time, but to avoid any risk of exceeding the Takt time (TT), because of the variations of the cycle times and thus the risk of not satisfying the customer's demand, it is necessary to space the cycle times and in particular the ideal cycle time ICT from the Takt time, hence the need to respect the condition: $ICT \leq TT - c$, with "c" a value to be defined.
- Condition 4 – before distributing the operations to the line workstations, the minimum number of operators required (NOP) must be calculated, taking into account the above conditions, by dividing the process time, which is the total cycle time of the workstations, by the ideal cycle time: $NOP = PT / ICT \geq PT / (TT - c)$. And by fixing a natural number of operators, the ICT must be calculated by the formula $ICT = PT / NOP$ [4].
- Condition 5 – after calculating the ICT, the cycle time interval [ICT-a, ICT+b] is deduced, and then all operations must be distributed over the calculated number of operators NOP in such a way that the cycle times of all workstations must fall within this interval.

It is highly recommended to develop new SWCTs for each position that correspond to the new situation following the improvement actions.

### Control phase

During this phase, the project team checks the effectiveness of the actions implemented, works on their documentation in order to standardize them, and trains the employees concerned on the new procedures developed [20]. By comparing the Yamazumi diagram and the efficiency value of the improved state with the initial state, it is possible to deduce how effective the implemented solutions were.

## CASE STUDY

After presenting and defining the proposed method for line balancing and improving efficiency, we decided to implement it on the Dura assembly line of an automotive wiring company specializing in the manufacture of electrical harnesses for car manufacturers.

**Table 1.** 5W1H applied to the problematic

| | | |
|---|---|---|
| WHAT | What is the problem | Low efficiency of the assembly line |
| | What is the impact of the problem | Low productivity and a lot of wastes |
| WHO | Who is affected by the problem | Engineering Department and Production Department |
| | Who should solve the problem | Engineering Department |
| WHERE | Where the problem appears | DURA assembly line |
| WHEN | When the problem appears | During production |
| HOW | How to measure the problem | Calculation of the efficiency and timing of cycle times and operations of each station |
| WHY | Why the problem must be solved | Improving the productivity and efficiency of the line |

## Define phase

For a good framing of the problem studied at the automotive wiring assembly line DURA, the 5W1H tool was used as shown in Table 1.

It is then essential to understand the manufacturing process of the Dura family wiring harness by describing each of its stages in detail, as explained in the Figure 6 and Table 2.

**Fig. 6.** DURA assembly line layout

**Table 2.** Dura assembly line process description

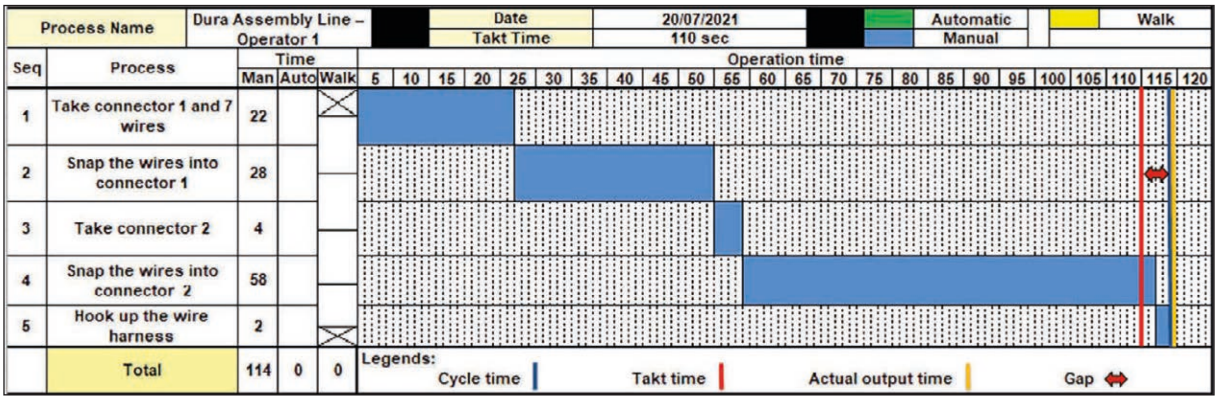
| Operator | Workstation | Process |
|---|---|---|
| Operator 1 | 1st insertion position | The operator snaps 7 terminals into two connectors |
| Operator 2 | 2nd insertion position | The operator continues to snap terminals on the two connectors, mounts the harness, and glues it with a black bandage, then an aluminum bandage, and finally another black bandage. He then takes the harness, mounts it on OLT, starts the electrical test, then glues the ticket and removes the harness |
| Operator 3 | 1st pre-blocking table | The operator picks up and mounts the harness, then picks up 13 wires and a connector, starts snapping the terminals, and puts the harness |
| Operator 4 | 2nd pre-blocking table | The operator picks up and mounts the harness, then picks up 10 circuits, snaps them into place, and finally removes the harness |
| Operator 5 | 1st assembly table | The operator takes 2 connectors and 4 wires, then makes the first snap and the first assembly on the board, then takes the harness and another wire and makes a second snap |
| Operator 6 | 2nd assembly table | The operator takes and prepares 3 wires, he then performs a snap and a bandage |
| Operator 7 | 3rd assembly table | The operator takes and prepares 2 wires, he then performs a snap, a bandage, a tube insertion, and a second and third bandage, he then moves the connector and performs a fourth bandage, a tube insertion, and finally a fifth bandage |
| Operator 8 | 4th assembly table | The operator takes a tube and performs a tube insertion, a first bandage, a repositioning of the counterparts, a second bandage, another tube insertion, and finally a third bandage |
| Operator 9 | 5th assembly table | The operator performs a first bandage, a tube insertion, a repositioning of the counterparts, a second bandage, another tube insertion, a third bandage, and finally another repositioning of the counterparts |
| Operator 10 | 6th assembly table | The operator takes a tube, then performs a first bandage, a tube insertion, and a second bandage. Then he inserts another tube and performs a third bandage, and finally a bandage on the node |
| Operator 11 | 7th assembly table | The operator performs a repositioning of the counterparts, then takes and inserts 4 clips, then performs a bandage, an insertion of 2 straps, an insertion of 3 clips, and finally an insertion of the tube |
| Operator 12 | 8th assembly table | The operator makes a bandage on the node, a bandage on 2 clips, then takes and inserts 7 clips, then cuts the clips and the straps by gun, and finally dismantles and removes the harness |
| Operator 13 | Channel mounting table | The operator prepares channels, picks up and mounts the harness, mounts channels and straps, performs a bandage, then cuts straps by gun, and finally dismantles and removes the harness |
| Operator 14 | Clips test table | The operator takes and mounts the harness, then performs a test clip, turns on the green button, takes and sticks the ticket, and finally dismantles and hooks the harness |
| Operator 15 | Dimensional table | The operator picks up and mounts the bundle, then checks the dimensions, and finally disassembles and hangs the product |
| Operator 16 | Electrical test/Offline test (OLT) | The operator picks up and mounts the bundle, then performs a first test, then prepares and mounts covers, clips, and straps, and finally cuts them by gun |
| Operator 17 | OLT + product packaging | The operator performs a second test, sticking the ticket, then moves the harness, packages it, scans it, and finally puts it on the pallet |

## Mesure phase

In this phase, we will proceed to the calculation of the key indicators, starting with the Takt time through the quantity of 250 pieces to be produced per shift, taking into consideration a 20-minute break [4]:

$$\text{Takt time} = \text{Available time} / \text{Demand} = \\ = 7{,}66 * 3600 / 250 = 110{,}3 \approx 110 \text{ sec} \tag{1}$$

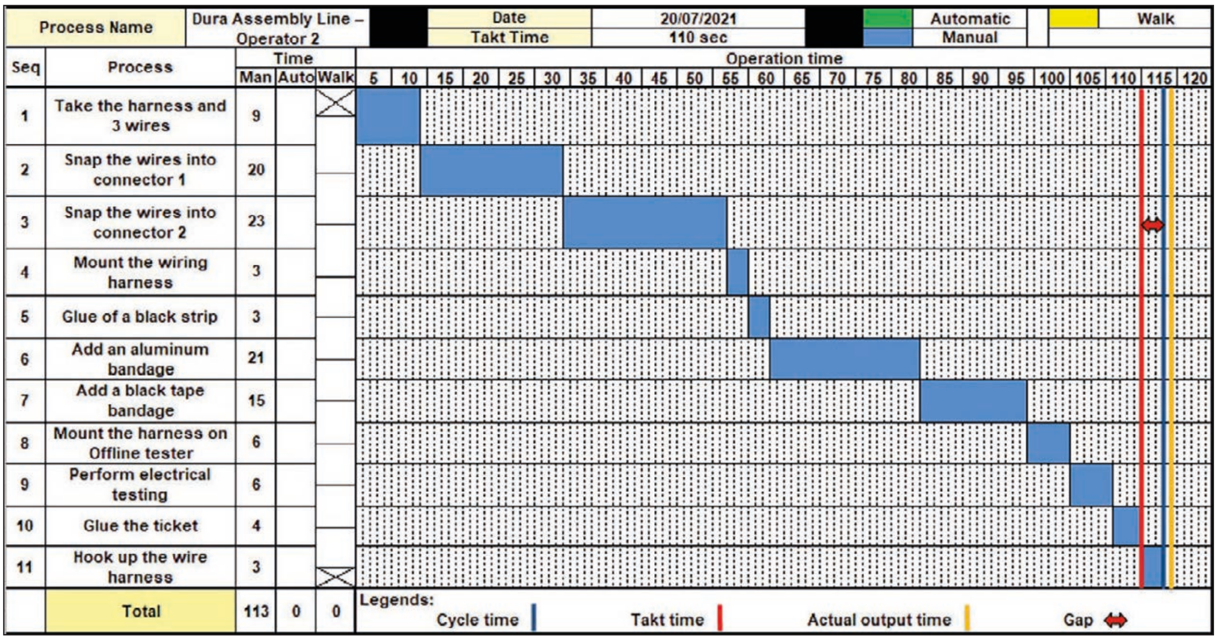
Then the cycle times of the 17 stations of the assembly line are timed with the execution time of each process and the elaboration of the



| Process Name | Dura Assembly Line – Operator 1 | Date | 20/07/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take connector 1 and 7 wires | 22 | | |
| 2 | Snap the wires into connector 1 | 28 | | |
| 3 | Take connector 2 | 4 | | |
| 4 | Snap the wires into connector 2 | 58 | | |
| 5 | Hook up the wire harness | 2 | | |
| | Total | 114 | 0 | 0 |

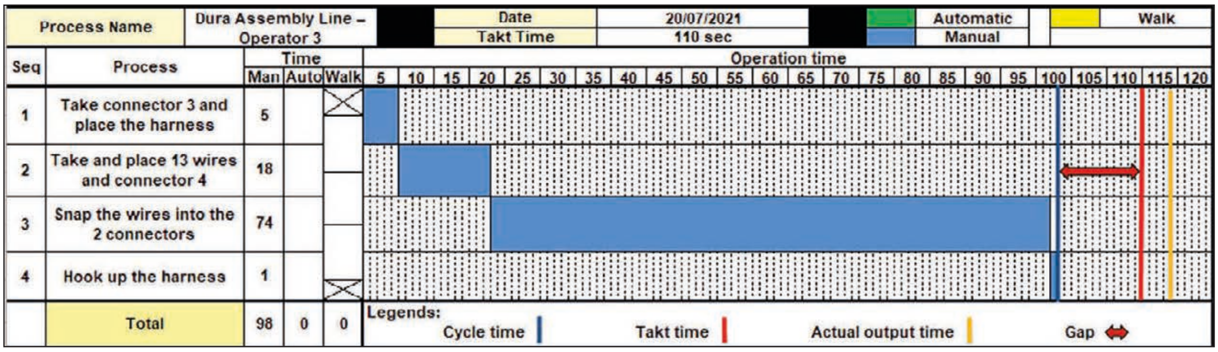
**Fig. 7.** Standardized work combination table of operator 1 before improvement



| Process Name | Dura Assembly Line – Operator 2 | Date | 20/07/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take the harness and 3 wires | 9 | | |
| 2 | Snap the wires into connector 1 | 20 | | |
| 3 | Snap the wires into connector 2 | 23 | | |
| 4 | Mount the wiring harness | 3 | | |
| 5 | Glue of a black strip | 3 | | |
| 6 | Add an aluminum bandage | 21 | | |
| 7 | Add a black tape bandage | 15 | | |
| 8 | Mount the harness on Offline tester | 6 | | |
| 9 | Perform electrical testing | 6 | | |
| 10 | Glue the ticket | 4 | | |
| 11 | Hook up the wire harness | 3 | | |
| | Total | 113 | 0 | 0 |

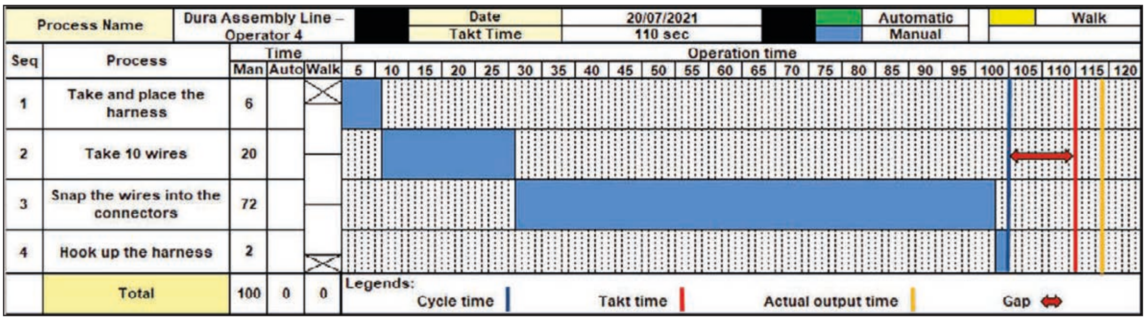
**Fig. 8.** Standardized work combination table of operator 2 before improvement



| Process Name | Dura Assembly Line – Operator 3 | Date | 20/07/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take connector 3 and place the harness | 5 | | |
| 2 | Take and place 13 wires and connector 4 | 18 | | |
| 3 | Snap the wires into the 2 connectors | 74 | | |
| 4 | Hook up the harness | 1 | | |
| | Total | 98 | 0 | 0 |

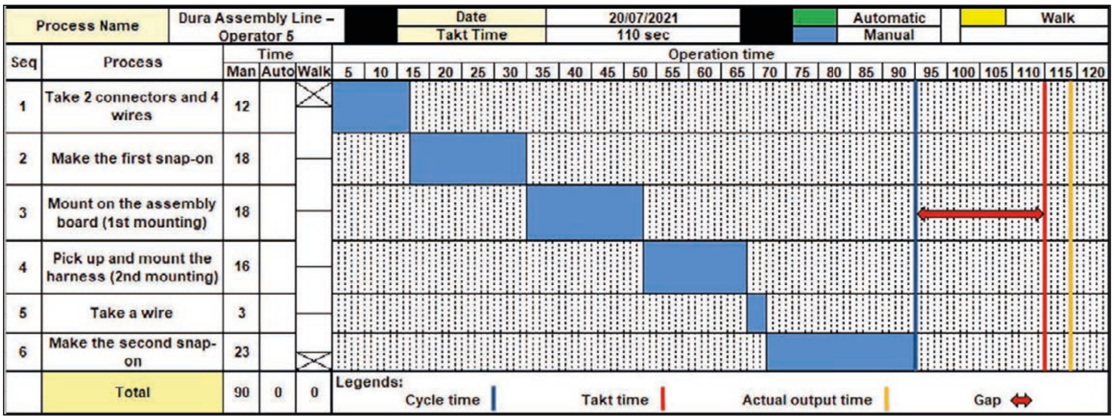
**Fig. 9.** Standardized work combination table of operator 3 before improvement



| Process Name | Dura Assembly Line – Operator 4 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take and place the harness | 6 | | |
| 2 | Take 10 wires | 20 | | |
| 3 | Snap the wires into the connectors | 72 | | |
| 4 | Hook up the harness | 2 | | |
| | Total | 100 | 0 | 0 |

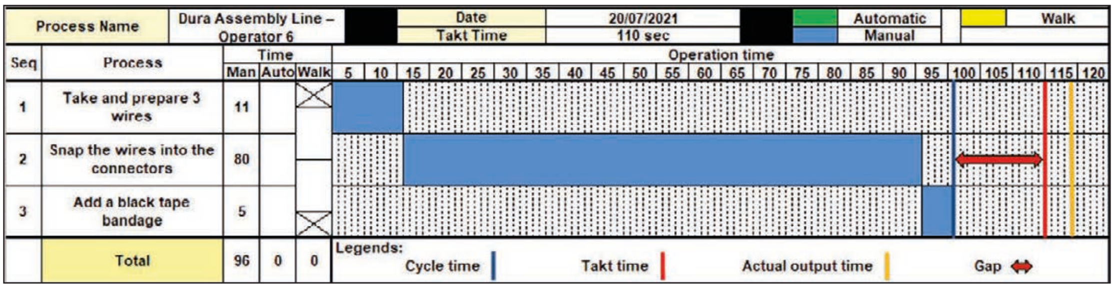
**Fig. 10.** Standardized work combination table of operator 4 before improvement



| Process Name | Dura Assembly Line – Operator 5 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take 2 connectors and 4 wires | 12 | | |
| 2 | Make the first snap-on | 18 | | |
| 3 | Mount on the assembly board (1st mounting) | 18 | | |
| 4 | Pick up and mount the harness (2nd mounting) | 16 | | |
| 5 | Take a wire | 3 | | |
| 6 | Make the second snap-on | 23 | | |
| | Total | 90 | 0 | 0 |

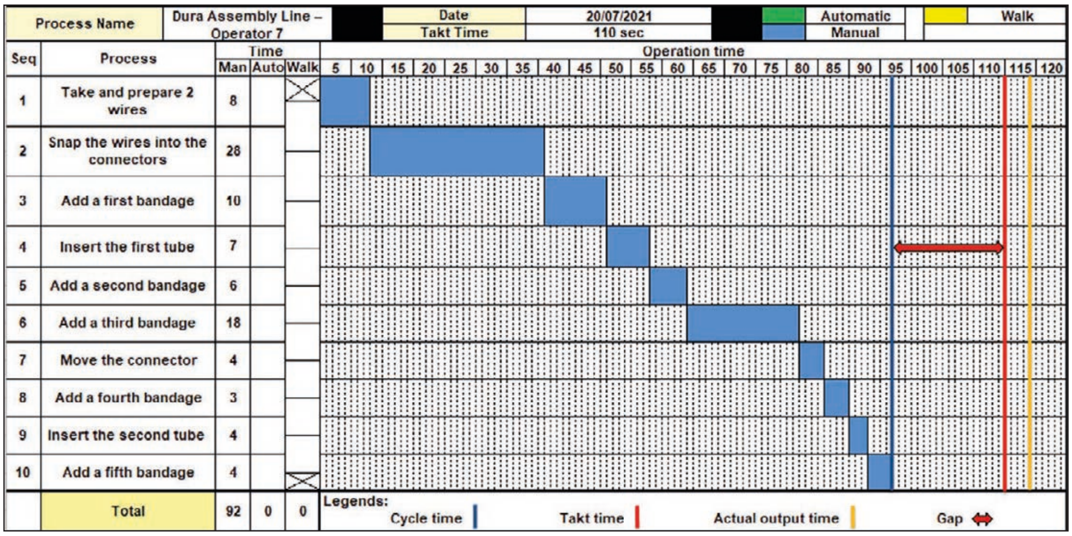
**Fig. 11.** Standardized work combination table of operator 5 before improvement



| Process Name | Dura Assembly Line – Operator 6 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take and prepare 3 wires | 11 | | |
| 2 | Snap the wires into the connectors | 80 | | |
| 3 | Add a black tape bandage | 5 | | |
| | Total | 96 | 0 | 0 |

**Fig. 12.** Standardized work combination table of operator 6 before improvement



| Process Name | Dura Assembly Line – Operator 7 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take and prepare 2 wires | 8 | | |
| 2 | Snap the wires into the connectors | 28 | | |
| 3 | Add a first bandage | 10 | | |
| 4 | Insert the first tube | 7 | | |
| 5 | Add a second bandage | 6 | | |
| 6 | Add a third bandage | 18 | | |
| 7 | Move the connector | 4 | | |
| 8 | Add a fourth bandage | 3 | | |
| 9 | Insert the second tube | 4 | | |
| 10 | Add a fifth bandage | 4 | | |
| | Total | 92 | 0 | 0 |

**Fig. 13.** Standardized work combination table of operator 7 before improvement

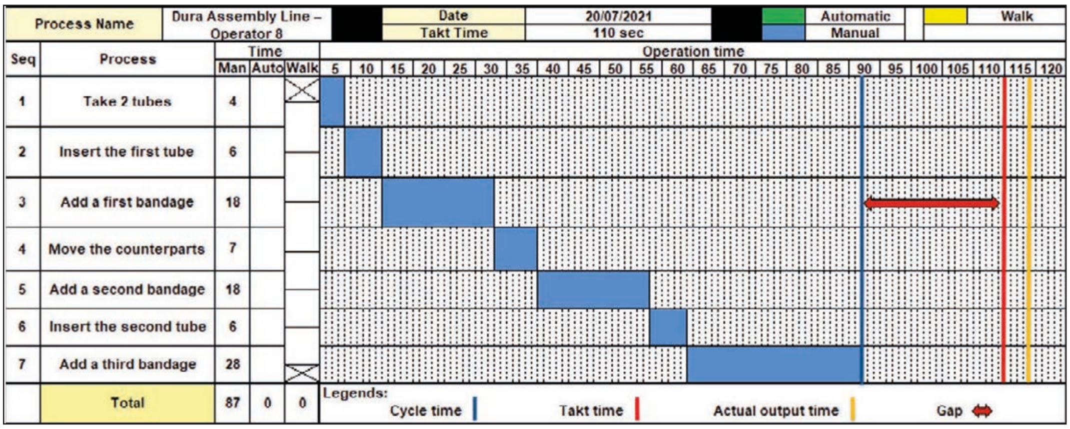
corresponding SWCT, as explained in the materials and method and shown in Figures 7 to 23.

The first four workstations are mainly dedicated to inserting the terminals of the electrical wires into the connectors with a few bandages and an initial electrical test.

The next eight stations consist of positioning the beam on the assembly boards and fixing it to the counterparts, mainly to apply the necessary bandages and insert terminals, clips, and straps.

The last five processes are dedicated to channel assembly, clip testing, electrical testing, dimensional control, and packaging.

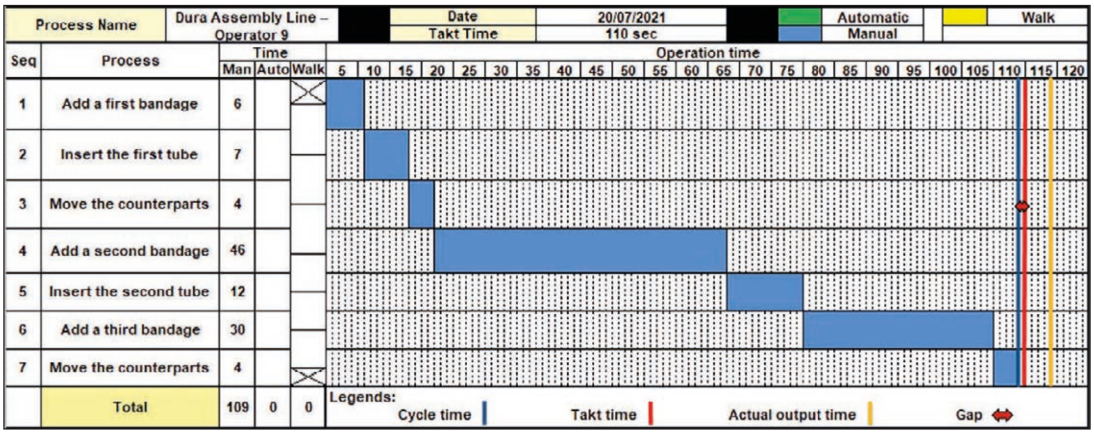
Having drawn up the tables of standardized work combinations for the 17 workstations, we can see that, in principle, some cycle times exceed



| Process Name | Dura Assembly Line – Operator 8 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Take 2 tubes | 4 | | |
| 2 | Insert the first tube | 6 | | |
| 3 | Add a first bandage | 18 | | |
| 4 | Move the counterparts | 7 | | |
| 5 | Add a second bandage | 18 | | |
| 6 | Insert the second tube | 6 | | |
| 7 | Add a third bandage | 28 | | |
| | Total | 87 | 0 | 0 |

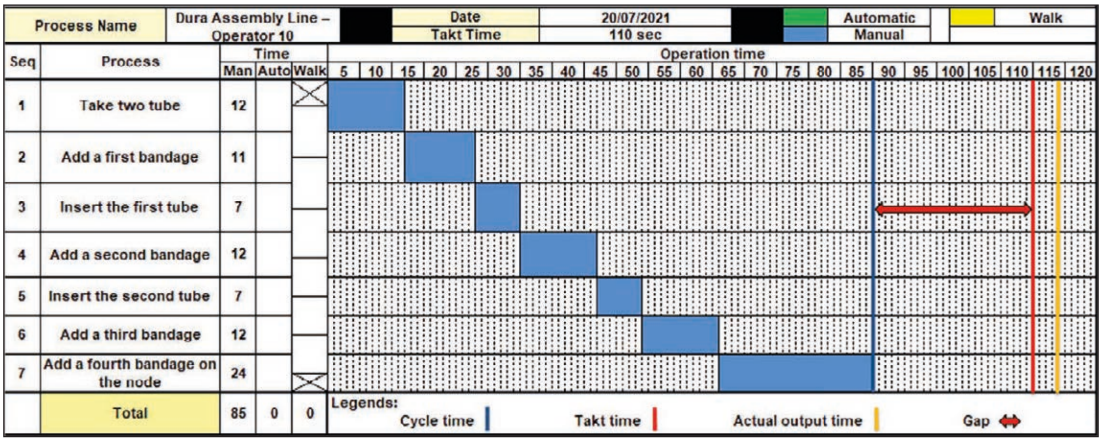
**Fig. 14.** Standardized work combination table of operator 8 before improvement



| Process Name | Dura Assembly Line – Operator 9 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Add a first bandage | 6 | | |
| 2 | Insert the first tube | 7 | | |
| 3 | Move the counterparts | 4 | | |
| 4 | Add a second bandage | 46 | | |
| 5 | Insert the second tube | 12 | | |
| 6 | Add a third bandage | 30 | | |
| 7 | Move the counterparts | 4 | | |
| | Total | 109 | 0 | 0 |

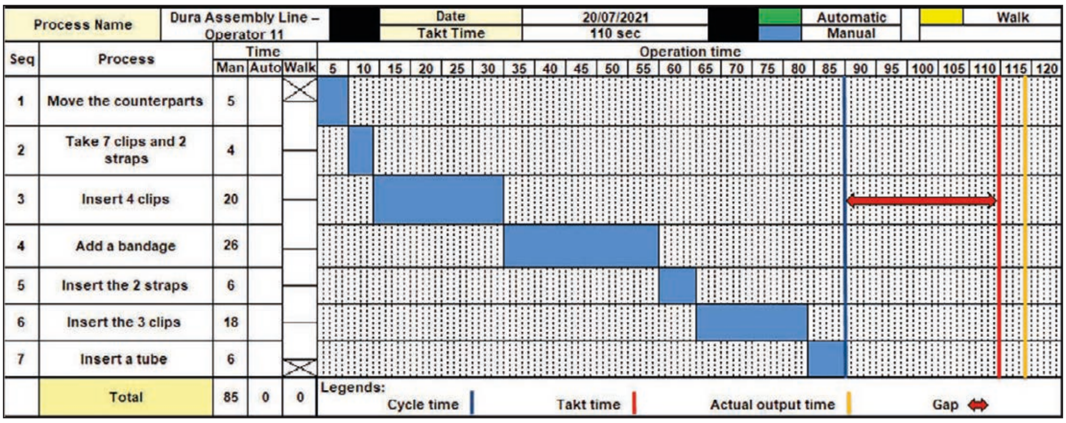
**Fig. 15.** Standardized work combination table of operator 9 before improvement



| Process Name | Dura Assembly Line – Operator 10 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Take two tube | 12 | | |
| 2 | Add a first bandage | 11 | | |
| 3 | Insert the first tube | 7 | | |
| 4 | Add a second bandage | 12 | | |
| 5 | Insert the second tube | 7 | | |
| 6 | Add a third bandage | 12 | | |
| 7 | Add a fourth bandage on the node | 24 | | |
| | Total | 85 | 0 | 0 |

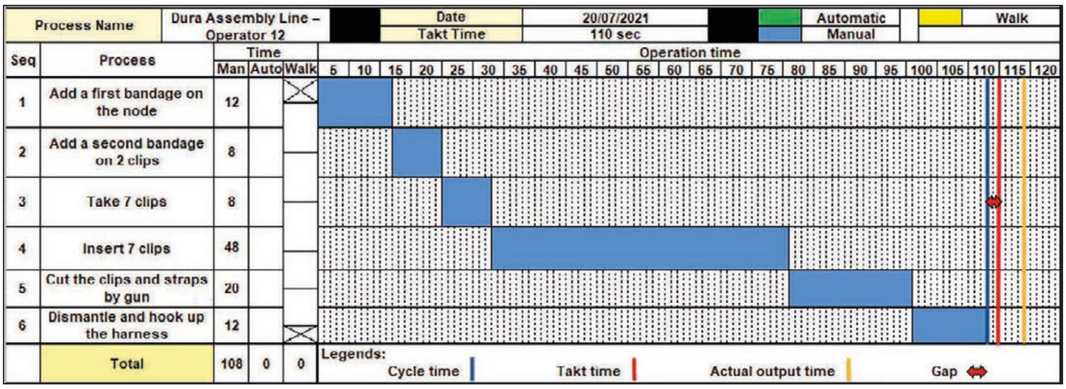
**Fig. 16.** Standardized work combination table of operator 10 before improvement



Process Name: Dura Assembly Line – Operator 11
Date: 20/07/2021
Takt Time: 110 sec
🟩 Automatic
🟦 Manual
🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Move the counterparts | 5 | | |
| 2 | Take 7 clips and 2 straps | 4 | | |
| 3 | Insert 4 clips | 20 | | |
| 4 | Add a bandage | 26 | | |
| 5 | Insert the 2 straps | 6 | | |
| 6 | Insert the 3 clips | 18 | | |
| 7 | Insert a tube | 6 | | |
| | Total | 85 | 0 | 0 |

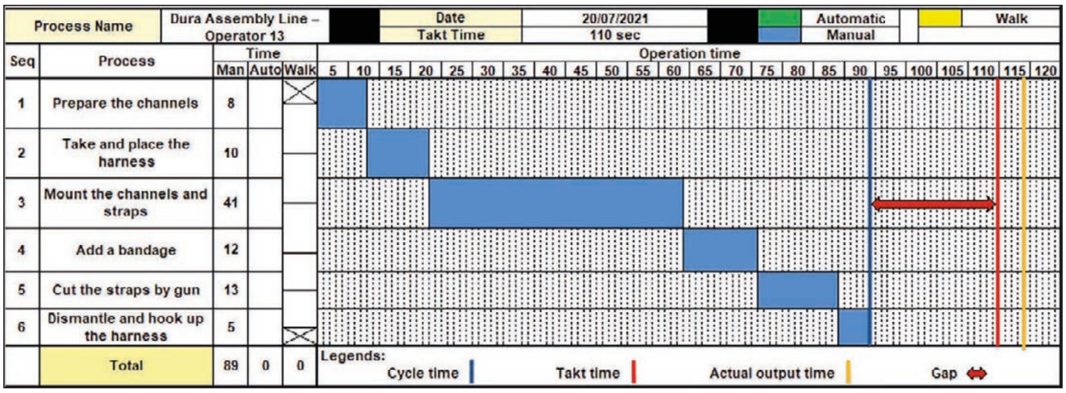
**Fig. 17.** Standardized work combination table of operator 11 before improvement



Process Name: Dura Assembly Line – Operator 12
Date: 20/07/2021
Takt Time: 110 sec
🟩 Automatic
🟦 Manual
🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Add a first bandage on the node | 12 | | |
| 2 | Add a second bandage on 2 clips | 8 | | |
| 3 | Take 7 clips | 8 | | |
| 4 | Insert 7 clips | 48 | | |
| 5 | Cut the clips and straps by gun | 20 | | |
| 6 | Dismantle and hook up the harness | 12 | | |
| | Total | 108 | 0 | 0 |

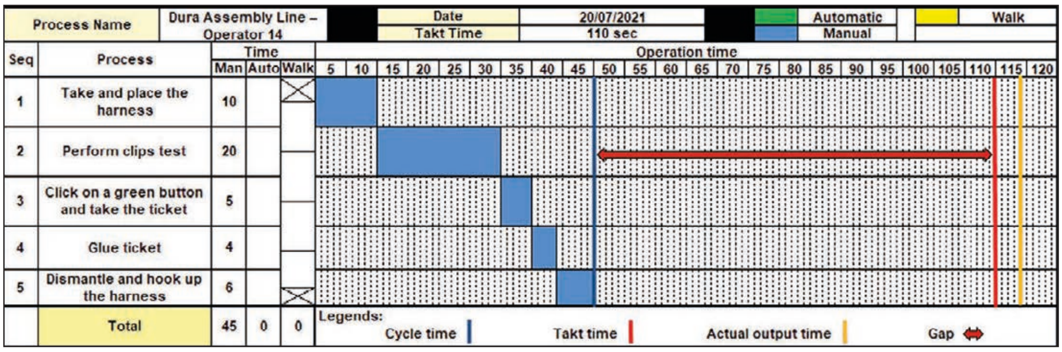
**Fig. 18.** Standardized work combination table of operator 12 before improvement



Process Name: Dura Assembly Line – Operator 13
Date: 20/07/2021
Takt Time: 110 sec
🟩 Automatic
🟦 Manual
🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Prepare the channels | 8 | | |
| 2 | Take and place the harness | 10 | | |
| 3 | Mount the channels and straps | 41 | | |
| 4 | Add a bandage | 12 | | |
| 5 | Cut the straps by gun | 13 | | |
| 6 | Dismantle and hook up the harness | 5 | | |
| | Total | 89 | 0 | 0 |

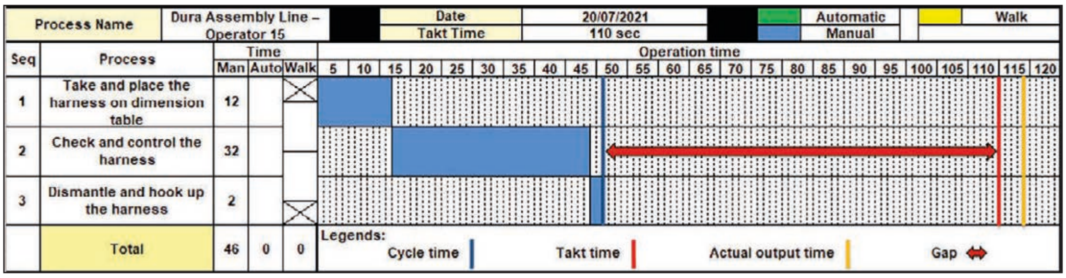
**Fig. 19.** Standardized work combination table of operator 13 before improvement



Process Name: Dura Assembly Line – Operator 14
Date: 20/07/2021
Takt Time: 110 sec
🟩 Automatic
🟦 Manual
🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take and place the harness | 10 | | |
| 2 | Perform clips test | 20 | | |
| 3 | Click on a green button and take the ticket | 5 | | |
| 4 | Glue ticket | 4 | | |
| 5 | Dismantle and hook up the harness | 6 | | |
| | Total | 45 | 0 | 0 |

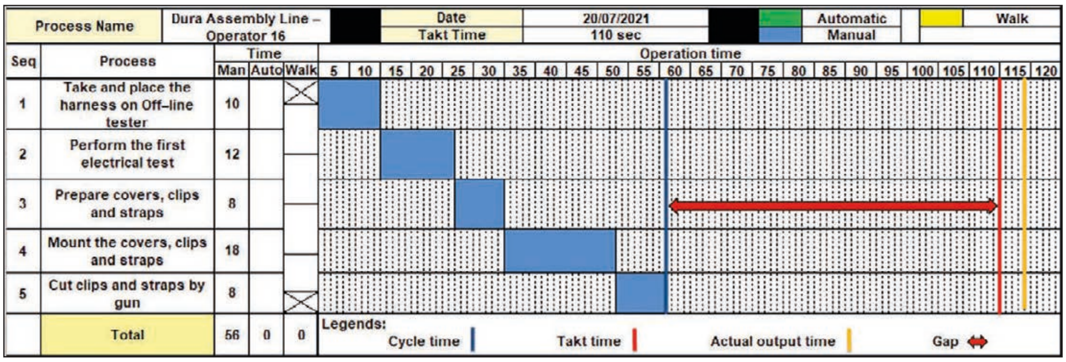
**Fig. 20.** Standardized work combination table of operator 14 before improvement



| Process Name | Dura Assembly Line – Operator 15 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take and place the harness on dimension table | 12 | | |
| 2 | Check and control the harness | 32 | | |
| 3 | Dismantle and hook up the harness | 2 | | |
| | Total | 46 | 0 | 0 |

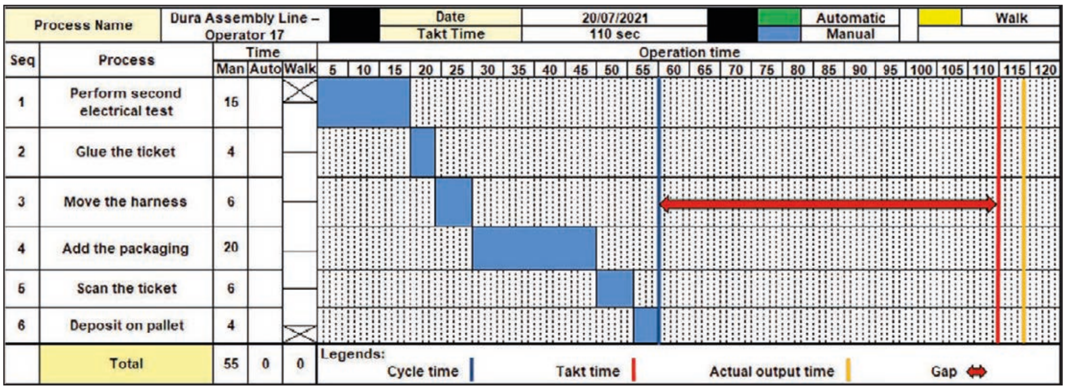
**Fig. 21.** Standardized work combination table of operator 15 before improvement



| Process Name | Dura Assembly Line – Operator 16 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take and place the harness on Off-line tester | 10 | | |
| 2 | Perform the first electrical test | 12 | | |
| 3 | Prepare covers, clips and straps | 8 | | |
| 4 | Mount the covers, clips and straps | 18 | | |
| 5 | Cut clips and straps by gun | 8 | | |
| | Total | 56 | 0 | 0 |

**Fig. 22.** Standardized work combination table of operator 16 before improvement



| Process Name | Dura Assembly Line – Operator 17 | Date | 20/07/2021 | 🟩 Automatic | 🟨 Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Perform second electrical test | 15 | | |
| 2 | Glue the ticket | 4 | | |
| 3 | Move the harness | 6 | | |
| 4 | Add the packaging | 20 | | |
| 5 | Scan the ticket | 6 | | |
| 6 | Deposit on pallet | 4 | | |
| | Total | 55 | 0 | 0 |

**Fig. 23.** Standardized work combination table of operator 17 before improvement

the Takt time and that, overall, the workstations are very unbalanced.

We then deduce the calculation of the efficiency of the current state, whose formula is [4]:

$$\text{Efficiency} = (\text{Process Time} / \text{Takt time} * * \text{Number of operators}) * 100\% \quad (2)$$

with:

$$\text{Process Time} = \text{Total workstation cycle time} = 114+113+98+100+90+96+92+87+ +109+85+85+108+89+45 +46+56+55=1486 \text{ s} \quad (3)$$

we find:

$$\text{Efficiency} = (1468/110*17) *100\% = 78\% \quad (4)$$

## Analyze phase

Based on the measurement data and the SWCT, a first analysis can be made following the elaboration of the Yamazumi or operator balance chart, as shown in the Figure 20.

We notice a big difference between the cycle times on the workstations of the line, which makes some of them more loaded than the others and thus creates bottleneck stations and high waiting times. Indeed, we notice that the highest cycle time is that of the 1st insertion station, which represents a bottleneck station with a cycle time equal to 114 seconds, exceeding the Takt Time set at 110 seconds. In addition to this station, we find the second one, which also exceeds the Takt Time with a

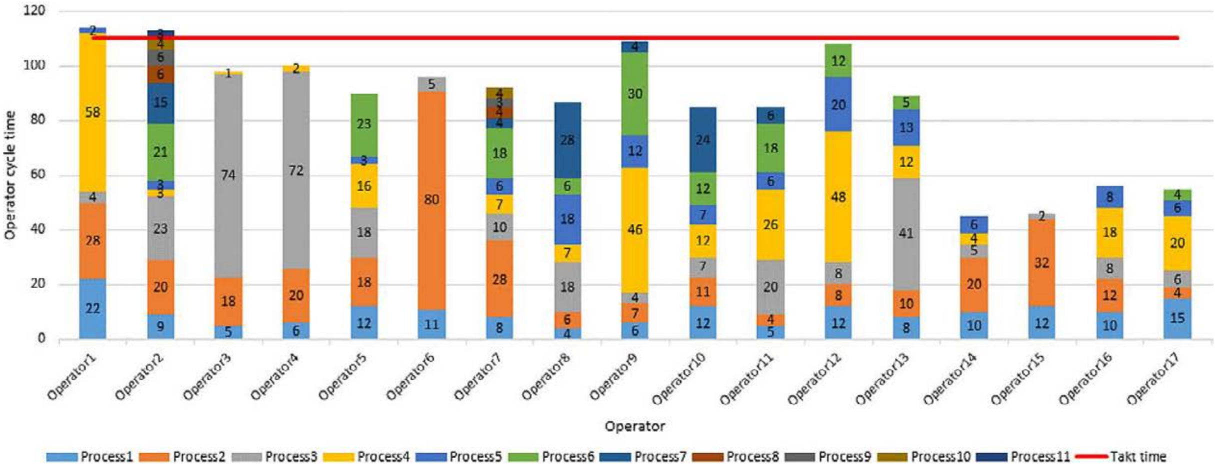


**Fig. 24.** Operator balance chart (Yamazumi chart) before improvement

cycle time equal to 113 seconds, which makes the line unable to satisfy the quantity requested by the customer per shift, while the cycle times of some workstations are much lower than the Takt Time.

In order to dig deeper into the analysis of the root causes of the low efficiency of the line, we used the Ishikawa diagram and the 5 whys tools

**Table 3.** 5whys applied to the detected cause

| Effect | Low efficiency |
|---|---|
| Why | The process contains several wastes |
| Why | High waiting time |
| Why | Some positions are more loaded than others |
| Why | Incorrect line balancing |
| Why | Lack of a capacity study of needed resources |

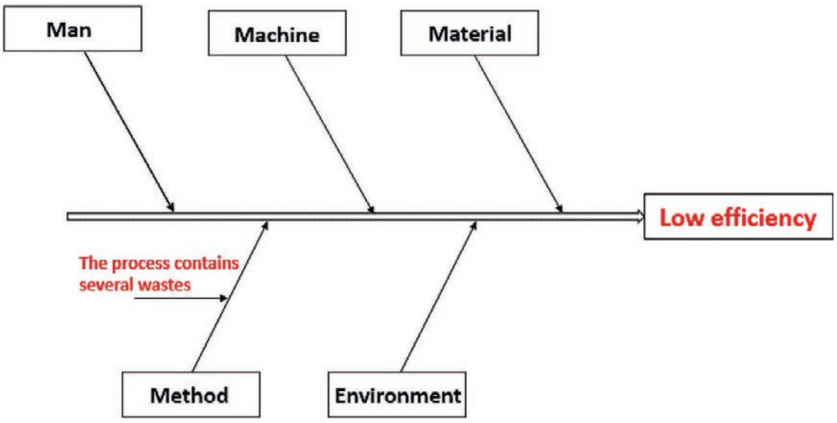


**Fig. 25.** Ishikawa diagram of the problematic

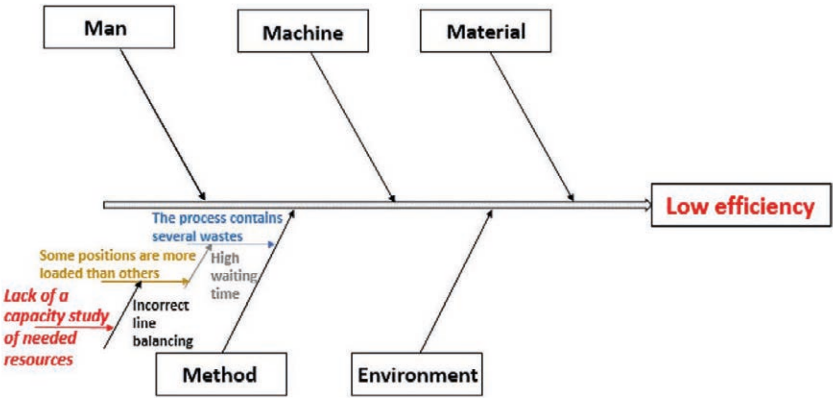


**Fig. 26.** Combination of the Ishikawa diagram and the 5 whys

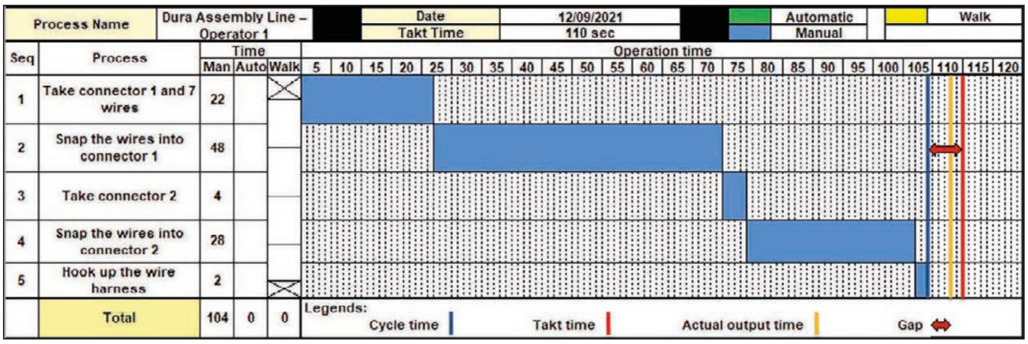
combined, as shown in Figures 21 and 22 and Table 3.

Hence the need for a more robust capacity study to balance the Dura assembly line and avoid all types of waste that impact efficiency.

## Improve phase

After analyzing the current state it is time to improve it by following the 5 conditions of line balancing:

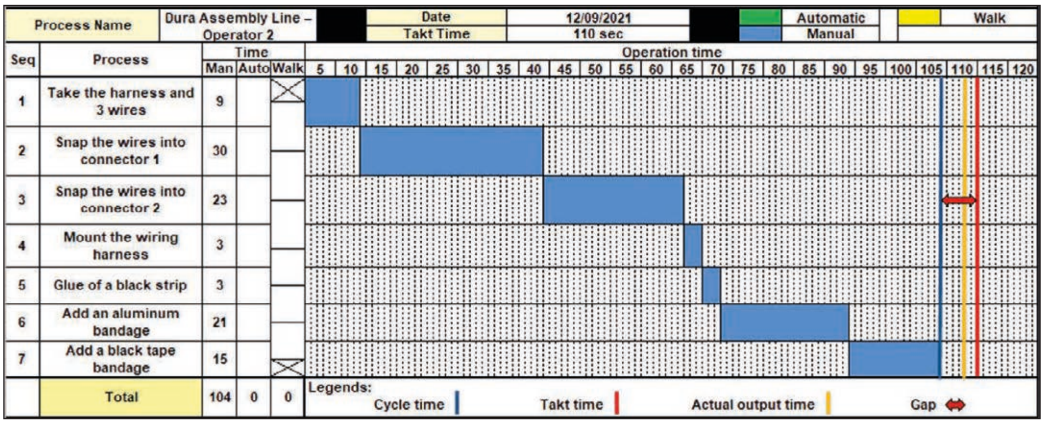
- Condition 1 – the process time, or the total of the cycle times of the stations, is equal to 1468 seconds, but in this situation, this total time has been obtained after improvements already made previously on this level, and the global process does not contain any more waste due to useless movements or overprocessing, on the other hand, the losses due to waiting times are obvious.
- Condition 2 – taking into account the complexity of some operations in the manufacturing process of the wiring harness and the fact



Process Name: Dura Assembly Line – Operator 1 | Date: 12/09/2021 | Takt Time: 110 sec | 🟩 Automatic | 🟦 Manual | 🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take connector 1 and 7 wires | 22 | | |
| 2 | Snap the wires into connector 1 | 48 | | |
| 3 | Take connector 2 | 4 | | |
| 4 | Snap the wires into connector 2 | 28 | | |
| 5 | Hook up the wire harness | 2 | | |
| | Total | 104 | 0 | 0 |

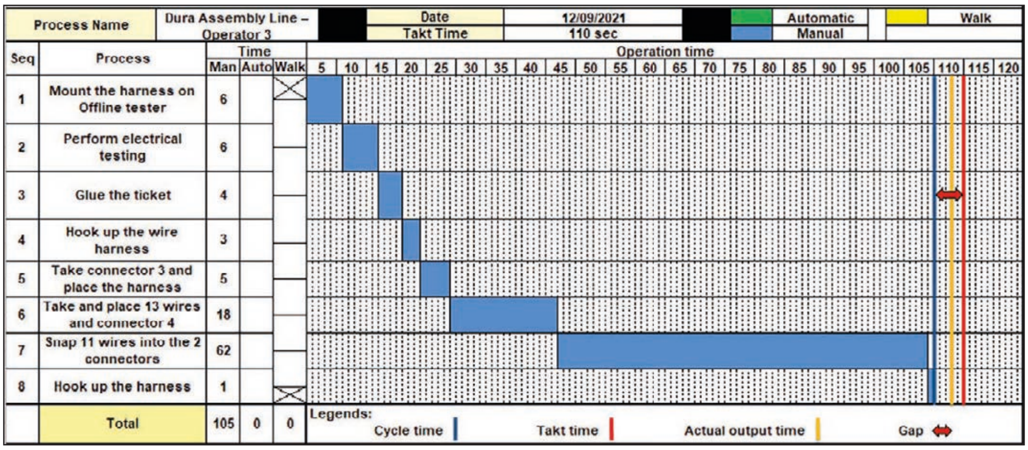
**Fig. 27.** Standardized work combination table of operator 1 after improvement



Process Name: Dura Assembly Line – Operator 2 | Date: 12/09/2021 | Takt Time: 110 sec | 🟩 Automatic | 🟦 Manual | 🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take the harness and 3 wires | 9 | | |
| 2 | Snap the wires into connector 1 | 30 | | |
| 3 | Snap the wires into connector 2 | 23 | | |
| 4 | Mount the wiring harness | 3 | | |
| 5 | Glue of a black strip | 3 | | |
| 6 | Add an aluminum bandage | 21 | | |
| 7 | Add a black tape bandage | 15 | | |
| | Total | 104 | 0 | 0 |

**Fig. 28.** Standardized work combination table of operator 2 after improvement



Process Name: Dura Assembly Line – Operator 3 | Date: 12/09/2021 | Takt Time: 110 sec | 🟩 Automatic | 🟦 Manual | 🟨 Walk

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Mount the harness on Offline tester | 6 | | |
| 2 | Perform electrical testing | 6 | | |
| 3 | Glue the ticket | 4 | | |
| 4 | Hook up the wire harness | 3 | | |
| 5 | Take connector 3 and place the harness | 5 | | |
| 6 | Take and place 13 wires and connector 4 | 18 | | |
| 7 | Snap 11 wires into the 2 connectors | 62 | | |
| 8 | Hook up the harness | 1 | | |
| | Total | 105 | 0 | 0 |

**Fig. 29.** Standardized work combination table of operator 3 after improvement

that the largest cycle time must be less than the Takt time, we have chosen the values a = 6 and b = 3 so the interval will be [ICT-6, ICT+3].

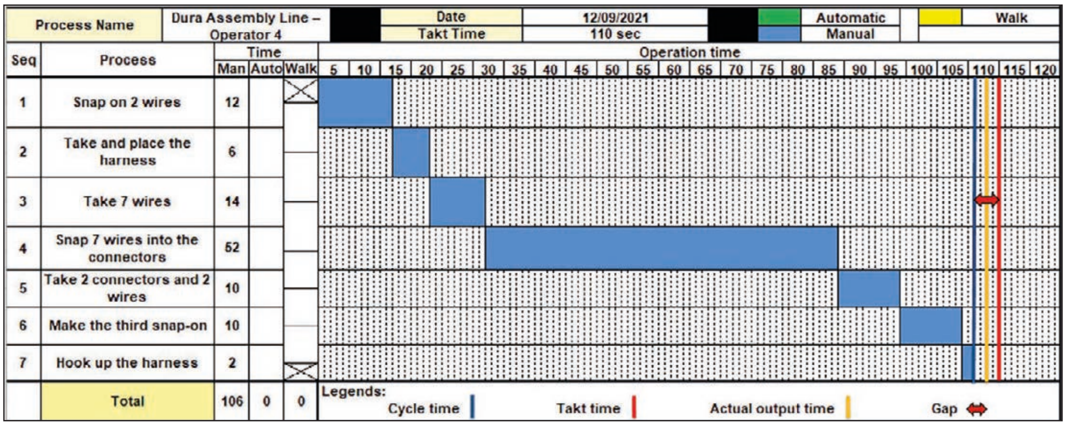
- Condition 3 – as long as the maximum cycle time will be ICT+3 and agreeing to leave a margin of 2 seconds in relation to the Takt time, we will have ICT+3 ≤ TT - 2 which makes ICT ≤ TT - 5 so we have set the value c = 5.
- Condition 4 – applying the formula:

$$\mathrm{NOP} = \mathrm{PT} / \mathrm{ICT} \geq \mathrm{PT} / (\mathrm{TT} - 5) \qquad (5)$$

with: TT = 110 seconds we will have:

$$\mathrm{NOP} \geq 1468/(110 - 5) = 13{,}98 \text{ operators} \qquad (6)$$

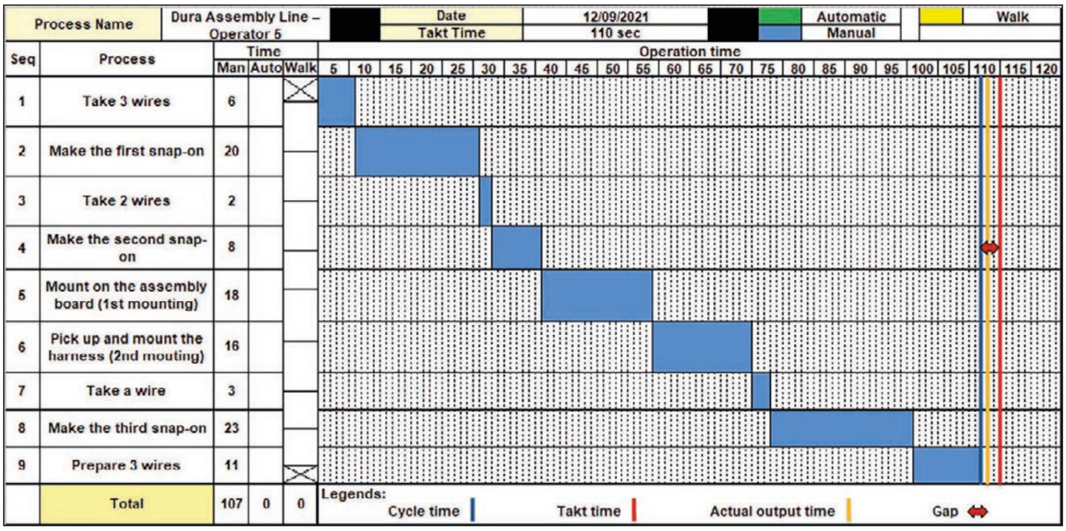
Thus we have obtained 14 operators as the optimal number that will allow us to achieve the objective.



| Process Name | Dura Assembly Line – Operator 4 | Date | 12/09/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Snap on 2 wires | 12 | | |
| 2 | Take and place the harness | 6 | | |
| 3 | Take 7 wires | 14 | | |
| 4 | Snap 7 wires into the connectors | 52 | | |
| 5 | Take 2 connectors and 2 wires | 10 | | |
| 6 | Make the third snap-on | 10 | | |
| 7 | Hook up the harness | 2 | | |
| | Total | 106 | 0 | 0 |

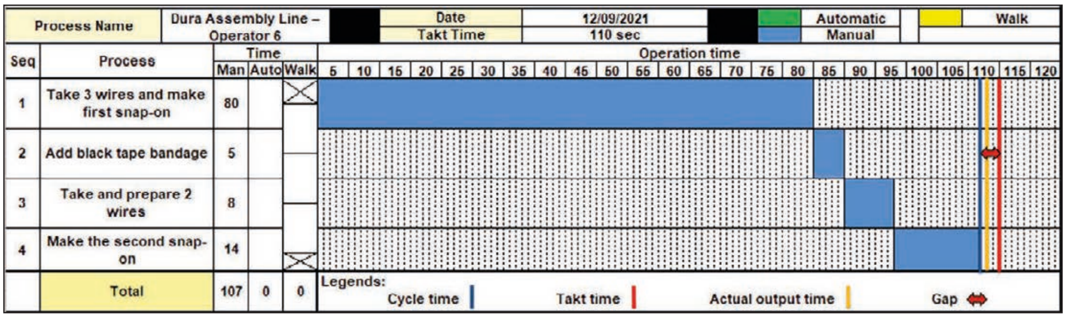
**Fig. 30.** Standardized work combination table of operator 4 after improvement



| Process Name | Dura Assembly Line – Operator 5 | Date | 12/09/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take 3 wires | 6 | | |
| 2 | Make the first snap-on | 20 | | |
| 3 | Take 2 wires | 2 | | |
| 4 | Make the second snap-on | 8 | | |
| 5 | Mount on the assembly board (1st mounting) | 18 | | |
| 6 | Pick up and mount the harness (2nd mouting) | 16 | | |
| 7 | Take a wire | 3 | | |
| 8 | Make the third snap-on | 23 | | |
| 9 | Prepare 3 wires | 11 | | |
| | Total | 107 | 0 | 0 |

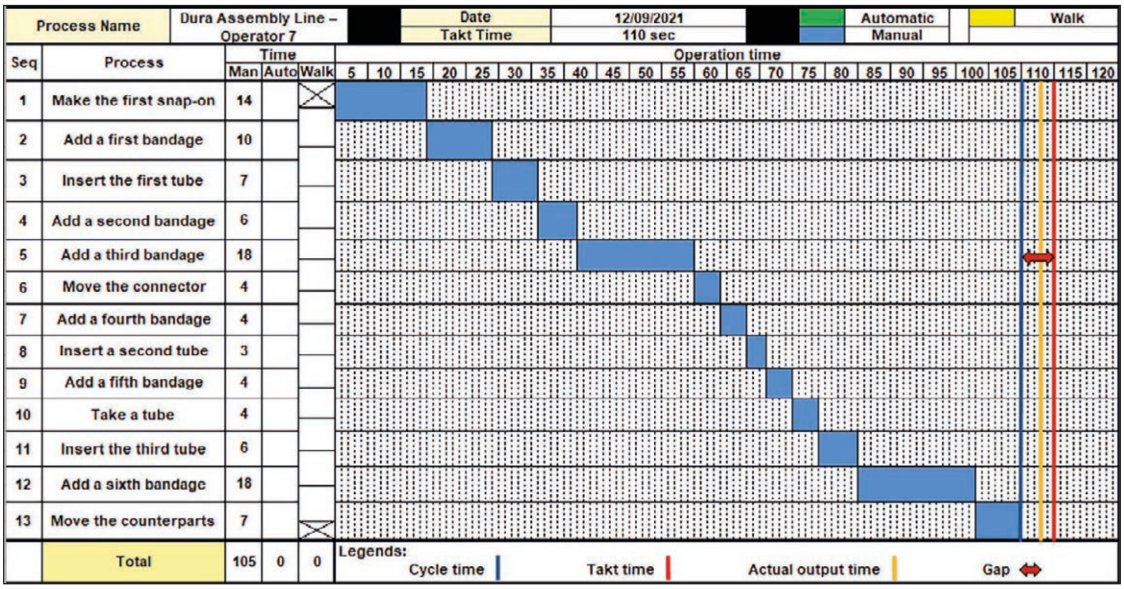
**Fig. 31.** Standardized work combination table of operator 5 after improvement



| Process Name | Dura Assembly Line – Operator 6 | Date | 12/09/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Take 3 wires and make first snap-on | 80 | | |
| 2 | Add black tape bandage | 5 | | |
| 3 | Take and prepare 2 wires | 8 | | |
| 4 | Make the second snap-on | 14 | | |
| | Total | 107 | 0 | 0 |

**Fig. 32.** Standardized work combination table of operator 6 after improvement



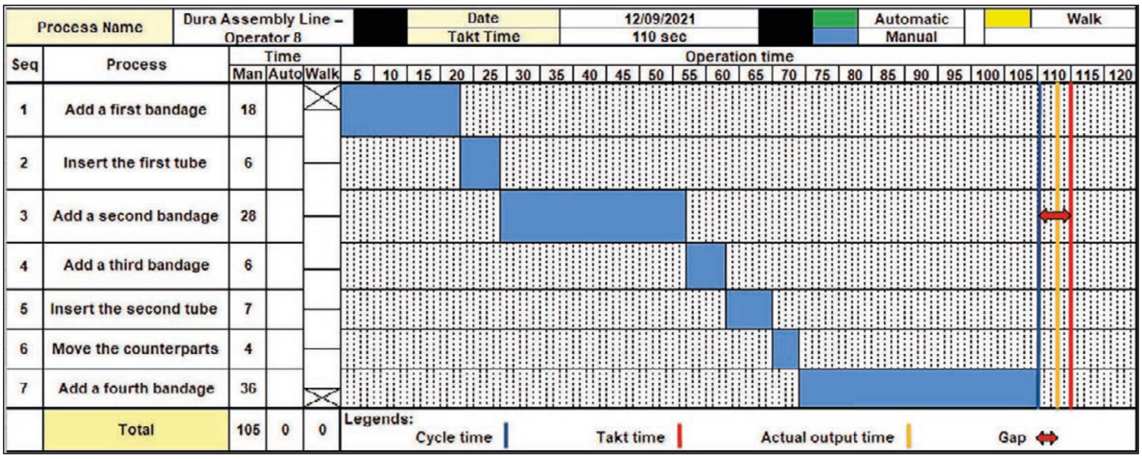
| Process Name | Dura Assembly Line – Operator 7 | Date | 12/09/2021 | 🟩 | Automatic | 🟨 | Walk |
|---|---|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 | Manual | | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Make the first snap-on | 14 | | |
| 2 | Add a first bandage | 10 | | |
| 3 | Insert the first tube | 7 | | |
| 4 | Add a second bandage | 6 | | |
| 5 | Add a third bandage | 18 | | |
| 6 | Move the connector | 4 | | |
| 7 | Add a fourth bandage | 4 | | |
| 8 | Insert a second tube | 3 | | |
| 9 | Add a fifth bandage | 4 | | |
| 10 | Take a tube | 4 | | |
| 11 | Insert the third tube | 6 | | |
| 12 | Add a sixth bandage | 18 | | |
| 13 | Move the counterparts | 7 | | |
| | Total | 105 | 0 | 0 |

Operation time: 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Legends: Cycle time | Takt time | Actual output time | Gap ⬌

Fig. 33. Standardized work combination table of operator 7 after improvement



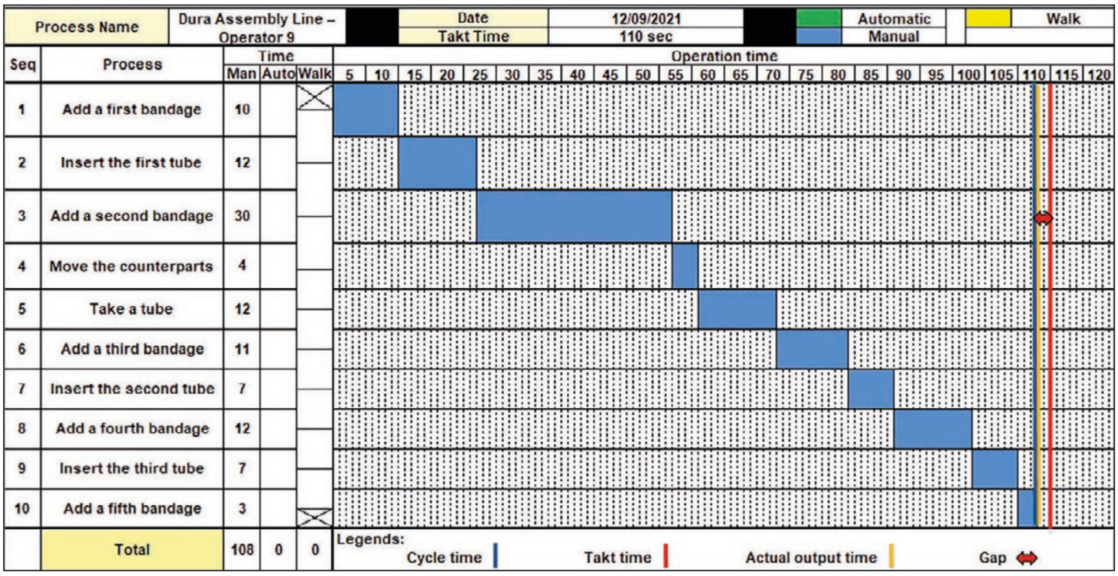
| Process Name | Dura Assembly Line – Operator 8 | Date | 12/09/2021 | 🟩 | Automatic | 🟨 | Walk |
|---|---|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 | Manual | | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Add a first bandage | 18 | | |
| 2 | Insert the first tube | 6 | | |
| 3 | Add a second bandage | 28 | | |
| 4 | Add a third bandage | 6 | | |
| 5 | Insert the second tube | 7 | | |
| 6 | Move the counterparts | 4 | | |
| 7 | Add a fourth bandage | 36 | | |
| | Total | 105 | 0 | 0 |

Operation time: 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Legends: Cycle time | Takt time | Actual output time | Gap ⬌

Fig. 34. Standardized work combination table of operator 8 after improvement



| Process Name | Dura Assembly Line – Operator 9 | Date | 12/09/2021 | 🟩 | Automatic | 🟨 | Walk |
|---|---|---|---|---|---|---|---|
| | | Takt Time | 110 sec | 🟦 | Manual | | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Add a first bandage | 10 | | |
| 2 | Insert the first tube | 12 | | |
| 3 | Add a second bandage | 30 | | |
| 4 | Move the counterparts | 4 | | |
| 5 | Take a tube | 12 | | |
| 6 | Add a third bandage | 11 | | |
| 7 | Insert the second tube | 7 | | |
| 8 | Add a fourth bandage | 12 | | |
| 9 | Insert the third tube | 7 | | |
| 10 | Add a fifth bandage | 3 | | |
| | Total | 108 | 0 | 0 |

Operation time: 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

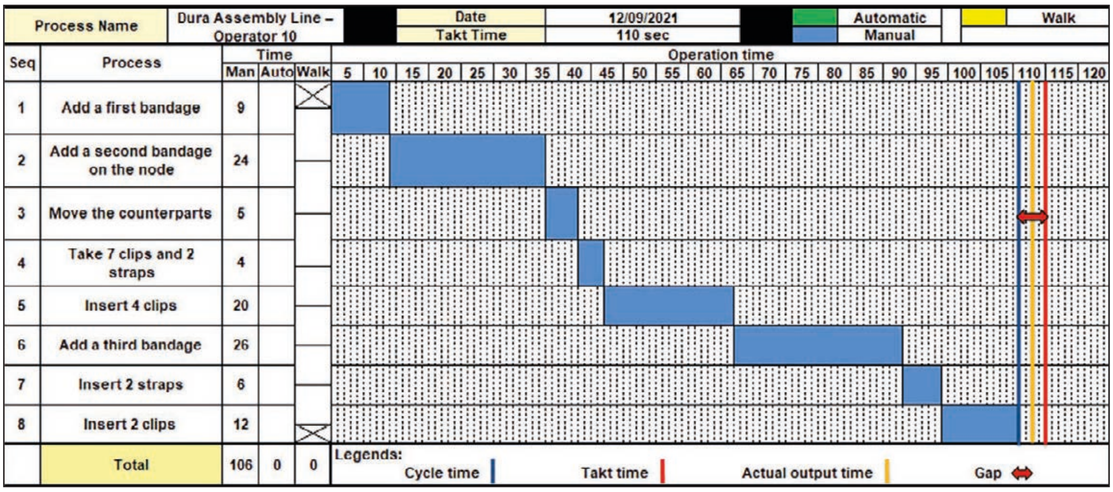
Legends: Cycle time | Takt time | Actual output time | Gap ⬌

Fig. 35. Standardized work combination table of operator 9 after improvement

We pass to the calculation of the ideal time of cycle ICT by the formula:

$$\text{ICT} = \text{PT} / \text{NOP}$$
$$\text{ICT} = 1468 / 14 \tag{7}$$
$$\text{ICT} = 104{,}86 \text{ s} \approx 105 \text{ s}$$

- Condition 5 – therefore, the distribution of operations and the balancing of the line must be done in such a way that the cycle times of the different stations must be included in the interval equal to [ICT-6, ICT+3] = [99,108].



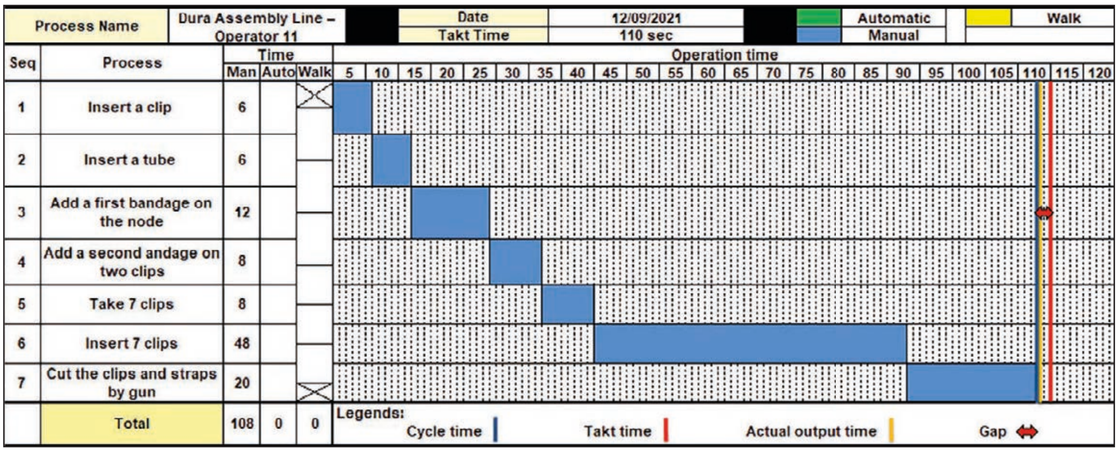
| Process Name | Dura Assembly Line – Operator 10 | Date | 12/09/2021 | Automatic 🟩 | Walk 🟨 |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual 🟦 | |

| Seq | Process | Time: Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Add a first bandage | 9 | | |
| 2 | Add a second bandage on the node | 24 | | |
| 3 | Move the counterparts | 5 | | |
| 4 | Take 7 clips and 2 straps | 4 | | |
| 5 | Insert 4 clips | 20 | | |
| 6 | Add a third bandage | 26 | | |
| 7 | Insert 2 straps | 6 | | |
| 8 | Insert 2 clips | 12 | | |
| | Total | 106 | 0 | 0 |

Operation time: 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Legends: Cycle time | Takt time | Actual output time | Gap ⇔

**Fig. 36.** Standardized work combination table of operator 10 after improvement



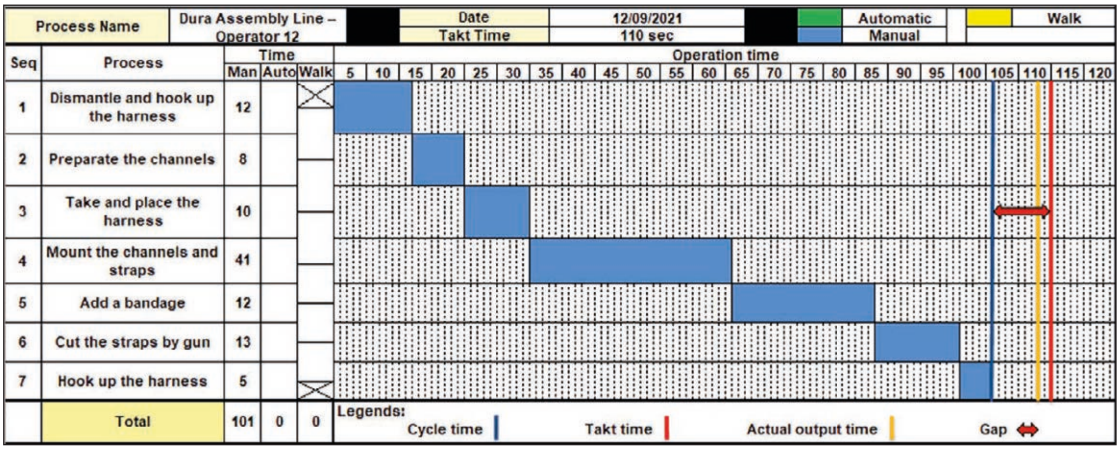
| Process Name | Dura Assembly Line – Operator 11 | Date | 12/09/2021 | Automatic 🟩 | Walk 🟨 |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual 🟦 | |

| Seq | Process | Time: Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Insert a clip | 6 | | |
| 2 | Insert a tube | 6 | | |
| 3 | Add a first bandage on the node | 12 | | |
| 4 | Add a second andage on two clips | 8 | | |
| 5 | Take 7 clips | 8 | | |
| 6 | Insert 7 clips | 48 | | |
| 7 | Cut the clips and straps by gun | 20 | | |
| | Total | 108 | 0 | 0 |

Operation time: 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Legends: Cycle time | Takt time | Actual output time | Gap ⇔

**Fig. 37.** Standardized work combination table of operator 11 after improvement



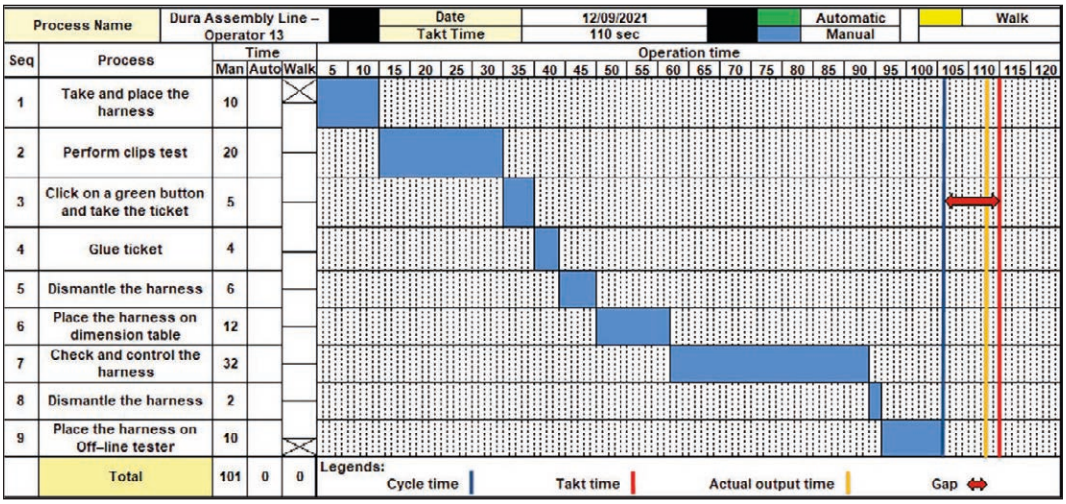
| Process Name | Dura Assembly Line – Operator 12 | Date | 12/09/2021 | Automatic 🟩 | Walk 🟨 |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual 🟦 | |

| Seq | Process | Time: Man | Auto | Walk |
|---|---|---|---|---|
| 1 | Dismantle and hook up the harness | 12 | | |
| 2 | Preparate the channels | 8 | | |
| 3 | Take and place the harness | 10 | | |
| 4 | Mount the channels and straps | 41 | | |
| 5 | Add a bandage | 12 | | |
| 6 | Cut the straps by gun | 13 | | |
| 7 | Hook up the harness | 5 | | |
| | Total | 101 | 0 | 0 |

Operation time: 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Legends: Cycle time Takt time Actual output time Gap ⇔

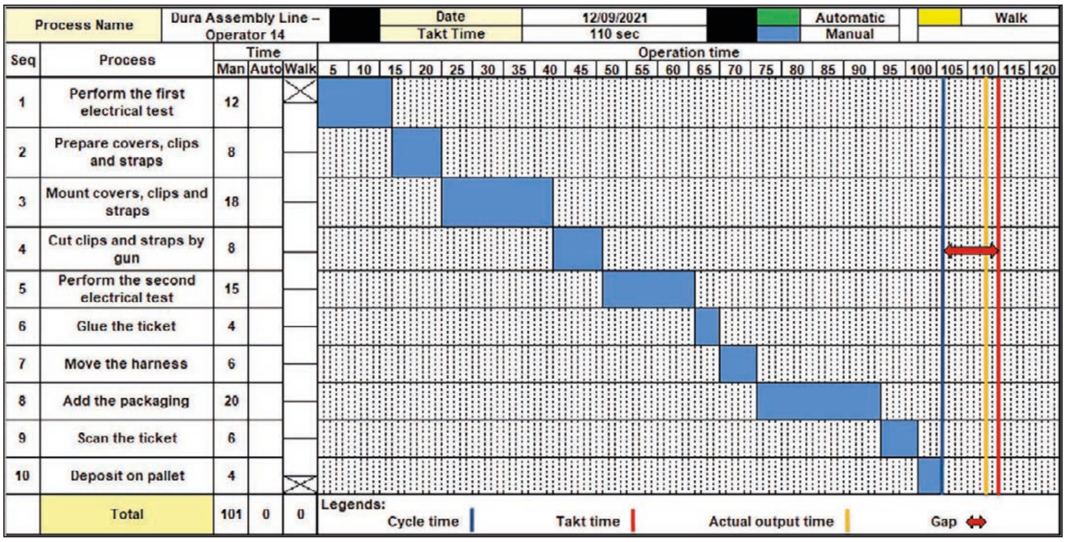
**Fig. 38.** Standardized work combination table of operator 12 after improvement



| Process Name | Dura Assembly Line – Operator 13 | Date | 12/09/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Take and place the harness | 10 | | |
| 2 | Perform clips test | 20 | | |
| 3 | Click on a green button and take the ticket | 5 | | |
| 4 | Glue ticket | 4 | | |
| 5 | Dismantle the harness | 6 | | |
| 6 | Place the harness on dimension table | 12 | | |
| 7 | Check and control the harness | 32 | | |
| 8 | Dismantle the harness | 2 | | |
| 9 | Place the harness on Off–line tester | 10 | | |
| | Total | 101 | 0 | 0 |

**Fig. 39.** Standardized work combination table of operator 13 after improvement



| Process Name | Dura Assembly Line – Operator 14 | Date | 12/09/2021 | Automatic | Walk |
|---|---|---|---|---|---|
| | | Takt Time | 110 sec | Manual | |

| Seq | Process | Time Man | Time Auto | Time Walk |
|---|---|---|---|---|
| 1 | Perform the first electrical test | 12 | | |
| 2 | Prepare covers, clips and straps | 8 | | |
| 3 | Mount covers, clips and straps | 18 | | |
| 4 | Cut clips and straps by gun | 8 | | |
| 5 | Perform the second electrical test | 15 | | |
| 6 | Glue the ticket | 4 | | |
| 7 | Move the harness | 6 | | |
| 8 | Add the packaging | 20 | | |
| 9 | Scan the ticket | 6 | | |
| 10 | Deposit on pallet | 4 | | |
| | Total | 101 | 0 | 0 |

**Fig. 40.** Standardized work combination table of operator 14 after improvement

In fact, the method based on the 5 conditions requires us in this situation to eliminate 3 workstations and ensure that the cycle times of the remaining 14 workstations are included in the interval [99,108]. To do this, we have decomposed the process operations into small tasks lasting a few seconds and combined them once again, respecting both the required cycle time interval and the necessary chronology of the harness manufacturing process.

Hence, the process is redefined and the operations are distributed over 14 operators instead of 17, as shown in the following SWCT in Figures 27 to 40.

After having elaborated the new SWCT of the 14 stations of the DURA assembly line, we proceeded with the training of the 14 operators on the new manufacturing process and the sensitization towards waste in order to avoid the creation of operations with no added value. Then the new elaborated process was practically implemented.

## Control phase

After the implementation of the new process, we were able to ensure a balance between the workstations of the line by reconciling the cycle times, which are all inferior to the Takt time as mentioned during the capacity study and as shown in the Yamazumi chart in figure 37 below, which allows us to cover and satisfy the customer’s demand with the elimination of waste and especially the waiting times:

As for efficiency, the new value following the improvements is:

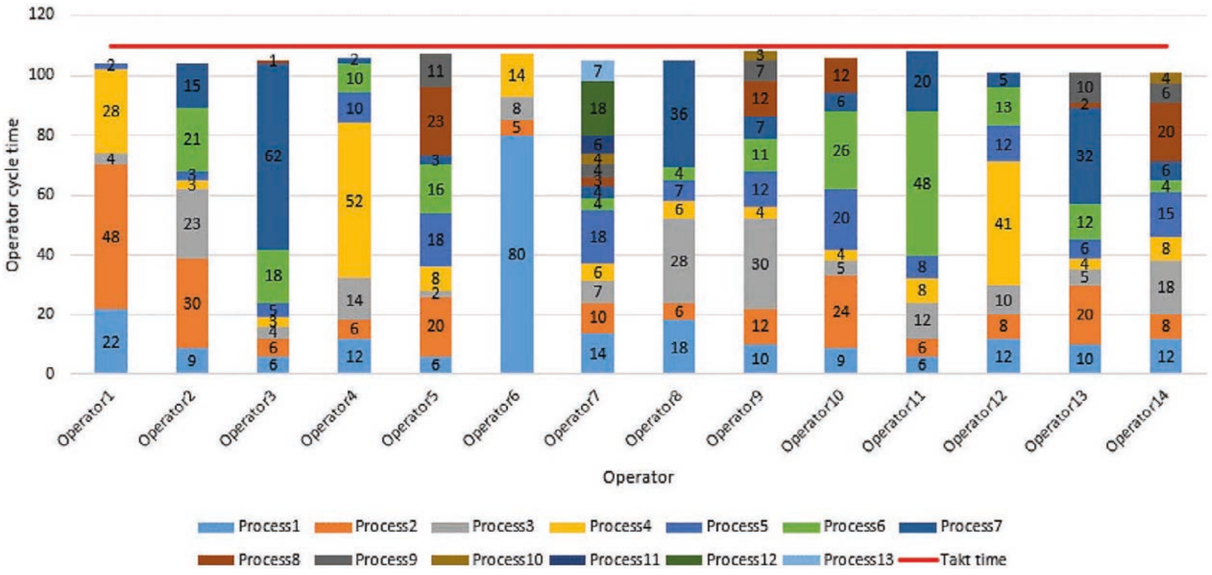


**Fig. 41.** Operator balance chart (Yamazumi chart) after improvement

$$\begin{gathered}\text{Efficiency} = (\text{Process Time} \,/\, \text{Takt time} \,* \\ *\ \text{number of operators}) * 100\% \\ \text{Efficiency} = (1468 \,/\, 110*14) \,* \\ *\ 100\% = 95\%\end{gathered} \tag{8}$$

Thus, we were able to improve the efficiency by about 17% from a value of 78% to 95%.

## DISCUSSION

The use of Lean Manufacturing tools has clearly shown its effectiveness, especially with the line balancing methodology based on the 5 conditions, which directly achieves the ideal situation for workstation balancing with maximum optimization of resources.

The application of the proposed methodology to the case study of the Dura wiring assembly line led to a 78% to 95% improvement in efficiency, thanks to a reduction in the number of operators from 17 to 14. This was only possible thanks to precise calculations of the optimum values to ensure perfect load balancing between workstations while respecting Takt time and ensuring that the customer's request was met in terms of lead time.

Indeed, the 5 conditions for balancing the load of the workstations remain general and valid for any line balancing problem or even for a capacity study of a new assembly line, as long as the choice of the values "a", "b" and "c" remains to be defined by the project team according to the complexity of the decomposition of the line operations and thus redistribute them according to the balancing requirements. On the other hand, this methodology will be less effective when the line contains machines with long cycle times that cannot be decomposed, in which case it is necessary to adapt the line to these cycle times.

Efficiency is a key performance indicator that is generally linked to production lines containing mostly manual operations or just a few machines, but the most important industrial indicator for automated and robotized production lines is the overall equipment effectiveness (OEE), the improvement of which will be the objective of future research work, especially with the emergence of new technologies in industry 4.0.

## CONCLUSIONS

In this article, we have studied a very common problem in industrial companies, namely the low value of efficiency due to the poor balancing of production line items.

After studying the literature, we found that most of the previous research consisted of approaches to reduce waste and balance the line based on iterative attempts until satisfactory results were achieved.

Then, we proposed a methodology based on the DMAIC approach and Lean Manufacturing tools, reinforced by line balancing techniques, especially the Yamazumi diagram, and supported in particular by the 5 conditions developed to achieve the ideal situation for balancing workstations in a direct way.

This method leads to a significant improvement in load balancing between the stations and, thus, to a considerable improvement in the efficiency of the assembly lines. This was observed in the case study of the efficiency of the Dura assembly line, which was improved from 78% to 95% thanks to the reduction in the number of stations on the line from 17 to 14 and thus the optimization of manpower and space used, as well as the balancing of the load of the stations with cycle times close to but not exceeding the Takt time, which ensures the capacity of the line to satisfy the customer's demand on time.

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