Time-Based Factory Efficiency Analysis | I.C. Engine Assembly Line

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Abstract

Cold test stations are commonly arranged as sequential processes along a complete engine production line. The production line consists of several stations for engine building purposes, and before the engine exits the production line it passes through different validation and testing stations, such as leak testing stations, piston protrusion stations (known as torque to turn stations), and cold test stations. Each of these stations has a sequence of operation that is performed automatically or semi-automatic with the support of an operator. The waiting time until the engine finishes the operation in one station is called “cycle time”. The longer the cycle time the less efficient the production line. Cold testing stations are considered the most complicated and time-consuming, yet important test stations for engine and powertrain development. The lengthy cycle time affects the overall efficiency of the production line. This paper investigates the problem of the cycle time difference between consequent stations and its effect on the overall efficiency of the factory. New techniques and operations research methods are introduced aiming to recover from such a manufacturing obstacle. This research is investigating the limitations of a manufacturing operation standpoint. Each test station is treated as a block that simulates the actual station, and the overall factory workflow is described. Time-based equations governing block time, idling time, and utilization of the system are introduced, and the factory efficiencies are calculated and compared. After identifying the problem, a practical solution is explained.

Keywords: Factory Analysis; Cold Test; Manufacturing; Engine Testing; Assembly Line; Production Line; Process Analysis; Process Enhancement; Cycle Time; Takt Time; Process Optimization.

1.0 Introduction

The automotive industry is increasingly leaning towards the implementation of automated machinery to reduce human error during the engine and powertrain development process, and to increase the production capacity to fulfill the market's high demand while keeping a low price per unit. The manufacturers' target is to deliver their products and materials quickly at a low cost without compromising the quality [1].

The vehicle assembly line uses semi and fully automated production lines. Behind the scenes of the vehicle assembly lines, there are engine and transmission assembly lines followed by validation and testing lines. The testing lines are production loops where the assembled engine is passing through to assure the quality of the assembly process and validate the product before using in-vehicle [2].

Engine testing production line is typically including test stations for testing various physical engine parameters that are directly related to engine performance.

Tested parameters are representing engine reliability, durability, and toughness. The engine testing loop includes a group of test stations in a sequential order, where the test stations are aligned in series or parallel to each other for process enhancement purposes. A standard testing loop includes a leak tester that confirms the engine seals to be free of water or oil leaks, and to ensure the pressure values in the engine passages meet the design requirements, and a "torque to turn" test station that tests the torque resistance generated by design clearances when spinning the crankshaft-pistons assembly.

The piston protrusion test station is dedicated to testing the assembled piston head geometry to meet the design clearance from the intake and exhaust valves. In addition, fuel line testing and electrical continuity testing are performed [3].

The included testing stations vary greatly depending on the engine type, the engine build location, and the confidence percentage/defect rate of the engine assembly line.

Parameters such as the output torque, breakaway torque, valves pressure, engine block vibrations, and engine horsepower are tested using a cold test station. Other parameters such as the pressure drop and fluid flow rate are tested using a leak test or power line test station [4,5].

Regardless of the testing type performed within the testing and validation process; each test station has a sequence of operation that is represented in terms of cycle time, and the testing loop is governed by an overall takt time to meet the daily output threshold.

For the maximum productivity of the validation process, each engine is loaded on a pallet that is transferred automatically on the production line to the next testing stations. Testing station's location along the production line, transfer speed between stations, and cycle time of each station is predetermined during the process design phase, which helps predict the target throughput and bottlenecks of the production line.

Production Plant metrics are an important factor to manage the health and the balance of the production process. Chen and others proposed rules of manufacturing effectiveness can be assured by identifying performance metrics as Bottleneck loading, On-Time Delivery, and WIP (work in progress). They proposed that the balance of the production line can be achieved by utilizing bottlenecks by avoiding starvation and material requirement planning [6].

Computer-Aided Software (CAD) is an efficient tool for optimizing the production design and calculating the expected throughput based on the current plant's parameters and design aspects using simulators, Statistical analysis, and lean optimization. These tools can be used to tune the designed parameters and enhance efficiency and productivity in production lines and supply chains [6-9].

This paper is examining the standard production line design of engine testing. Throughput governing equations were described, and the production line efficiency analysis was performed. The bottleneck stations were identified, and efficiency enhancement methodologies were proposed.

2.0 Production Line Structure

The design of the engine testing production line varies from one factory to another. The testing production line design depends on the number of testing stations included, the size of each testing station, the available space within the factory, and the production capacity planned [10]. The typical design layout consists of a series of testing stations in the simplest form. The need for a high-efficiency process demands a more complex line design to achieve the efficiency goals, which usually involves adding two or three stations of the same type in parallel or in series to reduce the cycle time and decrease the overall takt time.

$$\boldsymbol{T_K} = \frac{\boldsymbol{H}}{\boldsymbol{P}} \quad (1)$$

Where,

T_K: Theoretical Takt Time,

H: Available Daily Time [Minutes],

P: Daily Production Goal.

The illustrated production testing line in Figure 1 shows a simplified form of the actual production line, where the engine utilization direction, the process schematic, and the location of each testing station are shown. Table

1 shows the cycle time for each station and the utilization time (Travel Time) between each station and the next one.

Throughout the assembly and testing loops, the engine is loaded on a traveling pallet that is specifically designed to cruise on the conveyor belt during the assembly and testing process. During the testing process, the engine enters the automated and semi-automated testing stations and latches with specialty arms, and the engine gets positioned to the required angle to complete the test requirements. After finishing the test sequence of operation, the engine is loaded back to the pallet and cruises on the conveyor belt to the next testing station. The process is repeated until the engine passes all the testing sequences and gets validated for installation on the vehicle. The pallet speed (production line speed) is standardized to move at 15 km/h in a typical factory. The pallet travel time is used instead of speed for simplifying utilization calculations, where the distance between the testing stations is predefined by design.

Table 1: Testing Line properties.

Testing Station	Cycle Time [s]	Utilization Time [s]	MTBF [Hr]	MTTR [Min]	Reject Rate
Leak Test	32	15	4000	60	0%
Cold Test	100	15	4000	60	0%
Protrusion Test	32	15	4000	60	0%

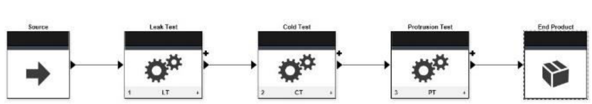

Figure 1 Testing Production Line Illustration.

2.1 Ghost Efficiency Dilemma

The daily production target and the daily production hours are predefined based on the financial and the resources allocation target of the factory; Hence the theoretical takt time is calculated to meet that target.

Running a testing patch to confirm that the production parameters are meeting the expected output is a good practice for avoiding unnecessary delays in the production launch.

The daily production target is carefully set based on the size of the production line, the number of stations included, the cycle time of each station, the utilization time between each station, and the takt time. In contrast, the production line design and stations cycle time are built around meeting the daily production target of the factory, while keeping in mind the limitations of achieving the testing sequence within the designed cycle time and the available space in the factory to build that production line.

The ideal production line assumes that each testing station is working at full capacity and the efficiency of each station is 100%, which assumes the factory overall efficiency to be 100%. In actual factory settings even using the best production line designs and the most durable testing stations; achieving a high-efficiency factory is a more complicated task than designing the production flow and allocating the right sequence for testing stations along the line. Each testing station is performing a set of tasks that are important to validate a certain physical property of the product. A fully automated testing station certainly performs repeatable results and better control over testing time and cycle time than a semi-automated station, however, each station is rated by the manufacturer with MTBF (Mean Time Before Failure) and MTTR (Mean Time to Repair); which challenges the factory's efficiency on the long run by machine failures and repair time to get it up and running. Some testing stations and semi-automatic testing stations in specific need setup time and machine operator interference, either each time the station is receiving a pallet or every certain number of iterations.

Ensuring the highest efficiency rate of the factory demands control over all the stations and pallets in terms of pallet release from the source, pallet speed, cycle time, pallet trafficking, and timing at each station.

Referring to Table 1 and Figure 1, Both "Leak Test" and "Protrusion Test" stations are allocating lower cycle time (32 seconds each) than the "Cold Test" (100 seconds). While the pallet utilization between stations is equal (15 seconds), running a single day production simulation with 800 units/(16 hrs.) day as a target output with a takt time of 1.2 minutes showed that the "Cold Test" station is the most efficient testing station with 99.92% efficiency (Figure 2) even though technically it is the least efficient station as calculating the nominal production rate (PR_n) of each station in isolation of the production line system, as shown in Table 2.

Table 2: Single Day Factory Efficiency Analysis.

Testing Station	Cycle Time [s]	Production Rate [unit/hr]
Leak Test	32	112.5
Cold Test	100	36
Protrusion Test	32	112.5

$$\mathbf{PR}_{n} = \frac{1}{Tc} \qquad (2)$$

Where,

PR_n: Nominal Production Rate.

Tc: Cycle time of station.

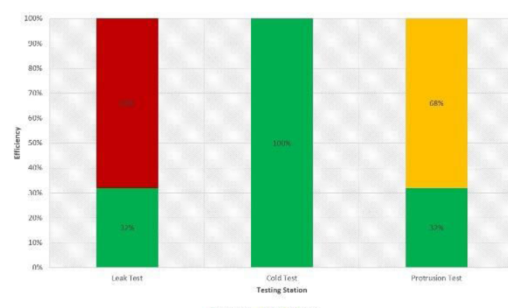

Figure 2 Production Line Efficiency Simulation.

The simulation is built on the assumption that the daily production target is the main goal, and the production line building time and stations setup time are ignored. Machine failure and repair times are ignored. The pallet transportation time between each station is assumed to be 15 seconds. The source is assumed to have unlimited stock of material and a pallet is being introduced each second to the production line while the line is not blocked with zero variability, and all stations are sequentially connected in series. The source is normally distributing material with fixed priority for output routing.

The factory ran for 22 hours and 15 minutes to achieve the daily production target of 800 units. The "Cold Test" is identified as the most efficient station with 100% efficiency, while the "Protrusion Test" was the least efficient in line with 32% efficiency. "Leak Test" was not identified as a low-efficiency station even though the efficiency is calculated as 32%. The utilization traffic percentage between each station and the next one is represented in Figure 3, where the pallet transportation between the source and the leak test, and between the leak test and the cold test is blocked while the routes from the cold test to the end of the line are idling and starving.

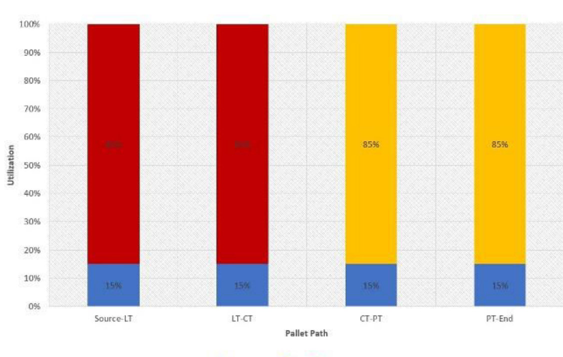

Figure 3 Pallet Utilization Simulation.

The efficiency of each station is depending on the cycle time of the station relative to the other stations, the cycle time relative to the system's takt time, utilization efficiency, and the daily production target. Ghost efficiency is demonstrated where the efficiency changes for the same station based on the perspective of the factory target, the station's properties, and the production line layout.

2.2 Production Line Efficiency Analysis

The efficiency of any factory should be time-based regardless of the actual engineering implementation and the technologies deployed to that factory. uptime, downtime, idle time, blocked time, and setup time of each station and for the whole system provide a simple time-based yet effective insight of the individual and overall efficiency while easily identifying inefficiencies and bottlenecks.

The production line efficiency can be better represented using a set of time-based Equations. The time-based Equations are beneficial in creating a common reference line for the operations and deliverables through a production period. The time spent idling, downtime, setup time, or blocked can be marked as inefficient or wasted production time, while the time spent up and running while performing the designed sequence is identified as an efficiency.

The time required for the pallet to reach a station is known as "Feed Time" T_j and can be described as a time-based mathematical expression using Eq. 3.

$$\boldsymbol{T_j} = \sum_{\boldsymbol{0}}^{\boldsymbol{j-1}} (\boldsymbol{\lambda_{j+1}} + \mu_{\boldsymbol{j}})$$
(3)

Where,

$\boldsymbol{T_j}$: Feed Time,

$\boldsymbol{\lambda_{j+1}}$: Pallet Travel Time,

$\mu_{\boldsymbol{j}}$: Station Cycle Time.

Blocking time at a certain station depends on how many pallets are introduced to the production line, the cycle time of each station, and the pallet travel time. Those relations can be represented in terms of travel time and cycle time as in Eq. 4.

$$\boldsymbol{B_j^i} = \sum_{j=1}^{n} (\boldsymbol{B_j^{i-1}} - \boldsymbol{\lambda_j} + \mu_j + \boldsymbol{\lambda_{j-1}} - \mu_{j-1})$$
(4)

Where,

$\boldsymbol{B_j^i}$: Blocking Time of pallet i at

station j,

$\boldsymbol{\lambda_j}, \boldsymbol{\lambda_{j-1}}$: Pallet Travel Time,

$\mu_{\boldsymbol{j-1}}, \mu_{\boldsymbol{j}}$: Station Cycle Time.

Any station that is idling due to the blocked pallets at preceding stations is declared as a starving station. Starving (Idling) time can be represented using the expression in Eq. 5.

$$\boldsymbol{S_j^i} = \sum_{\boldsymbol{j=2}}^{\boldsymbol{n}} \left(\boldsymbol{S_j^{i-1}} - \mu_j + \boldsymbol{\lambda_j} + \mu_{\boldsymbol{j-1}} - \boldsymbol{\lambda_{j-1}}\right)$$

$: j \geq 2, i \geq 2$ (5)

Where,

$\boldsymbol{S_j^i}$: Starving (Idling) Time at station j for pallet i,

$\boldsymbol{\lambda_j}, \boldsymbol{\lambda_{j-1}}$: Pallet Travel Time,

$\mu_{\boldsymbol{j}}, \mu_{\boldsymbol{j-1}}$: Station Cycle Time.

The summation in Eq.5 is starting from station 2 since station 1 does not starve. Station 1 is directly connected to the inventory source. The starving value should be positive, and whenever the starving does not exist; the value at that station would be zero or negative.

Theoretical takt time is described in Eq.1 while the actual takt time can be represented in terms of Equation 3 as shown in Eq.6.

$$T_K|A = \frac{T_j}{P_a} \qquad (6)$$

Where,

$T_K|A$: Actual Takt Time,

T_j: Feed Time,

P_a: Actual Produced Units.

The actual takt time provides an opportunity to evaluate the production rhythm in real-time and identify defects during various periods of the production day.

The productivity of each station or for the overall factory can be calculated in terms of feed time, blocking time, and daily available hours using Eq.7 below.

$$\boldsymbol{P} = \frac{\boldsymbol{D_T}}{\sum_1^N \sum_j^{j-1} (\boldsymbol{T_j} + \boldsymbol{B_j})} \tag{7}$$

Where,

P: Productivity [%],

D_T: Available daily time [seconds],

T_j: Feed Time [seconds],

B_j: Blocking Time [seconds].

N: Iteration number.

j: Station number.

The number of units produced at a certain time can be identified as instantaneous productivity, where the number of units produced at a certain time is a function of time spent relative to the sum of feed time and blocking time as extracted in Eq.8, 8' and 8''.

$$\boldsymbol{U(t)} = \mathbf{lim}\Big[_{t\to 0} \sum_{t=0}^{\infty} \frac{\mathbf{1}}{\boldsymbol{T_j} + \boldsymbol{B_j}}\Big] \boldsymbol{\delta t}$$

(8)

Eq.8 can be rewritten in the form shown in Eq. 8'.

$$\boldsymbol{U(t)} = \int_{\mathbf{0}}^{\infty} \frac{\boldsymbol{\delta t}}{\boldsymbol{T_j} + \boldsymbol{B_j}} \tag{8'}$$

Which can be simplified as Eq. 8''.

$$\boldsymbol{U} = \frac{\boldsymbol{t}}{\boldsymbol{T_j} + \boldsymbol{B_j}} \tag{8''}$$

Where,

U: Instantaneous productivity [units produced].

t: time consumed [seconds].

T_j: Feed Time [seconds].

B_j: Blocking Time [seconds].

After defining equations 3 through 8'' we can define the factory overall efficiency as a relation between the units produced per unit time relative to the targeted daily products.

$$E = \frac{U}{G} \tag{9}$$

Where,

U: Units produced per time cycle.

G: Goal (number of products targeted).

An actual production rate may be needed to find the rate at which the products are released. The actual production rate can be represented in terms of available time, production run time, and units produced.

$$PR_A = \frac{\boldsymbol{D_T}}{R} \times U_A \tag{10}$$

Where,

D_T: Available daily time [seconds].

R: Actual production runtime [seconds].

U_A: Actual units produced per time cycle.

Actual units produced follow Eq. 11.

$$U_A = \frac{\boldsymbol{R}}{L} \tag{11}$$

Where,

R: Actual production runtime [seconds],

L: Lead Time (Time for a single pallet to finish the line).

And run time can be represented as a function of feed time as shown in Eq. 12.

$$R = \sum_1^P \sum_{\boldsymbol{0}}^{\boldsymbol{j-1}} (\boldsymbol{\lambda_{j+1}} + \mu_{\boldsymbol{j}}) \tag{12}$$

Where,

R: Actual production runtime [seconds],

P: Number of daily produced products.

The ultimate production time without any utilization can be calculated using Eq. 13.

$$P_U = \sum_0^P \sum_{\boldsymbol{1}}^{\boldsymbol{j}} (\mu_{\boldsymbol{j}}) \tag{13}$$

3.1 Efficiency Equations Proofs

This paper proposed several time-based equations that can be conveniently used to measure the factory efficiency based on the production time consumed and produced products per time frame assigned by the analyst.

Governed Equations results are compared with the manual calculations to prove the accuracy of the associated production values.

3.1.1 Feed Time Equation

The feed time governed in equation 3 represents the time needed for the pallet and product to utilize from the source into the targeted station (j).

Assume we have a production line with three stations as shown in Figure 4. Stations cycle time and pallet utilization times are shown in Table 3.

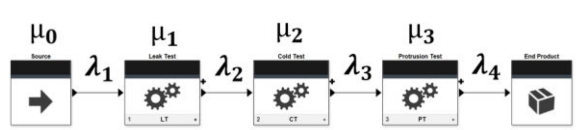

Figure 4 Simplified Production Line.

Table 3: Cycle time and utilization values.

j	**Cycle Time (μ_j) [s]**	**Utilization (λ_j) [s]**
1	32	15
2	100	15
3	32	15
4	0	15

Now let's calculate the feed time at station 1 (Leak Test). Visually you can calculate that by adding the pallet transfer time from the source to station 1 which Equals 15 seconds. Using equation 3 we substitute the values of λ_j and μ_j.

$$T_j = \sum_0^{j-1}(\lambda_{j+1} + \mu_j)$$

And $T_1 = \sum_0^{0}(\lambda_{j+1} + \mu_j)$

So $T_1 = \lambda_1 + \mu_0$.

Which leads to $T_1 = 15\ seconds$.

The same approach can be used to find T_3:

$$T_3 = \sum_0^{2}(\lambda_{j+1} + \mu_j)$$

Then $T_3 = \lambda_1 + \mu_0 + \lambda_2 + \mu_1 + \lambda_3 + \mu_2$

So $T_3 = 15 + 0 + 15 + 32 + 15 + 100$

$T_3 = 177\ seconds$, which is identical to the answer obtained by adding the times manually.

This equation becomes handy when having a complicated production line that requires calculating the feed time at a certain station along the line.

3.1.2 Blocking Time Equation

Blocking time is represented in Equation 4. Where it calculates the time that the next pallet spent waiting for the preceding pallet to get processed in the following station.

The proof of blocking time Equation can be achieved using Figure 4 as a reference and manually analyzing the blocking time of pallet (i) at the station (j) for a certain production cycle.

Visual blocking analysis for pallet 2 at station 1 shows that there should be 17 seconds of blocking time between the source and Leak Test station (station 1), where the first pallet released from the source will utilize for 15 seconds to reach station 1 then it will start the processing in that station for 32 seconds, and the moment pallet 1 enters station 1; Pallet 2 is released which utilizes for 15 seconds to reach station 1 and wait for 17 seconds (Blocking Time) until pallet one processing is complete and so on.

Using Eq. (4) The Blocking time for station 1 would be as follows:

$$B_j^i = \sum_{j=1}^{n}\left(B_j^{i-1} - \lambda_j + \mu_j + \lambda_{j-1} - \mu_{j-1}\right)$$

So

$$B_1^2 = B_1^{2-1} - \lambda_1 + \mu_1 + \lambda_{1-1} - \mu_{1-1}$$

Then

$$B_1^2 = -\lambda_1 + \mu_1 + \lambda_{1-1} - \mu_{1-1}$$

Substituting numbers from Table 3:

$$B_1^2 = -15 + 32 + 0 - 0$$

Which makes $B_1^2 = 17\ seconds$ matching the manual blocking time calculation demonstrated earlier.

Calculating blocking time expected at stations 2 and 3 can be proofed using the same approach.

Since the blocking time is always a positive value; A negative value means that the station is not blocked but starving, hence we can assume the blocking time at that station is zero.

3.1.3 Idling Time Equation

The starving (Idling) equation can be proven by comparing the manual calculations with the Equation outcome in a similar approach used to prove the blocking equation.

In the idling equation, we skip the first station since it is directly connected to the source that is assumed to always be ready to supply the demand of station 1.

Station 2 starvation can be manually estimated by tracing the first and second pallet in Figure 4 at station 2. The first pallet reaches station 2 and the second pallet reaches station 1 at the same time. Pallet 1 spends 100 seconds in station 2, while pallet 2 spends only 32 seconds in station 1 then travels for 15 seconds and reaches station 2 which requires 53 seconds to release pallet 1, which means the station is blocked and the starving is zero seconds.

Using Equation 5 we can calculate the starving time at stations 2 and 3:

$$S_j^i = \sum_{j=2}^{n} \left(S_j^{i-1} - \mu_j + \lambda_j + \mu_{j-1} - \lambda_{j-1} \right)$$

$$S_2^2 = S_2^{2-1} - \mu_2 + \lambda_2 + \mu_{2-1} - \lambda_{2-1}$$

So $S_2^2 = -68\ seconds$ which means that station 2 is not starving but blocked, so we can declare $S_2^2 = 0$.

In the same manner, the starving of pallet 2 at station 3 Equals:

$$S_3^2 = 68\ seconds$$

Using the same logic,

$$S_3 = 53\ seconds$$

So, station 3 is starving for 68 seconds before the next pallet is received.

4.0 Results

The overall efficiency of the factory is accurately calculated by considering the full design of the production line and not focusing on each station separately. Time-based representation of the factory performance helps identify the deficiencies along the production line and helps avoid the ghost efficiency dilemma.

The production line shown in figure 4 identified station 2 to be the least efficient station due to its long cycle time relative to the preceding and following stations and to the factory takt time.

To reduce the blocking time and idling time of the production line and consequently increase the factory overall efficiency; Station 2 (Cold Test station) was broken down into 3 sub-stations each having a cycle time of 33 seconds. Station 2 has a sequence of testing steps that takes 100 seconds to complete. Testing steps were distributed over 3 sub-stations as shown in figure 5. This approach helps maintain the pallet flow with high efficiency while reserving the engineering test sequence required for each product.

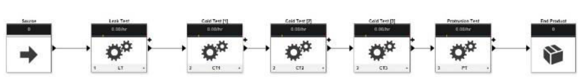

Figure 5 Redesigned Production Line.

The efficiency and utilization simulation results shown in figures 6 and 7, clearly confirm that the factory efficiency has a major enhancement compared to the simulation results of the previous production line design shown in figures 2 and 3.

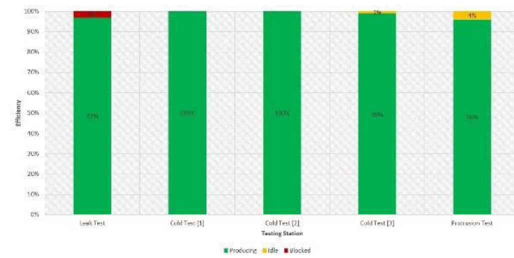

Figure 6 Enhanced Efficiency Design.

The efficiency results in figure 6 are showing that the Leak Test station is producing 97% of the production time compared to 32% production time with the original design. The Leak Test is blocked only 3% of the time compared to 68% with the original design, which makes the Leak Test station 67% more efficient with the proposed design over the original design. The Cold Test sub-stations are operating with 100% efficiency, which reduced the idling time for the Protrusion test station, which raised its efficiency to 96%.

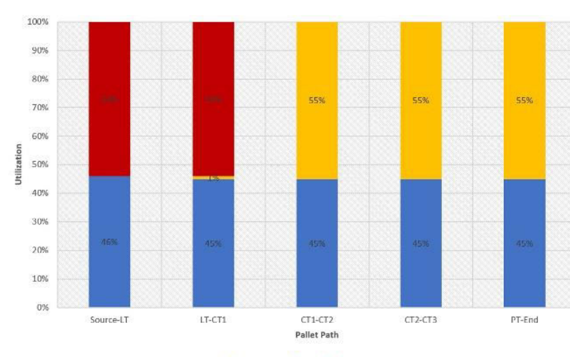

Figure 7 Enhanced Utilization Design.

Utilization performance is enhanced due to redesigning the production line and balancing the testing station's cycle times to be near to 33 seconds which is the takt time for the daily production goal of 800 units.

5.0 Conclusions

Assembly lines use semi and fully automated production stations. Each station has a different cycle time than the preceding ones. Single routed production lines are connecting all testing stations in series which makes the overall factory efficiency strongly depends on the efficiency of each station and the efficiency of product utilization along the production line.

Single routed production lines are more likely to have bottlenecks stations that are blocking the production flow. Blocking can be avoided in production lines by either creating a parallel production line for the high cycle time stations or by distributing the pallets into these stations. Another way of avoiding single routed blockage is by splitting the sequence of high cycle time stations into several stations where each handles a part of the station’s sequence with a cycle time value close to the factory takt time.

Efficiency can be easily miscalculated if each station is evaluated individually while taking the station’s uptime as a measurement of efficiency. A station with 100% uptime could be the bottleneck of the system and cause other stations' total uptime to decrease which creates a ghost efficiency dilemma.

Time-based representation of utilization time, starving time, and blocking time is an efficient way to analyze the overall factory efficiency relative to time consumed and units produced.

Future research is expected to study the impact of splitting high cycle time stations in series versus adding parallel stations. Studying the best approach to achieve factory optimum balance and the effectiveness of creating a time-based design of all stations while avoiding starving or blocking along the production line through pallet travel optimization.

Declarations

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Code availability Not applicable.

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Availability of data and material The data that support the findings of this study are available from the corresponding author upon reasonable request.

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