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Analysis of Possible Improvement Actions in an Automatic Assembly Line

Relatore : Prof. Tullio Antonio Maria Tolio
Correlatore : Dr. Maria Chiara Magnanini

Tesina di Laurea Magistrale di:
Yovita Sugionoputri
Matricola 940484

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“ *Therefore I say to you: Whatever things you ask, when you pray and believe, you will receive them, and you will have them.* “

- Mark 11:24 -

Abstract

Continuous measurement, evaluation, control, and improvement of the manufacturing system performance play an important role to support an agile, effective, and efficient manufacturing system to overcome challenges from globalization, demand fluctuation, and uncertain worldwide situations. Fluid-O-Tech is an Italian market leader of volumetric pumps and systems for liquids that uses Overall Equipment Effectiveness (OEE) to measure the performance of its automatic assembly line Generation 2 that produces micro gear pumps. The current performance of Generation 2 is characterized by a cycle time of 11, 5 sec/unit and an average throughput rate of 250,21 units/hour. The company aims to find the bottleneck problems and possible improvements so that a throughput rate of 300 units/hour can be achieved to satisfy increased demand in recent months.

Observations, data collection, and data analysis are performed to evaluate the performance of Generation 2. A deeper and quantitative analysis is conducted using: a continuous approximation of discrete deterministic model developed by Magnanini and Tolio (2017) using *Matlab* and Plant Simulation model using Tecnomatix Plant Simulation by Siemens. The main issues discovered are the quality of the available information and the low availability and performance of the assembly line. The suggested improvement actions are categorized as data collection, organizational, production control, and reconfiguration.

Keywords: Performance Evaluation, Overall Equipment Effectiveness (OEE), A Continuous Approximation of The Discrete Deterministic Model, Production Data, Micro-downtime, and Bottleneck Station.

Abstract

La misurazione, la valutazione, il controllo e il miglioramento continui delle prestazioni del sistema di produzione svolgono un ruolo importante per supportare un sistema di produzione agile, efficace ed efficiente per superare le sfide della globalizzazione, l'oscillazione della domanda e le situazioni incerte in tutto il mondo. Fluid-O-Tech è un leader del mercato italiano di pompe volumetriche e sistemi per liquidi che utilizza l'Overall Equipment Effectiveness (OEE) per misurare le prestazioni della sua linea di assemblaggio automatica Generazione 2 che produce pompe a micro ingranaggi. Le attuali prestazioni della Generazione 2 sono caratterizzate da un tempo di ciclo di 11,5 sec/unità e una velocità di trasmissione media di 250,21 unità/ora. L'azienda mira a trovare i problemi riguardanti il collo di bottiglia e possibili miglioramenti in modo da raggiungere una velocità di trasmissione di 300 unità/ora per soddisfare l'aumento della domanda negli ultimi mesi.

Osservazioni, raccolta dati e analisi dei dati vengono eseguite per valutare le prestazioni della Generazione 2. Viene condotta un'analisi più approfondita e quantitativa utilizzando: continuous approximation of discrete deterministic model sviluppato da Magnanini e Tolio (2017) utilizzando Matlab e Plant Simulation model utilizzando Tecnomatix Plant Simulation di Siemens. I principali problemi rilevati riguardano la qualità delle informazioni disponibili e la scarsa disponibilità e prestazioni della catena di montaggio. Le azioni di miglioramento suggerite sono classificate come raccolta dati, organizzazione, controllo della produzione e riconfigurazione.

Parole chiave: Valutazione di performance, Overall Equipment Effectiveness (OEE), Continuous Approximation of The Discrete Deterministic Model, Dati di produzione, Micro-fermata, e Stazione dei colli di bottiglia.

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Chapter 1

Introduction

1.1 General Industrial Context

In recent years, the emerging trend of globalization has given companies and industries much more chances to grow. At the same time, the opportunity to grow makes the market becomes more competitive than before. Consequently, companies and industries have to orient their overall business strategy towards an optimum global perspective to stay long.

A way to sustain the intense competition within the market is through the market presence in different countries. However, this kind of penetration leads to a more complex operational and supply chain strategy. Product demand fluctuation and uncertain worldwide situations require an agile, effective, and efficient manufacturing system. A manufacturing system itself can be defined as the set of machines, transportation elements, computers, storage buffers, people, and other items used together for manufacturing (Magnanini, 2015). An agile, effective, and efficient manufacturing system could be achieved by using more advanced technology and automation (and it is true in the case of high volume production), reliable production planning and supply chain, good organizational teamwork, and an integrated information system. These aspects can increase the visibility of business and production processes.

Moreover, continuous control and improvement within the manufacturing system are also crucial aspects in maintaining a company's competitive advantage and facing challenges. A performance measurement tool that has gained more popularity within industries is the so-called Overall Equipment Effectiveness (OEE). This tool is derived from the Total Productive Maintenance (TPM) concept and was first used by Seiichi Nakajima in 1989. OEE measurement considers three main aspects: availability, performance, and quality of product produced. These three main aspects measured the effectiveness of the equipment used in the system affected by six (seven as in more recent literature) losses.

Theoretically, the best practice OEE in a discrete manufacturing plant is 85% with a notion of 90% availability, 95% performance, and 99% quality. Meanwhile, in continuous process industries, the best practice OEE considered is 95%, with 98% availability, 98% performance, and 99% quality. With the help of such a tool, not only the performance of the manufacturing system can be evaluated, but also the possible improvement can be considered since a more profound analysis could highlight any poor machine's performance within the system. As a result, product quality and delivery reliability can be achieved to sustain in the competitive market.

1.2 Introduction to Fluid-O-Tech Case

The thesis work is based on a project carried out with the company Fluid-O-Tech. The project was conducted from December 2020 until July 2021. In this section, information about the company and the case will be presented.

1.2.1 Company Profile

Fluid-O-Tech is a market leader made in Italy of volumetric pumps and systems for liquid. Established in 1976 by Vittorio Andreis, Fluid-O-Tech serves demanding applications of various industries, such as automotive, industrial, food services, medical, and many more. With more than 70 years of experience, the company designs and produces several types of pumps. For instance: gear pumps (internal and external), peristaltic pumps, rotary vane pumps, solenoid pumps, electronic valves, and thermostatic valves are grouped based on the technology adopted.

Starting in 1991, the company has expanded its market by establishing Fluid-O-Tech Inc. in the United States. It has direct operations in Italy, United States, United Kingdom, China, and Japan. Their core values: customer, excellence, people, passion, sustainable growth, independence, no-waste, and continuity, are their fundamental basis in keeping on constant researches and innovations towards excellent quality in the global market. The company also has a solid international network which is proven by 240 partners and 120 suppliers worldwide to cover and satisfy the customers' needs in 50 countries.

Fluid-O-Tech's factory plant in Corsico, Italy, has four main areas: machining, assembling, testing, and warehousing. Most of the processes in the machining department (i.e., milling, cutting, drilling, grinding, toothing, and cleaning) are done automatically with one operator for each station. The machining department is connected by the Automatic Guided Vehicle (AGV) to the warehouse area that stores raw material, Work in Progress (WIP), and the final products. Besides the AGV, the warehouse department is also supported by manual and semi-automatic, 3-axis forklifts for the picking system. There are other two automatic vertical storage systems for spare parts used within the machining department.

The quality test of the final products is done 100% internally by the company. Thus, it has two areas of testing, which are equipped with testing machines that provide results in micron. There are three main departments within the assembling area: manual (with conveyor), semi-automatic, and automatic. The assembly parts come from 50% in-house and 50% outsource. Furthermore, to support the integration and visibility of the whole process, it uses Manufacturing Execution System (MES. Additional technologies such as material code detection and smart tooling are used to support the production process. As for the performance measurement itself, the company is using OEE.

1.2.2 The Use Case

The focus of the project is related to the assembly department, specifically the automatic assembly line. At the Corsico plant, Fluid-O-Tech has two automated assembly lines: Generation 2 and Generation 3. Both of them produce micro gear pumps for the automotive industry but with different materials for the body and different cycle times of the system. Generation 2 produces metallic body micro gear pumps with a cycle time of 11,5 sec/unit. Meanwhile, Generation 3 produces plastic body micro gear pumps with a 9 sec/ unit cycle time.

The company has only one assembly line for each generation, and both of them are handled by two operators with one chief operator (three people in total) in each shift. They work three shifts per day with 7,5 hours/ shift and five days/ week. At the beginning of each week (i.e., the first shift on Monday), the operators will perform a scheduled cleaning with a duration of more or less two hours. Besides the weekly cleaning, the operators are also responsible for loading and unloading the pallets of material into the vertical storage in the system; and doing corrective maintenance for any stop or failure in the system.

In recent months, there has been an unexpected demand growth for the metallic gear pump produced by Generation 2. In detail, Generation 2 produces two micro gear pumps: 11-00-01 (with premium type 11-00-06) and 11-00-02 (with premium type 11-00-05). The later ones contribute to more than 85% of the total demand. In the present state, on average, the throughput rate of the line is 250,21 units/ hour. In a “normal” operating condition (i.e., a condition where there is no significant or long failure or stoppage), the throughput rate of the line is 290 units/ hour. The introduction of demand growth made the company set a target throughput rate of 300 units/ hour.

As mentioned in the previous section, the company uses OEE as a performance measurement tool. Figure 1.1 presents the OEE achievement of Generation 2 from November 2020 until March 2021. The OEE results were relatively low compared to the theoretical best practice OEE for a discrete manufacturing plant. Remarkably, the results in terms of availability and performance are pretty fluctuating while the quality results achieved are more stable.

Month	H Macchina ON	H Macchina OFF	H Macchina Fermi	QTA Buoni Dichiarati	QTA Scarto Dichiarati	QTA Total	Disponibilità	Prestazione	Qualità	OEE
Nov-20	465,81	45,20	41,67	106.150	2.043	106.192	90,38%	91,13%	98,11%	80,81%
Dec-20	324,87	66,63	55,91	70.975	1.377	71.031	83,52%	85,05%	98,10%	69,68%
Jan-21	357,66	114,21	108,96	87.525	929	87.634	74,39%	91,24%	98,95%	67,17%
Feb-21	386,18	71,53	38,21	98.846	1.842	98.884	90,39%	87,68%	98,17%	77,80%
Mar-21	463,22	71,21	45,23	197.498	2.181	197.543	90,54%	87,06%	98,91%	77,97%

Figure 1.1 Company's OEE achievement in November 2020 – March 2021

Apart from that, a dynamic system with buffers on the conveyor characterizes Generation 2. If a failure happens, the propagation effect will likely affect the whole system after some time. If the failure occurs at the upstream machines, the downstream machines will starve after some time because the buffer is empty. On the other hand, if the failure happens in the downstream machines, the upstream machines will be blocked and produce a long queue of pallets on the conveyor, as is shown in Figure 1.2. Eventually, this condition could cause capacity loss and affect the overall OEE performance.

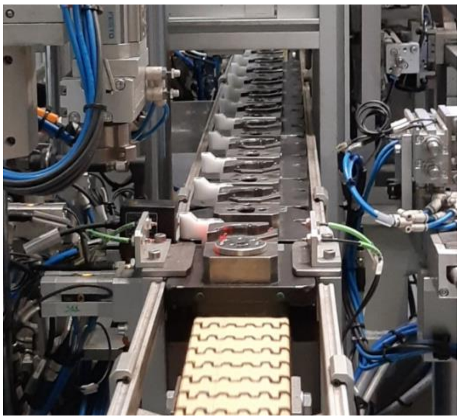


Figure 1.2 A long queue between Area 300 and 200 due to a long failure in Area 200

1.2.3 Problem Statement

The current condition of Generation 2 is characterized by a cycle time of 11,5 seconds/ unit (longer than Generation3), low results of monthly OEE, and an average throughput rate of 250,21 units/ hour. This condition cannot satisfy the company's target throughput rate of 300 units/ hour. Hence, it is expected to answer the main question: *What are the main issues within the assembly line Generation 2 that prevent the assembly line from achieving its target throughput rate?*

1.3 Objective

Considering the case described and question that arose in the previous section, the objectives of this thesis are:

1. To evaluate the performance of assembly line Generation 2 in terms of the root cause of the low throughput rate and the bottleneck.
2. To provide possible improvements and/ suggestions to increase the throughput rate of assembly line Generation 2, which eventually will increase the OEE.

1.4 Thesis Structure

The structure of this paper is as follows:

- Chapter 1 provides the General Overview of the work, including the introduction of the use case, problem statement, and objectives.
- Chapter 2 provides State of the Art as the basic foundation in analyzing the case, developing modelling and simulation, justifying the main problem, and providing a possible solution.
- Chapter 3 provides a more detailed Description of the Use Case.
- Chapter 4 provides the Data Analysis process, including sets of available information and data processing.
- Chapter 5 describes the Model Generation phase.
- Chapter 6 explains the Results that answer the problem statement and objectives presented in the previous chapters.
- Chapter 7 provides the Conclusion.

Chapter 2

State of the Art

2.1. Assembly System

The action of fitting together the parts of a machine or other objects resulting in a product is called assembly (De Lit and Delchambre, 2003). An assembly line consists of workstations (WS) connected through a conveyor or similar material handling equipment. Manufacturing a product on an assembly line requires partitioning the total amount of work into a set V = {1,…,n} of elementary operations named tasks. In order to perform a task, a set of equipment and/ or a skilled operator is needed. Performing a task j takes time (t_j). In the end, the total workload necessary for assembling a product is measured by the sum of task times (t_{sum}).

A correct assignment of tasks into a station to find a feasible line balance supports an efficient assembly system. This can be done by observing the tasks and then visually summarising the elements through a precedence diagram. A precedence diagram helps understand the tasks' technological and organizational constraints, making the task assignment easier. It consists of nodes that present the task and time to perform the task. Figure 2.1 shows an example of a precedence diagram with nine tasks and a range of 2-9 seconds of task time.

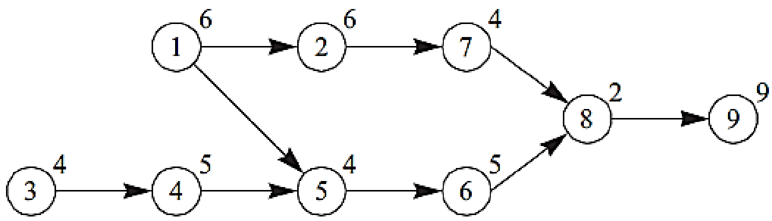


Figure 2.1 An example of a precedence diagram

Assigning a task to the stations should consider several constraints (Tuncel and Topaloglu, 2012). The main important ones are related to the cycle time and precedence constraints. In the assembly system, certain operations are performed repeatedly in each station at a certain time (maximum or average time available for each work cycle) called cycle time (t_{CT}). When a fixed common cycle time (t_{FCT}) is given to pacing a line, it is balanced if neither station's station time exceeds the common cycle time. In case of

$t_{CT} < t_{FCT}$, the station has an idle time of $t_{FCT} - t_{CT}$ time units in each cycle. Besides the cycle time and precedence constraints, other constraints could be zoning constraints, inclusion constraints (i.e., making a set of tasks assigned to the same station), and exclusion constraints (i.e., making the incompatible tasks assigned to different stations). Available space and distance between stations also worth to be considered.

2.1.1 The Classification of Assembly Line

There are five suggested criteria to investigate the type of assembly line, as shown in Figure 2.2. There are three types of product's models: single model, mixed model, and multi-model. An assembly line can be categorized as a *single model* if it assembles one or more products, but neither setups nor significant variations in operating times occur. In the case of the *mixed model*, the setup times between models could be significantly reduced because even if it assembles more than one product, the product has the same base. They are different only in specific attributes and it is an option. Meanwhile, different models are assembled using the same resources (e.g. a machine) but different cycle times in the *multi-model* category.

number of models	single model	mixed model	multi model
line control	paced	unpaced asynchronous	unpaced synchronous
frequency	first-time installation		reconfiguration
level of automation	manual lines		automated lines
line of business	automobile production		further examples

Figure 2.2 A classification of assembly line based on five criteria

The first category within the line control criterion is *paced-line*, where the assembly process in all stations is restricted by a specific cycle time given. In this case, advanced material handling equipment, called intermittent transport, is used to pace the line and force the operator to finish the task before the time elapsed. The second one is the *un-paced synchronous line* where the workpieces in the station are transferred at the same point of time according to the slowest station. Hence, the presence of a buffer is not necessary. The last category is the *un-paced asynchronous line*, where the movement of workpieces from one station to another or from the station to buffer is processed when the required operation in the station is completed unless another workpiece does not block the successive station. After the transfer, a new workpiece is processed unless the preceding station cannot deliver (starving). In this case, a buffer is placed between stations to minimize the waiting times, compensate temporary deviations in tasks times, or absorb variability between the processing times of two stations.

Furthermore, in an un-paced asynchronous line, the buffers would be meaningful if machine breakdowns are relevant due to the deterministic task times. Hence, the buffer capacity must be provided adequately. The introduction of buffers makes the configuration planning of an un-paced asynchronous assembly system need to consider the line balancing, the allocation of buffer capacity, and the estimation of throughput for further efficiency measures. It is essential to balance the line to smooth the work content in the long run. The correct assignment of work content might lead to a more efficient buffer allocation and improve the system's overall efficiency.

The *first-time installation* is considered when resources have not been purchased yet, and the assembly line is installed for the first time. In this case, the stations are treated as abstract entities to which a certain number of tasks can be assigned. In reality, the *reconfiguration* category is more common to be applied. The stations already exist, with cycle time often determined based on the sales forecast. Thus, the purpose of the reconfiguration is usually related to evenly distribute the work content among available stations to achieve higher throughput and higher quality of the product.

2.1.2 Flexible Assembly System

According to Sawik (1999), Flexible Assembly System (FAS) is a fully integrated production system consisting of computer numerically controlled assembly stations connected by an automated material handling system, all under the control of a central computer. This assembly system can simultaneously assemble various types and sizes of products at a high rate compared to the conventional one. Some types of equipment required within FAS are:

- A robot is an essential component. Selective Compliance Arm for Robotic Assembly (SCARA) robot is one of the most common robots used in an assembly process. This type of robot was specially designed for the vertical insertion of parts thanks to its four degrees of freedom. Besides, it can provide excellent repeatability and absolute accuracy due to its capability to perform at high speed and good accelerations.
- Accessories such as tools for fastening, grippers, and fixtures.
- On-site storage devices such as a rotating table and part feeders.
- Material handling devices such as an automated conveyor.
- Storage areas for components, sub-assembly parts, finished products, and tools.

A series of dedicated, special-purpose assembly stations linked with an automated material handling system with a unidirectional flow (i.e., the flow of lanes is fixed in one direction) characterizes a flexible assembly line in FAS configuration. In each station, there can be a single machine or identical parallel machines. The assembly operation is generally placed on a pallet that will move between stations through automatic conveyors or rails. Other characteristics of this assembly line are high volume and low variety of products, stable demand and design requirements, high productivity, and quick changeovers.

Moreover, machines are put in a finite workspace and the assembly times are relatively small. Therefore, the material handling system is vital in avoiding bottlenecks (i.e., machines that significantly impact the overall system throughput) and its underutilization. An evaluation of buffer capacity is included as a part of a FAS design process to seek the optimum buffer capacity needed to satisfy the production requirement. Large buffer spaces will waste the floor space and lead to a longer travel time. Meanwhile, a too-small buffer space will lead to machine blocking and low machine utilization.

In general, the main objective of FAS design is to balance the workload of each station so that the total assembly time assigned to each station is equal. This goal must be followed by good FAS scheduling. Scheduling decision is a critical feature in FAS since the buffer capacity is limited, and hence, there is always a possibility of blocking and starvation within the stations. Blocking is a condition when a station cannot move the product because the buffer downstream is full. Starvation is when the station is prevented from functioning because no product can be processed (i.e., buffer upstream is empty). The advantage of having FAS is its capability to accommodate changes in product design and demand. This benefit can lead to a dynamic reconfiguration of the assembly system on a basic concept of agility (i.e., an ability of a production system to produce various high-quality products in a short time at a low cost).

2.1.3 Bottleneck in an Assembly Line

The term “bottleneck” describes a point of congestion in an assembly line. A bottleneck station in an assembly line is a station that impedes the overall system's performance. Bottleneck usually occurs in an un-paced assembly line that is unbalanced (i.e., where workstations do not operate with equal processing time). The imbalance in the mean processing times between stations in an assembly line causes blocking and starvation, introducing slack into the production line, which constitutes a resource in the form of protective capacity. Thus, the bottleneck plays a crucial role in determining the overall capacity of the assembly since it constraints or limits the system.

According to Tan (2019), improving the bottleneck subsystem can significantly increase system competence, especially system throughput. By knowing the bottleneck station, the flow of the system can be improved by improving just one process rather than all its remaining parts. Thus, improvement efforts should start at identifying the bottleneck. The bottleneck within production or assembly lines are often shifting, making it difficult to be identified.

The current bottleneck detection method are categorized into analytical and simulation-based (Leporis and Králová, 2010). In the analytical method, a statistical distribution describes the system performance. This approach is suitable for long term prediction but unsuitable for short-term bottleneck detection and a real production process with a complex and dynamic structure. In this sense, simulation-based seems to be more helpful since it can provide sufficient information for short-term bottleneck detection in a complex system. In advanced simulation tools, the complete statistics are also presented, such as average utilization, waiting, blocking, breakdown, etc. In addition, a simulation model can identify the possibility for system improvements and verify the impact on the overall system performance. However, the disadvantage is it is time-consuming.

Some characteristics of a bottleneck station are:

- Have the largest expected processing time so that its capacity is the maximum attainable capacity for the line.
- Have the longest uninterrupted active time (i.e., a time when the machine or station produces parts).
- Have the smallest sum of a "turning point" of machine's blockage and starvation. A "turning point" is the trend of blockage and starvation changes from blockage being higher than starvation to starvation being higher than blockage (Li *et al.*, 2007).
- Have the lowest sum of probability of blocking and starvation.
- Have the longest queue of parts in front of the station with a combination of an empty buffer and long waiting times at the following station.
- Have the lowest efficiency in isolation. Thus, have the lowest production rate in isolation.

The bottleneck within serial production lines is not stable as they shift randomly due to machine downtimes. The presence of a bottleneck decreases the output and prolong the lead time. Since the bottleneck stations have the largest effect on the overall system throughput, they should be prevented from being starved and blocked as much as possible (Colledani, 2010). A way to mitigate the adverse effect coming from the bottleneck is by placing a buffer between the bottleneck station.

Conway and colleagues (1988) argued that buffer gives some degree of independent action to each stage of a production system. It allows increasing the average throughput through partially decoupling the stations from the unexpected shutdown (e.g., breakdown, broken/ missing tooling, operator unavailability, etc.). This is because buffers can limit the effect of starvation and blocking phenomena, protecting the machines from the propagation of failures throughout the line, thus reducing the idle time. Buffers also help to absorb variability. However, the higher the buffers placed, the higher the WIP level and cost. Therefore, the optimization of buffer capacity allocation is crucial.

According to Harris and Powell (1999), as the variance of processing times increases, the optimal allocation places more buffer capacity toward the centre of the line, the so-called *The Bowl Phenomenon*. Moreover, suppose the bottleneck station is the first station. In that case, the buffer allocated after the station can help to increase the throughput rate (Powell and Pyke, 1996) because the station dominates the throughput produced within the line. If the bottleneck station is in the centre of the line, the buffers placed either before or after the station are equally important, with more or less the same output obtained (Conway *et al.*, 1988) even though the input buffer tends to be full and the output buffer tends to be empty.

However, the required buffer capacity is substantially decreased once the bottleneck becomes more severe because the adjacent stations are almost finished before the bottleneck. In this case, the bottleneck "pulls" the buffer capacity toward itself to avoid idle time for the flow-limiting process. Meanwhile, a fast workstation "push" buffer capacity away as it acts like a buffer itself during its idle time. The effectiveness of extra buffer capacity will be eventually reduced when it exceeds the actual requirement. Therefore, the optimal buffer size should depend on the relative importance of the throughput to the cost of holding buffers and the characteristics of the bottleneck (Navee and Pansa, 2003).

The bottleneck factor has more effect on the throughput than the buffer factor. Thus, if the bottleneck problem is related to the cycle time, McNamara and colleagues (2016) suggested that to achieve 1% of improvement in throughput, the fastest stations must be placed toward the middle of the line and the slower stations each end of the line. The output could be maximized if more work is allocated to the first and last stations. If slower stations are placed toward the centre, two adjacent stations are impacted, worsening the effect. Otherwise, if the bottleneck factor is related to the machine's availability or performance, reducing downtime and increasing the repair rate would improve the throughput rate significantly than adding the buffer space.

2.2. Manufacturing Execution System

The globalization phenomena challenge the company on how to manage cross-function teams and cross-country interaction. When it comes to manufacturing, a sophisticated corporation among different departments in the company, such as production, research and development, quality control, warehouse, procurement, engineering, is a crucial aspect. Thus, Manufacturing Execution Systems (MES) is introduced to improve the efficiency and accuracy of the manufacturing process.

MES is a software solution ensuring the quality and efficiency of a manufacturing process are established and proactively and systematically enforced. It bridges the gap between the planning and controlling system using online information to collect and provide information and direction within the production activities and manage manufacturing resources: people, equipment, and inventory. Moreover, to support the online management decisions, it usually includes a direct connection to function, such as Statistical Process Control (SPC), Time & Attendance, Product Data Management, Maintenance Management, and other similar tools.

According to McClellan (2001), there are seven core functions of the MES:

1. *Planning system interface*

   In order to make the MES keep on properly informing the planning system about plant activities (e.g., work order progress, inventory changes, and labour), the communications should be in two ways. Hence, the MES should be directly coupled to the planning system to accept work orders and other input and provide real-time information.

2. *Work orders*

   The MES manages changes on orders, establishes and changes schedules, and maintains a prioritized sequenced plan. It can accept the work order through manual entry or automatically. In addition, it can keep a constant real-time view of the status and backlog of the work orders.

3. *Workstations*

   The MES should include the direct control interface and connection with each workstation since this part is responsible for implementing the work order plan. The MES provides the current and total load of the stations using routing data and time standards to manages requests of delivery inventory, tooling, etc.

4. *Inventory tracking and management*

   The regular updates to the planning system allow maintaining the current map of all inventory and storage locations.

5. *Material movement*

   The MES controls material movement in the plant both manually or automatically. In the case of manual movement, it issues a request to print move tickets. Meanwhile, automatic movement will command the material handling system control PLCs, such as ASRS, AGV, conveyors, robots, etc.

6. *Data collection*

   This is a crucial function for management to gathers real-time information so that the system can remain current. Data from the shop floor can be collected, collated, and dispersed thanks to various sensing devices and control interfaces. This is the primary channel for all personnel to communicate with the MES. The communication itself can be done either through information input or output by the system operators or electronic recognition of events. This function also includes direct connections with PLCs to download and/or collect information from the system.

7. *Exception Management*

   The MES should be able to take changes or exceptions of a plan and respond with alternative actions, helping the personnel make immediate decisions.

Many advantages offer from the application of MES within a company, such as:

- Reduce manufacturing cycle time.
- Reduce inventory of work-in-process.
- Reduce paperwork between shifts.
- Reduce lead time.
- Reduce or eliminate data entry time.
- Eliminate lost paperwork/ blueprints.
- Improve product quality and customer services.
- Empower plant operations people.

Above all, the implementation of MES supports the need for immediate, current, and online information that allows the user to make the correct decisions regarding the application of inventory, plant resources, and people.

2.3. Overall Equipment Effectiveness

For many years since its appearance in a book called *TPM Development Program: Implementing Total Productive Maintenance* written by Seiichi Nakajima in 1989, the Overall Equipment Effectiveness (OEE) has been used by many companies to measure their manufacturing system performance. The OEE tool comes from the Total Predictive Maintenance (TPM) concept, which aims to achieve zero breakdowns and defects related to the equipment. It may help understand how a manufacturing area is performed and what can limit its effectiveness (Hansen, 2001).

Before the concept of OEE was launched, the availability or downtime was used to monitor the performance of the equipment. However, this approach leads to different output results even though the percentage of the availability and downtime are the same for two different conditions. For instance, a condition has one breakdown of 10 hours out of 100 hours, and the other has ten breakdowns of 1 hour out of 100 hours; the latter will produce less output. This happens because each time a machine breaks down, there is a high probability of a quality loss (e.g. scrap or rework) and speed loss due to the need to ramp the machine up back to full speed. Therefore, OEE was developed also considering the quality of output produced. As a result, OEE is calculated as a product of availability, performance, and quality. It is usually represented as a percentage.

$$\boldsymbol{OEE = Availability\ x\ Performance\ x\ Quality} \tag{2.1}$$

In more detail:

$$\boldsymbol{Availability = \frac{Available\ time - All\ recorded\ downtime}{Available\ time}} \tag{2.2}$$

where

All recorded downtime: the summation of planned downtimes, setup or changeover downtimes, and unplanned downtimes.

Planned downtime: the budgeted and approved downtime during the required production time authorized by management at least 48 hours in advance. Any extension of this type of downtime will be classified as unplanned downtime.

Setup or changeover downtime: the elapsed time from the last good output produced to the new good output produced at the required speed following a setup or changeover to a different product.

Unplanned downtime: all downtime recorded other than planned downtime and setup downtime.

$$\boldsymbol{Performance = \frac{Actual\ speed}{Ideal\ speed}\ x\ \frac{Total\ quantity\ produced}{(Available\ time - All\ recorded\ owntime)x\ Actual\ speed}} \tag{2.3}$$

where *Speed* refers to the speed of the line and is measured in output per time

$$\boldsymbol{Quality} = \frac{\boldsymbol{Good\ output\ produced}}{\boldsymbol{Total\ quantity\ produced}} \tag{2.4}$$

Some literature mentioned that in traditional thinking, the best practice OEE in a discrete manufacturing plant is 85% on the notion of 90% Availability x 95% Performance x 99% Quality while in a continuous manufacturing plant is 95% on the notion of 98% Availability x 98% Performance x 99% Quality. The best practice OEE may differ from a company to another, and it should be based on the business requirement and target.

Those three main aspects in OEE calculation are affected by 6 Big Losses:

Availability

1. Breakdown losses (i.e., time and quantity losses due to equipment failure).
2. Setup and adjustment losses.

Performance

1. Idling and minor stoppage (i.e., downtime less than 5 minutes) losses.
2. Reduced speed losses (i.e., the difference between equipment design speed and actual operating speed).

Quality

1. Quality defect and rework losses.
2. Start-up (yield) losses.

The 7^{th} loss is introduced under the availability aspect in more recent literature. This is so-called *Planned Downtime* which includes losses due to meal breaks, regular maintenance periods, starting of the shift, toolbox meeting, etc. In addition, according to Muchiri and Pintelon (2008), the losses can be categorized into two: losses due to external reasons (i.e., losses caused by factors that are beyond the company's control, such as logistic problem) and losses due to internal reasons (i.e., losses caused by elements within the company's control). They included the 7 Big Losses into the later one under operational related losses.

Some examples of activity to eliminate or minimize losses:

1. Detect, predict, and restore deterioration.
2. Establish repair methods (make a standard method to prevent repair errors).
3. Maintain basic equipment conditions and standard operation to avoid incorrect operation.
4. Improve design weaknesses.

In more recent years, there has been a shift in the paradigm for the purpose of OEE as argued by Kennedy (2018): OEE should be seen and used as a “driver” for improvement and not only as a performance measure to be compared or benchmark between equipment and sites. Since the OEE is seen as a “driver” of improvement, the increase of OEE should be 100% correlated to the good output produced. By means, if the OEE is increased by 10%, then 10% more good output should be made, or the same amount of good output is made with 10% less time. This concept makes the OEE measurement able to support ongoing continuous improvement within the production area.

Hansen (2001) suggests several steps to conduct allowing the improvement of the manufacturing system through OEE:

1. Calculate the OEE value of the current performance.
2. Define the critical processes and bottlenecks. Focus on collecting and analyzing data of the root cause. Conduct observation under a particular duration to understand all variables influencing the OEE and continuously record production data.
3. Once the root cause of the bottleneck is determined, establish an ideal vision of the bottleneck.
4. Build a plan to tackle the bottleneck and achieve the goal made. Communicate this vision and plan with the team. Some changes to basic procedures without the capital necessity that can be performed in advance to reduce the bottleneck are changing supply or distribution policy to manage bottleneck and changing maintenance methods or substituting different materials to improve equipment reliability.
5. Educate all workers within the team about how to measure the OEE and collect and reconcile information. Understanding the categories for data collection and how losses impact OEE will synergize the team, allowing a quick elimination of the root problems.
6. Generate resources (e.g., money, people, training, and time) to make changes possible. Not forget to mention the introduction of new technologies, including condition-based maintenance, predictive maintenance, etc.

An essential central aspect in calculating OEE is a clearly defined standard definition and collection of loss information. A clear defined standard is related to the assignment of the downtime category and the decision of whether to include it in the calculation or not. In addition, the frequency of the category events should be well-recorded as well. In this way, the small changes in performance could be captured. The loss information gathered, together with the Pareto chart analysis, will highlight the root cause (or the largest) of the loss and eventually help create a potential correct improvement action. Pareto chart analysis can be made at some level to have a more detailed analysis of the loss.

The correct assignment of downtime losses leads to correct performance measurement, specifically the availability rate assessment. The equipment failure downtime determines the equipment availability. According to Fleischer *et al*. (2006), the availability rate is affected by reliability, maintainability, and maintenance readiness. *Reliability* refers to the length of time when equipment is operational and measured by Mean Time Between Failures (MTBF). The frequency of the category events collected will help provide the reliability analysis in a more detailed way. *Maintainability* refers to how much time is needed to bring back a machine to an operating condition after the failure occurs, and it is measured by Mean Time to Repair (MTTR). Muchiri and Pintelon (2008) suggested that planned or scheduled downtime should not be included in the OEE calculation. *Maintenance readiness* ensures that the personnel, tool, and components are ready to perform and fix the problem once a failure happens. In this way, a shorter time is needed to make the machine operational again.

Meanwhile, a Total Effectiveness Equipment Performance (TEEP) is introduced to measure the overall equipment effectiveness relative to the calendar time. In its calculation, planned or scheduled downtime is included. Through the improvement of these parameters, the equipment availability could be increased. Reliability, availability, and maintainability can be promoted through the correct steps in collecting and analyzing data.

2.4. Data Mining of Production Data

The evolution of data warehousing technology and the rapid growth of big data accelerate the adoption of data mining techniques. According to IBM, data mining is a process of uncovering patterns and other valuable information from large data sets. It is also known as Knowledge Discovery in Data (KDD). It helps the company transfer raw data into useful knowledge to improve organizational decision-making through insightful data analyses.

Data mining has been used in manufacturing since the 1990s. Nowadays, it is applied in many different areas in manufacturing, such as production, scheduling, predictive maintenance, fault detection, design, quality control, and decision support system. It captures so much attention since it helps analyze data to identify hidden patterns in the parameters that control the manufacturing process or improve product quality. A significant benefit of data mining in manufacturing is that the required data for analysis can be collected during the normal operating process (i.e., it does not need any additional dedicated process for data collection).

In recent years, interesting areas for manufacturing research has been moving towards optimal machining parameters (to minimize machining errors that could lead to a slower production rate and higher cost) and preventive maintenance (as a key importance in the manufacturing process). This could be done with the help of data mining towards the pattern extraction of available production databases containing equipment operating events, failure events, or behaviour of the relevant equipment at the time of failure. An application could be, as mentioned by Leporis and Králová (2010): the bottleneck identification based on the analysis of the production log file recording the relevant data about the events that occurred during the simulation run (start and finish of the operation, repair, tool change, etc.).

Moreover, there are two general classes of data mining: descriptive and predictive. Descriptive data mining aims to discover a pattern, such as product configurations formed in mass customization applications. Predictive data mining aims to determine or predict an outcome, such as stock level, through models development.

Researchers have proposed several techniques, but data mining usually consists of four main steps:

1. *Setting objectives*

2. *Data gathering and preparation, including data dimensionality reduction*

   Data collection and preparation is a crucial step within data mining. Modern databases usually contain a large volume of data. Thus, unrelated data should be eliminated from the data-set to reduce the data mining effort.

3. *Applying data mining algorithms*

   Some data mining algorithms are decision tree algorithms, decision rule algorithms, Bayesian algorithms, neural networks, clustering, and regressions.

4. Evaluating results and visualization

   The understanding of the relationships between data items to make a decision. Visualization techniques to support the understanding of the result.

The challenges within data mining are related to the fact that production data can contain errors due to data entry and how to manage different data types. Thus, adopting an event-driven architecture for the logging machine status allows a log to be generated when needed instead of active pulling machine events from the machine controller (Lu and Xu, 2019).

2.5. Performance Evaluation of A Manufacturing System

Cassandras and Lafortune (2008) characterizes a manufacturing system by dynamic or static, stationary (time-invariant) or non-stationary (time-varying), linear or non-linear, discrete-state/time or continuous-state/time, event-driven or time-driven, and stochastic or deterministic. There have been many methods proposed to model a manufacturing system. Papadopoulos *et al*. (2019) reviewed and summarized the classification of timed models of manufacturing systems on the emphasis of Markov models. The timed model is based on a concept of Discrete-Event Dynamic System (DEDS) dominating the modelling of a manufacturing system. It considers dynamic, stationary (time-invariant), non-linear, discrete-state, and event-driven systems. The timed model is commonly used since it can answer quantitative questions and is widely applicable. Some timed models mentioned in the literature are Markov Process, Queuing Network, Stochastic Automata Network, Timed Petri Net Models, Performance Evaluation Process Algebra, etc.

Since a manufacturing system configuration is quite complex, with many decision variables and a high investment involved, the system's performance should be monitored, controlled, and continuously evaluated. In this way, the company can exploit the resource optimally to satisfy demand and stay competitive within the market. Evaluating a manufacturing system’s performance is usually related to throughput or production rate, mean sojourn or holding time of the system, availability, and system reliability.

Given the importance of evaluating a manufacturing system's performance, some studies have been conducted to show the relevance of each model and technique. Based on Tolio and Matta (1998), classical analytical tools, appropriate analytical tools, and simulation can evaluate the performance of a manufacturing system. However, these tools have some weaknesses. The hypothesis of exponential processing time and infinite buffer capacity between the machines is normally not acceptable in the classical analytical tool. A lot of effort in modelling and long simulation runs are needed in the case of simulation. Therefore, they created an alternative tool, called an approximate analytical tool, which requires a small computational effort, but can model unreliable machines with deterministic processing time and a finite buffer capacity.

In a serial production line or transfer line (i.e., a manufacturing system where the jobs serially move within workstations) and assembly or disassembly line, decomposition and aggregation methods play a dominant role in the modelling, analysis, and performance evaluation. The decomposition method breaks down an original long line into two pseudo-machines and one buffer subline. To ensure that the flows in and out of each buffer in all sublines are equal to that of the original line, a set of decomposition equations are derived and simultaneously solved by introducing a decomposition algorithm. Once the algorithm converges, the parameters of the pseudo-machines are evaluated. There are four main types of decomposition methods as below:

Model	**Discrete deterministic**	**Discrete exponential**	**Continuous deterministic**	**Continuous approximation of discrete deterministic**
Machine processing times	Deterministic and equal for all machines	Stochastic	Deterministic, each machine can have a different value	Deterministic, each machine can have a different value
Buffer capacity	Finite and discrete capacity	Finite and discrete capacity	Finite and continuous capacity	Finite and continuous capacity
Flow of parts	Discrete flow	Discrete flow	Continuous flow	Continuous approximation of discrete flow
Machine states	Multiple ups (with equal processing times) Multiple downs	Multiple ups (with different processing times) Multiple downs	Multiple ups (with different processing times) and multiple downs	Multiple ups (with different processing times) and multiple downs
Application domain	Automatic synchronous systems	Manual synchronous systems	Automatic asynchronous systems with large buffers	Automatic asynchronous systems

Table 2.1 A classification of decomposition methods
(Source: Manufacturing Engineering Course Material)

On the other hand, the concept of aggregation allows aggregating every two machines into a new aggregated machine, which is then aggregated with the following machine to generate another new aggregated machine. This concept then is repeated until the end of the line, and the parameters of aggregated machines are convergent. Thanks to the aggregation concept, issues such as bottlenecks, lead time, and energy consumption can be studied.

2.5.1 Performance Evaluation of Continuous Line

In general modelling approaches, a manufacturing system is introduced as machines (M_1, M_2,…, M_m) separated by buffers (B_1, B_2,…, B_m), as shown in Figure 2.3. The parts enter the system from the input machines and exit from the output machine. The system can be in a specific state at each time instant, and this could be represented as $S = (x_1, \dots, x_m, \dots, x_{M-1}, S_1, \dots, S_m, \dots, S_M)$ where S_m represents the state of machine $M\{m\}$, m = 1, 2, …, M and x_m represents the state of buffer $B\{m\}$.

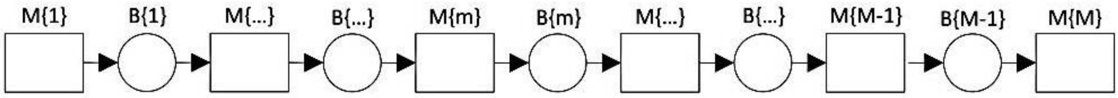


Figure 2.3 A model of a manufacturing system

Some general assumptions are introduced in terms of parts:

- One part type is produced.
- Parts are discrete and each machine processes one part at a time.
- The dispatching policy is First In First Out (FIFO).
- Parts are not scrapped or reworked

In order to evaluate the performance of a long line, a continuous two-machine line with a single-up and single-down state is often used as a starting point. In this case, the system is composed of two machines (upstream machine M^u and downstream machine M^d) decoupled by a buffer as shown in Figure 2.4. This method is based on the line decomposition approach, and the composition is so-called Building Block (BB). The Building Blocks are solved with the exact analytical method based on Markovian analysis proposed by Gershwin *et al.* (2002). In this way, the complexity can be reduced to make it easier to analyze in an exact way.

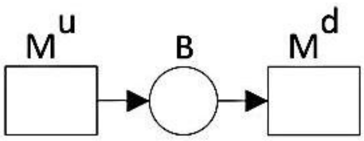


Figure 2.4 A building block (BB) in a decomposition method

Machines within the BB are called pseudo-machines. They mimic the behaviour of the entire portion of the real line upstream or downstream of the considered buffer. The upstream machine processes a material or a part at a certain time, called cycle time CT^u, and put it into the buffer B. The buffer B itself has a finite capacity N. Then, the downstream machine will take the material or part from the buffer to process it at a cycle time CT^d. The upstream machine is assumed to be never starved, while the downstream machine is assumed to be never blocked. A set of parameters of the pseudo-machines must be assigned for each BB so that the behaviour of the original system can be well-represented. The parameters refer to all values of the variables that rule the interruption of the flow of the parts in each buffer.

2.5.1.1 Machine Characterization

The machines are described by a continuous-time discrete state-based Markov chain representation with some general assumptions as below:

- The system is asynchronous (i.e., each machine can start or finish one part at any time independently from other machines).
- Processing times of the machines are deterministic, may be different between the machines, and are included the time to load and unload the part.
- Machines are unreliable and failures are operation-dependent (ODF).
- Failures and repairs are assumed to be random and can happen at any time.

A machine with a cycle time CT will have a production rate (i.e., the number of goods that can be produced in a given time unit) μ and it is calculated as:

$$\mu = \frac{1}{CT} \left[\frac{part}{time\ unit}\right] \tag{2.5}$$

Moreover, there are two states: *up*-state and *down*-state for each machine i and are defined as $S[i], i = 1, 2$. In detail:

- $S[i], i = 1$ is the *up*-state U, where the machine is in operational mode with a production rate $\mu(S[i]) = \mu \neq 0$.
- $S[i], i = 2$ is the *down*-state D, where the machine is in non-operational mode with a production rate $\mu(S[i]) = \mu = 0$.

As regards the *down*-state, Operation Dependent Failure (ODF) is held as one general assumption. Meaning that machines can fail only if they are operational. A machine with a production rate μ can have a failure rate p which is calculated based on its Time to Failure (TTF). TTF is assumed to be exponentially distributed with a parameter of Mean Time to Failure (MTTF). According to Colledani *et al*. (2010), MTTF is the mean operative time between the end of the repair of a failure and the occurrence of a new failure of the same type. The higher the failure rate, the shorter the MTTF, which means the machine stays in the *up*-state less.

$$p = \frac{1}{MTTF} \left[\frac{1}{time\ unit}\right] \tag{2.6}$$

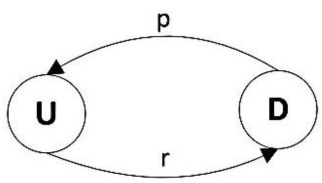
When a machine is down, a repair action is performed for a certain duration. Repair time has a time-dependent characteristic, meaning that the repair rate is independent from the processing rate of the machine and repair transitions can happen even if the machine is not producing. A machine with a production rate μ can have a repair rate r which is calculated based on its Time to Repair (TTR). TTR is assumed to be exponentially distributed with a parameter of Mean Time to Repair (MTTR). According to Colledani *et al*. (2010), MTTR is the mean time from the occurrence of the failure and the end of the repair process. The higher the repair rate, the shorter the MTTR, which means the machine stays in the *down*-state less.

$$r = \frac{1}{MTTR} \quad \left[\frac{1}{time\ unit}\right] \tag{2.7}$$

Meanwhile, Mean Time Between Failure (MTBF) can be obtained by summing MTTF and MTTR, but it is not exponentially distributed.

$$MTBF = MTTF + MTTR \tag{2.8}$$

The state-based representation of each machine is described by matrix Q in which the transition rates (failure rate and repair rate) among defined states is included. The transition rate shows the change of the states from up to down and vice versa of a machine. A simple case considers a single-up and single-down state for each machine. In this case, the Markov Chain and transition rate matrix will be as below:



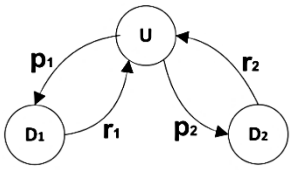
(a) Markov Chain

$$Q = \begin{bmatrix} 0 & p \\ r & 0 \end{bmatrix}$$

(b) Transation rate matrix

Figure 2.5 Markov chain and transition rate matrix of a single-up and single-down machine

In a more complex situation, a machine can have more than one failure (multiple failures). The Markov Chain and transition rate matrix of a machine in case of a single-up and multiple-downs is as below:



(a) Markov Chain

$$Q = \begin{bmatrix} 0 & p_1 & p_2 \\ r_1 & 0 & 0 \\ r_2 & 0 & 0 \end{bmatrix}$$

(b) Transation rate matrix

Figure 2.6 Markov Chain and transition rate matrix of a single-up and multiple-downs machine

Furthermore, the availability of a machine according to its dynamic is represented by the efficiency in isolation e. It can be used to identify the bottlenecks of the line. In the case of a single-up and single-down, the efficiency in isolation can be computed as below:

$$e = \frac{r}{r + p} \tag{2.9}$$

Meanwhile, in case of single-up and multiple-downs with k failures, the efficiency in isolation can be computed as below:

$$e = \frac{1}{1 + \sum_{k=1}^{k} \frac{p_k}{r_k}} \tag{2.10}$$

The maximum production rate of a machine in a case where it was never impeded by the other machines or buffers is called production rate in isolation p. It represents the maximum throughput obtainable by the line in the ideal case, and it can be calculated as below:

$$p = \mu .\ e \ \left[\frac{parts}{time\ unit}\right] \tag{2.11}$$

2.5.1.2 Buffer Characterization

The presence of buffers can limit starvation and blocking phenomena, protecting the machines from the propagation of failures throughout the line, thus reducing the idle time. Some general assumptions for the buffer are:

- The buffer capacity N is assumed to be finite.
- The buffer level can change in a continuous fashion with variable x and $0 \leq x \leq N$.
- The material in the buffer is considered continuous since the flow of parts is approximated by a continuous flow of material.

2.5.2 System State

At the system level, the behaviour of each machine may be limited by another. Thus, as shown in Figure 2.7, a general state-based is introduced to represent the system state. The limitation for the upstream machine from the downstream machine is represented by *B*, which is a blocking state. At the same time, the limitation for the downstream machine from the upstream machine is represented by *S*, which is a starvation state. The occurrence of the blocking and starvation itself is a result of the machine failures.

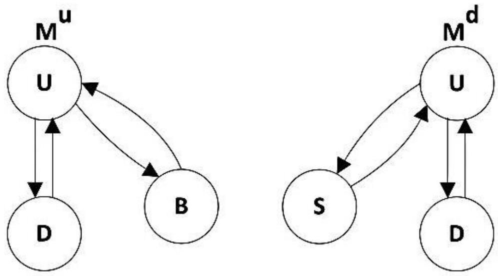


Figure 2.7 General state-based at the system level

The blocking state is a condition when the upstream machine is in an operational mode (i.e., not in a failure mode), but it goes idle because it is blocked by the full buffer downstream. The buffer is full because the downstream machine is failed. The system will remain in this state until the downstream machine is repaired.

$$\pi(Blocking) \neq 0$$

$\pi(Blocking)$ is a steady-state probability of upstream machine being blocked.

The starvation state is a condition when the downstream machine is in an operational mode, but it goes idle because the buffer upstream is empty (i.e., downstream is being starved). The buffer is empty because the upstream machine is failed. The system will remain in this state until the upstream machine is repaired.

$$\pi(Starvation) \neq 0$$

$\pi(Starvation)$ is a steady-state probability of downstream machines being starved.

The introduction of blocking and starvation phenomenon within the system makes the actual production rate, so-called throughput rate TH, is less than the production rate in isolation p. The relation between throughput rate, blocking, and starvation is represented by the flow rate-idle time relation:

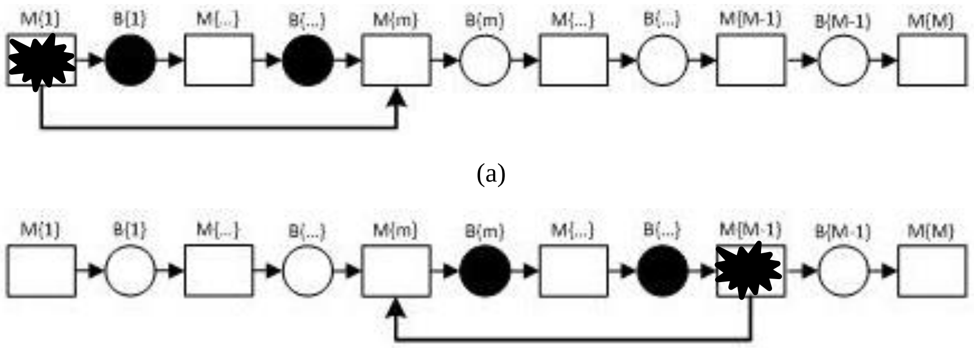
$$TH^u = \rho^u.(1 - \pi(Blocking)) \left[\frac{parts}{time\ unit}\right] \quad (2.12)$$

$$TH^d = \rho^d.(1 - \pi(Starvation)) \left[\frac{parts}{time\ unit}\right] \quad (2.13)$$

$$E[T] = \frac{\bar{n}}{TH} \quad (2.14)$$

where:
$E[T]$ = system time approximated from Little's Law
$\bar{n}$ = average number of parts in the buffer

In the case of the long lines, the propagation effect of blocking and starvation should be taken into account. The impact of the blocking and starvation will propagate due to a long failure of a machine. Given machine M{1} is failed (as shown in Figure 2.8 (a)), buffers B{1} and B{...} get empty after some time. As a result, machine M{m} will be starved and cannot produces any parts even if it is operational. The effect propagates downstream of the line. The same way happens in the blocking phenomenon, as shown in Figure 2.8 (b). Given machine M{M-1} is failed, buffers B{m} and B{...} get full after some time. Eventually, machine M{m} will be blocked and cannot produces any parts even if it is operational. The effect propagates upstream of the line.



(a)

(b)

Figure 2.8 Propagation effect of starvation and blocking

The presence of blocking and starvation and their propagation effect affect the overall performance of the long lines by reducing the system's capacity. Therefore, parameters below should be considered for each Integrated Machine M{m} with m = 1, 2,…, M and x_m represents the state of buffer B{m}:

- Efficiency in isolation of machine m

$$e_m = \frac{r_m}{r_m + m} \quad (2.15)$$

- The production rate in isolation of machine i

$$p_m = \mu .\ e_m \left[\frac{parts}{time\ unit}\right] \quad (2.16)$$

- Flow rate-idle time relation

$$TH[m] = \rho_m.(1 - \pi(Blocking) - \pi(Starvation)) \quad (2.17)$$

- System time

$$E[T] = \frac{\sum_{m=1}^{M-1} \overline{n_m} + \sum_{m=1}^{M} (1 - \pi_m(Starvation))}{TH} \quad (2.18)$$

2.5.3 A Decomposition Method with Continuous Approximation of Discrete Deterministic Flow

In 2017, Magnanini and Tolio introduced a decomposition method with a continuous approximation for the discrete deterministic asynchronous flow of long machine lines with finite buffer capacity. The model fits to solve the case within automatic asynchronous production lines. Therefore, it is used as the primary method for this thesis work.

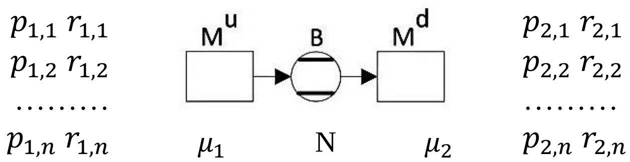


Figure 2.9 Continuous approximation of the discrete deterministic model

Additional general assumptions for this model are:

- The discrete flow of parts is approximated by the control mechanisms based on the buffer level.
- Machine failures are supposed to happen at the beginning of the operations on a part. Therefore, when a failure happens, there are no parts partially machined on the machine.
- The blocking discipline is Blocking after service (BAS). Thus, the working position of the upstream machine is added to the buffer capacity (N+1).
- The time in which the part is physically transferred and therefore keeps busy both a position in the buffer and the working position on the machine is considered to be negligible.

The application of the decomposition technique consists of three steps:

- Step 1: Characterization of two-machine lines (*building blocks*) with exact analytical solutions available
- Step 2: Characterization of machines (*integrated machines*) at the system level by means of decomposition equations.
- Step 3: Application of an algorithm to solve decomposition equations efficiently.

These three steps are further explained in the following paragraphs.

In the continuous-time models, the discrete nature of the physical parts is lost. Therefore, a threshold-based control policy is used for the first step to model an exact continuous model for the approximation of deterministic asynchronous two-machine lines with finite buffer capacity. The threshold-based control policy models the blocking state B for the upstream pseudo-machine when the buffer is in $N \leq x \leq N+1$, and the starvation state S for the downstream pseudo-machine when the buffer is in $0 \leq x \leq 1$, as shown in Figure 2.10.

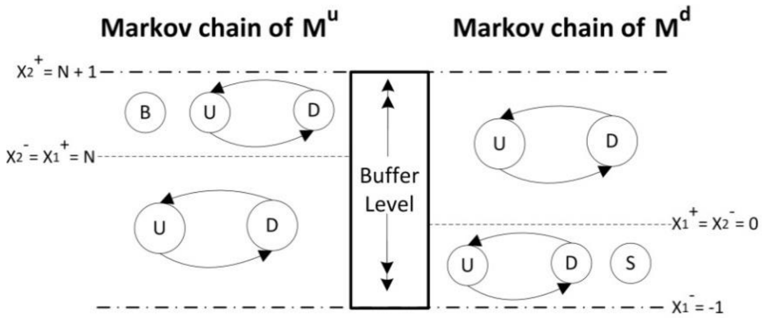


Figure 2.10 Building block of threshold-based control policy

Figure 2.11 shows the dynamics of each BB affected by the blocking and starvation cycle.

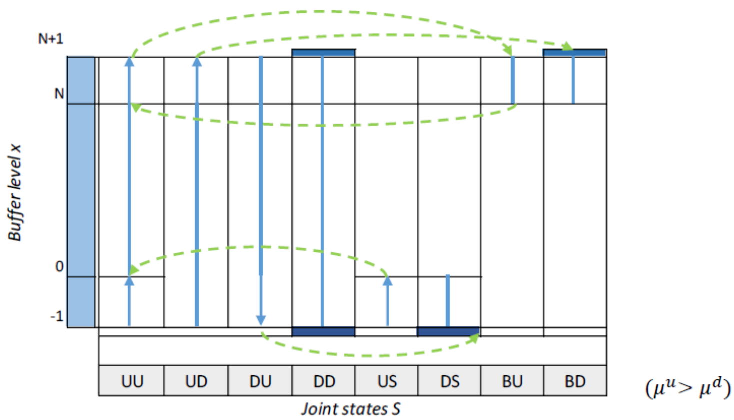


Figure 2.11 The dynamics of each building block
(Source: Magnanini and Tolio, 2021)

The blocking cycle starts when the buffer level increasing and M^ugoes blocked. Then M^dgets repaired and M^u waiting for the first free place. The blocking operational cycle starts when the buffer level increasing and M^ugoes blocked. Once M^d empties one place in the buffer, M^ucan start producing again. Meanwhile, the starvation cycle begins when the buffer level decreasing and M^dgoes starved. Then M^ugets repaired so that M^dwaiting for the first part and then starts producing again

As the second step, the decomposition method, which has a two-level solution approach, is introduced. The two-level solution approach is machine-level: Integrated Machine $M[m]$ and buffer-level: Building Block $BB(m)$ as shown in Figure 2.12. This step aims at characterizing the Integrated Machines from the output of the building blocks.

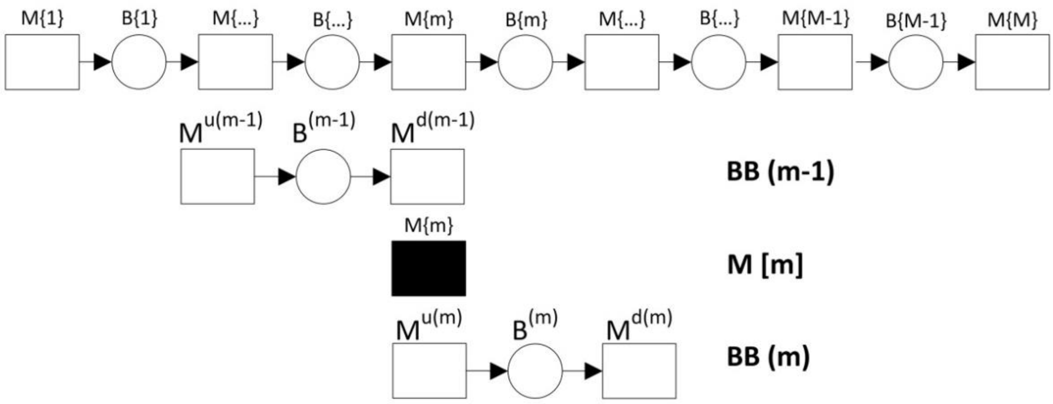


Figure 2.12 A decomposition of continuous approximation of the discrete deterministic model

Both $M^{u(m)}$ and $M^{d(m)}$ are pseudo-machines that have a local failure (i.e., failure due to itself) and remote failure (i.e., failure due to other machines). A Building Block $BB(m)$ represents the entire line centred in one buffer, and the limiting phenomena should be propagated along the $BB(m)$.

The Integrated Machine $M[m]$ adds starvation and blocking state, which represents the interaction of the machine with the rest of the system to the behaviour of machine $M\{m\}$ of the original line (local state). This is because starvation and blocking states depend on the level of the neighbouring buffer. Going directly from an upstream limitation to a downstream limitation (or vice versa) is impossible without first being back in the (local) operational state. Hence, the only way to get into starvation or blocking state is that machine $M[m]$ produces parts. The characteristic of the Integrated Machine $M[m]$ is shown in Figure 2.13 with $L^{[m]}$ refers to local state [U, D]; $S^{[m]}$ refers to upstream limiting state $[0^-, R^-]$; and $B^{[m]}$ refers to downstream limiting state $[0^+, R^+]$.

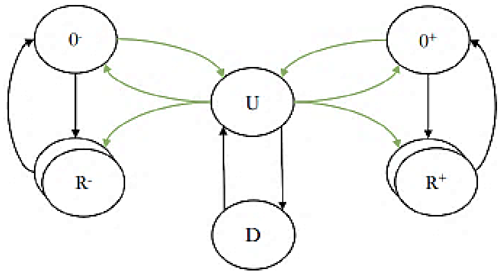


Figure 2.13 Characterization of M[m]

Furthermore, the decomposition equations are based on the flow balance equation $\prod(i) * q[ij] = g(i)$ and they define the missing rates of the transition rate matrix of the Integrated Machine $M[m]$ from the Building Block $BB(m-1)$ and $BB(m)$. The transition rate matrix of an Integrated Machine $M[m]$ itself is as below:

$$Q^{[m]} = \begin{bmatrix} Q_{LL} & Q_{LS} & Q_{LB} \\ Q_{SL} & Q_{SS} & Q_{SB} \\ Q_{BL} & Q_{BS} & Q_{BB} \end{bmatrix} = \begin{bmatrix} Q_{LL} & [Q_{L0^-}\ Q_{LR^-}] & [Q_{L0^+}\ Q_{LR^+}] \\ \begin{bmatrix} Q_{0^-L} \\ 0 \end{bmatrix} & \begin{bmatrix} Q_{0^-0^-} & Q_{0^-R^-} \\ Q_{R^-0^-} & Q_{R^-R^-} \end{bmatrix} & 0 \\ \begin{bmatrix} Q_{0^+L} \\ 0 \end{bmatrix} & 0 & \begin{bmatrix} Q_{0^+0^+} & Q_{0^+R^+} \\ Q_{R^+0^+} & Q_{R^+R^+} \end{bmatrix} \end{bmatrix}$$

Also, the missing transition rates to be defined are:

First set: entering the limiting states

- Entering the upstream limitation $[Q_{L0^-}\ Q_{LR^-}]$

  $q^{[m]}[U0^-] = \frac{g\ (x_1^{-(m-1)}, \Lambda_1^{(m-1)})}{\prod^{d\ (m-1)}(S^d=U)}$ where $\Lambda_1^{(m-1)} = [UU], v\ (uu) < 0$

  $q^{[m]}[UR^-] = \frac{g\ (x_1^{-(m-1)}, \Lambda_1^{(m-1)})}{\prod^{d\ (m-1)}(S^d=U)}$ where $\Lambda_1^{(m-1)} = [DU]$

- Entering the downstream limitation $[Q_{L0^+}\ Q_{LR^+}]$

  $q^{[m]}[U0^+] = \frac{g\ (x_3^{+(m)}, \Lambda_3^{(m)})}{\prod^{u\ (m)}(S^u=U)}$ where $\Lambda_3^{(m)} = [UU], v\ (uu) > 0$

  $q^{[m]}[UR^+] = \frac{g\ (x_3^{+(m)}, \Lambda_3^{(m)})}{\prod^{u\ (m)}(S^u=U)}$ where $\Lambda_3^{(m)} = [UD]$

Second set: exiting the limiting states

- Exiting the upstream limitation $\begin{bmatrix} Q_{0^-L} \\ 0 \end{bmatrix}$: the only way is to wait for the upstream machine to process the first part and put it in the buffer.

  $q[0^-U] = \frac{g\ (x_1^{+(m-1)}, \Lambda_1^{(m-1)})}{\prod^{(m-1)}(S^d=0^-)}$

  $q[R^-U] = 0$

- Exiting the downstream limitation $\begin{bmatrix} Q_{0^+L} \\ 0 \end{bmatrix}$: the only way is to wait for the downstream machine to process the first part and free a place in the buffer.

  $q[0^+U] = \frac{g\,(x_3^{-(m)}, \Lambda_3^{(m)})}{\Pi^{(m)}(S^u = 0^+)}$

  $q[R^+U] = 0$

Third set: transition between the limiting states

- While a machine is in an upstream limiting state, each state change depends entirely on the upstream machine.

  $Q_{SS} = \begin{bmatrix} Q_{0^-0^-} & Q_{0^-R^-} \\ Q_{R^-0^-} & Q_{R^-R^-} \end{bmatrix} = Q^{u(m-1)}$

- While a machine is in a downstream limiting state, each state change depends entirely on the downstream machine.

  $Q_{BB} = \begin{bmatrix} Q_{0^+0^+} & Q_{0^+R^+} \\ Q_{R^+0^+} & Q_{R^+R^+} \end{bmatrix} = Q^{d(m)}$

The third step has a goal to have the convergence of the performance measures where each Building Block $BB(m)$ represents the entire line centred in the buffer $B\{m\}$, and each Integrated Machine $M[m]$ represents the whole line centred in the machine $M\{m\}$. Hence, the throughput computed in each $BB(m)$ or $M[m]$ must be the same (conservation of flow), and they are iteratively characterized and solved through the decomposition equations until the throughput convergence.

Chapter 3

Description of the Case

In this chapter, the use case is described in a detailed manner. The current situation (starting from now will be referred to as the AS-IS situation) of the assembly line Generation 2 is analyzed. The analysis was conducted through line observation, data collection, and discussion with the team. According to that, a preliminary problem is identified, allowing the breakdown of a more detailed objective set for this project.

3.1 Product

The assembly line Generation 2 produces micro gear pumps with metallic bodies. The company has two types of metallic micro gear pumps: 11-00-01 (with premium type 11-00-06) and 11-00-02 (with premium type 11-00-05). The later ones contribute more than 85% of the total demand.

The difference between these two types lies in the front body, rear body, OR ring, and machines used. The pump 11-00-01 and 11-00-06 use OR Sagomati with additional two OR rings. Moreover, to produce types 11-00-01 and 11-00-06, machines Gr. 202 and Gr.220 are needed. Figure 3.1 shows the illustration of the pump. Worth noting that the project focuses only on types 11-00-02 and 11-00-05 since they dominate the demand.

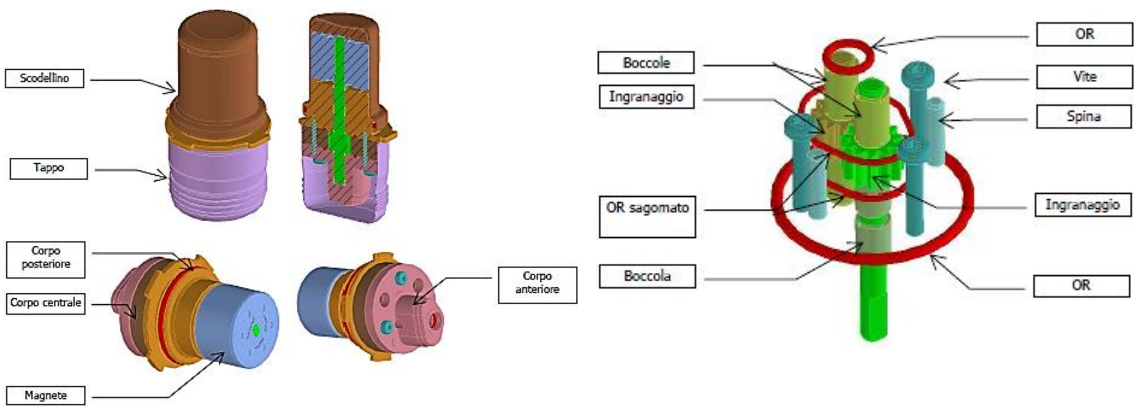


Figure 3.1 Micro gear pump

3.2 Assembly Process

The assembly line Generation 2 has seven main areas, as shown in Figure 3.2.

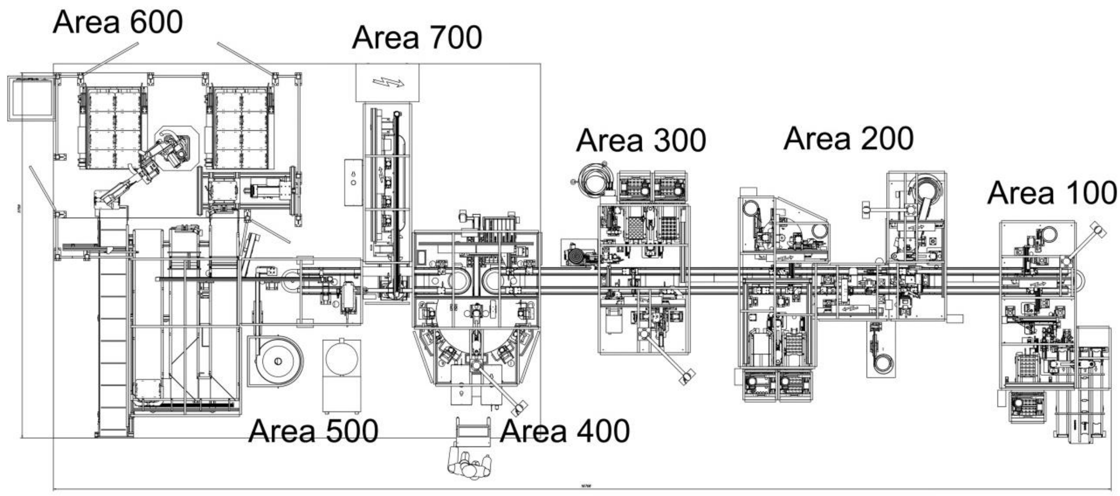


Figure 3.2 Layout of the assembly line Generation 2

The primary function of each area is as below:

Area 100: Loading central body and driving gears.
Area 200: Loading bushings, a magnet, and a cup.
Area 300: Loading front, rear body, and OR rings; Crimping process and test.
Area 400: Hydraulic test; Pallet cleaning; Unloading scrap.
Area 500: Laser marking; Loading a cover.
Area 600: Unloading finished pumps.
Area 700: Premium pump testing.

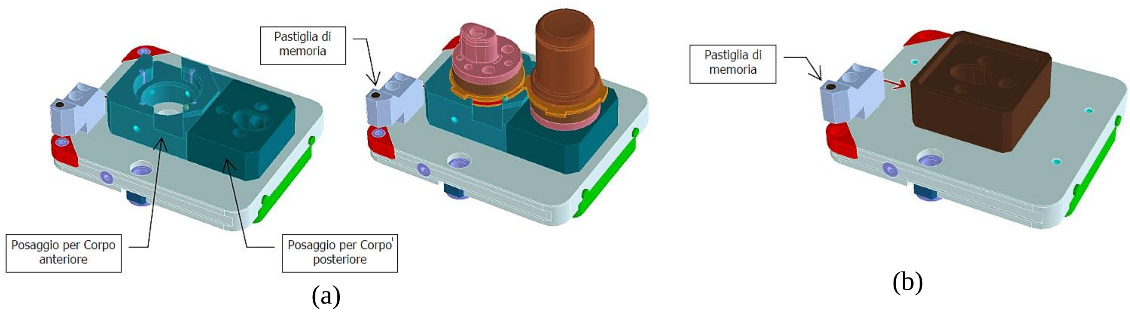


Figure 3.3 Pallet Flex 1 (a) and Pallet Flex 2 (b)

The areas are connected through conveyors, which creates two close-loops intersecting in Area 400. Most of the areas within the first closed-loop perform the assembly process, while the second closed-loop is more related to the testing and preparing the finished pumps to be packed. The work-in-progress pump travels within areas on a pallet, named *Pallet Flex 1* and *Pallet Flex 2*, as shown in Figure 3.3. Both pallets are equipped with an RFID memory pad to monitor the whole processing phase. The *Pallet Flex 1* travels within the first closed-loop and visits Area 100, 200, 300, and 400. The *Pallet Flex 2* travels within the second closed-loop and visits Area 400, 500, 600, and 700. The dimension of the pallet is 11,5cm x 10cm x h = 3cm and based on the analytical calculation, the conveyors' speed is around 0,22 m/sec.

The assembly process starts in Area 300, where a robot (Gr.301) moves a front body from vertical storage (Gr.320-321) to machine Gr.323 and a rear body from vertical storage (Gr.310-311) to machine Gr.312. Both machines, Gr.323 and Gr.312, insert one OR ring to each body. Once the OR ring placement is finished, robot Gr.301 takes the front and rear body and puts them on a *Pallet Flex 1* waiting under machine Gr.330. Once the pallet is complete with one rear body and one front body, machine Gr.330 centres the front body position and releases the pallet.

Then, the *Pallet Flex 1* moves to Area 200. In Area 200, machine Gr.210 takes the bodies and places them on a fixture placed on a rotary table (Gr.201). Gr.201 has four fixtures. Once the bodies are loaded, they will visit machine Gr.212 firstly, where three long bushings with a diameter of 10 mm are inserted. Secondly, they will visit machine Gr.214, where two short bushings with a diameter of 7 mm are inserted. After completing these steps, machine Gr.210 takes the bodies and places them back on *Pallet Flex 1* waiting on the conveyor.

The following assembly processes are performed within Area 100. First, the pallet will go to machine Gr.110, where two plugs will be inserted into the body. Then, the pallet will go to another section of Area 100, where more machines are placed. Once the pallet arrived in this section, machine Gr.120 will take the front body and move it to a rotary table (Gr.101). A robot (Gr.102) and machine Gr.140 prepare two gears (one short and one long) and a central body before the main assembly process is performed. Once the front body is ready, machine Gr.130 will load the gears and the central body on the front body. After the main assembly processes are done, they will be picked from Gr.101 and placed back on the *Pallet Flex 1* by machine Gr.120. In this section, vertical storage (Gr.160-161) is used to store the central body and (Gr.150) is used to store the gears.

Next, the *Pallet Flex 1* will enter Area 200 again. The first machine that will be visited is Gr.240, where the front and rear bodies are assembled. Machine Gr.250 will insert three screws. Then, both machines Gr.260 and Gr.261 will tighten the screws. Machine Gr.270 will rotate the in-progress pump. Then, a magnet and a cup will be loaded on the pump by machine Gr.282 and Gr.292, respectively. The magnet is stored in vertical storage (Gr.280-281). Meanwhile, vertical storage (Gr.290-291) keeps the cup. In addition, a robot (Gr.203) is used to pick and place the magnet and cup to machines Gr.282 and Gr.292 for assembly purposes.

Once all components are inserted, the *Pallet Flex 1* is moving to Area 300 again. At this point, the pallet will visit machine Gr.341 firstly for the crimping process. Then, machines Gr.351 and Gr.352 will test the result of the crimping process performed previously. It is worth noting that machines Gr.351 and Gr.352 work in parallel, and both of them must be filled up with pallets before the testing process is performed.

Another test is performed within Area 400. In this case, some liquid will be injected into the pump for the hydraulic test purpose. There are six testing machines which are Gr.410, 415, 420, 430, 435, and 440. They work in parallel but are independent of each other. Moreover, a robot (Gr.401) will pick the pump from the *Pallet Flex 1* and place it on the testing machine. Once the testing process is finished, the robot will pick and place the pump to a *Pallet Flex 2*, allowing the pump to move in the second closed-loop. Meanwhile, the empty *Pallet Flex 1* will move to a cleaning machine (Gr.470) before entering back to machine Gr.330. In the case of rejected or scraped pump, it will be placed back to the *Pallet Flex 1* and moved to waste conveyor lanes (Gr.460-461).

The second close-loop starts when the robot (Gr.401) places a good pump on a *Pallet Flex 2*. First, the pallet will visit Area 700, where a testing process for the premium pump is performed. There are four testing machines (Gr.710, 720, 730, 740) work in parallel but are independent and a pick and place robot (Gr.700). After that, the pallet will go to Area 500.

Area 500 has two sections. The first one consists of machine Gr.510 where a laser marking process is performed. The second one consists of machines Gr.520 and Gr.530 where they load the pump's cover. Once the cover is placed, machine Gr.520 will move the finished pump to a blister in Area 600, where the unloading and packing processes are performed. The empty *Pallet Flex 2* that exiting Area 500 will go to a cleaning machine (Gr.450) before entering the testing Area 400 again.

In order to sum up the assembly process and to have a better understanding of tasks carried out by each machine, the correlation between machines, and the process flow that the workpiece must pass, a precedence diagram is developed as is shown in Figure 3.4 in the Appendix. Moreover, to conclude the observation regarding the assembly process, the processing time of each machine is measured manually since the system does not record it automatically. Ten samples for each machine were taken considering a perfect operating condition (i.e., a condition where there is no failure, stoppage, waiting, blocking, etc.). Then, the average processing time is calculated and used for further analysis.

3.3 Information System and Sensor Installed

The company uses Manufacturing Execution System (MES) to support the integration of its information system. In addition, the assembly line supports Human-Machine Interaction (HMI) with some monitors that display data about the current state of the machines and production processes in real-time and help control the ongoing process within each area, as shown in Figure 3.5. The presence of a monitor within each area, two big monitors above the line, and one main monitor close to the line help the operator easily monitor the assembly line and solve problems related to stoppages.

Figure 3.5 A monitor that shows the current state of the assembly line in real-time

The monitors can provide real-time of the current state of the machines and production processes because of the presence of many sensors located within each area closer to each machine. The sensors might be a camera, photocells, fibres, laser, pressure sensor, data matrix reader, etc. that checking the presence of the part, the correctness of the position, the successfulness of the assembly process, and ensuring the correct operation of the machines. An example is shown in Figure 3.6 point C, where a COGNEX camera is placed in machine Gr.323 to perform OR ring presence check.

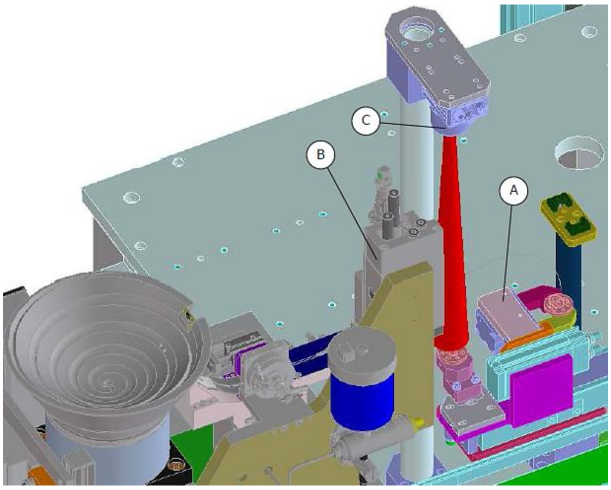


Figure 3.6 A COGNEX camera in Gr.323 to check the presence of OR ring

The monitor shows the station that is running normally in green colour. Once the sensor detects any malfunction, it will transfer the signal to the monitor to display a warning presented with yellow colour. If the warning lasts longer, meaning that the system cannot solve the issue itself, the colour displayed turns red, giving an alarm to the operator. In this case, interference from the operator is needed to solve the problem. Figure 3.7 shows the changes monitor's display related to the alarm.

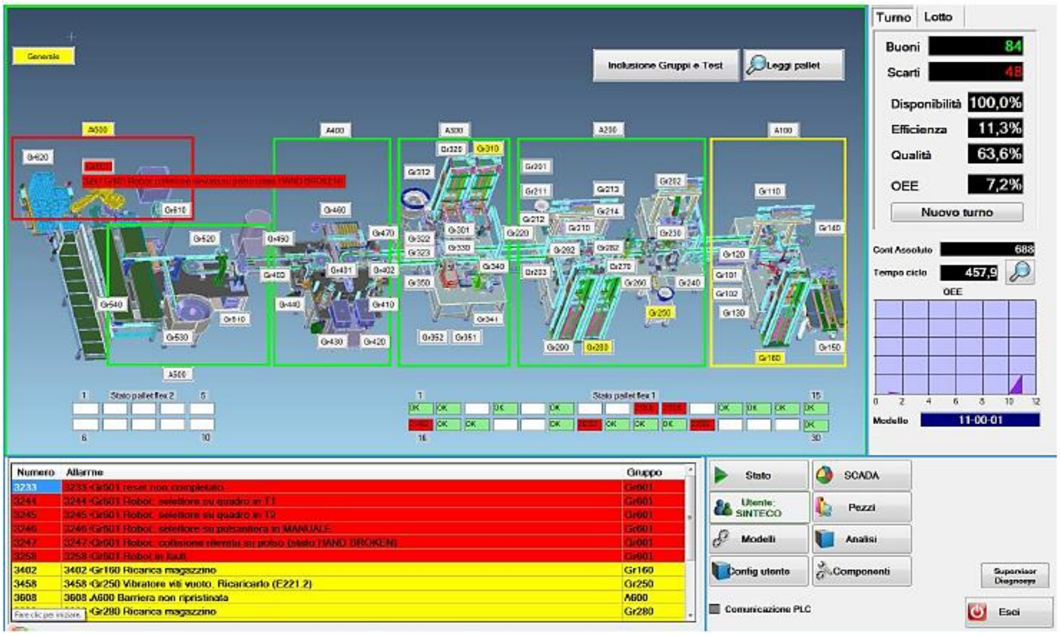


Figure 3.7 Monitor's display related to the occurrence of failure and alarm

One crucial sensor that is not connected to the monitoring display system but is used to control the assembly process is the proximity sensor for buffer capacity. The buffer of assembly line Generation 2 is the pallets waiting on the conveyor between stations. The buffer capacity (i.e., the number of pallets waiting to enter a station on the conveyor) is finite and limited by a stopper (i.e., the proximity sensor) position, as shown in Figure 3.8. A proximity sensor is a sensor that can detect the presence of objects nearby without having physical contact with the object. If the pallets waiting to enter a station reach the sensor position, the sensor will signal the upstream station not to release another pallet to the conveyor lanes.

Figure 3.8 Proximity sensor as a stopper to limit buffer capacity

Unfortunately, most of the sensors placed in the assembly line mainly focus on monitoring the correctness of the assembly process. There is only one sensor to collect data related to the performance of the assembly line. It is placed at the end of the line, where the finished pump is moved from machine Gr. 520 to the blister in Area 600. It collects data related to the exit time of a finished pump (starting from now will be called inter-departure time).

Furthermore, data related to what is happening within the production process is not recorded and stored automatically as a database. The only data that is stored automatically are data related to the machine's alarm (based on the sensor) and the inter-departure time. The machine's processing time can be seen through the monitor, but it is not stored as a database. Meanwhile, data related to the machine's failure is not collected and stored automatically by the system. The AS-IS situation of the information system installed itself turns to be a preliminary problem identified in this project since it is not supporting the quality of available information, adding difficulty in the continuous improvement process.

3.4 Preliminary Analysis of the Current Production Performance

As mentioned briefly in Chapter 1, there has been an unexpected demand growth for the metallic gear pump produced by Generation 2 in recent months. The AS-IS performance of assembly line Generation 2 is characterized by a cycle time of 11,5 seconds/ unit and an average throughput rate of 250,21 units/ hour.

According to the data gathered at the initial stage, the total quantity produced per day is unstable. An example of production in November 2020 is taken and shown in Figure 3.9. If the operating time is 22,5 hours per day, the total quantity produced per day should be around 7.000 units. In reality, the total amount made per day fluctuated, resulting in a lower average compare to the expected value. As a further consequence, the OEE results were relatively low (as shown in Figure 1.1 in Chapter 1).

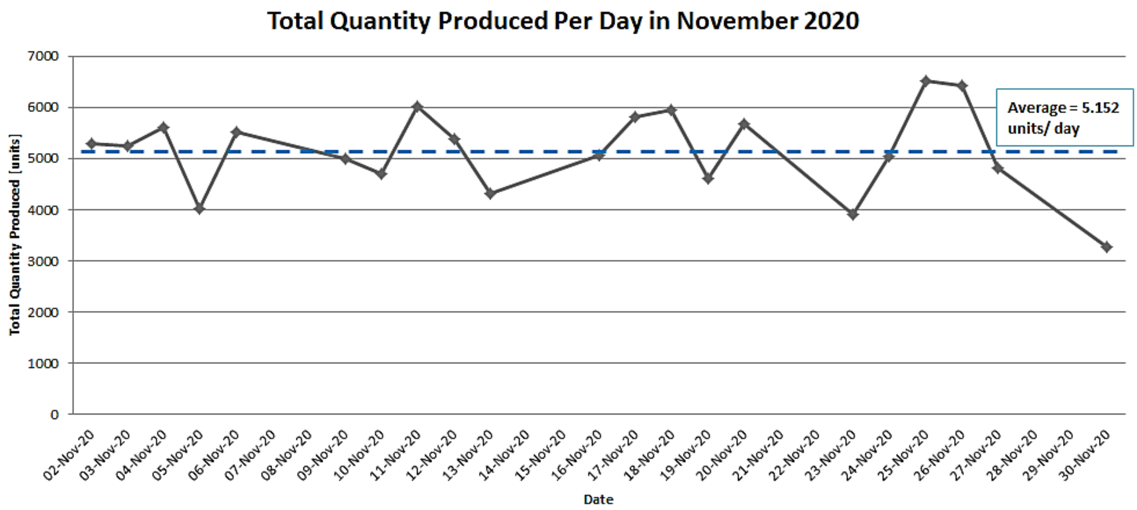


Figure 3.9 Total quantity produced per day in November 2020

Subsequently, a deeper analysis is carried out based on the performance of the shift. The correlation between the inter-departure time and total quantity produced is analyzed. An example of production on the 10th of December 2020 is taken and shown in Figure 3.10. According to that, it can be concluded that the lower the machine's operating hour, the lower the total quantity produced for each shift. This initial conclusion can give a brief image of how the availability and performance of the current situation of Generation 2 affect the overall OEE achievement.

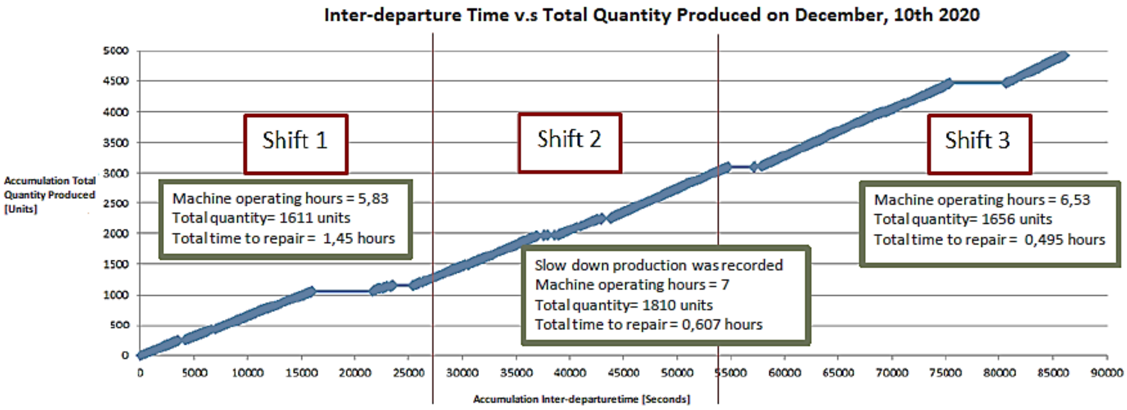


Figure 3.10 The correlation between inter-departure time and total quantity produced

Based on these initial stages of analysis, the company targeted throughput rate of 300 units/ hour is likely impossible to be achieved. The preliminary issues identified within the assembly line Generation 2 are:

1. The available information from the information system.
2. The availability and performance of the assembly line.

Consequently, some more profound questions arose, such as:

1. What is the effect of the quality of the available information on the performance evaluation and possible continuous improvement?
2. What are the root causes of the relatively low availability and performance of the assembly line?
3. Which area or machine is more problematic or potentially becomes the bottleneck of the assembly line?
4. What are the possible improvement actions?

The preliminary issues identified and the four questions will be justified and explained in the following chapters.

Chapter 4

Data Analysis

In this chapter, data available within the information system is presented, selected, collected, processed and analyzed as below schema allowing the use of the data for further analysis and modelling purposes. Worth noting that data preparation, processing, and analysis are done manually.

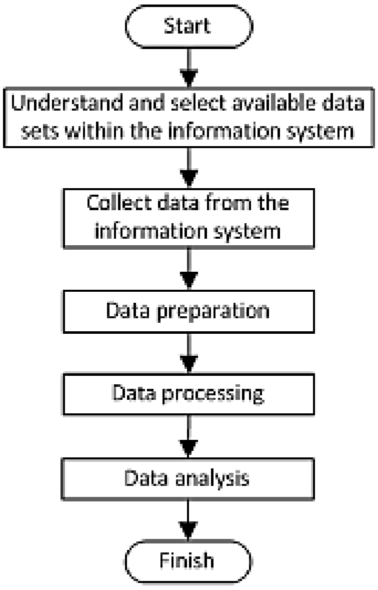


Figure 4.1 Flowchart of the overall data analysis process

4.1 Sets of Available Data

Some sets of data about the performance of the assembly line and events that happen during the operating hours are collected and stored automatically by the information system installed. Another set of data is collected manually by the operator but then stored within the information system. Sets of data that can be collected from the information system and valuable for this project are:

1. Data about OEE achievement result

Data related to the OEE achievement result is gathered on both a daily and monthly basis. The daily basis data has more detailed information. It breaks down in-depth each shift on each day according to each production phase (i.e., production, setup, unsaturation) and each product type. It collects information about the quantity produced (good and scrap), the assembly line's operating hours based on different categories (on, off, setup, stop, calendar), and each shift's performance achievement. In addition, it also provides information about extraordinary events that happen during the production phase, such as slowdown production, slowdown for a maintenance problem, lack of material, etc. The monthly-basis data also provides information about the quantity produced and the assembly line's operating hours based on different categories but as a whole of Generation 2 (regardless of the product type). Moreover, it provides information about the main OEE measurement aspects: availability, performance, and quality achieved within that month.

2. Data about the inter-departure time of a finished pump

The recorded time represents the exit of a finished pump from the assembly line; thus, it is called the inter-departure time of a finished pump (it should be more or less equal to the cycle time of the assembly line: 11,5 seconds/ unit). The information system automatically collects and stores this data thanks to a sensor at the end of the assembly process, where the finished pump is moved from machine Gr. 520 to the blister in Area 600. Each time the sensor detects a finished pump, a set of data related to the date, time, the finished pump's serial number, and the batch number of the blister and the pump's components are collected.

3. Data about machine's alarm

The presence of sensors in each area and close to each machine allows detecting incorrect processes or failures. Together with the information system installed, it is then turned into alarms that give a signal of warning to the operator. The information system automatically and continuously stores the alarms produced as a data set. It contains information about the date and time when the alarm occurs and a brief description of the alarm itself (i.e., alarm number, machine number, and cause of the alarm). Unfortunately, this data does not provide information related to the duration of how long the alarm last. Thus, the use of this data as independent data will not give so much valuable information.

4. Data about machine's stoppages or failures (Fermi Macchina)

Data related to the machine's stoppages or failure is not recorded and stored automatically by the system. Therefore, all stoppages which happen during the production are manually recorded by the operator. The operator must assign the stoppages based on available category, as is shown in Table 4.1. In addition, he must register the initial time, finish time, reason, and related machine number. This information is stored in the database as "*Fermi Macchina*" data. Worth noting that the category of *Micro Fermata* was introduced in January 2021, and it supposes to cover all stoppage under 5 minutes.

Code	Category
CF001	Problema attrezzature
CF002	Ricarico materiale
CF003-A	Mancanza materiale
CF003-B	Mancanza materiale interno
CF005	Manutenzione autonoma
CF008	Guasto impianto
CF010	Fermo qualita
CF011	Manutenzione non pianificata
CF012	Manutenzione migliorativa
CF013	Manutenzione preventiva
CF015	Comunicazione PLC interrotta/ fermo ICT
CF019	Mancanza operatore
CF020	Piazzamento/spiazzamento
CF022	Taratura linea
CF023	Fermo manutenzione
CF024	Pulizia
CF027	Prove di lavorazione
CF029	Formazione
CF034	Cambio modello
CF036	Mancanza materiale di fornitura
	Micro - micro fermata
	Startup - startup

Table 4.1 Category of machine's stoppage

4.2 Data Preparation and Processing

After all of the useful available data sets are downloaded from the information system, preparation procedures are done manually as below:

Step 1: preparation of data about the inter-departure time of a finished pump

1. Keep data columns such as *Seriale* and *Data Prod*, and delete the remaining.
2. Split the information inside *Data Prod* into two columns named *Date* and *Time*.
3. Calculate the different values between two consecutive rows in the column *Time*. This value is the inter-departure time of a finished pump.

Seriale	Data prod.	Date	Time	Inter-departure Time	Inter-departure Time [Sec]
6394861	01/03/2021 06:05:40	01/03/2021	06:05:40		
6394862	01/03/2021 06:06:15	01/03/2021	06:06:15	00:00:35	35
6394864	01/03/2021 06:08:04	01/03/2021	06:08:04	00:01:49	109
6394865	01/03/2021 06:08:16	01/03/2021	06:08:16	00:00:12	12
6394866	01/03/2021 06:08:27	01/03/2021	06:08:27	00:00:11	11
6394863	01/03/2021 06:08:39	01/03/2021	06:08:39	00:00:12	12
6394867	01/03/2021 06:08:51	01/03/2021	06:08:51	00:00:12	12
6394868	01/03/2021 06:09:02	01/03/2021	06:09:02	00:00:11	11
6394869	01/03/2021 06:09:14	01/03/2021	06:09:14	00:00:12	12
6394870	01/03/2021 06:09:25	01/03/2021	06:09:25	00:00:11	11
6394871	01/03/2021 06:09:37	01/03/2021	06:09:37	00:00:12	12

Figure 4.2 An example of the inter-departure time data

Step 2: preparation of Fermi Macchina data

1. Delete unnecessary data columns such as *Reparto*, *Macchina*, *Op.Creazione*, *Op.Causalizzazione*, *Op.Modifica*, and *Modifica*.
2. Split the information inside *Data Inizio* into two columns named *Initial Date* and *Initial Time*. These columns are the primary keys for filtering.
3. Add a new column and calculate the duration of stoppage or failure in seconds.
4. Add a new column and extract the number of the machine failed from column *Note*. If there is more than one machine in a line, duplicate the line so that each machine has its own line.

Data Inizio	Initial Date	Initial Time	Data Fine	Durata	Duration [Sec]	Causale	Machine No.	Note
24/06/2020 21:57	24/06/2020	21:57:49	24/06/2020 22:07	9 min.38 sec.	578	CF008 - GUASTO IMPIANTO		PORTA MAGAZZINO SCODELLINI E MAGNETI ROTTA
24/06/2020 23:31	24/06/2020	23:31:36	24/06/2020 23:57	26 min.11 sec.	1572	CF008 - GUASTO IMPIANTO	Gr. 110	GR.600 GR.130 GR.110
24/06/2020 23:31	24/06/2020	23:31:36	24/06/2020 23:57	26 min.11 sec.	1572	CF008 - GUASTO IMPIANTO	Gr. 130	GR.600 GR.130 GR.110
24/06/2020 23:31	24/06/2020	23:31:36	24/06/2020 23:57	26 min.11 sec.	1572	CF008 - GUASTO IMPIANTO	Gr. 600	GR.600 GR.130 GR.110
25/06/2020 06:23	25/06/2020	06:23:39	25/06/2020 06:31	7 min.51 sec.	472	CF005 - MANUTENZIONE AUTONOMA		
25/06/2020 17:59	25/06/2020	17:59:59	25/06/2020 18:23	23 min.29 sec.	1409	CF020 - PIAZZAMENTO/SPIAZZAMENTO	Gr.700	GR 700 SOST. VITI PINZE
25/06/2020 21:51	25/06/2020	21:51:45	25/06/2020 22:02	10 min.24 sec.	625	CF012 - MANUTENZIONE MIGLIORATIVA	Gr. 351	GR.351 PULIZIA POSAGGIO+GR.700 PULIZIA STAZIONI
25/06/2020 21:51	25/06/2020	21:51:45	25/06/2020 22:02	10 min.24 sec.	625	CF012 - MANUTENZIONE MIGLIORATIVA	Gr.700	GR.351 PULIZIA POSAGGIO+GR.700 PULIZIA STAZIONI
26/06/2020 00:14	26/06/2020	00:14:22	26/06/2020 00:20	6 min.12 sec.	372	CF012 - MANUTENZIONE MIGLIORATIVA	Gr. 261	GR.261 SOSTITUITA PUNTA AVVITATORE PER USURA
26/06/2020 13:59	26/06/2020	13:59:04	26/06/2020 14:18	19 min.17 sec.	1158	CF008 - GUASTO IMPIANTO		

Figure 4.3 An example of *Fermi Macchina* data

Step 3: preparation of data about machine's alarm

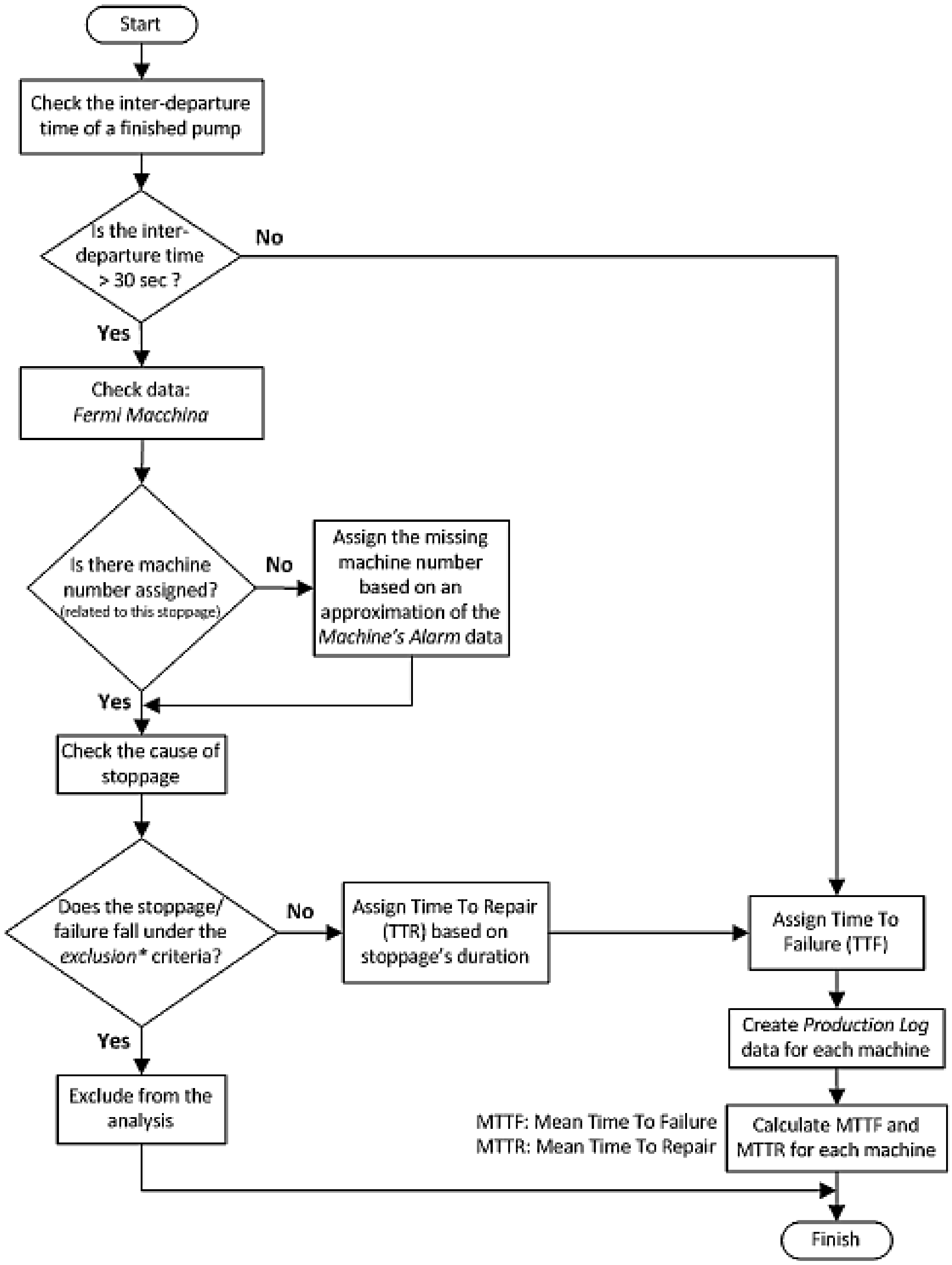
1. Delete unnecessary data columns such as *Mese*, *Lotto*, *Turno*, *Tipo*, *Grouppo*, *Area*, and *Durata*.
2. Split information inside column *Data Evento* into two columns named *Date* and *Time*. These columns are the primary keys for filtering.

Data Evento	Date	Time	Allarme
01/03/2021 06:02:43	01/03/2021	06:02:43	1 Termico Bob. Lancio Corrente non OK (E0.0 non ON)
01/03/2021 06:05:23	01/03/2021	06:05:23	164 Ar.200 Presenza Aria Su Sgancio Isola non OK (E3.7 non ON)
01/03/2021 06:06:59	01/03/2021	06:06:59	1827 Gr323 Passaggio OR non rilevato. Vibratore vuoto? (E354.3 mai ON)
01/03/2021 06:09:54	01/03/2021	06:09:54	2846 Gr520 Stoppaggio Pallet non IN (OUT E512.0, IN E512.2)
01/03/2021 06:09:56	01/03/2021	06:09:56	319 Gr120 Presenza pallet su stazione non ON (E120.6)
01/03/2021 06:12:14	01/03/2021	06:12:14	1827 Gr323 Passaggio OR non rilevato. Vibratore vuoto? (E354.3 mai ON)
01/03/2021 06:13:11	01/03/2021	06:13:11	2846 Gr520 Stoppaggio Pallet non IN (OUT E512.0, IN E512.2)
01/03/2021 06:13:19	01/03/2021	06:13:19	1827 Gr323 Passaggio OR non rilevato. Vibratore vuoto? (E354.3 mai ON)
01/03/2021 06:13:50	01/03/2021	06:13:50	1827 Gr323 Passaggio OR non rilevato. Vibratore vuoto? (E354.3 mai ON)
01/03/2021 06:14:21	01/03/2021	06:14:21	2846 Gr520 Stoppaggio Pallet non IN (OUT E512.0, IN E512.2)

Figure 4.4 An example of machine's alarm data

Once all the data is ready, then the data processing is conducted. Data processing aims to manually create production log data (i.e., data that records all events that occur within a machine during the production time) since there is no automatic production log data generation for each machine. This kind of data is necessary to obtain parameters: Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) because the evaluation of the assembly line Generation 2 will focus on the availability and performance of the line. MTTF measures equipment's reliability while MTTR measures equipment's maintainability. MTTR comes from the parameter Time to Repair (TTR), which is based on the duration of the machine's stoppage. MTTF comes from the parameter Time to Failure (TTF), which is based on the TTR approximation.

The three sets of data that have been prepared followed the data processing procedure as the Figure below. Worth noting that data processing was done manually in the present state.



***Exclusion criteria: long (> 5 hours) stoppages , weekly cleaning, scheduled maintenance, meeting, etc.**

Figure 4.5 Flowchart of the data processing procedure

A short example of the manual production log data development is taken from machine Gr.312, and it is shown in Figure 4.6. From the figure, it can be seen that not all shifts were included. For example, the 1st and 2nd shifts on January 18th 2021, were excluded because there were scheduled weekly cleaning and scheduled maintenance by Sinteco. Also, the 2nd shift of January 20th 2021, was excluded because there was no production. The data inside rows highlighted in yellow were taken from the *Fermi Macchina*, and the duration was taken into account as TTR. The red colour within the yellow rows represents data from an approximation of the machine's alarm data. Meanwhile, the white rows are considered as TTF, which value is adjusted based on the TTR.

Gr. 312

Date	Note	Shift	Start Time	Finish Time	Code	Duration [sec]	Duration [hour]	
14-Jan-21	All shifts are included	Shift 1	06:00:00	08:51:44		02:51:44	2,862	TTF_i
			08:51:45	09:04:33	CF008	00:12:48	0,213	TTR_i
			09:04:34	13:30:00		04:25:26	4,424	
		Shift 2	13:30:01	21:00:00			7,5	
		Shift 3	21:00:01	04:30:00			7,5	
15-Jan-21	All shifts are included		06:00:00	04:30:00			22,50	
16-Jan-21	Saturday - Shift 1 only	Shift 1	06:00:00	13:30:00			7,5	
18-Jan-21	Shift 1 and 2 are excluded	Shift 3	21:00:01	04:30:00			7,5	
19-Jan-21	Shift 1 and 2 are excluded	Shift 3	21:00:01	04:30:00			7,5	
20-Jan-21	Shift 2 is excluded	Shift 1	06:00:00	13:30:00			7,5	
		Shift 3	21:00:01	22:25:09		01:25:08	1,419	
			22:25:10	22:25:59	Micro	00:00:49	0,014	
			22:26:00	22:26:39		00:00:39	0,011	
			22:26:40	22:27:09	Micro	00:00:29	0,008	
			22:27:10	22:29:27		00:02:17	0,038	
			22:29:28	22:31:10	Micro	00:01:42	0,028	
			22:31:11	00:21:33		01:50:22	1,839	
			00:21:34	00:21:46	Micro	00:00:12	0,003	
			00:21:47	04:30:00		04:08:13	4,137	

Figure 4.6 Manually developed production log data for machine Gr.312

After making production log data and identifying MTTF and MTTR, parameters such as failure rate, repair rate, and efficiency in isolation are calculated for each machine. The calculations were done by using the equation mentioned in Chapter 2.5.1.1. The parameters for each machine can be seen in Table 4.2 in the Appendix.

4.3 Data Analysis

Data about the OEE achievement result is used to preliminary analyze the current production performance as explained in Section 3.4 in Chapter 3. Here, the *Fermi Macchina* data is used to find the root cause of relatively low machine's availability and performance. The data used in the study was from January to March 2021 since the *Micro Fermata* category was introduced in January 2021.

As of the occurrence of the stoppage, shown in Figure 4.7, the category of *Micro Fermata* (i.e., micro stop) has the highest value with 508 cases. It is followed by *Guasto Impianto* (i.e., system failure) and *Manutenzione Autonoma* (i.e., autonomous maintenance) with 204 and 64 cases respectively

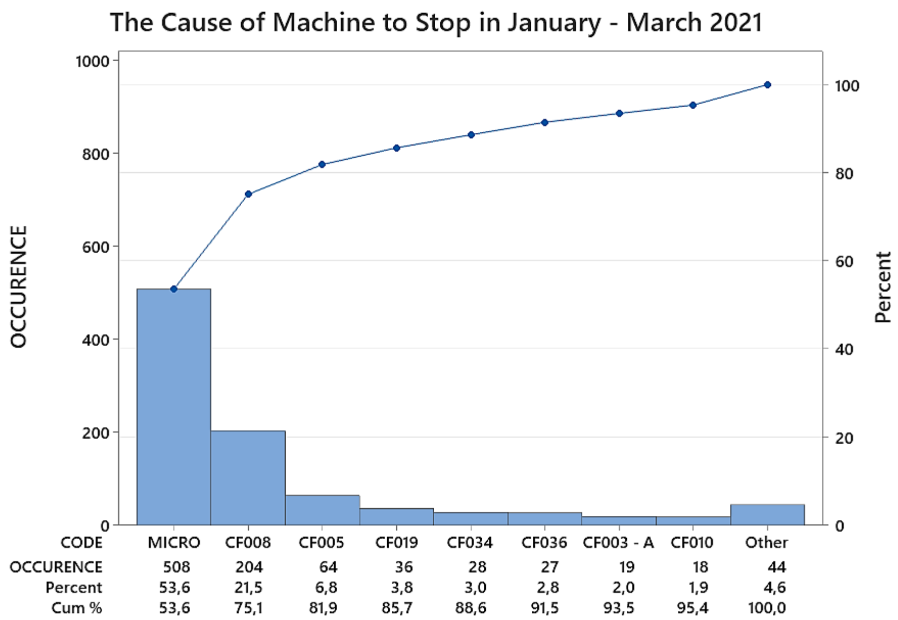
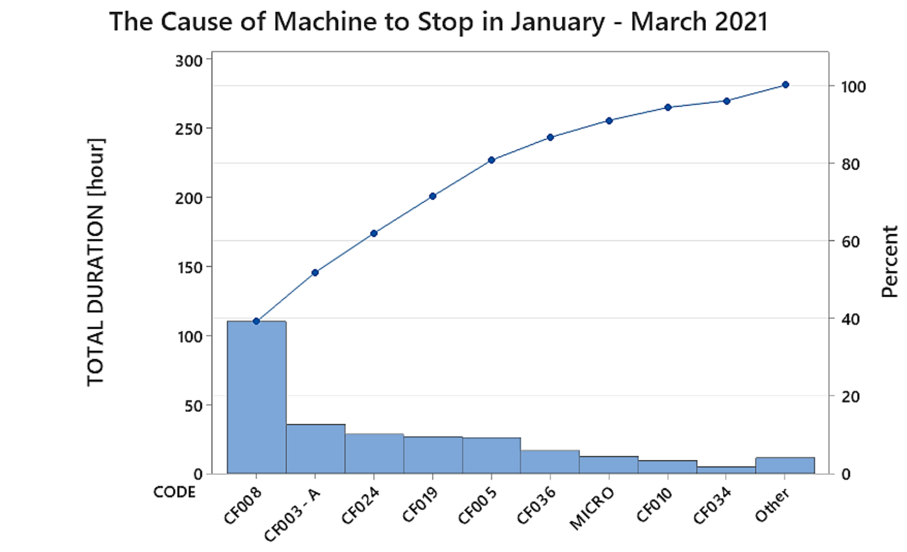


Figure 4.7 The cause of machine to stop based on its occurrence

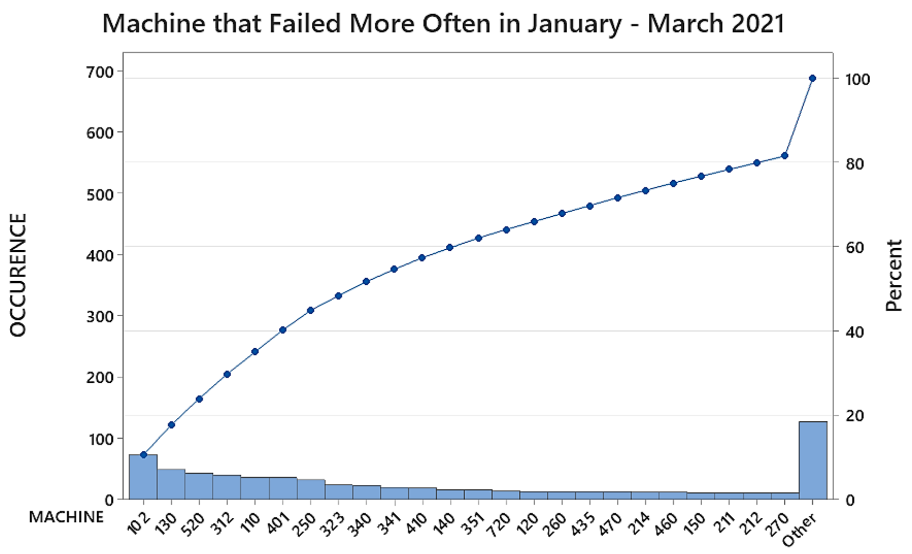
Next, the severity of the stoppage or failure on the line's performance can be understood better by knowing the total duration. Therefore, a Pareto chart is made, as it is shown in Figure 4.8, considering this purpose. The cause of the machine to stop related to *Guasto Impianto* has the highest total duration with 109,9 hours. It is followed by *Mancanza Materiale* (i.e., lack of material) and *Pulizia* (i.e., cleaning) with 35,6 and 28,4 hours respectively.



CODE	CF008	CF003 - A	CF024	CF019	CF005	CF036	MICRO	CF010	CF034	Other
TOTAL DURATION [hour]	109,9	35,6	28,4	26,7	26,1	16,5	12,3	9,4	4,8	11,3
Percent	39,1	12,7	10,1	9,5	9,3	5,9	4,4	3,3	1,7	4,0
Cum %	39,1	51,8	61,9	71,4	80,7	86,6	90,9	94,3	96,0	100,0

Figure 4.8 The cause of machine to stop based on its total duration

According to the occurrence and total duration, stoppage related to *Guasto Impianto* is indicated to be the main problem affecting the availability and performance of the line. Hence, it is worth investigating which machine failed more often (i.e., has worse performance) than the others. Figure 4.9 shows a brief image of machines that failed more often from January until March 2021. This Pareto chart compromises stoppage falls in *Guasto Impianto*, *Manutenzione Autonoma*, and *Micro Fermata*. These three are mostly related to system failure according to the note assigned by the operator.



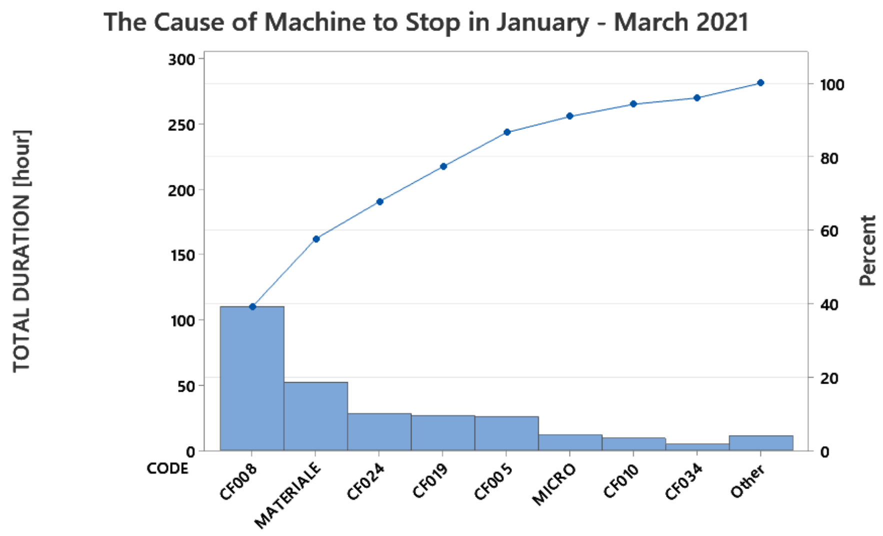
MACHINE	102	130	520	312	110	401	250	323	340	341	410	140	351	720	120	260	435	470	214	460	150	211	212	270	Other
OCCURENCE	73	49	43	40	36	36	32	24	23	20	19	16	16	14	13	13	13	13	12	12	11	11	11	11	127
Percent	11	7	6	6	5	5	5	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	18
Cum %	11	18	24	30	35	40	45	48	52	55	57	60	62	64	66	68	70	72	73	75	77	78	80	82	100

Figure 4.9 Machine that failed more often in January – March 2021

Based on the chart, the robot (Gr.102), a pick and place SCARA robot in Area 100, fails more often than the other machines. Even though this kind of Pareto chart can be made, the preciseness of the graph cannot be guaranteed since it is based on the available data, where some stoppages were not considered due to lack of machine number assigned. As has been mentioned before, the machines' stoppages are recorded manually by the operator, and in most cases, the information inserted is incomplete. In total, there are 884 out of 1011 (around 83,5%) stoppages in January – March 2021 that do not have complete information. Eventually, a further credible investigation cannot be performed due to the quality of available data.

Another important point related to the total duration of stoppage based on category is the lack of material issues. As shown in Figure 4.8, *Mancanza materiale* (CF003-A) holds the second position in terms of total duration. In fact, there are four types of stoppage related to the supply material: *Ricarico materiale* (CF002), *Mancanza materiale* (CF003-A), *Mancanza material interno* (CF003-B), and *Mancanza materiale di fornitura* (CF036). Thus, it is worth understanding the real impact of lack of material supply on the line's performance by merging those four.

A Pareto chart is made, as shown in Figure 4.10, for this purpose. By merging all stoppages related to the material supply, we can point out its hidden severe impact on the line's overall performance. According to the data, the lack of material issues contributes to the machine stop by 18.5%. Their total duration is halves of the one caused by system failure. In addition, based on the data, the lack of material issue has the highest maximum duration of 17,8 hours, while the stoppage related to the system failure is 7,98 hours.



CODE	CF008	MATERIALE	CF024	CF019	CF005	MICRO	CF010	CF034	Other
TOTAL DURATION [hour]	109,9	52,0	28,4	26,7	26,1	12,3	9,4	4,8	11,3
Percent	39,1	18,5	10,1	9,5	9,3	4,4	3,3	1,7	4,0
Cum %	39,1	57,6	67,8	77,3	86,6	90,9	94,3	96,0	100,0

Figure 4.10 The cause of machine to stop based on its total duration with the aggregation of problem-related to the lack of material

The effect of lack of material on the production might be underestimated since it is hidden under some categories. In fact, this could affect the availability of the machines since it can be considered as breakdown losses that lead to time and quantity losses. By taking an example of production on March, 10th 2021, where there was a lack of material issue with a total duration of 3,32 hours, it can be calculated that the availability dropped to 85,2%. Consequently, the total unit produced was 23% less than a 100% availability condition.

In addition, based on the inter-departure time data taken at the end of the assembly line shown in Figure 4.11, it can be seen that the effect of lack of material is quite severe in the throughput rate of the line. The lack of material makes the inter-departure time of finished pumps jump very high (see points 3 and 5) compared to the one related to the robot collision (see point 6: a stop due to the system failure but assigned in the category of *Manutenzione Autonoma*). By all means, this kind of jump will eventually affect the throughput rate on average. Hence, making the company unable to reach the targeted throughput rate.

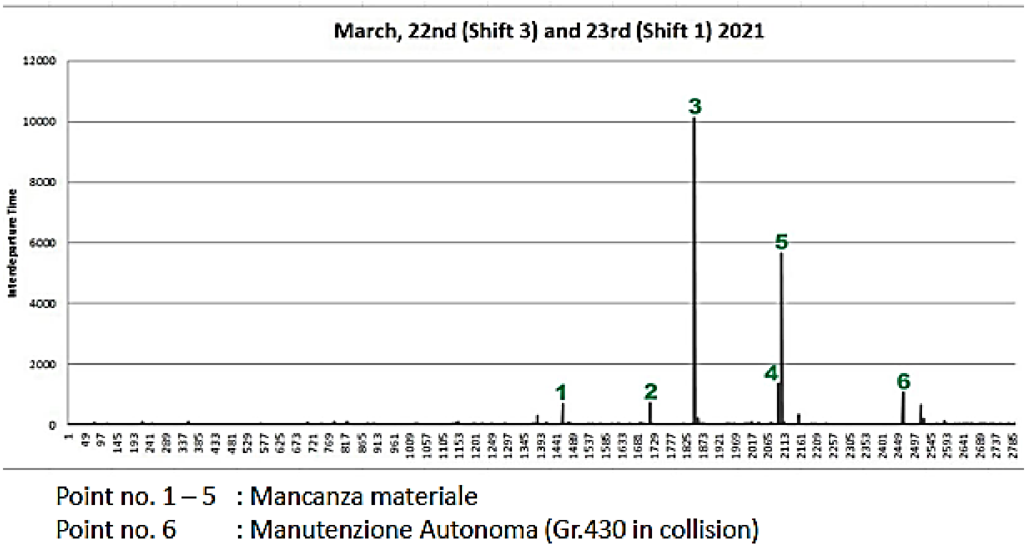


Figure 4.11 Inter-departure time of finished pump considering lack of material issue

The last focus of analysis is related to the *Micro Fermata* category since this failure occurs quickly but frequently. In this analysis, the inter-departure time data was used. The inter-departure time between finished pumps should be more or less equal to the cycle time of the assembly line (around 11,5 -12 seconds). If a failure occurs, the propagation effect will increase the difference between the two recorded data at a certain point of time which is not so long from the time of the failure itself. Thus, it will be possible to highlight the losses by translating this data into a graphical representation.

An example of a shift with a normal operating condition is taken for this analysis. Here, the third shift on March, 19th 2021, is selected. A graphical representation of the inter-departure time of the finished pumps is created and is shown in Figure 4.12. Based on the figure, it can be seen that the inter-departure time was quite fluctuating, with some high jumps pointed out by numbers 1 – 14. In consequence, the reason behind these 14 jumps was identified through *Fermi Macchina* data.

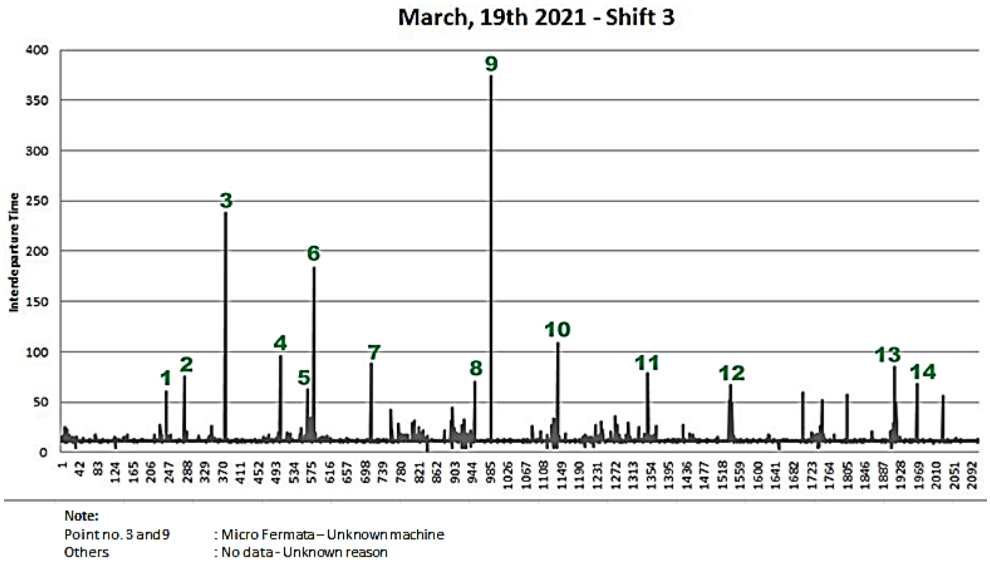


Figure 4.12 The Inter-departure time of the finished pumps in the 3rd shift of March 19th 2021

In accordance with the *Fermi Machina* data, only 2 out of 14 points were recorded within the database. These two are points number 3 and 9. Both were registered under the category of *Micro Fermata* but without any further information (i.e., no specific reason or machine's number). Meanwhile, the other "jumps" were not assigned and recorded by the operator. From this analysis, it can be concluded that minor stoppages, idling, or reduced speed events are not properly recorded and stored by the system and the operator. Indeed, this could affect the performance evaluation and continuous improvement process since the minor stoppages, idling, or reduced speed plays an essential role within the availability and performance of the machine and assembly line.

Chapter 5

Model Generation

Two models developed in this thesis work are the Performance Evaluation model using *Matlab* software and the Plant Simulation model using *Tecnomatix Plant Simulation* by *Siemens*. The differences between the two of them are:

Performance Evaluation Model	Plant Simulation Model
A mathematical (Markov Chain)-based model	A simulation-based model
The assembly line is aggregated into stations	The assembly line is developed based on all machines, including material handling.
Provide a closer look to the reality	Provide a very close look to the reality
Provide approximate solution	Provide confidence interval
Parameters needed: • For each station - Production rate - Failure rate - Repair rate • Buffer capacity between the stations	Parameters needed: • For each machine - Processing time - Mean Time To Repair (MTTR) - Availability • For material handling - Size (e.g., length) - Speed or processing time - Capacity
A simplified and quick analysis; easier to manipulate	More effort is needed and time-consuming

Table 5.1 The differences between Performance Evaluation and Plant Simulation model

In this chapter, the development of both will be explained in a more detailed way considering all parameters calculated in the previous section. The validation of both models is also presented. Then, the models are used to analyze the AS-IS situation of the assembly line, aiming to justify the preliminary problem identified and develop possible solutions to improve the assembly line.

5.1 Performance Evaluation Model

A decomposition approach: a continuous approximation of discrete deterministic model is chosen to evaluate the performance of assembly line Generation 2. It models the system based on the Markov Chain model that is developed mathematically, considering a realistic hypothesis closer to reality with an approximate solution. In this Approximate Analytical Model (AAM), the assembly line Generation 2 is aggregated into stations, allowing a simplified and quick analysis. It takes into account the dynamic, buffer capacity, failure rate, and repair rate of the stations.

The development of a precedence diagram and the manual measurement of processing times performed in advance is used as a basis for station assignment. Here, the machines are grouped into several stations considering some assumptions below:

1. A single-model product is produced on the assembly line.
2. The precedence relationships among the tasks are known.
3. A task cannot be split among two or more stations.
4. All tasks must be processed.
5. Due to technological constraints, some tasks should be performed together and therefore assigned to the same station.
6. The layout of the assembly line cannot be changed. Therefore, the distance and area between machines are considered zoning constraints.
7. A pallet is moved between the stations by a conveyor that has a certain speed.

Considering the complexity of machines and processes within a station, the cycle time of each station is defined as an inter-departure time of a pallet from a station. It is deterministic, including load and unloading time, and independent between stations. Furthermore, to configure efficient station modelling, a fixed common cycle time (t_{FCT}) is considered. It is also used to pace the line (as an upper boundary). In this case, the t_{FCT} is equal to 12 sec/ unit and it is calculated based on available time and target quantity produced in a week.

$$t_{FCT} = \frac{\text{Available Time}}{\text{Target Quantity}} = \frac{112{,}5\ [\frac{\text{hours}}{\text{week}}]}{33.750\ [\frac{\text{units}}{\text{week}}]} = 0{,}003\ \frac{\text{hours}}{\text{unit}} = 12\ \frac{\text{sec}}{\text{unit}}$$

Once the assumptions and t_{FCT} are defined, machines are grouped into 15 stations and a buffer is placed between each station. Indeed, the buffer refers to the pallets on the conveyor waiting to be processed by the station. A stopper position limits the buffer capacity, as explained in Section 3.3 in Chapter 3. The buffer capacity between each station can be seen in Table 5.2. To clarify the naming, buffer B1 refers to the buffer between stations 1 and 2.

Name	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16
Capacity	5	3	3	2	2	2	7	5	9	2	2	5	6	3	5	5

Table 5.2 Buffer capacity between stations

The next step within the station assignment is calculating cycle time and the production rate for each station. As mentioned earlier, each station's cycle time is defined as an inter-departure time of a pallet from a station. Thus, to calculate the cycle time, the total processing time of all main tasks within the station is divided by the number of parts or pallets processed. To better understand this concept, taken as an example of station six where there are four machines: Gr.250, 260, 261, and 270. These machines have a total work content (i.e., the sum of processing time of all main tasks within machines) of 24,53 seconds. Each machine works on one pallet at one time. So, the cycle time of station 6 is:

$$t_{CT\ station\ 6} = \frac{\text{The total work content of station 6}}{\text{No.of pallets to be worked in station 6 at one time}} = \frac{24{,}53 \text{ sec}}{4 \text{ pallets}} = 6{,}13 \, \frac{\text{sec}}{\text{pallet}}$$

Then, the production rate (μ) of station six can be calculated as:

$$\mu_{station\ 6} = \frac{3600 \text{ sec/hour}}{t_{CT\ station\ 6}} = 587{,}28 \, \frac{\text{pallets}}{\text{hours}}$$

The result of the station assignment in detail can be seen in Table 5.3 in Appendix. While a brief schema for this station assignment, including the buffers, can be seen in the figure below.

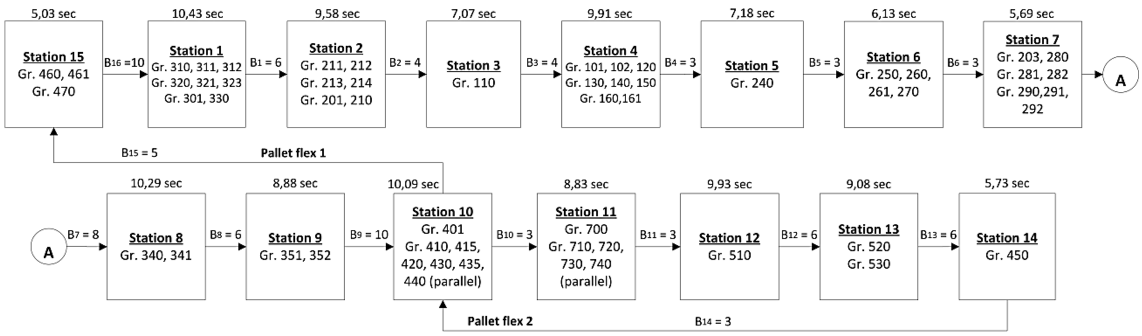


Figure 5.1 A brief schema on station assignment result

The parameters of each machine obtained and presented in Table 4.2 are used to calculate failure rate, repair rate, and efficiency in isolation for each station. Even though later on the evaluation model will be developed as a Single-Up and Single-Down model, the efficiency in isolation was calculated firstly assuming a Single-Up and Multiple-Downs model (equation 2.10) to give a closer look to reality. The repair rate of each station was calculated as the average repair rate of all machines within the station (equation 5.2). Then, by having an assumption that the efficiency in isolation based on a Single-Up and Multiple-Downs model is equal to a Single-Up and Single-Down model (equation 5.1), the failure rate of the station was determined as the function of the station's efficiency in isolation and repair rate (equation 5.3). At last, the production rate in isolation for each station is calculated.

$$e_{SU-SD} = e_{SU-MD} = e \qquad (5.1)$$

$$r_{SU-SD} = \frac{r_1 + r_2 + \cdots + r_n}{n} \qquad (5.2)$$

$$p_{SU-SD} = f\ (e, r_{SU-SD}) \qquad (5.3)$$

An example of this calculation is taken from station 6. As mentioned before, there are four machines in station 6 with previously calculated parameters as below:

Machine	MTTF [hour]	MTTR [hour]	Failure Rate [1/hour]	Repair Rate [1/hour]
250	51,253	0,452	0,020	2,211
260	120,876	0,264	0,008	3,792
261	225,930	0,263	0,004	3,799
270	180,803	0,137	0,006	7,296

Table 5.4 Parameters for each machine in station 6

Based on the above parameters:

- The efficiency in isolation of the station is equal to:

  $e_6 = \frac{1}{1 + \sum_{k=1}^{4} \frac{p_k}{r_k}}$ = 0,9872 = 98,72%

- Then, the repair rate (r_6) is equal to:

  $r_6 = \frac{2{,}211 + 3{,}792 + 3{,}799 + 7{,}296}{4}$ = 4,274 per hour

- The failure rate (p_6) is equal to:

  $f_6 = f(e_6, r_6)$ with $e_6 = \frac{r_6}{p_6 + r_6}$ so, $p_6 = \frac{r_6}{e_6} - r_6 = \frac{4.274}{0.872}$ – 4,274 = 0,055 per hour

As a result, the parameters calculated for all stations are as below:

Station	Cycle time [sec/unit]	Production rate [unit/hour]	Failure rate [1/hour]	Repair rate [1/hour]	Efficiency in isolation	Production rate in isolation [unit/hour]
1	10,43	345,16	0,063	6,837	0,991	342,03
2	9,58	375,78	0,050	7,237	0,993	373,23
3	7,07	509,19	0,019	4,466	0,996	507,05
4	9,91	363,27	0,500	37,466	0,987	358,48
5	7,18	501,39	0,001	6,327	1,000	501,31
6	6,13	587,28	0,055	4,274	0,987	579,78
7	5,69	632,69	0,025	9,068	0,997	630,92
8	10,29	349,85	0,018	2,375	0,993	347,25
9	8,88	405,41	0,013	5,642	0,998	404,50
10	10,09	356,79	0,076	3,980	0,981	350,14
11	8,83	407,70	0,025	4,490	0,994	405,41
12	9,93	362,57	0,003	0,940	0,996	361,30
13	9,08	396,48	0,022	7,962	0,997	395,38
14	5,73	628,16	0,002	5,381	1,000	627,97
15	5,03	715,71	0,009	12,858	0,999	714,90

Table 5.5 Parameters calculated for each station

Once the parameters were ready, the model was built under some assumptions that led to the analysis based on a continuous time-mixed state Markov process.

General assumptions on the stations:

1. Machines are unreliable, and failures are operation dependent.
2. The processing time of the stations is assumed to be deterministic, different between stations, and include time to load and unload the part.
3. The system is asynchronous.
4. Stations are modeled in a single-up and single-down state.
5. Failures and repairs are assumed to be random and can happen at any time.
6. Time to failure is assumed to be exponentially distributed with the parameter Mean Time to Failure (MTTF).
7. Time to repair is assumed to be exponentially distributed with the parameter Mean Time to Repair (MTTR).
8. The input station is never starved, and the output machine is never blocked.

General assumptions on the parts:

1. One part type is produced, and parts are discrete.
2. The dispatching policy is First In First Out (FIFO).
3. Buffer capacity is finite, and the buffer level can change continuously.
4. The discrete flow of parts is approximated by a control mechanism based on the buffer level.
5. The blocking discipline considered is Blocking after service (BAS). Thus, the working position of the upstream machine is added to the buffer capacity, which makes it become N+1.
6. No part enters the system from machines other than input machines, and no part exits the system from machines other than output machines.

In addition, in this modelling, stations 14 and 15 are excluded from the analysis because these stations do not perform any assembly process and are reliable. Thus, their effect within the evaluation of the model is not so significant. The model focuses only on stations performing the main process: stations 1-13 with buffers B1-B12.

Furthermore, the software used has a maximum evaluation capacity of nine stations in the case of Single-Up and Single-Down. For this reason, 13 stations are divided into two groups, so-called *Line 1* and *Line 2*, during the evaluation process. *Line 1* consists of stations 1-8 (including buffer B1-B7), while *Line 2* consists of stations 8-13 (including buffer B8-B12), as shown in Figure 5.2. Given the introduction of this kind of sub-division, the throughput rates between Line 1 and 2 are different, and it is not true in reality. Hence, further decomposition within the line is presented.

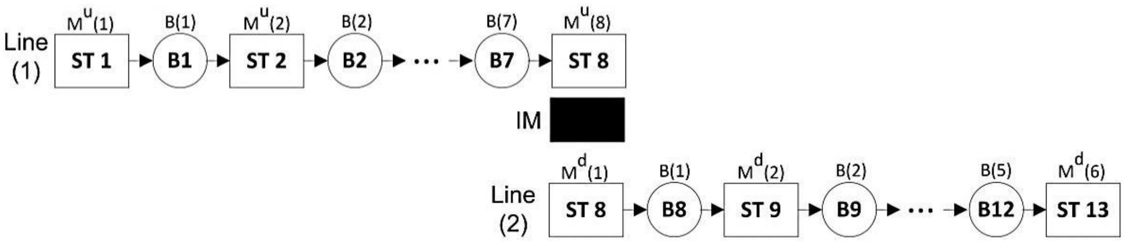


Figure 5.2 Sub-division of *Line 1* and *Line 2* in the Performance Evaluation model

A further decomposition is introduced, as shown in Figure 5.3, through the presence of an Integrated Machine (IM). Considering that the performance of station 8 in *Line 1* is not affected by any blocking and t station 8 in *Line 2* is not affected by any starvation, the IM aims to add the missing behaviour to the corresponding lines as an additional down-state. It will introduce blocking probability to station 8 in *Line 1* and starvation probability to station 8 in *Line 2*.

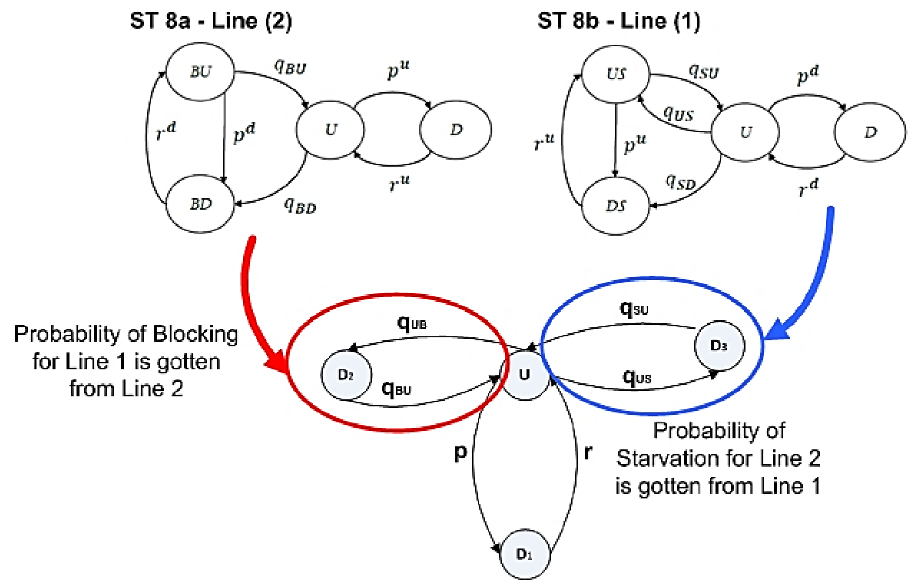


Figure 5.3 Decomposition of the Integrated Machine station 8

The logic performed in the evaluation of the model is described below:

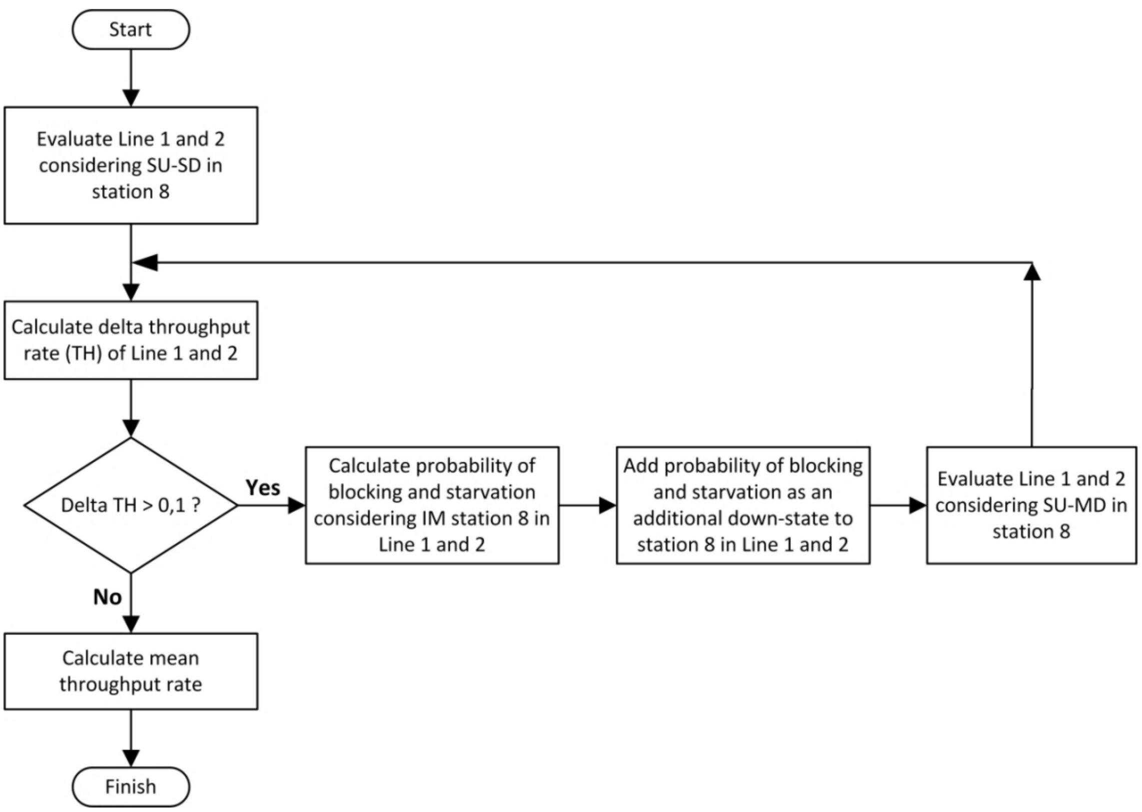


Figure 5.4 Flowchart of the evaluation logic of the Performance Evaluation model

5.2 Plant Simulation Model

Unlike the one evaluated in *Matlab* software, the Plant Simulation model built-in *Tecnomatix Plant Simulation* by *Siemens* concerns almost all machines within the assembly line, including the material handling (conveyors), as shown in Figure 5.5.

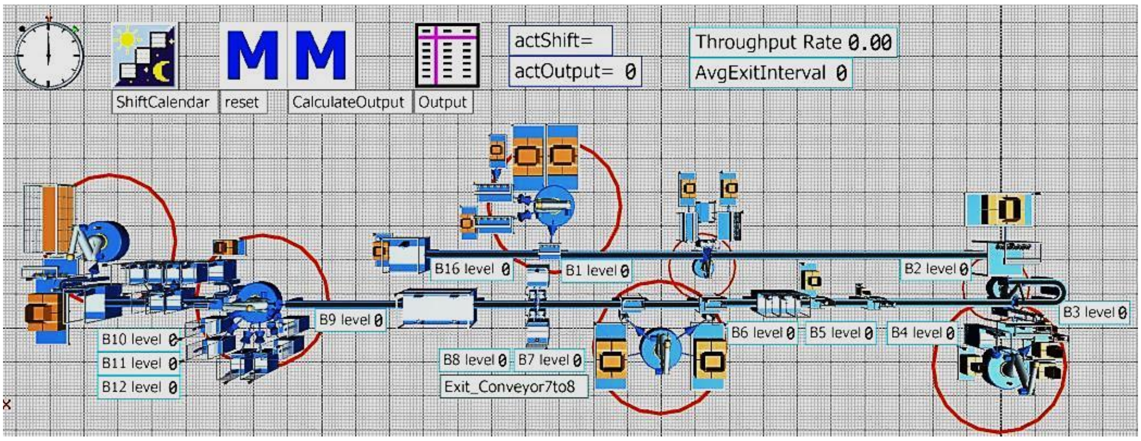


Figure 5.5 The 3D model of Generation 2 in Tecnomatix Plant Simulation

As a starting point, some general assumptions are made as below:

1. Machine Gr.460 and Gr.461 are excluded since they are not performing any assembly process and are reliable. Thus, their effect on the performance of the model is not so significant.
2. The loops of the lines are presented through interval time in releasing the pallet within *Source_Flex1* (for loop *Pallet Flex 1*) and *Source_Flex2* (for loop *Pallet Flex 2*). The interval time is equal to 10 seconds.
3. Area 600 is represented by the *Drain* where the output is counted.
4. Some machines such as Gr.201, Gr.101, Gr.150, Gr.340, and Gr.700 are represented by two objects instead of one. Meanwhile, some machines, such as Gr.310 - Gr.311, Gr.320 - Gr321, etc., are combined. This assumption is made for simplicity and due to software features constraints.
5. Some additional machines are presented only to support the modelling.
6. The number of pallets is assumed to be enough to saturate the line.

Furthermore, within each machine, parameters such as processing time, availability (this value is taken from efficiency in isolation of each machine), and MTTR are set according to the calculation made previously (see Table 4.2). Also, the parameters for the conveyor, such as the length, capacity (i.e., number of pallets that can wait on the conveyor), and speed, are set. The simulation was run with a duration of three calendar days with three shifts/ day and 7,5 hours/ shift.

5.3 Models Validation

A comparison of both models' performance according to some parameter configurations is performed to validate the models. As mentioned before, the Performance Evaluation model is constructed based on stations, while the Plant Simulation model is based on machines. Therefore, the parameters used between models are different but correlated, and station three is chosen to simplify the process since there is only one machine in it. The parameters' configuration is the following:

Performance Evaluation Model	**Plant Simulation Model**
Production rate of station 3: μ	Cycle time of machine Gr.110: CT
Repair rate of station 3: r	MTTR of machine Gr.110: $MTTR$ Availability of machine Gr.110: e
Buffer capacity: N (in this case, buffer before and after the station will be used: B_2 and B_3)	

Table 5.6 Parameters' configuration for models validation

Moreover, these four parameters will be expanded into two levels: low and high, as shown in Table 5.7. Thus, it will create 16 different cases of a fractional factorial plan as shown in Table 5.8 in Appendix.

Level	CT **[sec/unit]**	μ **[unit/hour]**	$MTTR$ **[hour]**	r **[1/hour]**	e **[%]**	B_2 **[pallets]**	B_3 **[pallets]**
Low	5,30	678,93	0,168	5,955	99,68	3	3
High	8,84	407,36	0,280	3,573	99,47	8	8

Table 5.7 Two-level of parameters' configuration for model validation

The performance measurement statistically evaluated is the throughput rate. Both models are compared through the percentage error of the measured performance:

Steady-state throughput rate: $error\%TH = \frac{|TH\ model - TH\ simulation|}{TH\ simulation}$ x 100%

As a result, the mean $error\%TH$ equals 2,45%, with a minimum value of 1,7% and a maximum of 2,88%. Detailed results of each case are reported in Table 5.9 in Appendix. The analytical model can be considered relatively accurate with respect to the simulation model.

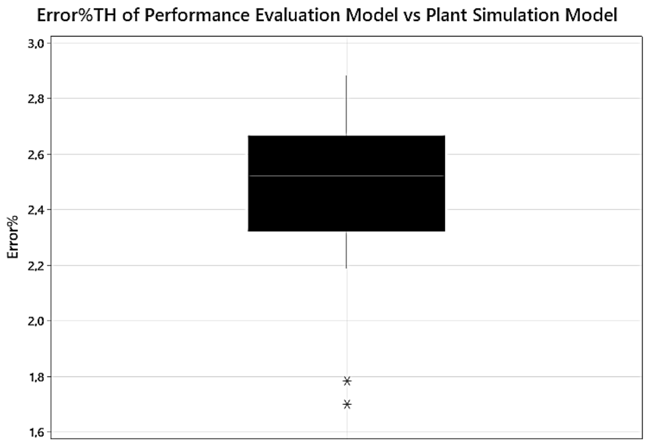


Figure 5.6 Box-plot of error%TH

5.4 AS-IS Situation Model Analysis

The result of performance evaluation in a continuous approximation of discrete deterministic model considering the AS-IS situation of the assembly line is a throughput rate of 322,31 units/ hour. Meanwhile, the result of the average buffer level is as follows:

Name	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
Capacity	1,13	0,84	2,45	0,22	0,43	0,85	5,71	0,17	3,66	0,18	1,28	0,02

Table 5.10 Average buffer level of AS-IS situation in the Performance Evaluation model

In addition, the model allows further analysis considering the performance of each station. This analysis aims to identify the bottleneck station through the probability of being up (operational), down (non-operational), starved, and blocked. Indeed, this feature could help to justify the preliminary problem identified in Chapter 3. Table 5.11 shows the result of the performance of each station considering the AS-IS.

Station	Up	Down	Starved	Blocked
1	0,934	0,0086	0	0,0574
2	0,8578	0,0059	0,0494	0,0869
3	0,6331	0,0027	0,1462	0,2181
4	0,8874	0,0118	0,0384	0,0624
5	0,6429	0,0001	0,2586	0,0984
6	0,5489	0,0071	0,2784	0,1657
7	0,5095	0,0013	0,2133	0,2759
8	0,9213	0,0322	0,0464	0,0253
9	0,795	0,0018	0,1715	0,0316
10	0,9034	0,0173	0,0632	0,0162
11	0,7906	0,0044	0,165	0,04
12	0,889	0,0028	0,1062	0,002
13	0,8132	0,0022	0,1846	0

Table 5.11 Stations' performance in the AS-IS situation

On the other side, the Plant Simulation model that is developed with a high level of detail considering all machines gave a result of an average throughput rate of 311,78 units/ hour with details below:

Date	Shift	Total Quantity [units]	Throughput rate (unit/hour)
01/07/2021	Shift-1	2.336	311,47
01/07/2021	Shift-2	2.342	312,27
01/07/2021	Shift-3	2.380	317,33
02/07/2021	Shift-1	2.350	313,33
02/07/2021	Shift-2	2.438	325,07
02/07/2021	Shift-3	2.177	290,27
05/07/2021	Shift-1	2.391	318,80
05/07/2021	Shift-2	2.394	319,20
05/07/2021	Shift-3	2.237	298,27

Table 5.12 The simulation result of AS-IS situation in Tecnomatix Plant Simulation

In addition, by using Tecnomatix Plant Simulation, it is possible to check the model considering the best performance of each machine (i.e., the availability of all machines is set to 100%). Besides aiming to check the correctness of the model's flow, this also could help to understand the throughput rate of the assembly line if all machines work perfectly without any failure. Thus, the throughput rate of the line is affected only by the processing time of each machine. The throughput rate achieved considering the best performance of each machine is 322,84 units/ hour. Moreover, as can be seen in Figure 5.7, the conveyors that are placed before machine Gr.330 (before station 1), before machine Gr.120 (before station 4), and before machine Gr.340 (before station 8) are full with pallets. Meanwhile, the conveyor placed before the robot Gr.401 is considered fluctuating and tends to be almost full.

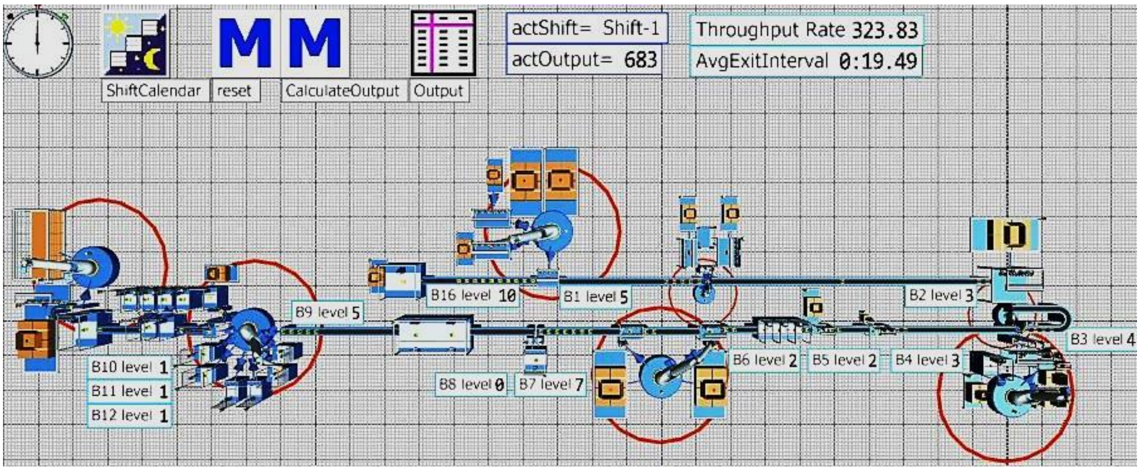


Figure 5.7 Plant Simulation Model considering 100% availability of all machines

A summary of the throughput rate result for both models considering the AS-IS situation is presented below:

AS-IS Condition	Performance Evaluation Model	Plant Simulation Model
100% availability for all machines	-	322,84 units/hour
Normal	322,31 units/hour	311,78 units/hour

Table 5.13 A summary of simulations result for the AS-IS situation

Based on the throughput rate obtained in the case of the AS-IS situation, shown in Table 5.13, the current assembly line performance can be considered capable of achieving the target throughput rate of 300 units/ hour. However, in reality, this target is rarely achieved by the line. Considering this phenomena, a comparison is conducted between the models' results with the actual condition through the percentage error of the measured performance.

Since both models were built based on a "normal" operating condition, the throughput rate of the actual condition used as a benchmark is 290 units/ hour (not the one that is 250,21 units/ hour). With the same approach as before, the percentage of error is calculated as below:

$$\text{Error\%TH}_{\text{model or simulation}} = \frac{|\,TH\ model\ or\ simulation - TH\ real|}{TH\ real} \times 100\%$$

$$\text{Error\%TH}_{\text{Performance Evaluation}} = \frac{|\,322{,}31 - 290|}{290} \times 100\% = 11{,}14\%$$

$$\text{Error\%TH}_{\text{Plant Simulation}} = \frac{|\,311{,}78 - 290|}{290} \times 100\% = 7{,}51\%$$

These two error percentage results could be considered relatively high. The reason behind this could be related to the fact that minor stoppages, idling, or reduced speed events are not properly recorded and stored in the system by the operator, as discussed in *Section 4.3* in *Chapter 4*. Once the input data is incomplete, it could reduce the accuracy of the models developed since the focus of the measurement conducted is related to the availability and performance of the machines. Furthermore, the error percentage of the Plant Simulation Model is lower than the one of the Performance Evaluation Model is because the Plant Simulation Model is developed in a more detailed way. Hence, it gives a very close look to reality.

Chapter 6

Results

There are two main objectives aimed to be achieved by this thesis work. Moreover, four issues arose, highlighting the main two objectives: the effect of the quality of the available information on the performance evaluation; the root causes of the relatively low availability and performance of the line; station or machine that is more problematic or potentially becomes the bottleneck of the line; and the possible improvement actions related to the identified problems. In this chapter, the results of the justification for these four issues will be explained.

6.1 The Quality of Available Information

The quality (i.e., adequateness and accuracy) of available information within the information system of the assembly line Generation 2 affects the evaluation process:

1. It increases the duration, complexity, and error made during data processing.
2. It reduces the preciseness of continuous improvement actions since:
   a. It reduces the accuracy of performance measurement of each machine (e.g., the development of production log data).
   b. It disables a further investigation on the specific machine that has worse performance.
   c. It reduces the accuracy of models developed, as described in Chapter 5.

The two main problems that are affecting the quality of available information are:

1. *The collection of production performance data only at the end of the line*

According to the theory presented in Section 2.2, OEE is supposed to be a tool to measure the performance of the equipment. However, in this case, the system only collects and stores data about the production performance at the end of the line (i.e., the inter-departure time data). Hence, it would be difficult to understand the availability and performance of each machine to make evaluation and improvement.

2. *The assignment of the root cause of the machine stoppages*

The assignment of the cause (category) of the machine stops is done manually by the operator. Indeed this leads to problems such as the preciseness and completeness of data inserted. In reality, 884 out of 1011 (around 83,5%) stoppages in January–March 2021 stored are with incomplete information such as missing machine numbers and exact reasons. Besides, there is no standard on how the operator must choose the machine's stoppages category. Some cases were found where some registered stoppages have been assigned to different categories even though the reasons mentioned are similar. Not forget to mention those stoppages which were assigned together in terms of category and duration because they occurred at the same time.

In order to solve these two problems, the improvement suggested is placing a sensor at the end of each station and working on automatic data collection in case of stoppages and failures. The combination of the two suggested improvements simplifies the overall data analysis process, as shown in the figure below.

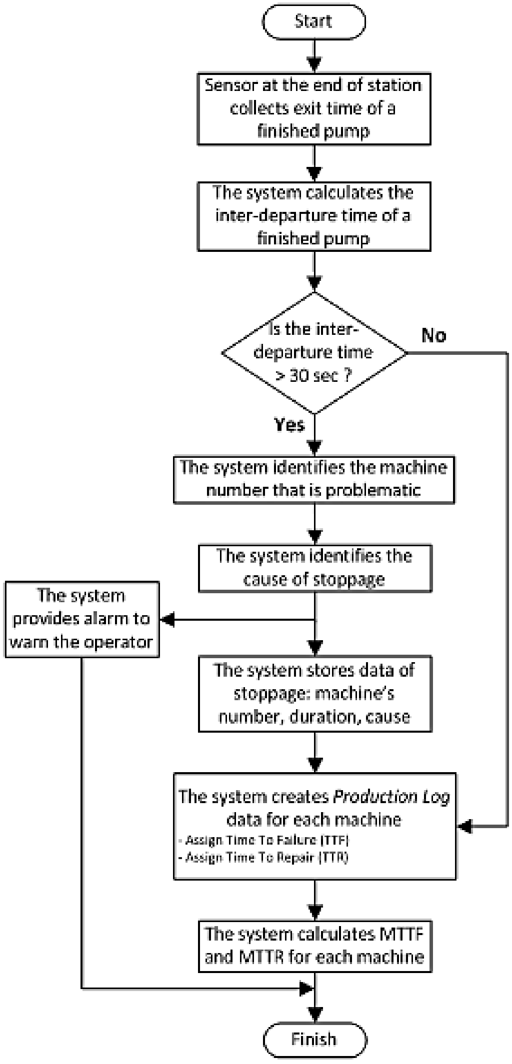


Figure 6.1 Flowchart of data processing process with sensor and automatic data collection

Compared to the current process (shown in Figure 4.5), the presence of a sensor at the end of each station and an automatic data collection in case of stoppages and failures shorten the overall process. It also increases the adequateness and accuracy of stored information and reduces the complexity of a human's data processing. Further, it can eliminate human error in data collection and increase the preciseness of machine performance evaluation. Moreover, quick feedback and alert in any slowdown process or minor stoppages allow immediate corrective or predictive maintenance. However, if the cause of stoppages cannot be assigned automatically by the system, a standard procedure for the category assignment must be established so that the reason for the failure can be identified clearly and not redundant nor ambiguous. Eventually, the proper justification of the machines with worse performance can lead to a correct solution or improvement action.

6.2 The Availability and Performance of The Assembly Line

According to the data analysis performed and explained in Chapter 4, the cause of relatively low machine's availability and performance is the stoppages related to *Guasto Impianto* (i.e., system failure), *Materiale* (i.e., lack of supply material), and *Micro Fermata* (i.e., micro stoppages). *Guasto Impianto* failure holds the first position in terms of total duration. Lack of material issue is a hidden problem under four different categories that contribute 18,5% from the total duration of the stoppage. Meanwhile, *Micro Fermata* holds the highest occurrence, but the company is facing issues in the quality of data collection for minor stoppages, idling, or reduced speed.

Since a further investigation of a machine that has the worse performance cannot be done due to the quality of available information, the focus of the analysis is shifted to the aggregate level: identification of the possible bottleneck station of the assembly line. The bottleneck is commonly known as the system constraint, which negatively impacts the production output. Therefore, a bottleneck station must be detected and improved to increase the system throughput (Godratt and Cox, 2004).

The assessment of the bottleneck station concerns the stations' performance presented in Chapter 5. Moreover, they are evaluated according to the five characteristics of the bottleneck station mentioned in Section 2.1.3 in Chapter 2: the longest cycle time, the longest uninterrupted active time (i.e., considering the station's probability of being up), the lowest sum of blocking and starvation probability, the longest queue of parts in front of the station with the shortest queue after the station, and the lowest production rate in isolation. Figure 6.2 shows the bottleneck station assessment where station 1 can be considered the bottleneck upstream while station 8 is the bottleneck downstream. In addition, stations 4 and 10 could be possible additional problems affecting the overall performance of the assembly line.

	Characteristics of bottleneck station				
Rank	The highest cycle time	The highest uninterrupted active time	The lowest sum of starvation and blocking probability	The longest queue of parts in front of station & the shortest queue after the station	The lowest production rate in isolation
1	Station 1	Station 1	Station 1	Station 1	Station 1
2	Station 8	Station 8	Station 8	Station 8	Station 8
3	Station 10	Station 10	Station 10	Station 10	Station 10
4	Station 12	Station 12	Station 4	Station 4	Station 4

Figure 6.2 Bottleneck stations assessment

In order to improve the availability and performance of the line and to limit the adverse effect of the bottleneck stations, some improvement actions are proposed under three categories: organizational, production control, and reconfiguration.

1. Organizational

Lack of material contributes to the line stop as much as 18.5% with a total duration of 52 hours. The availability of the line will drop to 85,2% because of 3,32 hours of lack of material. Considering the severity of this issue, the company should manage its supply chain and inventory management policy efficiently and effectively, mainly since the company works with 120 suppliers worldwide. However, no further suggestion is made regarding the logistic and supply chain configuration solution since they are not the main focuses of this thesis work.

2. Production Control

According to Zennaro *et al.* (2018), minor stoppages or micro-downtime is the most relevant loss that influences OEE in an automated flow line and thus the whole plant's efficiency. This kind of downtime is characterized by low duration but with high frequency. Therefore, it will have a more significant impact rather than a long failure. Based on *Fermi Macchina* data from January until March 2021, there are 508 micro-stoppages (i.e., stoppages with a duration of fewer than 5 minutes) in total. This accounts for 53,6% of the line efficiency in terms of production lost. The number might be higher since, in some cases, there is more than one machine that fails in one recorded data. Therefore, the company really needs to work on the quality of available information so that the minor stoppage or micro-downtime can be automatically recorded in terms of causes, duration, frequency, and machine number. Underestimating this issue could lead to errors in measuring the machine's performance and achieving OEE improvement. Based on research performed by Zennaro *et al.* (2018), eliminating 57% micro-downtime in the system can improve the OEE by 16,20%. Hence, in this case, by eliminating 53,6% of micro-downtime, the OEE can be enhanced by 15,42%.

3. Reconfiguration

In the case of the reconfiguration category, there are three improvement actions proposed:

- Reduction of station’s cycle time
- Maximization of buffer capacity between stations
- Parallelization of bottleneck station 8

a) *Reduction of station’s cycle time*

Most of the stations within the assembly line are equipped with one main robot or machine aiming to load and unload the part. In a few cases, the time needed to load and unload the part is relatively high than the primary process's processing time. An example is station 8, which is the bottleneck of the downstream that consists of two machines: Gr.340 and Gr.341. Machine Gr.340 performs loading and unloading with 3,72 seconds on average to perform this task, which is around 30% of the total cycle time of the station.

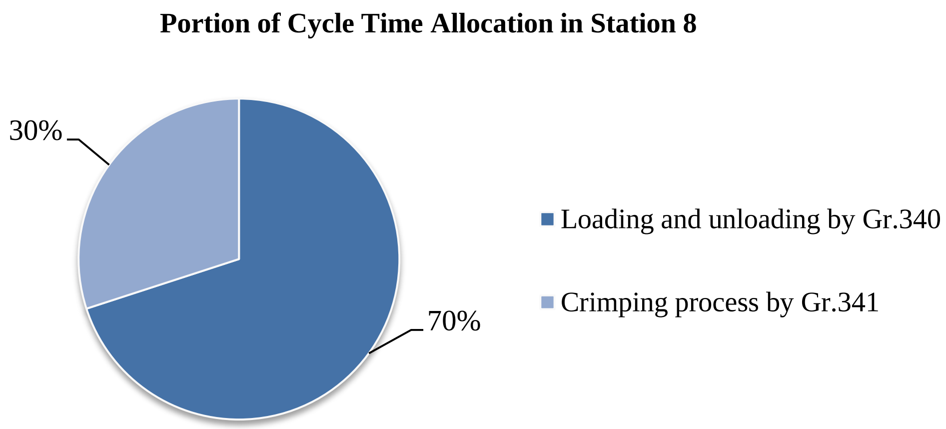


Figure 6.3 Portion of cycle time allocation in station 8

The cycle time reduction, considering the reduction of the loading and unloading time that is non-value-added activity, is seen as a way to increase the overall throughput rate of the assembly line. In order to justify this argument, the Performance Evaluation model is used to evaluate stations 1, 8, and 10, which have the longest cycle time in the assembly line, considering a reduction of 1-5% of the total cycle time. Figure 6.4 shows the result of the evaluation. With a reduction of cycle time up to 5%, the throughput rate can be improved to 325,15 units/ hour for station 1; 324,84 units/ hour for station 8; and 322,65 units/ hour for station 10.

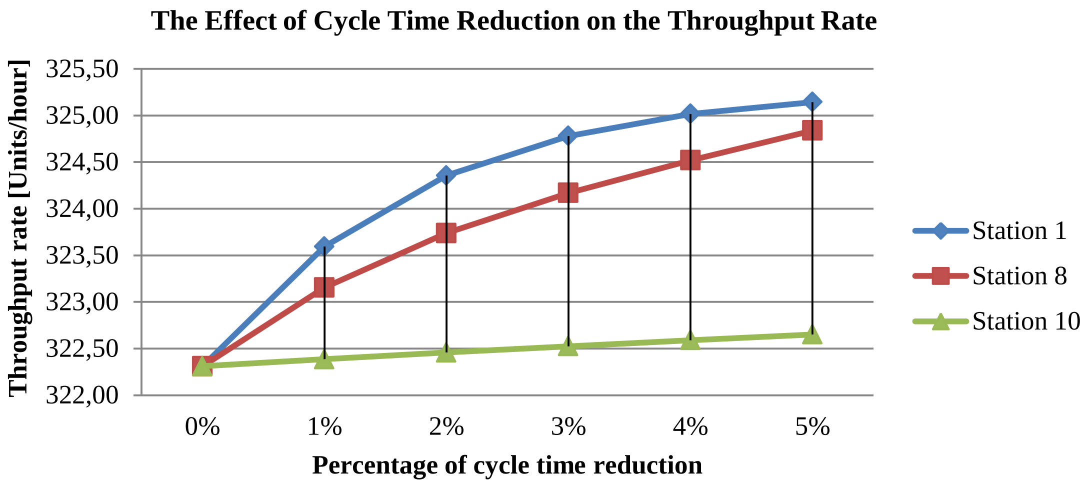


Figure 6.4 The effect of cycle time reduction on the throughput rate of stations 1,8 and 10

From the figure, it can be seen that reducing the cycle time of the bottleneck station, especially station 1, can improve the overall throughput rate of the line. However, the company might not implement this solution immediately since it must consider the safety (machine or robot's movement). This solution needs coordination with the machine's builder. Thus, this could be taken into account as the future development of the line.

b) *Maximization of buffer capacity between stations*

The second proposed improvement action is maximizing buffer capacity between stations. This could be done by adjusting the stopper position, exploiting the length of the conveyor to absorb more pallets. In this way, a flexible buffer capacity can be created according to the need to coop with the variability related to the line's performance. The advantage of this solution is that it can be implemented immediately.

In the interest of understanding the effect of the proposed solution, a measurement of the conveyor's length between stations was done as a starting point. Then, the maximum buffer capacity is calculated by dividing the length of the conveyor by the size of the pallet (rounded-down). As a result, the maximum buffer capacity for each buffer (not including B13, B14, and B15 because stations 14 and 15 are not performing any assembly process thus, the effect would not be significant) is as table below:

Name	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B16
Capacity	5	3	3	2	2	2	7	5	9	2	2	5	5
Max Capacity	17	34	8	15	5	4	10	7	14	3	5	9	13

Table 6.1 Maximum buffer capacity between stations

There are three main scenarios of solution in the case of maximizing buffer capacity between stations, which are:

- Scenario 1: Maximizing all buffer capacities: B1–B12.
- Scenario 2: Maximizing buffer capacities near bottleneck stations 1 and 8: B1, B7, and B8.
- Scenario 3: Maximizing buffer capacities near stations 4 and 10: B3, B4, B9, B10.

Scenario 1

Both the Performance Evaluation and Plant Simulation model evaluates this scenario quantitatively and Figure 6.5 shows the result. Based on the evaluation, this proposed solution can increase the throughput rate by 1-2%. As argued by Klos and Patalas-Maliszewska (2018), the throughput of the assembly system rises in tandem with the increasing capacity of all buffers. The buffer capacity can enhance the throughput by reducing the effect of possible disruptions (e.g., failure) within the machines. As a consequence, it can increase the efficiency of the production line.

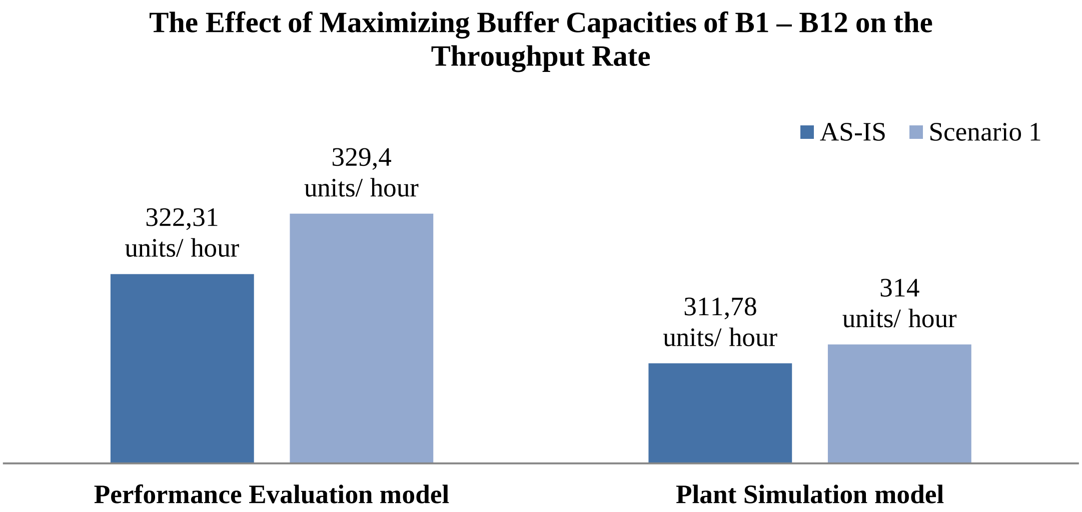


Figure 6.5 The result of scenario 1

Scenario 2

Some literature, such as the one discussed by Navee and Pansa (2003), suggests that the buffer placement should be towards the bottleneck station because the bottleneck station drives the overall throughput and makes it important to ensure that it is neither blocked nor starved. The two bottleneck stations identified within the assembly line Generation 2 are stations 1 and 8. Thus, this scenario focuses on these two stations.

The general assumption for the modelling and simulation is that the input station (i.e., station 1) never starves. Therefore, the maximized buffer capacity to solve bottleneck station 1 is buffer B1. A Performance Evaluation model is used to analyze this proposed solution quickly. As a result, by exploiting the conveyor's length, making B1 equals 17 pallets, the throughput rate can be improved to 324,67 units/hour. In other words, by adding one buffer capacity within B1, the throughput rate will increase on average 0,2 units/ hour. The graphical representation of the result is shown in the figure below.

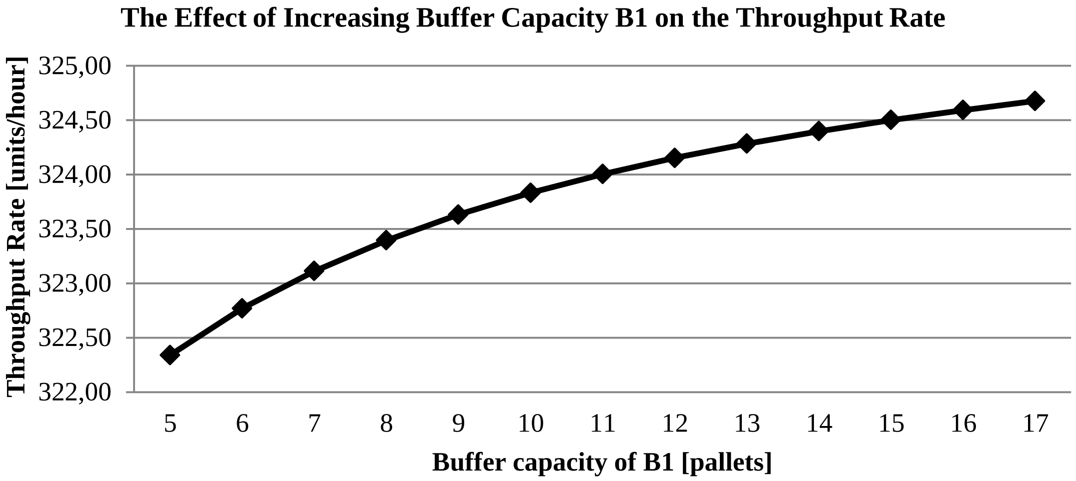


Figure 6.6 The effect of increasing buffer capacity B1 on the throughput rate

As Powell and Pyke (1996) argued if the bottleneck station is station 1, the buffer allocated after the station can help increase the throughput rate because station 1 dominates the throughput produced within the line. However, the maximum effect of adding more buffer capacity in B1 occurred at the capacity equal to 6 pallets where the throughput rate is equal to 322,77 units/hour. Afterwards, the effect on the increment of the average throughput rate is not significant.

The second station considered the bottleneck is station 8 (with a cycle time of 10,29 sec/unit). The position of station 8 itself is critical because it is in the centre of the line with the upstream station (station 7) and downstream station (station 9) that are faster (with a cycle time of 5,69 sec/unit and 8,88 sec/unit respectively). Moreover, the behaviour of station 9, which is a parallel station (Gr.351 and Gr.352) that will start to test the pumps only when the capacity is full, makes station 8 more crucial.

When the slower station (i.e., the bottleneck station) is in the centre of the line, two adjacent stations are impacted. The buffers placed either before or after the station are equally important, with more or less the same output obtained (Conway *et al.*, 1988) even though the input buffer tends to be full and the output buffer tends to be empty. Therefore, both B7 and B8 are considered in the proposed solution.

Based on the evaluation of the Performance Evaluation model, shown in Figure 6.7, by maximizing the buffer capacity of B7, the throughput rate improves to 323,64 units/hour (0,43 parts per 1 additional buffer capacity). Even if the buffer space before the bottleneck station tends to remain or nearly full because it is slow, it is used to ensure the supply of the parts to the bottleneck station. Hence, the throughput tends to increase at a decreasing rate when buffer capacity increases.

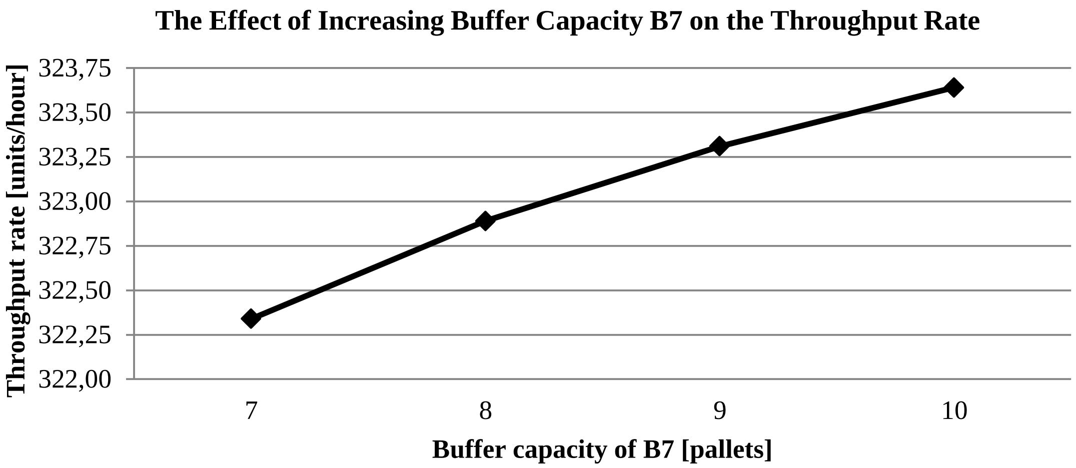


Figure 6.7 The effect of increasing buffer capacity B7 on the throughput rate

Based on the evaluation of the Performance Evaluation model, shown in Figure 6.8, by maximizing the buffer capacity of B8, the throughput rate improves to 322,48 units/hour. Even if the buffer space after the bottleneck tends to remain or nearly empty and has a low impact (0,07 parts per 1 additional buffer capacity), the extra spaces allocated in this buffer helps to avoid any blocking caused by the variation of operating times between the bottleneck and the following station. Additionally, maximizing both buffer B7 and B8 capacities improves the throughput rate to 323,74 units/hour.

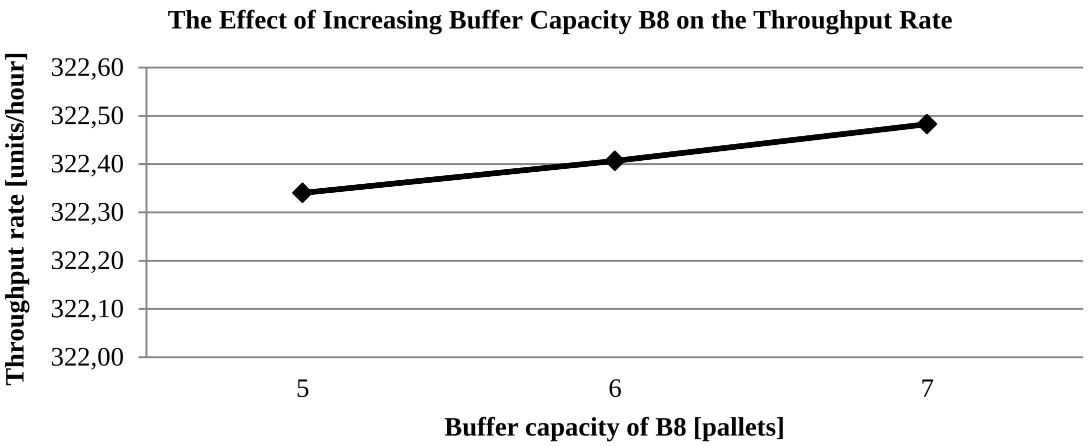


Figure 6.8 The effect of increasing buffer capacity B8 on the throughput rate

Considering the same additional capacity equal to 2 pallets, the increment of the throughput rate is higher in maximization of the buffer capacity B7 (i.e., buffer before station 8) than B1 (i.e., buffer after station 1) and B8 (i.e., buffer after station 8), as shown in Figure 6.9. This could be explained under the *Bowl Phenomenon* theory, which suggests placing optimal allocation of buffer capacity toward the centre of the line as the variance of processing times increases (Harris and Powel, 1999).

The variability of the processing time (as well as breakdowns, etc.) produces blocking and starvation phenomena, decreasing the line's efficiency. They become the most critical aspect once they occur in the centre of the line because the effect is the most severe by affecting both preceding and subsequent stations. Hence, more storage space allocated in the centre can protect the adverse effect and have more influence on throughput than the one placed toward the front or end of the line. Moreover, as shown in Table 5.11, station 8 has the probability of starvation higher than blocking. Thus, the maximation of buffer capacity B7 has a higher impact than B8, considering bottleneck station 8.

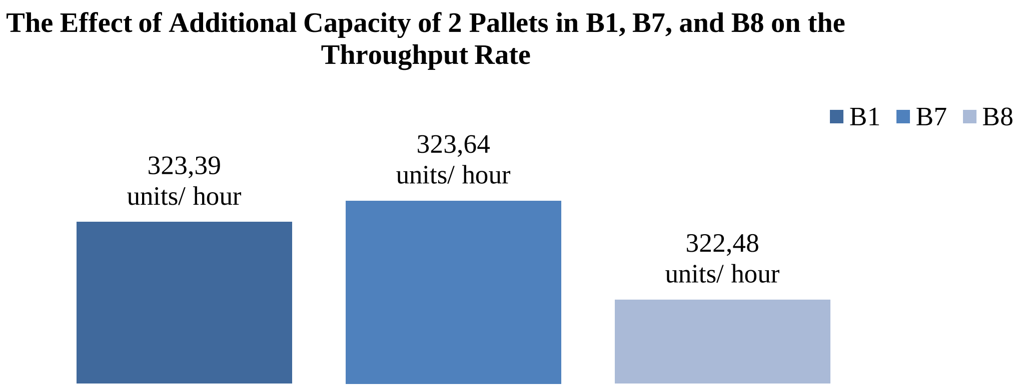


Figure 6.9 The effect of additional capacity of 2 pallets in B1, B7, and B8 on the throughput rate

Scenario 3

According to bottleneck assessment (shown in Figure 6.2), stations 4 and 10 could be possible additional problems affecting the overall performance of the assembly line. Thus, scenario 3 aims to understand the effect of maximizing buffer capacities near stations 4 and 10, which are B3, B4, B9, and B10. In order to have a quick analysis, the Performance Evaluation model is used to evaluate this scenario.

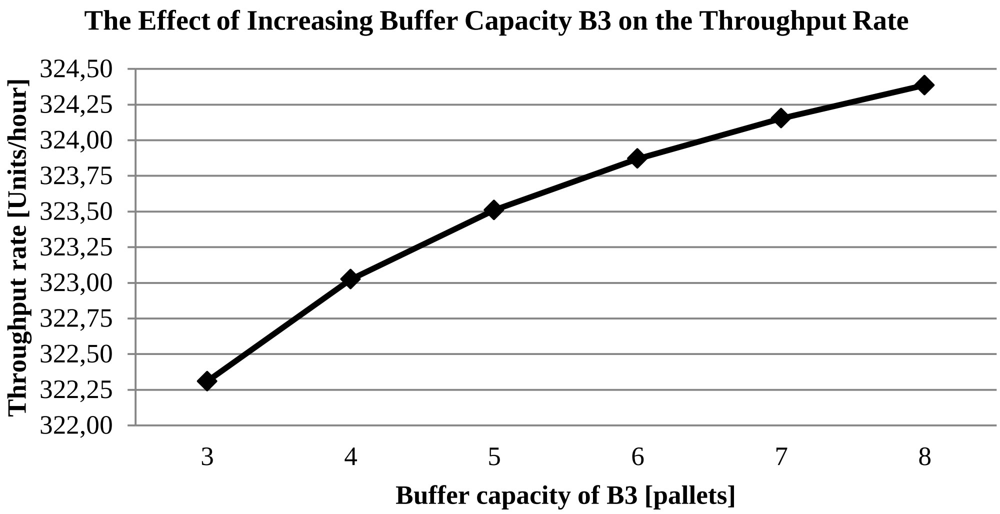


Figure 6.10 The effect of increasing buffer capacity B3 on the throughput rate

As shown in Figure 6.10, by maximizing the buffer capacity of B3, the throughput rate improves to 323,39 units/hour. Meanwhile, by maximizing the buffer capacity of B4, the throughput rate improves to 325,93 units/hour, as shown in the following figure.

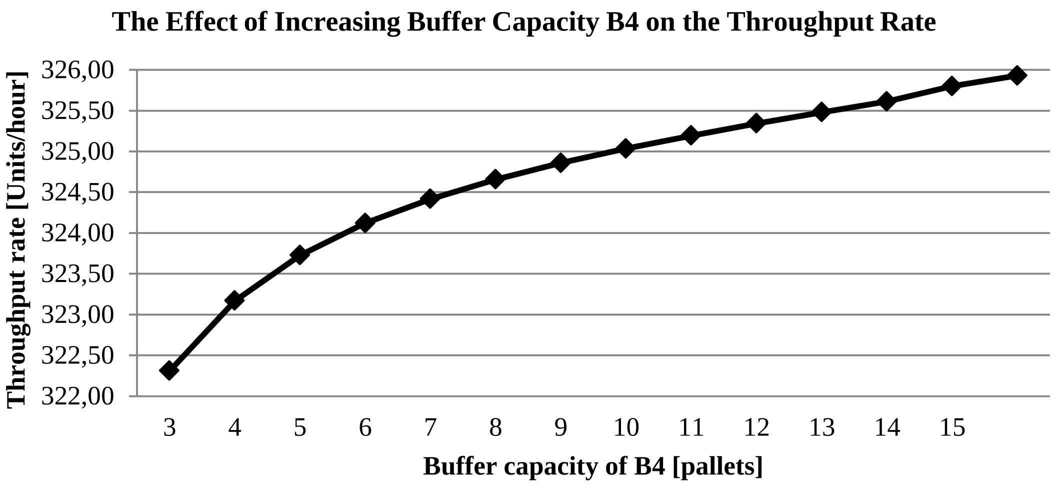


Figure 6.11 The effect of increasing buffer capacity B4 on the throughput rate

Considering the same additional capacity equal to 5 pallets, by maximizing the capacity of B4, the throughput rate obtained is higher than the one of B3, as shown in Figure 6.12. This is because station 4 has a probability of blocking higher than starvation (as shown in Table 5.11). Thus, the maximation of capacity buffer B4 has a higher impact than B3.

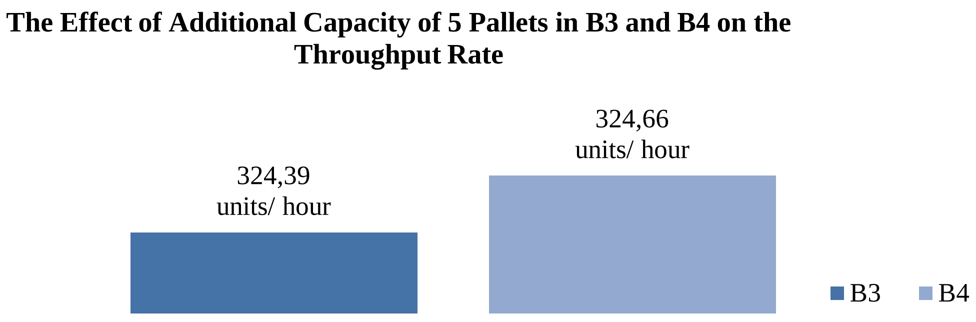


Figure 6.12 The effect of additional capacity of 5 pallets in B3 and B4 on the throughput rate

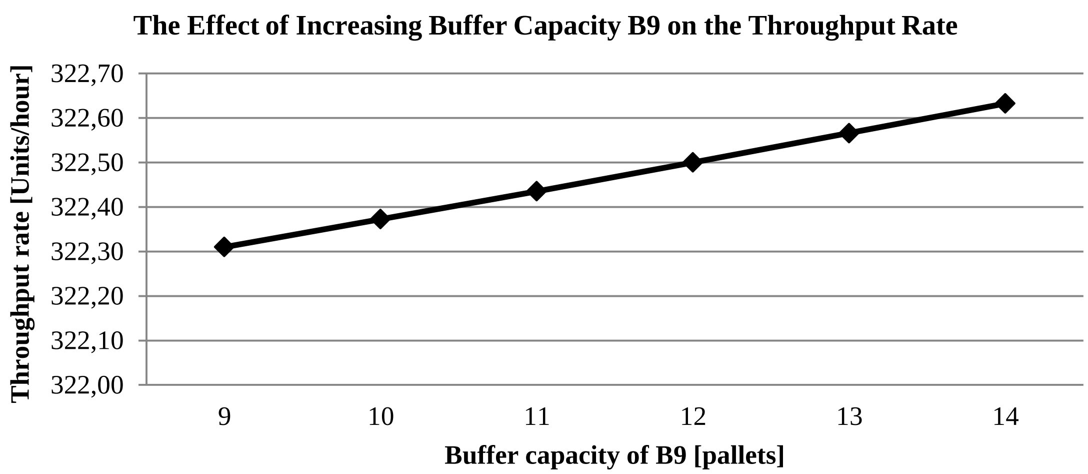


Figure 6.13 The effect of increasing buffer capacity B9 on the throughput rate

As shown in Figure 6.13, by maximizing the buffer capacity of B9, the throughput rate improves to 322,63 units/hour. Meanwhile, maximizing buffer capacity B10 increases the throughput rate to 322,34 units/hour, as shown in Figure 6.14. The throughput rate obtained by optimizing the capacity of B9 is slightly higher than the one of B10 because station 10 has a probability of starvation higher than blocking. Thus, the maximation of capacity buffer B9 has a higher impact than B10.

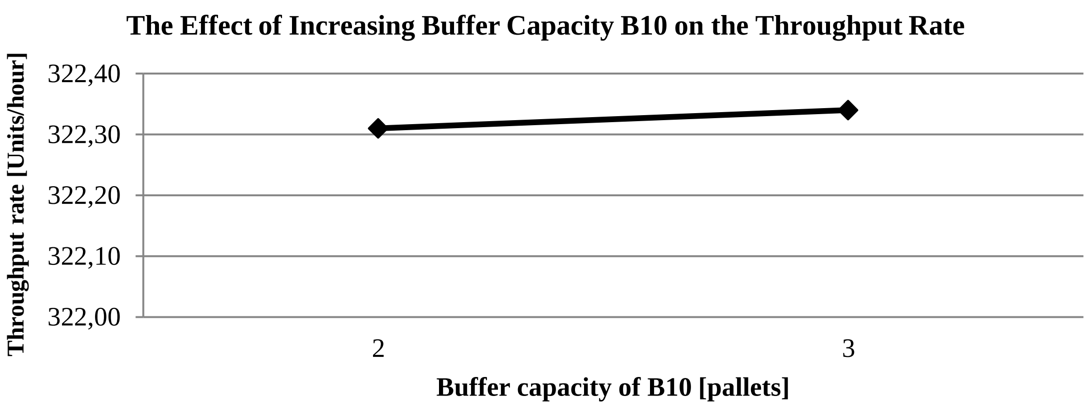


Figure 6.14 The effect of increasing buffer capacity B10 on the throughput rate

c) *Parallelization of bottleneck station 8*

Since the presence of the bottleneck station in the centre of the line is critical, the second possible solution is adding one more station 8 and making them work in parallel. Both models are evaluated concerning this, and the result is shown in the figure below.

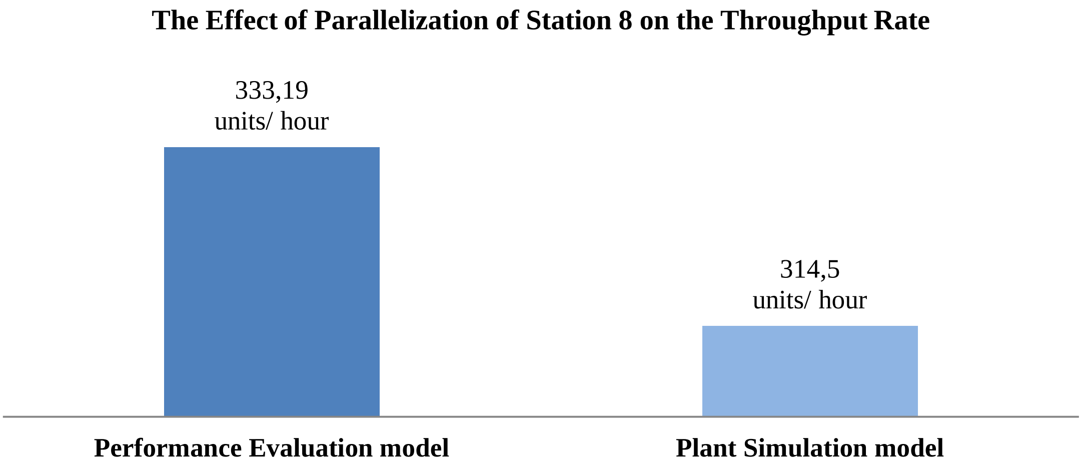


Figure 6.15 The effect of parallelization of station 8 on the throughput rate

Compared to the one related to buffer maximization (scenario 1), the result of this solution is higher. The *Bowl Phenomenon* theory once again supports the analysis. As McNamara and colleagues (2016) argued, placing the fastest stations toward the middle of the line and the slower stations at each end with the mean times disposed of in a “bowl” shape could lead to around 1% improvements in throughput. Note that additional buffer capacity is not substantially needed once the bottleneck becomes more severe (i.e., higher processing time and breakdowns). The fast workstations between the bottleneck “push” the buffer capacity away, acting as a buffer itself during its idle time. The buffer factor has less effect on the throughput rather than the bottleneck factor. Therefore, even if the additional buffer capacity allocation can improve performance, it will not reduce the bottleneck problems themselves. Consequently, the throughput obtained from parallelization is higher than the buffer maximization because the central station (station 8) is faster.

However, considering the complexity and cost of adding one more station into the assembly line, the solution related to the parallelization of station 8 might not be implemented immediately. Suppose the parallelization of station 8 is feasible. Combining this solution and the maximization of buffer capacity B1-B12 can lead to a throughput rate of 336,9 units/ hour (increased by 4% according to the Performance Evaluation model) and 316,22 units/ hour (increased by 1,5% according to the Plant Simulation model).

Summary of proposed improvement actions related to availability and performance of the assembly line

1. **Organizational**: improve supply chain and inventory management policy's efficiency and effectiveness to avoid supply material issues. No further discussion since it is not the focus of this thesis work.

2. **Production control**: improve data collection process (i.e., quality of available information and automatic collection process) in terms of micro stoppages, idling, and reduced speed to minimize micro downtime that currently accounts for 53,6% of the line efficiency in terms of production lost, so that the OEE can be increased by 15,42%.

3. **Reconfiguration**

   The recap of improvement actions suggested, including the evaluation result based on the Performance Evaluation model, is in the following table:

Improvement actions	Detail	Throughput Rate [units/hour]
Reduction of station's cycle time	Reduction of 5% for station 1	325,15
	Reduction of 5% for station 8	324,84
	Reduction of 5% for station 10	322,65
Maximization of buffer capacity between stations	Buffer B1-B12	329,40
	B1 = 17 pallets	324,67
	B7 = 10 pallets	323,64
	B8 = 7 Pallets	322,48
	B7 = 10 pallets and B8 = 7 Pallets	323,74
	B3 = 8 pallets	324,39
	B4 = 17 pallets	325,93
	B9 = 14 pallets	322,63
	B10 = 3 pallets	322,34
Parallelization of bottleneck station 8		333,19
Parallelization of bottleneck station 8 and maximization of capacity B1 – B12		336,90

Table 6.2 A recap of proposed improvement actions under the reconfiguration category

To conclude:

- The reduction of station's cycle time has the most significant impact on station 1.
- Maximization of buffer capacity B1–B12 leads to the throughput rate improvement to 329,4 units/ hour.
- To minimize the adverse impact of bottleneck station 1, increasing the buffer capacity of B1 is the best option.

- To minimize the adverse impact of bottleneck station 8, increasing the buffer capacity of B7 is the best option.
- To minimize the possible negative impact from station 4, increasing the buffer capacity of B4 is the best option.
- To minimize the possible negative impact from station 10, increasing the buffer capacity of B9 is the best option.
- The most significant effect of adding one extra pallet in the buffer capacity considering the four critical stations (i.e., stations 1, 4, 8, and 10) happens in B4.
- The additional buffer capacity allocation depends on the probability of blocking and starvation of each station.
- Parallelization of bottleneck station 8 leads to the throughput rate improvement of up to 333,19 units/ hour.
- Parallelization of the bottleneck station 8 with maximization of buffer capacity B1-B12 leads to the throughput rate improvement to 336,9 units/ hour.

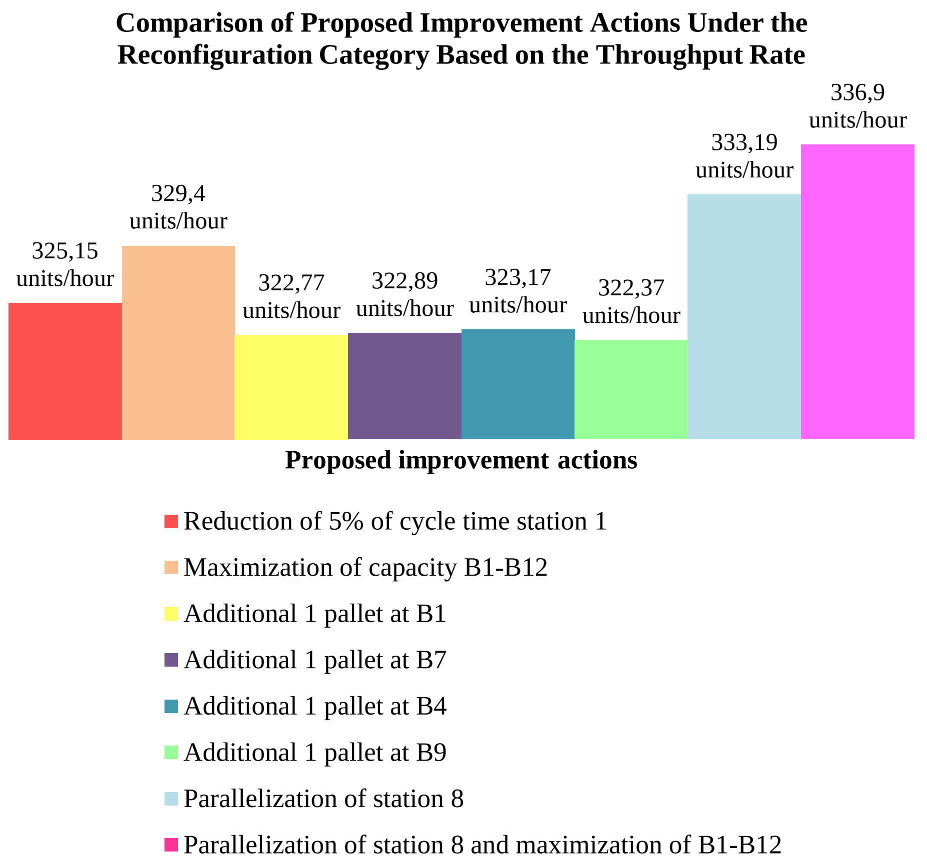


Figure 6.16 A recap of proposed improvement actions under the reconfiguration category based on the throughput rate

Chapter 7

Conclusion

The increase of demand for micro-gear pumps produced by the assembly line Generation 2 is not fully supported by the system point of view and consequently, the performance of the overall assembly line. The OEE result achieved in November 2020 until March 2021 shows fluctuation in terms of availability and performance. The average throughput rate of the line is 250,21 units/hour and 290 units/hour if considering a normal operating condition. Following the analysis performed, there are two main problems within the assembly line Generation 2: the quality of available information and the availability and performance of the assembly line.

Problem-related to the quality of available information is caused by data collection system and assignment of the root cause of machine stoppage. This issue increases the duration, complexity, and error made during data processing; reduces the accuracy of performance measurement and models developed; and reduces the preciseness of proposed continuous improvement actions. The availability and performance of the assembly line are affected by stoppages or failures related to *Guasto Impianto* (i.e., system failure), *Materiale* (i.e., lack of supply material), and *Micro Fermata* (i.e., micro stoppages). In addition, the bottleneck stations within the assembly line are station 1 and station 8, with additional potentially problematic stations 4 and 10.

It is worth noting that improving the quality of available information as a starting point will lead to an optimal evaluation of equipment's availability and performance since it depends on the accuracy of the data collection. Besides, by ensuring a smooth supply of the materials, the overall availability of the line can be fully exploited, and the assessment of equipment's performance can mainly focus on the internal factor. The elimination of the system's failure together with the minor-stoppage (micro-downtime) can be performed in advance. Adding more buffer capacity, reducing the cycle time, and parallelization can be done in the following reconfiguration process.

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APPENDIX

Matlab Code for the Performance Evaluation Model

```
clear all
clc

% Station characterization
    % Station 1 (Machine: 310,311,312,320,321,323,301,330)
    Qhat1 = [0 0.063; 0 0];
    Qarrow1 = [0 0; 6.837 0];
    mu1 = [345.16; 0];

    % Station 2 (Machine: 211,212,213,214,201,210)
    Qhat2 = [0 0.050; 0 0];
    Qarrow2 = [0 0; 7.237 0];
    mu2 = [375.78; 0];

    % Station 3 (Machine: 110)
    Qhat3 = [0 0.019; 0 0];
    Qarrow3 = [0 0; 4.466 0];
    mu3 = [509.19; 0];

    % Station 4 (Machine: 101,102,120,130,140,150,160,161)
    Qhat4 = [0 0.5; 0 0];
    Qarrow4 = [0 0; 37.466 0];
    mu4 = [363.27; 0];

    % Station 5 (Machine: 240)
    Qhat5 = [0 0.001; 0 0];
    Qarrow5 = [0 0; 6.327 0];
    mu5 = [501.39; 0];

    % Station 6 (Machine: 250,260,261,270)
    Qhat6 = [0 0.055; 0 0];
    Qarrow6 = [0 0; 4.274 0];
    mu6 = [587.28; 0];


    % Station 7 (Machine: 203,280,281,290,291)
    Qhat7 = [0 0.025; 0 0];
    Qarrow7 = [0 0; 9.68 0];
    mu7 = [632.69; 0];

    % Station 8 (Machine: 340,341)
    Qhat8 = [0 0.018; 0 0];
```

```
    Qarrow8 = [0 0; 2.375 0];
    mu8 = [349.85; 0];

    % Station 9 (Machine: 351,352)
    Qhat9 = [0 0.013; 0 0];
    Qarrow9 = [0 0; 5.642 0];
    mu9 = [405.41; 0];

    % Station 10 (Machine: 401,410,415,420,430,435,440)
    Qhat10 = [0 0.076; 0 0];
    Qarrow10 = [0 0; 3.980 0];
    mu10 = [356.79; 0];

    % Station 11 (Machine: 700,710,720,730,740)
    Qhat11 = [0 0.025; 0 0];
    Qarrow11 = [0 0; 4.49 0];
    mu11 = [407.70; 0];

    % Station 12 (Machine: 510)
    Qhat12 = [0 0.003; 0 0];
    Qarrow12 = [0 0; 0.94 0];
    mu12 = [362.57; 0];

    % Station 13 (Machine: 520, 530)
    Qhat13 = [0 0.022; 0 0];
    Qarrow13 = [0 0; 7.962 0];
    mu13 = [396.38; 0];

% Loading the system
S1 = struct('mu', mu1, 'Qhat', Qhat1, 'Qarrow', Qarrow1);
S2 = struct('mu', mu2, 'Qhat', Qhat2, 'Qarrow', Qarrow2);
S3 = struct('mu', mu3, 'Qhat', Qhat3, 'Qarrow', Qarrow3);
S4 = struct('mu', mu4, 'Qhat', Qhat4, 'Qarrow', Qarrow4);
S5 = struct('mu', mu5, 'Qhat', Qhat5, 'Qarrow', Qarrow5);
S6 = struct('mu', mu6, 'Qhat', Qhat6, 'Qarrow', Qarrow6);
S7 = struct('mu', mu7, 'Qhat', Qhat7, 'Qarrow', Qarrow7);
S8 = struct('mu', mu8, 'Qhat', Qhat8, 'Qarrow', Qarrow8);
S9 = struct('mu', mu9, 'Qhat', Qhat9, 'Qarrow', Qarrow9);
S10 = struct('mu', mu10, 'Qhat', Qhat10, 'Qarrow', Qarrow10);
S11 = struct('mu', mu11, 'Qhat', Qhat11, 'Qarrow', Qarrow11);
S12 = struct('mu', mu12, 'Qhat', Qhat12, 'Qarrow', Qarrow12);
S13 = struct('mu', mu13, 'Qhat', Qhat13, 'Qarrow', Qarrow13);


% Buffer
B1 = 6; %Between station 1 and 2, N = 6 (max 18)
B2 = 4; %Between station 2 and 3, N = 4 (max 18-34)
B3 = 4; %Between station 3 and 4, N = 4 (+ other side 5)
```

```
 B4 = 3; %Between station 4 and 5, N = 3 (max 16)
 B5 = 3; %Between station 5 and 6, N = 3 (max 6)
 B6 = 3; %Between station 6 and 7, N = 3 (max 5)
 B7 = 8; %Between station 7 and 8, N = 8 (max 11)
 B8 = 6; %Between station 8 and 9, N = 6 (max 8)
 B9 = 10;%Between station 9 and 10, N = 10 (max 15)
 B10 = 3;%Between station 10 and 11, N = 3 (max 4)
 B11 = 3;%Between station 11 and 12, N = 3 (max 6)
 B12 = 6;%Between station 12 and 13, N =6(max 7+other side
3)

 %res = Line_Evaluate(station,buffer)
 res1 = Line_Evaluate([S1 S2 S3 S4 S5 S6 S7 S8],[B1 B2 B3 B4 B5
B6 B7])
 res2 = Line_Evaluate([S8 S9 S10 S11 S12 S13],[B8 B9 B10 B11
B12])
 Y = res2.th - res1.th;
 deltaTH = abs(Y)

% logical variable to control iteration
 finish = false;
 %iteration count
 count = 1;
 %check flag
 itercheck=0;

 while (~finish)
 %Check res1
 Q_res1 = res1.sys.IM(8).Q;
 IM8 = Line_Explore_IM(res1,8);

     if count == 1
         qUS = sum(res1.sys.IM(8).Q(1,3:end));
         PiD_8 = IM8.Prob(2);
         PiS = sum(IM8.Prob(3:end));
     else
         qUS = sum(res1.sys.IM(8).Q(1,4:end));
         PiD_8 = sum(IM8.Prob(2:3));
         PiS = sum(IM8.Prob(4:end));
     end

 % Assign res2
 PiU_8 = IM8.Prob(1);
 qSU = (PiU_8*qUS)/PiS;

 Qhat8a = [0 0.018 qUS; 0 0 0; 0 0 0]
 Qarrow8a = [0 0 0; 2.375 0 0; qSU 0 0]
 mu8a = [349.854; 0; 0];
```

```
 S8a = struct('mu', mu8a, 'Qhat', Qhat8a, 'Qarrow', Qarrow8a);
 res2 = Line_Evaluate([S8a S9 S10 S11 S12 S13],[B8 B9 B10
B11 B12])
 Y = res2.th - res1.th;
 deltaTH = abs(Y)

 if (deltaTH > 0.1)
 % Assign res1
 Q_res2 = res2.sys.IM(1).Q;
 IM1 = Line_Explore_IM(res2,1);
 PiU_1 = IM1.Prob(1);
 PiD_1 = sum(IM1.Prob(2:3));
 PiB = sum(IM1.Prob(4:end));
 qUB = sum(res2.sys.IM(1).Q(1,4:end));
 qBU = (PiU_1*qUB)/PiB;

 Qhat8b = [0 0.018 qUB; 0 0 0; 0 0 0]
 Qarrow8b = [0 0 0; 2.375 0 0; qBU 0 0]
 mu8b = [349.854; 0; 0];
 S8b = struct('mu', mu8b, 'Qhat', Qhat8b, 'Qarrow', Qarrow8b);
 res1 = Line_Evaluate([S1 S2 S3 S4 S5 S6 S7 S8b],[B1 B2 B3
B4 B5 B6 B7])
 Y = res2.th - res1.th;
 deltaTH = abs(Y)
 end

        %iteration count
        count=count+1;

        if (deltaTH < 0.1)
            finish=true;
            itercheck=1;
            meanTH = (res2.th + res1.th)/2
        end
 end
```

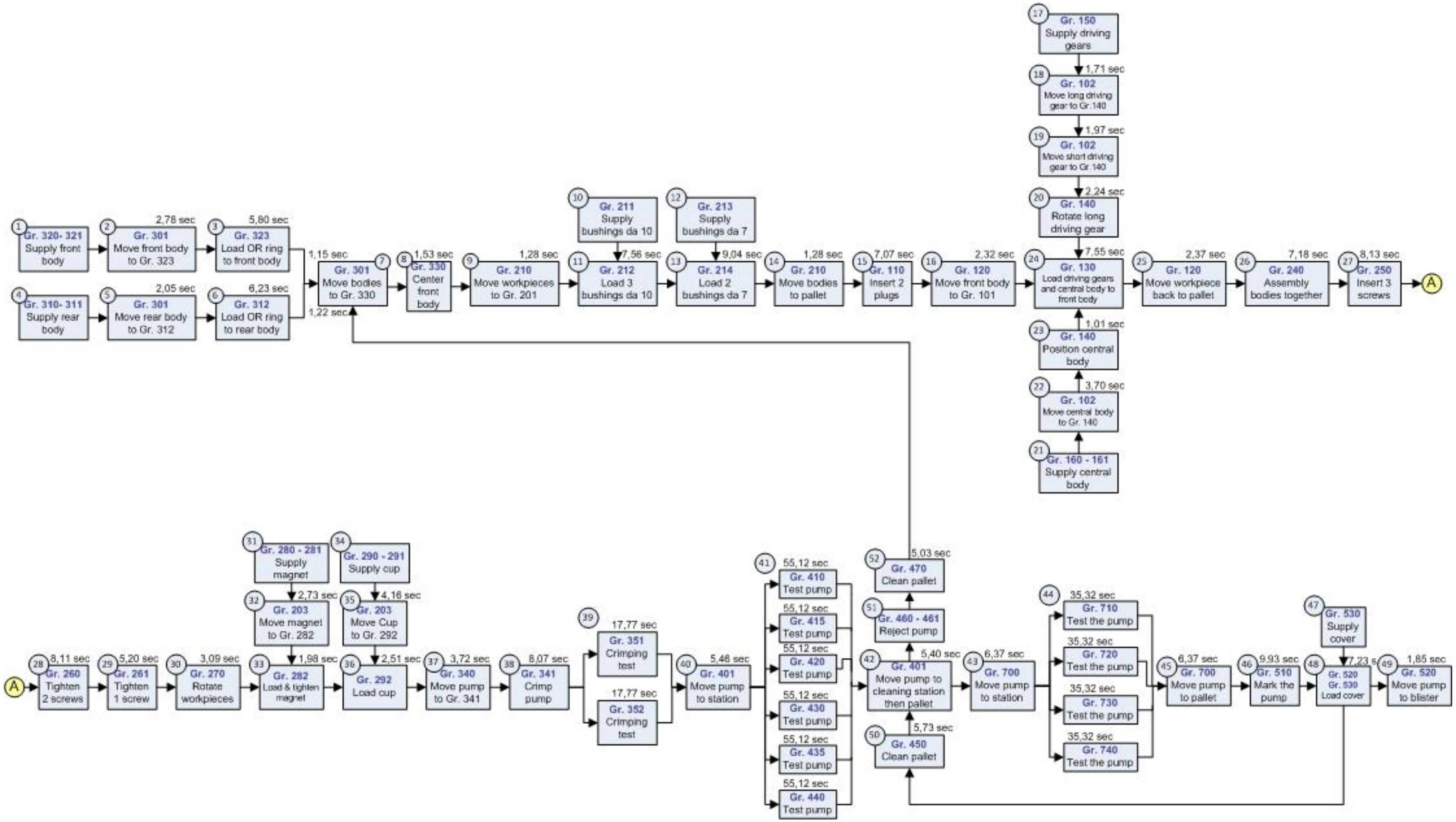

Figure 3.4 Precedence diagram of the assembly process

Machine	MTTF [hour]	MTTR [hour]	Failure rate [1/hour]	Repair rate [1/hour]	Efficiency
310	1809,273	0,000	0,001	0,000	100,00%
311	1809,273	0,000	0,001	0,000	100,00%
312	38,693	0,076	0,026	13,082	99,80%
320	451,967	0,467	0,002	2,142	99,90%
321	1809,273	0,000	0,001	0,000	100,00%
323	81,955	0,284	0,012	3,521	99,65%
301	358,795	0,073	0,003	13,649	99,98%
330	225,671	0,558	0,004	1,793	99,75%
211	129,593	0,195	0,008	5,120	99,85%
212	114,374	0,119	0,009	8,397	99,90%
213	225,864	0,337	0,004	2,970	99,85%
214	150,411	0,394	0,007	2,538	99,74%
201	1809,273	0,000	0,001	0,000	100,00%
210	301,496	0,058	0,003	17,159	99,98%
110	52,996	0,224	0,019	4,466	99,58%
120	128,999	0,113	0,008	8,814	99,91%
102	27,559	0,170	0,036	5,873	99,39%
101	1809,273	0,000	0,001	0,000	100,00%
130	33,969	0,180	0,029	5,558	99,47%
140	200,149	0,152	0,005	6,575	99,92%
150	164,444	0,038	0,006	26,549	99,98%
160	904,633	0,006	0,001	171,429	100,00%
161	1809,273	0,000	0,001	0,000	100,00%

Machine	MTTF [hour]	MTTR [hour]	Failure rate [1/hour]	Repair rate [1/hour]	Efficiency
240	904,557	0,158	0,001	6,327	99,98%
250	51,253	0,452	0,020	2,211	99,13%
260	120,876	0,264	0,008	3,792	99,78%
261	225,930	0,263	0,004	3,799	99,88%
270	180,803	0,137	0,006	7,296	99,92%
203	226,023	0,155	0,004	6,443	99,93%
280	361,811	0,053	0,003	18,774	99,99%
281	1809,273	0,000	0,001	0,000	100,00%
282	150,664	0,118	0,007	8,498	99,92%
290	361,660	0,243	0,003	4,120	99,93%
291	1809,273	0,000	0,001	0,000	100,00%
292	258,353	0,133	0,004	7,505	99,95%
340	78,153	0,387	0,013	2,587	99,51%
341	180,511	0,462	0,006	2,163	99,74%
351	120,937	0,195	0,008	5,139	99,84%
352	258,328	0,163	0,004	6,145	99,94%
401	47,509	0,206	0,021	4,847	99,57%
410	58,458	0,271	0,017	3,695	99,54%
415	120,561	0,366	0,008	2,731	99,70%
420	258,153	0,367	0,004	2,728	99,86%
430	106,717	0,161	0,009	6,215	99,85%
435	120,316	0,324	0,008	3,083	99,73%
440	163,235	0,219	0,006	4,559	99,87%

Table 4.2 Parameters calculated for each machine

Machine	MTTF [hour]	MTTR [hour]	Failure rate [1/hour]	Repair rate [1/hour]	Efficiency
700	452,207	0,147	0,002	6,792	99,97%
710	300,718	0,156	0,003	6,397	99,95%
720	128,815	0,452	0,008	2,215	99,65%
730	301,219	0,391	0,003	2,556	99,87%
740	1809,273	0,000	0,001	0,000	100,00%
510	302,297	1,064	0,003	0,940	99,65%

Machine	MTTF [hour]	MTTR [hour]	Failure rate [1/hour]	Repair rate [1/hour]	Efficiency
520	41,887	0,093	0,024	10,719	99,78%
530	358,967	0,192	0,003	5,204	99,95%
450	602,967	0,186	0,002	5,381	99,97%
460	127,009	0,055	0,008	18,246	99,96%
461	1809,273	0,000	0,001	0,000	100,00%
470	162,955	0,049	0,006	20,327	99,97%

Table 4.2 Parameters calculated for each machine (continued)

Station	Task Description	Mean Processing Time [sec]	Standard Deviation	Total Work Content [sec]	Quantity [unit]	Cycle Time [sec/unit]	Cycle Time [hour/unit]	Production Rate [unit/hour]
1	Gr. 320 - 321 Supply front (anteriore) body	0,00	0,00	20,86	2	10,43	0,0029	345,125
	Gr. 301 Move front (anteriore) body to Gr.323	2,78	0,16					
	Gr. 323 Load OR to front (anteriore) body	5,80	0,08					
	Gr. 310 - 311 Supply rear (posteriore) body	0,00	0,00					
	Gr. 301 Move rear (posteriore) body to station Gr. 312	2,15	0,20					
	Gr. 312 Load OR to rear (posteriore) body	6,24	0,08					
	Gr. 301 Move front body (anteriore - Gr323) to pallet 1	1,15	0,04					
	Gr. 301 Move rear body (posteriore - Gr312) to pallet 1	1,22	0,03					
	Gr. 330 Center front body	1,53	0,02					
2	Gr. 210 Move workpiece to rotary table Gr.201	1,28	0,15	19,16	2	9,58	0,0027	375,783
	Gr. 211 Supply bushing da 10	0,00	0,00					
	Gr. 212 Load 3 long bushings da 10	7,56	0,13					
	Gr. 213 Supply bushing da 7	0,00	0,00					
	Gr. 214 Load 2 short bushings da 7	9,04	0,08					
	Gr. 210 Move workpiece back to pallet	1,28	0,14					
3	Gr. 110 Insert 2 plugs	7,07	0,09	7,07	1	7,07	0,0020	509,194

Table 5.3 Station assignment result in detail

Station	Task Description	Mean Processing Time [sec]	Standard Deviation	Total Work Content [sec]	Quantity [unit]	Cycle Time [sec/unit]	Cycle Time [hour/unit]	Production Rate [unit/hour]
4	Gr. 120 Move front body to station Gr.101	2,32	0,08	9,91	1	9,91	0,0028	363,123
	Gr. 150 Supply driving gears	0,00	0,00					
	Gr. 102 Move long driving gear to Gr.140	1,71	0,10					
	Gr. 102 Move short driving gear to Gr.140	1,97	0,15					
	Gr. 140 Position long driving gear	2,24	0,07					
	Gr. 160 - 161 Supply central body	0,00	0,00					
	Gr. 102 Move central boday to Gr. 140	3,70	0,05					
	Gr. 140 Position the central body	1,01	0,09					
	Gr. 130 Load gears and central body to front body	7,55	0,14					
	Gr. 120 Move workpiece back to pallet	2,37	0,16					
5	Gr. 240 Assembly front and rear body together	7,18	0,08	7,18	1	7,18	0,0020	501,393
6	Gr. 250 Insert 3 screws	8,13	0,34	24,53	4	6,13	0,0017	587,28
	Gr. 260 Tighten 2 screws	8,11	0,14					
	Gr. 261 Tighten 1 Screw	5,20	0,05					
	Gr. 270 Rotate the workpiece	3,09	0,06					
7	Gr. 280 - 281 Supply magnet	0,00	0,00	11,38	2	5,69	0,0016	632,856
	Gr. 203 Move the magnet to Gr. 282	2,73	0,11					
	Gr. 282 Load and tighten the magnet on the workpiece	1,98	0,07					
	Gr. 290 - 291 Supply cup	0,00	0,00					
	Gr. 203 Move the cup to Gr. 292	4,16	0,10					
	Gr. 292 Load the cup on the workpiece	2,51	0,17					

Table 5.3 Station assignment result in detail (continued)

Station	Task Description	Mean Processing Time [sec]	Standard Deviation	Total Work Content [sec]	Quantity [unit]	Cycle Time [sec/unit]	Cycle Time [hour/unit]	Production Rate [unit/hour]
8	Gr. 340 Move pump to Gr.341 (has 2 grips)	3,72	0,17	10,29	1	10,29	0,0029	349,854
	Gr. 341 Crimp the pump	8,07	0,08					
9	Gr. 351 - 352 (parallel) Crimping test	17,77	0,12	17,77	2	8,88	0,0025	405,223
10	Gr. 401 Move the pump to testing stations	5,46	1,30	60,52	6	10,09	0,0028	356,925
	Gr. 410/ 415/ 420/ 430/ 435/ 440 Flow test	55,12	5,35					
	Gr. 401 Move the pump to clean section and then to pallet	5,40	0,71					
11	Gr. 700 move the pump to testing stations	6,37	0,41	35,32	4	8,83	0,0025	407,715
	Gr. 710/ 720/ 730/ 740 Test the workpiece	35,32	0,35					
	Gr. 700 move the pump back to pallet	6,37	0,41					
12	Gr. 510 Mark the pump	9,93	0,20	9,93	1	9,93	0,0028	362,574
13	Gr. 530 Supply cover	0,00	0,00	9,08	1	9,08	0,0025	396,519
	Gr. 520 Move the pump to position	2,47	0,23					
	Gr. 520 and 530 Load cover to the pump	4,76	0,09					
	Gr. 520 Move the pump to blister	1,85	0,22					
14	Gr. 450 Clean pallet flex 2	5,73	0,14	5,73	1	5,73	0,0016	628,163
15	Gr. 460 Move the scrap piece to Gr. 461	0,00	0,00	5,03	1	5,03	0,0014	715,421
	Gr. 470 Clean pallet flex 1	5,03	0,08					

Table 5.3 Station assignment result in detail (continued)

Case	CT	μ	$MTTF$	$MTTR$	p	r	e	ρ	B_2	B_3
1	5,30	678,93	52,996	0,168	0,019	5,955	0,9968	676,78	3	3
2	5,30	678,93	52,996	0,168	0,019	5,955	0,9968	676,78	3	8
3	5,30	678,93	52,996	0,168	0,019	5,955	0,9968	676,78	8	3
4	5,30	678,93	52,996	0,168	0,019	5,955	0,9968	676,78	8	8
5	5,30	678,93	52,996	0,280	0,019	3,573	0,9947	405,22	3	3
6	5,30	678,93	52,996	0,280	0,019	3,573	0,9947	405,22	3	8
7	5,30	678,93	52,996	0,280	0,019	3,573	0,9947	405,22	8	3
8	5,30	678,93	52,996	0,280	0,019	3,573	0,9947	405,22	8	8
9	8,84	407,36	52,996	0,168	0,019	5,955	0,9968	676,78	3	3
10	8,84	407,36	52,996	0,168	0,019	5,955	0,9968	676,78	3	8
11	8,84	407,36	52,996	0,168	0,019	5,955	0,9968	676,78	8	3
12	8,84	407,36	52,996	0,168	0,019	5,955	0,9968	676,78	8	8
13	8,84	407,36	52,996	0,280	0,019	3,573	0,9947	405,22	3	3
14	8,84	407,36	52,996	0,280	0,019	3,573	0,9947	405,22	3	8
15	8,84	407,36	52,996	0,280	0,019	3,573	0,9947	405,22	8	3
16	8,84	407,36	52,996	0,280	0,019	3,573	0,9947	405,22	8	8

Table 5.8 Cases of a fractional factorial plan for model validation

Case	Throughput Rate		$error\%$
	Performance Evaluation	Plant Simulation	
1	321,59	315,96	1,78
2	324,48	316,67	2,47
3	324,44	316,67	2,45
4	325,87	316,74	2,88
5	321,27	315,9	1,70
6	324,15	315,96	2,59
7	324,11	315,96	2,58
8	325,64	316,81	2,79
9	323,35	316,07	2,30
10	324,75	316,49	2,61
11	324,82	316,67	2,57
12	325,78	316,86	2,82
13	322,82	315,91	2,19
14	324,21	316,67	2,38
15	324,27	316,71	2,39
16	325,24	316,74	2,68

Table 5.9 Result of models validation