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EVALUATION AND IMPROVEMENT OF A PLASTIC PRODUCTION SYSTEM USING INTEGRATED OEE METHODOLOGY: A CASE STUDY

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Abstract:
Overall equipment effectiveness (OEE) is a key indicator to measure the effectiveness of production systems. This paper aims to evaluate and improve a plastic production line based on OEE evaluation. An integrated framework is proposed to enhance the production system efficiency. This paper presents the data for a Plastic production line in Jordan under real working conditions. The data covers three months. A framework process to improve the OEE of the Plastic production system was proposed. Six major stoppage losses were inspected with the help of Pareto analysis. Furthermore, the actual availability, efficiency, and quality rate measures, together with the whole OEE for each working day, week, and month of the production line were shown. The methodology is based on determining the OEE of a Plastic production line after determining the causes of failures. The fishbone diagram tool is used to determine the root causes of failures. To improve the OEE measure, several losses are identified. The results reveal that the company should improve its policy to improve the production line's performance and reduce losses. Top management should also pay attention to reducing the speed losses, which consist of 58.1%, and eliminate the planned and unscheduled disruptions covering 12.73% of all losses. This can be achieved by establishing a proper operation management procedure and strategy. This, in turn, optimized the equipment's effectiveness. The quality procedure should include the changeover program that may be executed every day. Similarly, all preventive maintenance procedures for the six machines should be properly executed in predetermined intervals. There are several limitations in the research. Firstly, the research case study is only the plastic production system. Secondly, the research is related to the downtime or stoppage by analyzing it using fishbone diagram. Further, supported by other techniques such as the Pareto chart, six big losses analyses and CED. This research conducted on a Plastic industry. However, similar studies can be carried out in future in other manufacturing industries like electronic, pharmaceutical, textile industries, etc., and service industry. However, as future research work the contributions of this paper with other lean manufacturing concept like six sigma, quality function deployment, TQM, and just-in-time manufacturing, can also be conducting to assess the overall production line efficiency. On the other hand, several statistical tests can be implemented based on data collected of TPM performance indicators. The proposed method supports policymakers in their decision-making process on the operations management line. Furthermore, it improves the production systems' productivity quality, and performance, reducing unplanned stoppages and breakdowns, and reducing maintenance costs.

Key words: *Overall equipment effectiveness, fishbone diagram, DMAIC, availability, quality, performance, and Continuous improvement process*

INTRODUCTION

In a rapidly changing and dynamic environment, competition is very high. To remain competitive, businesses try to improve their productivity [1]. Manufacturing firms are one of the essential sectors that help in increasing economic growth due to the utilization and competition in the economy and business. The objective of the manufacturing sector is to produce profitable goods which can be achieved through a good maintenance system. This maintained system increases equipment availability by reducing machine stoppage and downtime. OEE of the system can be increased by 20% be addressing the stoppage and failures issues [2]. The OEE has come to be a major concern for modern manufacturing technological systems [3]. OEE is one of the vital techniques and indicators to measure equipment's effectiveness [4, 5, 6, 7, 8]. One of the core objectives is to improve the manufacturing system efficiency through the OEE indicator [9]. The indicator is a key top-down performance measurement system [10]. Productivity and quality are two significant metrics for measuring performance in the manufacturing sector [11]. OEE is an essential quantitative tool to ensure sure productivity of the manufacturing system. Is a manufacturing production improvement system using simulation analysis and metrics. "Total productive maintenance" (TPM) is a key technique that can minimize equipment downtime and production losses which contributes effectively to enhancing industries' effectiveness and competitiveness [12]. TPM aims to improve the effectiveness of industry facilities'. This includes machine maintenance and all activities in industry, including improving employees motivation [13]. TMP implementation is a time-consuming tool that needs dedicated resources [14]. TPM shows equipment maintenance through a complete production system [15]. Maintenance procedure plays a crucial role in the industrial sector where its cost may be considered a significant part of production cost [16]. TPM is a change management methodology that affects the efficiency of manufacturing systems [17]. OEE is an evaluation index of TPM by comparing the potential operational performance level with the ideal plant performance. The operational level is reduced by different losses [18]. OEE can be improved by minimizing rework and production losses and increasing equipment availability [19]. OEE is a tool to measure the performance of a maintenance system by calculating machine availability, production efficiency (performance), and machine quality [20]. OEE is a crucial tool for equipment improvement [8]. OEE is a vital indicator to measure TPM and lean maintenance [21, 22]. OEE is a quantitative tool measuring the single machine's productivity and the production line effectiveness [23, 24]. The low value of OEE has an influence on production costs and working hours (direct labor and factory overhead) [25].

The food sector is considered by automated flow manufacturing systems. An automated flow line manufacturing system is used to manufacture products with high volumes and high production rates through several machines connected by transport systems and working in sequence [9]. A dairy product is a food produced from milk. Defects and failures on the production line can lead to quality and performance losses as well as material and human cost losses. Under the context of TPM, OEE may help in improving the quality, performance, and availability.

This paper shows data collection and analysis for plastic product factories. OEE was computed for the production system. Moreover, six major stoppage losses (speed reduction, minor stoppages, setup and adjustment, reduced yield, equipment failures, and process defects) and identified and evaluated using the Pareto chart.

The developed tool can be conducted to six machines of the production system to improve the efficiency, quality, and availability of the production system. Lack of knowledge about methodology. A lack of knowledge about methodologies that guide the decision maker can guide decision makers to wrong decisions [26]. The analysis helps managers in making the best decisions on the operational level and recommends some solutions to improve performance. OEE applications are different in various production systems. The fishbone diagram reveals the main causes of decreasing productivity, availability, and, quality [27]. However, its applications in the food industry especially in Jordan are unique. DMAIC and fish and bone diagrams are integrated to improve the OEE in this paper. The integrated tool may apply in several industries and manufacturing systems.

The paper is structured as: Section 2 analyzes the literature review. The next section provides the objectives of this research. Section 4 reveals the developed methodology and the OEE framework of this research. Section 5 computes OEE and the related components and analyzes the results and the last section covers the conclusion of the paper and a discussion of the results.

BACKGROUND

"OEE" is applied to measure the performance of the manufacturing system. "OEE" has been applied to improve equipment productivity particularly, in the semiconductor industry [1, 10]. OEE is applied to detect the losses and indirect and direct costs [11]. OEE is one of the indicators that can be applied to measure equipment availability, efficiency, and quality [6, 8, 20, 28, 29]. OEE is proposed as an operational improvement measure [30]. OEE is a vital tool for eliminating and identifying production losses which help in improving the efficiency of production systems [31, 32]. The categories of these losses can be classified into six categories: minor stoppage loss, adjustment loss, breakdown loss, speed loss, and quality defects, start-up loss, and rework loss [33, 34]. OEE can be applied in different situations, such as simulating several scenarios to determine which is the best scenario that may achieve developed results [35]. A framework is developed using OEE to develop a quantitative classroom observation method and improve productivity in school [36]. An examination of the operational losses behind the OEE (quality, availability, and performance) is performed on wind energy systems [37] thus, this research applies the OEE metric calculation in the energy sector. Furthermore, OEE is measured for the manufacturing of vegetable oil, where the data is collected for twenty-two months and the results are analyzed using Minitab 21 software [38]. Analytic Hierarchy Process (AHP) in the process industry is depicted as energy-efficient attributes of OEE as a decision-making tool. Group of factors that may lead industries toward crucial outcomes like improved productivity, increased customer satisfaction, and improved quality [39].

Four main loss groups are proposed. The first group related to the planned outages which can determine the controlled stops like preventive maintenance tasks. The second group deals with unplanned and uncontrolled stops like breakdown downtime. The third group concerns the performance losses which qualified the minor stoppages and the cycle time. The fourth group is related to quality losses which cover all wasted time due to non-compliance production [40]. TPM may lead to significant improvement in equipment productivity which can be attained by optimizing the OEE [41, 42]. Accordingly, OEE as a vital performance indicator is a crucial and significant metric for management and measuring, analyzing, and controlling the performance of manufacturing systems. OEE is a methodology that helps policy-makers in evaluating the manufacturing production units efficiency [43]. OEE is a key performance indicator for modern manufacturing units [44]. OEE helps in measuring the performance of factory-level and diagnostics the factory-level [10]. OEE is used in traditional manufacturing to assess production capacity effectiveness [30, 45]. OEE optimization can help in improving the production system and mitigate the negative effects of failures and breakdowns. OEE can be optimized by increasing the number of shifts, purchasing new equipment, outsourcing production, and increasing over time. Optimizing OEE will improve production capacity, enhance quality, and decrease stoppage and downtime. Availability, performance , and quality are the key components required to calculate the OEE [1, 46].

An integrated methodology is formulated to rise the curing press production rate and minimize maintenance costs and press downtime using failure mode and effect analysis [47]. OEE and lean manufacturing relation is studied [48]. Lean production is impacted by firm performance goals in the context of operations strategy [49]. Lean approach and "value stream mapping" are applied to enhance the company performance in Bangladesh [50]. Lean is a management system developed its main aim as a group of techniques in the production field like "just in time" (JIT) to a human-centric method [51]. This management tool focuses on eliminating waste in production companies and factories to improve their performance and operation [52, 53]. Lean management approaches are focused on sustaining and achieving the strategic objectives of an organization [54]. Production companies have applied lean manufacturing to enhance their operation and performance [55, 56]. OEE metric and the key factors that influence this metric are calculated and determined in the pharmaceutical industry accordingly, and the bottleneck in this production line is identified [57]. Lean manufacturing system using SMED "single minute exchange of die" technique is applied in Aluminum company to improve the OEE. SMED helps in increasing the OEE by improving the availability of machines [58]. A decision-making methodology is proposed for OEE in additive manufacturing systems [43]. OEE measures help in analyzing operational efficiency in a manufacturing system and its integrated part from the total productive maintenance is presented. Further, The OEE and the losses are classified [59]. A performance expression fuzzy model is proposed to help policy-makers in their decision-making process of improvement like a productivity indicator [60]. OEE and its factors are calculated for the pharmaceutical industry [57]. Garza-Reyes et al., (2010), examine the relationship between process capability and OEE, how they interact with each other and influence the decision-making process. An integrated approach is developed to assess the performance of a manufacturing line based on OEE [61]. The relationship between OEE and risk priority number in the fuzzy process in a sugar factory is identified [62]. FMEA is a crucial analytical tool in reliability engineering [63, 64, 65]. A socks manufacturing line is investigated to develop a traditional maintenance plan based on OEE to enhance the maintenance with the best product quality and better machine performance using statistical tools [34]. OEE is a measure for a flexible manufacturing system through improving the plant reliability and the equipment by reducing several losses [66]. OEE is improved for the autoclave process in the Aerospace industry through the implementation of time studies [67]. Production productivity is evaluated by improving the OEE indicator and process control in the tiles manufacturing industry. The proposed model is integrated the statistical process control, OEE, and "autonomous maintenance". This model helps in improving the productivity performance of manufacturing systems [68]. OEE metric is utilized to indicate how OEE improves the performance in a mining industry where OEE is identified as a significant reason for not achieving the industry targets [69]. A new OEE formulation is developed based on the process method in maintenance using two parts. The new formulation can help maintenance managers have three dimensions (time, quality, and financial criteria) [70]. The relationship between the management of the factory and the production line operation is investigated. OEE helps in enhancing the operation management and the design of bottling production lines [6]. Different machine learning methods are applied to predict the OEE of an automotive cable production industry. These methods provide predictor models with improved and better performances [31]. An improved OEE method is developed for a full process cycle in the steel market. This improvement method improves the steel industry's performance by considering all market losses [22]. OEE is a performance measurement indicator that helps to understand and eliminate equipment losses accordingly and manage the equipment's effectiveness [71]. A total productive maintenance model was developed for medium-sized enterprises (SMEs) then, the OEE indicator was studied before and after implementation [72]. To evaluate the OEE, a time study methodology is applied [73]. A framework for improving road transport efficiency is proposed and validated using the OEE metric [74]. OEE is used to capture fluctuations to decrease equipment downtime and improve the plant maintenance business [75]. OEE is evaluated as a measured metric of production using the smart system's technique, this technique mitigating some OEE weaknesses [76]. A new technique is proposed to identify the complex manufacturing systems bottlenecks by considering the manufacturing system output and the influences from its downstream and upstream systems [77]. An integrated framework of FMEA (failure mode and effect analysis) and Pareto charts are applied to improve the OEE in a plastic company, where the OEE is improved by an increase of 52,44% [78]. The implementation of a maintenance system utilizing a systematic approach to improve the OEE integrated with TPM is studied and analyzed [79]. The performance measurement through OEE is investigated in the Iranian automotive industry. In this research two different assembly lines Peugeot and Sports Utility Vehicle were studied [80]. Furthermore, OEE is improved of a Harding 600 II series Vertical Machining Centre by subsystem modifications [81]. OEE is integrated with a discrete event simulation system to test and improve the Lithium-Ion Batteries production system in [82]. OEE is utilized to assess the relationship between fit manufacturing model and "Business Performance" through the mediation of OEE [3]. Phogat & Gupta, (2017) state that the absence of measurement of OEE is one of the key problems of maintenance and manufacturing operations. A global process effectiveness metric is [84]. A new formulation indicator is proposed based on the maintenance process approach utilized to operational maintenance processes and for improved maintenance. This new indicator helps managers to have three analysis criteria (cost, time, and quality) [70]. OEE is a key tool that can be used to qualify the efficiency and effectiveness of operational performance during work time [85]. The overall equipment effectiveness aims to reduce complex manufacturing problems. Human knowledge plays a crucial role in improving the production procedure [86].

OEE measures the manufacturing system effectiveness for a single system or integrated system. This measures is a crucial decision support tool for continuous improvement of performance and reliability [87]. Losses in performance and efficiency can be categorized into six groups as shown in Figure 1.

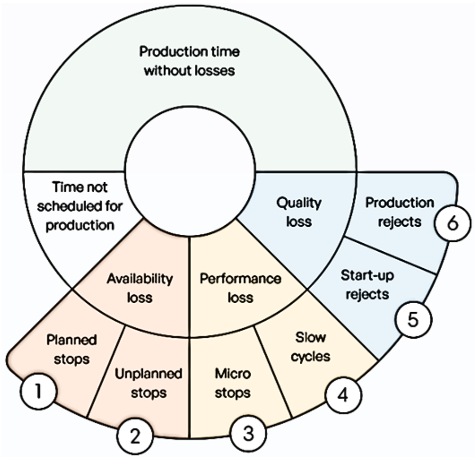

Fig. 1 Equipment Six Big Losses

Figure 1 reveals that equipment failures (unplanned outages) and minor stops (planned outages) are defined as operating time losses and are used for availability calculation. The other parts are related to the defect losses which are used to calculate the performance efficiency. The final OEE component is the quality which can be calculated from the production and start-up defects.

The first OEE component calculation is availability. Availability can be measured by dividing the actual operating time by loading time as expressed in equation 2. Where "operating time" is "loading time" minus the "downtime" while loading time is the available planned time per time for the production process. Downtime is the total time when production is stopped during the setup process, maintenance and repair work, adjustment, and equipment failures.

$$\text{OEE} = \text{“Availability” (A)} \times \text{“Performance Efficiency” (P)} \times \text{“Quality” (Q)} \quad (1)$$

$$\text{Availability} = \text{“Operating time”/Loading time} \quad (2)$$

The second component of OEE calculation is performance efficiency, which can be expressed as the ratio of the net operating time to operating time. Net operating time is the operating time minus the performance time losses.

$$\text{Performance Efficiency} = \text{“Net operating time”/ “Operating time”} \quad (3)$$

The last component of OEE calculation is the quality rate which depends on the processed amount and the defect amount and can be expressed as equation 4.

$$\text{Quality} = \text{“Processed amount– Defect amount”/ ”Processed amount”} \quad (4)$$

However, the ideal values for all these components are (availability > 90%, performance > 95%, and quality > 99%). These values give OEE results by > 85% [85].

The six types of losses provide comprehensive and valuable information that can be used to drive effective actions. The effective actions and the combined structured review with the type of losses can be examined in Figure 2.

Fig. 2 Six Big Losses Aligned with the Company's Levels

The information is transformed into effective actions through a decision-making process along all company levels (strategic, tactical, and operations levels). Accordingly, effective actions are aligned with all company levels. This framework is the foundation step that can be applied in this paper.

RESEARCH METHODOLOGY

The aim of this research is to calculate OEE in a plastic production system in Jordan to assess the current operation management system. The data was collected over three months. The actual availability, performance efficiency and quality measures, together with the whole OEE for each day, week and month of the production line. The methodology is based on determining the OEE of the plastic production system in Jordan before and after determining the causes of failures. The fishbone diagram is utilized to find out the root causes of failures in the Plastic production system. The fishbone diagram reveals the main causes of decreasing productivity, availability, and quality. The cause and effect analysis (fishbone diagram) was conducted on four factors machine, method, man, and material. This tool is used to identify the cause of the highly reduced speed based on the calculation of six big losses were conducted using four components (machine, method, man, and material).

DMAIC (Define, Measure, Analyze, Improve, Control) is used to minimize variation and improve performance. DMAIC is a data drive quality tool used to improving process. DMAIC and fish and bone diagrams are integrated to improve the OEE in this paper. The proposed integrated methodology supports the continuous improvement process principle.

The selected company is one of the largest plastic, bakery, fruit juice, and dairy company in Jordan. The company was located in Zarqa in 2015. The company grew rapidly from a dairy company to the largest vertically integrated food company, covering the entire supply chain, from dairy farming, packaging. manufacturing, and distribution. The production process consists of two main modeling molding: injection molding process and blowing molding process executed by six machines. The collected data includes manufacturing and design data for six machines, downtime losses, planned downtime, changeover, and several failures for all machines in the same company.

This research aims to

1. Evaluate the availability, performance, and quality of a plastic production system in Jordan by integrating the DMAIC and fishbone diagram with calculating the OEE measure.
2. Investigate and analyze the main causes that lead to a decrease in the performance of a plant.
3. Study the performance of six machines in a plastic company and identify the most critical machine that has the lowest performance.
4. Identifying and prioritizing the machine helps in determining the most crucial machine and the proper corrective actions.

The injection molding process starts with taking the raw materials in the form of granules or tiny pellets. Accordingly, it is fed through a hopper and melted [88, 89]. Afterward, it is injected under pressure into the mold to produce the required shapes and checked if there are any defective items. The injection molding process has three stages: the cooling stage, the filling stage, and the ejection stage. The cooling stage significantly influences product quality and process productivity [90].

Injection molding is the most broadly used form of plastic processing. The molding and the blowing processes are illustrated in Figures 3 and 4.

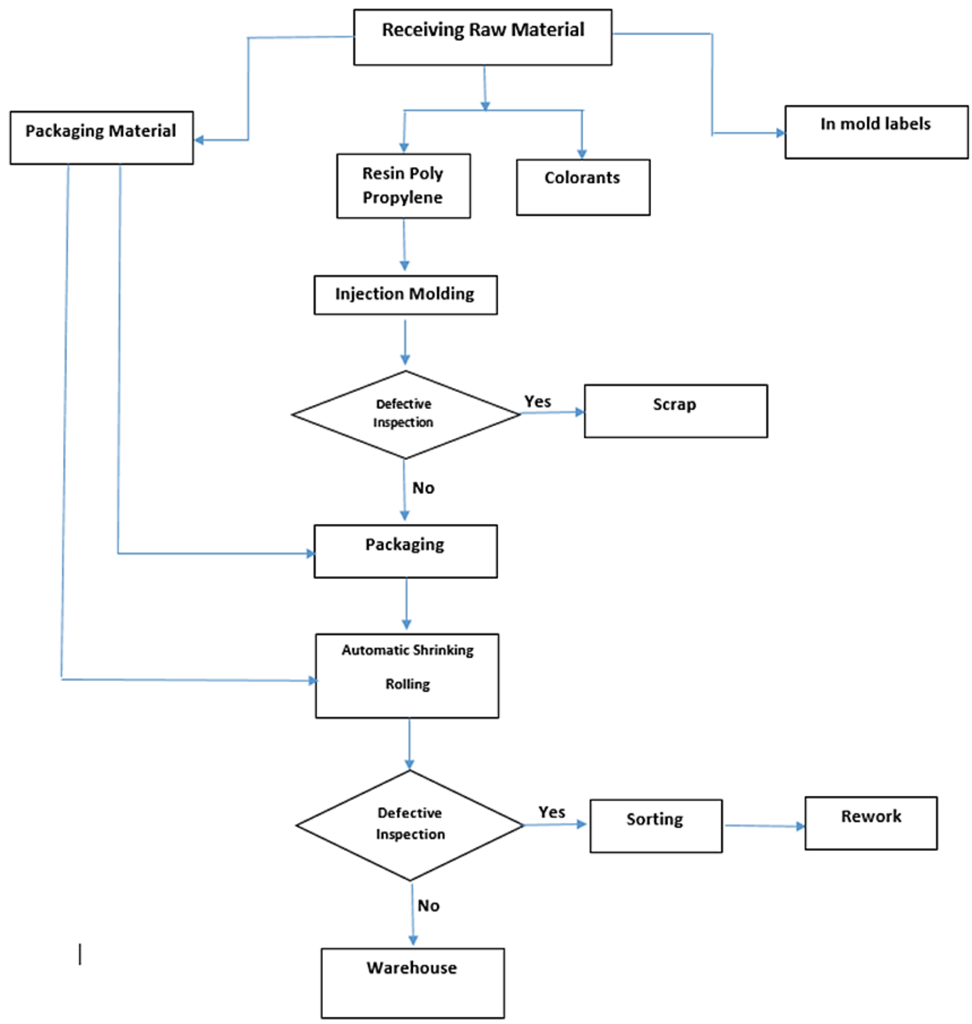

Fig. 3 Process Flow for Injection Molding

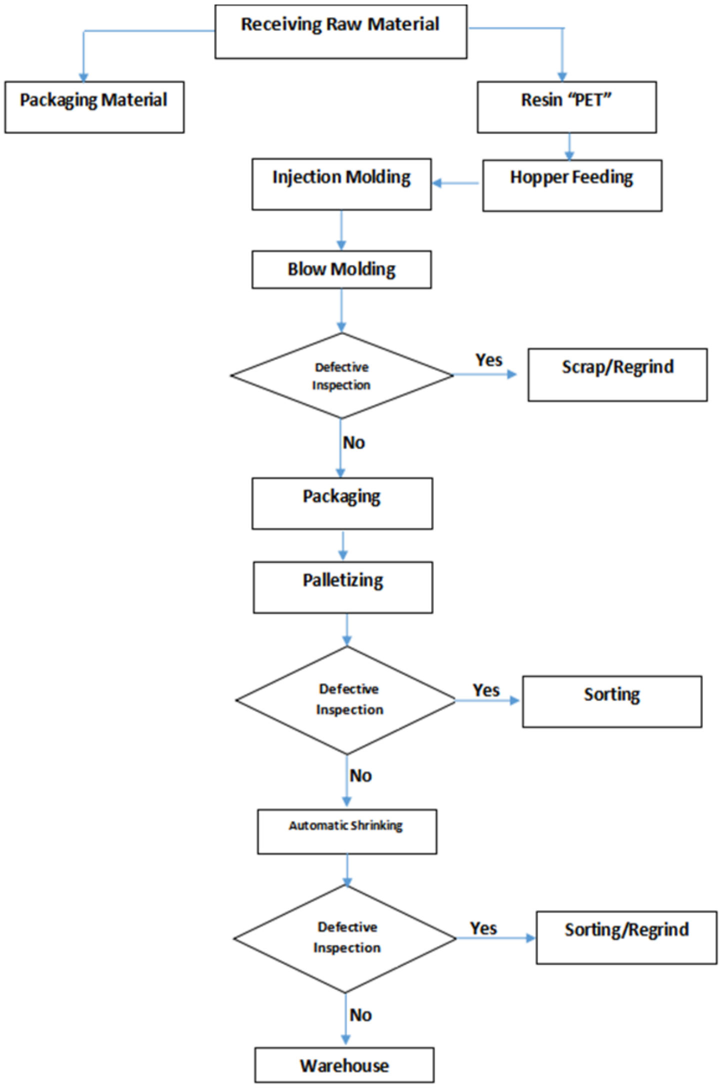

Fig. 4 Process Flow for Blowing Molding

Cause and Effect Diagram Phase

This paper aims to evaluate the operation management in the Plastic Industry by calculating the OEE. The data was collected over 3 months in 2020 for six running machines. After the OEE is calculated for all machines and then for all systems accordingly, the analysis step is started. The DMAIC is a lean Six Sigma tool that can be employed to improve the OEE [91].

The executed steps to produce this paper started by collecting the required data. The collected data includes manufacturing and design data for six machines, downtime losses, planned downtime, changeover, and several failures for all machines. The data is categorized to calculate the quality, availability, and performance, and rate accurately as seen in Table 1.

Table 1

The actual OEE value compared with the world target

	"A"	"P"	"QR"	"OEE"
World Class	"90%"	"95%"	"99%"	"85%"
Manufacturing System Average	87%	55%	99%	47.30%
Difference	-3%	-40%	0%	-38%

Accordingly, the three components of the OEE indicator are calculated for each machine and then, for all plants. From this data, the major loss can be identified then, the six big losses can be determined. To understand and analyze the causes of decreasing availability, performance, and quality, a fishbone diagram is utilized. This tool helps in identifying the main causes of decreasing the OEE indicator. Figure 5 illustrates the main causes of decreasing OEE indicators for all component's quality, availability, and performance.

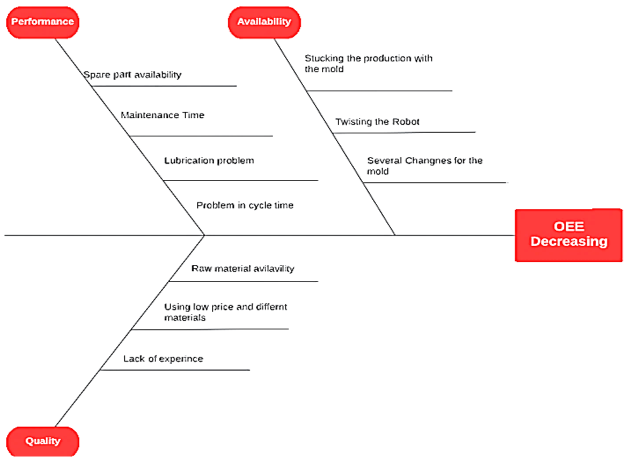

Fig. 5 Cause – Effect Diagram for Decreasing the OEE

The three components of the OEE measure are calculated for this paper as noted in Table 1. Table 1 displays that the lowest value of the three OEE components is the performance value (55% for the plant).

Figure 6 shows the performance percent for the six machines where machine 6 has the minimum performance value (38%).

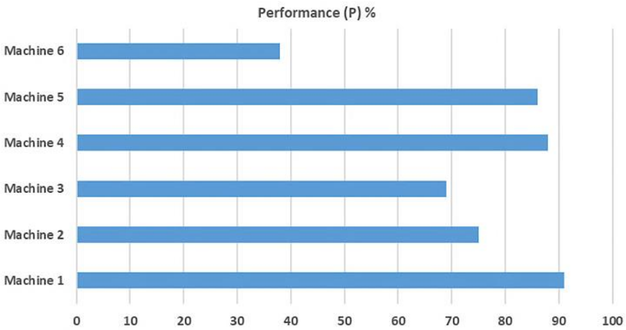

Fig. 6 Performance Percent for the Six Machines

Another fishbone diagram is built to investigate the main causes of decreasing the performance efficiency of machine six. The fishbone diagram for machine 6 is shown in Figure 7.

Figure 7 indicates that the manual processing way and the quality of materials are key factors in reducing Machine Six performance efficiency.

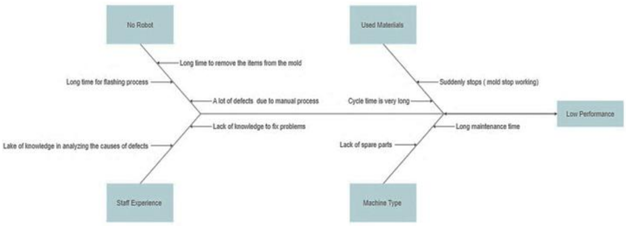

Fig. 7 Cause and Effect Diagram for Machine 6 (has the minimum performance percent)

On the other hand, and based on Table 1, the second low value from the OEE component is the availability factor with 87%. The availability of each machine can be shown in Figure 8.

From Figure 8, it can be noted that machine 3 has the lowest availability factor with (76%).

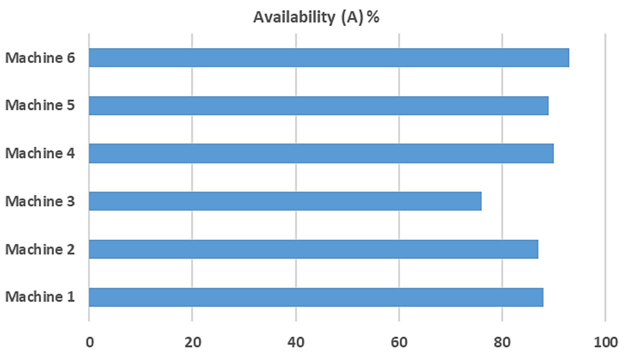

Fig. 8 Availability Percent for the Six Machines

Machine 3 has a lot of stopped hours. The fishbone diagram is used as an analysis tool to investigate the main causes of increasing the unplanned stops in machine 3. The fishbone diagram in Figure 9 shows that twisting the robot is the main cause of increasing the unplanned stops. Further, using a lot of molds per week increases the change over time. On the other hand, the bad material quality leads to an increase the maintenance and calibration time. If a random failure occurs for the production line, the stopped machine may stop the line where the material of the line may have to be scrapped due to quality deterioration. However, the changeover time may reduce the available "operating time" but it is difficult to show in calculating OEE [92].

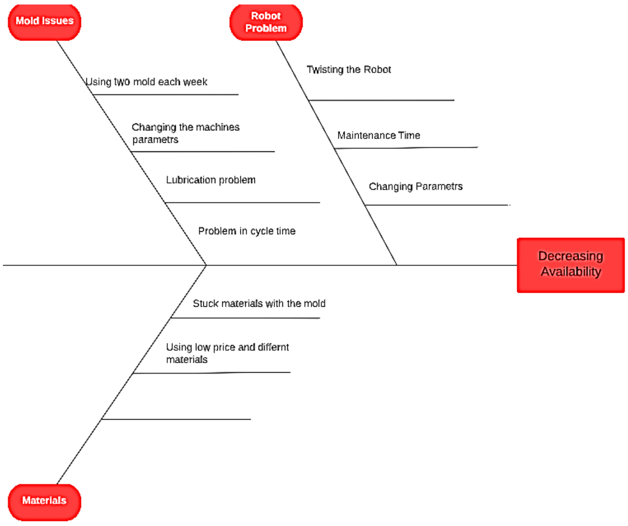

Fig. 9 Cause and Effect Diagram for Machine 3 (has the minimum availability percent)

The novelty of this paper is the integrated methodology to improve the OEE of a production system in Jordan, based on DMAIC and fishbone diagram. The fishbone diagrams help in investigating the main causes that lead to a decrease in the OEE indicator. On the other hand, DMAIC is used to minimize variation and improve performance. Analysis of the collected data helps in understanding the importance of deifying the six big losses. The proposed integrated methodology supports the continuous improvement process principle.

The developed integrated methodology was applied in the plastic industry. This methodology can be applied in other production systems to improve the OEE measure. Which in turn improves productivity, reduces the outage hours, and improves the quality rate.

OEE calculation and analysis

The OEE involves three factors, the first factor is availability which indicates the equipment reliability. The second factor is performance which measures production. This factor is influenced by the speed of the production. The third factor is quality, which refers to good production volume. To calculate the OEE indicator, the operational data of the three OEE factors are collected daily by the operation and maintenance team and also from the archiving system. The work-class target for the OEE is 85% and the related factors are (availability is 90%, performance is 95% and quality is 99%). The OEE calculation for the six machines in the plant is tabulated in Table 2.

Table 2 reveals that the plant availability and performance are lower than the world target (87% and 55%) respectively. The availability factor involves all the production stops (planned and unplanned events). On the other hand, the performance factor includes all production events operating at less than the running speed. The actual performance measure is 55% while the world-class is 95%. However, the quality factor is 99% which equals the world target. The quality factor includes all the rejected items (products that do not meet quality standards).

The overall OEE performance is very low (47.3%) while the target is 85%. To study and analyze the causes of these results, the OEE is calculated for each machine. The OEE measure and the related factors are examined in Table 2. As shown, the minimum value is for the performance factor accordingly, a deep-root analysis should be conducted to arrive at the main causes of lower performance. The performance for the six machines is shown in Figure 10.

Table 2
OEE Actual Calculations for all Machines

OEE (M1)= A*P*Q= 79.8%										
Machine Number	Availability=NOT/NAT= (88%)					Performance Efficiency =NCT/ACT = (91%)		Quality Rate =GP/TP= (99.7%)		
Machine 1 (M1)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	564	16	64.8	548	483	5.55	6.1	1368945	4052	1372997

OEE (M2)= A*P*Q= 65%										
Machine Number	Availability=NOT/NAT= (87%)					Performance Efficiency =NCT/ACT = (75%)		Quality Rate =GP/TP= (99.7%)		
Machine 2 (M2)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	423	12	51.7	411	359	4.8	6.4	1527308	5215	1532524

OEE (M3)= A*P*Q= 51%										
Machine Number	Availability=NOT/NAT= (76%)					Performance Efficiency =NCT/ACT = (69%)		Quality Rate =GP/TP= (97%)		
Machine 3 (M3)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	319	11.5	73	308	234	6.58	9.54	397651	12436	410087

OEE (M4)= A*P*Q= 79%										
Machine Number	Availability=NOT/NAT= (90%)					Performance Efficiency =NCT/ACT = (88%)		Quality Rate =GP/TP= (99.7%)		
Machine 4 (M4)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	327	13.5	31.46666	314	285	5.76	6.53	745794	2191	747985

OEE (M5)= A*P*Q= 76%										
Machine Number	Availability=NOT/NAT= (89%)					Performance Efficiency =NCT/ACT = (86%)		Quality Rate =GP/TP= (99.6%)		
Machine 5 (M5)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	162	7	17	155	138	13.19	15.37	594392	2476	596868

OEE (M6)= A*P*Q= 32%										
Machine Number	Availability=NOT/NAT= (93%)					Performance Efficiency =NCT/ACT = (38%)		Quality Rate =GP/TP= (90%)		
Machine 6 (M6)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	282	8	18	274	256	26.18	69.32	27737	2974	30711
Plant Availability = Total net operating time/Total net available time =87%										
Plant Performance =Total nominal cycle time/Total actual cycle time = 55%										
Plant Quality Rate = Total good product/Total product = 99%										

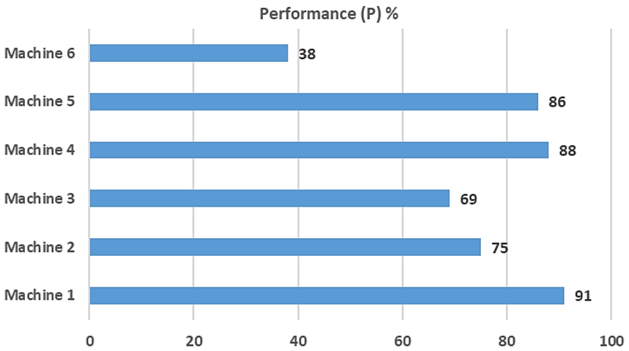

Fig. 10 Performance Percent for the Six Machines

As shown in Figure 10, machine 6 has a minimum performance value of 38%. "The cause and effect diagram" tool is used to analyze the main causes of the lower performance of machine 6. The cause-effect diagram displays that the type of used material and using a manual procedure (no robot) can lead to a reduce in the performance of the machine. Moreover, the second lower factor in the OEE measure is the availability factor (87%). A cause and effect diagram is used to analyze the causes of decreasing the availability of the plant. Figure 8 shows the availability of the six machines in the plant. Figure 8 shows that machine 3 has a lower availability (76%) which is less than the world target (90%). To study the causes of this low availability factor, a cause and effect diagram is constructed for machine 3 as shown in Figure 9.
The "overall OEE performance of the line is low" (47.3%), considering the target of 85% as world-class performance. The main causes for these large differences are speed losses and scheduled and unplanned breakdowns of the equipment. Figure 11 represents the Pareto diagram which reveals the different categories of losses from the most to the least frequent. It shows which is the most critical issue to solve the issue immediately.

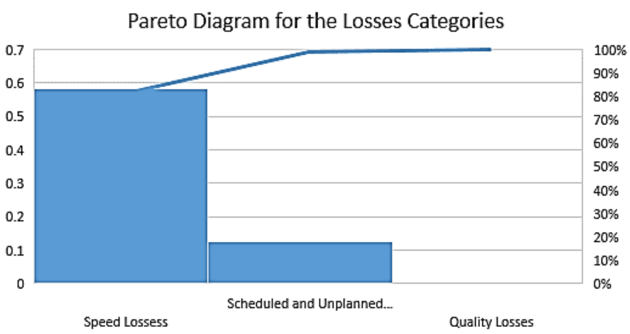

Fig. 11 Pareto Diagram for Interruptions of the Production System

Based on the above analysis, the following notes and suggestions can be formulated:

– As illustrated in the Pareto chart (Figure 11), the most severe problem of the plastic production line is based on the performance (speed losses) which stands for 58.1% of all the losses. Practically, speed losses are defined as mitigating the production system speed. The main causes for this reduction can be summarized by: burned-out equipment, worn-out tools, blockage, lack of experience for staff, lack and poor standard operating procedures for maintenance activities, lubrication, etc. However, a reduction in production speed can consume (9-15%) of the available capacity [93]. Thus, the main target is to decrease these losses. This may be achieved by the suitable operation management of the system. Further, improve the operator's experience and skills through training and education programs.
– The second part of OEE calculation is the availability which covers 12.7% of all the losses. This factor is related to eliminating unscheduled stoppages. These stoppages are caused by sudden breakdowns, equipment damage, failure, and unplanned-maintenance. This could be achieved by appropriate maintenance strategies to optimize equipment effectiveness. To prevent breakdowns and failures, preventive maintenance (cleaning, inspection, tightening, and lubrication) should be done by the operator's staff.
– The third part is related to quality losses which consist of 0.62 of all losses. This part results from rejected parts damaged parts, rework tolerance adjustment, etc. Rejected and reworked items can be reduced by improving the operator's skills. Operators must prepare the equipment before starting the process (change over process). On the other hand, a quality control process is needed during steady-state production.

One of the main causes of decreasing the OEE measure is using materials that did not meet the requirements of the machine thus, a new material with a high flow rate is recommended. Replacing the old materials with new ones improves the OEE. The machine stoppages and the defective products decreased. Accordingly, the OEE improved (increased from 80% to 93%) for machine 1 while the defective products and the stoppages of machine 2 were decreased which led to increased productivity (OEE increased from 65% to 89%), (51% to 81% for machine 3), (79% to 94% for machine 4). On the other hand, installing a Robot for machine 6 improves the OEE by decreasing the stoppages and the defective products which in turn increases the OEE from 32% to 83%. Accordingly, the OEE for all the plans was improved and increased from 47.3% to 86%. Table 3 represents the OEE calculation results after the execution of some suggestions.
The above-mentioned suggestions help in eliminating the difficult and inconvenient consequences of the planned and planned disruptions. Accordingly, the efficiency, availability, and productivity. The production system can be improved. This in turn will increase the profit by decreasing stopped hours and eliminating set-up time.

Table 3
OEE Actual Calculations for all Machines after changing bad materials and using a Robot

OEE (M1)= A*P*Q= 92.9%										
Machine Number	Availability=NOT/NAT= (96%)					Performance Effecicncy =NCT/ACT = (97%)		Quality Rate =GP/TP= (99.9%)		
Machine 1 (M1)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	142	5	5.2	137	131.8	5.55	5.7	362176	372	362548
OEE (M2)= A*P*Q= 89%										
Machine Number	Availability=NOT/NAT= (93%)					Performance Effecicncy =NCT/ACT = (96%)		Quality Rate =GP/TP= (99.9%)		
Machine 2 (M2)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	142	4	9.1	138	128.9	4.8	5	624048	488.5	624536.5
OEE (M3)= A*P*Q= 81%										
Machine Number	Availability=NOT/NAT= (91%)					Performance Effecicncy =NCT/ACT = (90%)		Quality Rate =GP/TP= (99.9%)		
Machine 3 (M3)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	142	4	14	138	124	7.1	7.9	265186	1143.338	266329
OEE (M4)= A*P*Q= 94%										
Machine Number	Availability=NOT/NAT= (97%)					Performance Effecicncy =NCT/ACT = (97%)		Quality Rate =GP/TP= (99.9%)		
Machine 4 (M4)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	141	5	4	136	132	5.76	5.9	350221	354	350575
OEE (M5)= A*P*Q=94%										
Machine Number	Availability=NOT/NAT= (89%)					Performance Effecicncy =NCT/ACT = (86%)		Quality Rate =GP/TP= (99.6%)		
Machine 5 (M5)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	162	7	17	155	138	13.19	15.37	594392	2476	596868
OEE (M6)= A*P*Q= 83%										
Machine Number	Availability=NOT/NAT= (95%)					Performance Effecicncy =NCT/ACT = (88%)		Quality Rate =GP/TP= (99%)		
Machine 6 (M6)	Scheduled Time (ST) (HR)	Planned Breakdown (PB) (HR)	Unplanned Breakdown (UB) (HR)	Net Available Time (NAT) (HR)= ST-PB	Net Operating Time (NOT) (HR)= NAT-UB	Nominal Cycle Time (NCT) (Sec.)	Actual Cycle Time (ACT) (Sec.)	Good Products (GP) (unit)	Defect Products (Unit)	Total Products (TP) (units)
	141	4	8	137	129	26.18	29.7	35091	259.2	35350.2
Plant Availability = Total net operating time/Total net available time =94%										
Plant Performance =Total nominal cycle time/Total actual cycle time = 91%										
Plant Quality Rate = Total good product/Total product = 99.8%										
Plant OEE = 86%										

CONCLUSIONS

In this research, the OEE is calculated and compared with the world-class target. A fishbone diagram is constructed to diagnose the potential causes of problems. The main findings of the research can be summarized below according to the OEE components:

- The production system is available 87% of the time and 13% is unavailable due to planned and unplanned disruptions. The planned (scheduled disruption) has 3.27% while the unplanned count of 12.32%.
- The performance of the selected production system is 55%, which is very low compared with the world target (95%). Machines 3 and 6 have the lowest performance values with (68% and 38%) respectively. On the other hand, the quality rate is 99% which equals the world-class target.
- Machines 3 has the lowest available rate (76%) and also has a low performance rate (69%). Similarly, machine 6 has the lowest performance rate (38%) and lowest quality rate compared with other machines (90%). Thus, improvement can be executed on these machines.

The fishbone diagram reveals that the main causes of decreasing productivity, availability, and quality can be summarized as bad material, lack of experience, robot issues, and preventive maintenance time issues. To solve the basic material issue, buying a new material is recommended.

To improve the performance of the production line, the company should improve its policy to reduce losses. Top management should pay attention to reducing the speed losses that consist of 58.1% also, should eliminate the planned and unscheduled disruptions that cover 12.73% of all losses. This can be achieved by establishing proper operation management procedures and strategies. This, in turn, optimized the equipment's effectiveness. The quality procedure should include the changeover program that may be executed every day. Similarly, all preventive maintenance procedures for the six machines should be properly executed in a predetermined time interval. On the other hand, the company's quality and safety policies and strategies should be integrated.

One of the main causes of decreasing the OEE measure is using materials that did not meet the requirements of the machine thus, a new material with a high flow rate is recommended. Replacing the old materials with new ones improves the OEE. The machine stoppages and the defective products decreased. Accordingly, the OEE improved, and the defective products and the stoppages were decreased which led to increased productivity.

OEE measure helps in improving the effectiveness and the performance of production systems. Companies should decrease their losses and improving the line performance. The integrated model helps in reducing the six big losses and improves quality.

The results explore several implications on the company and society perspectives. A continuous maintenance process of the equipment increases the worker's engagement and enhances communication in the workplace. Furthermore, effective maintenance approaches decrease unplanned production stops and reduce the cost accordingly, and the industrial machine's lifetime will increase.

There are several limitations in the research. Firstly, the research case study is only the plastic production system. Secondly, the research is related to the downtime or stoppage by analyzing it using fishbone diagram. Further, supported by other techniques such as the Pareto chart, six big losses analyses and CED. This research conducted on a Plastic industry. However, similar studies can be carried out in future in other manufacturing industries like electronic, pharmaceutical, textile industries, etc., and service industry. However, as future research work the contributions of this paper with other lean manufacturing concept like six sigma, quality function deployment, TQM, and just-in-time manufacturing, can also be conducting to assess the overall production line efficiency. On the other hand, several statistical tests can be implemented based on data collected of TPM performance indicators.

The proposed integrated tool in this research is sufficiently flexible and can be modified to different scenarios due to its efficiency and simplicity in supporting decisions and improving continuous culture. In this paper, the sources of losses in the plastic company are identified and classified. The proposed tool has the potential to become the foundation of the adaptation of this measure in manufacturing companies. All previous research focuses on exploring and assessing the losses most of this research suggests a solution that emphasizes mitigating failures and losses. This research proposes solutions that can be implemented during the operational phase thus, the productivity can be improved in all stages. Losses quantification is an effective approach to improve priority decisions in the system. The developed framework in this research is impactful in monitoring the interaction between the required advancements to improve productivity for plastic production lines and OEE.

REFERENCES

[1] S.H. Huang *et al.*, "Manufacturing productivity improvement using effectiveness metrics and simulation analysis," *Int. J. Prod. Res.*, vol. 41, no. 3, pp. 513-527, 2003, doi: 10.1080/0020754021000042391.

[2] A. Mahajan, S. Devgan, and R. Zitoune, *Additive Manufacturing of Bio-implants*. Springer, 2024.

[3] R.I. Esmaeel, N. Zakuan, N.M. Jamal, and H. Taherdoost, "Understanding of business performance from the perspective of manufacturing strategies: Fit manufacturing and overall equipment effectiveness," *Procedia Manuf.*, vol. 22, pp. 998-1006, 2018, doi: 10.1016/j.promfg.2018.03.142.

[4] A.A. Dadashnejad and C. Valmohammadi, "Investigating the effect of value stream mapping on overall equipment effectiveness: a case study," *Total Qual. Manag. Bus. Excell.*, vol. 30, no. 3-4, pp. 466-482, 2019, doi: 10.1080/14783363.2017.1308821.

[5] S. Fore and L. Zuze, "Improvement of overall Equipment Effectiveness through TPM – by S Fore, L Zuze," *World Acad. Sci. Eng. Technol.*, vol. 61, no. December 2006, pp. 402-410, 2010.

[6] P.H. Tsarouhas, "Evaluation of overall equipment effectiveness in the beverage industry: A case study," *Int. J. Prod. Res.*, vol. 51, no. 2, pp. 515-523, 2013, doi: 10.1080/00207543.2011.653014.

[7] P.H. Tsarouhas, "Overall equipment effectiveness (OEE) evaluation for an automated ice cream production line: A case study," *Int. J. Product. Perform. Manag.*, vol. 69, no. 5, pp. 1009-1032, 2020, doi: 10.1108/IJPPM-03-2019-0126.

[8] S. Annamalai and D. Suresh, "Implementation of total productive maintenance for overall equipment effectiveness improvement in machine shop," *Int. J. Recent Technol. Eng.*, vol. 8, no. 3, pp. 7686-7691, 2019, doi: 10.35940/ijrte.C6212.098319.

[9] I. Zennaro, D. Battini, F. Sgarbossa, A. Persona, and R. De Marchi, "Micro downtime: Data collection, analysis and impact on OEE in bottling lines the San Benedetto case study," *Int. J. Qual. Reliab. Manag.*, vol. 35, no. 4, pp. 965-995, 2018, doi: 10.1108/IJQRM-11-2016-0202.

[10] K.M.N. Muthiah and S.H. Huang, "Overall throughput effectiveness (OTE) metric for factory-level performance monitoring and bottleneck detection," *Int. J. Prod. Res.*, vol. 45, no. 20, pp. 4753-4769, 2007, doi: 10.1080/00207540600786731.

[11] J.A. Garza-Reyes, S. Eldridge, K.D. Barber, and H. Soriano-Meier, "Overall equipment effectiveness (OEE) and process capability (PC) measures: A relationship analysis," *Int. J. Qual. Reliab. Manag.*, vol. 27, no. 1, pp. 48-62, 2010, doi: 10.1108/02656711011009308.

[12] F. Wang, "Total Quality Management & Business Evaluating the efficiency of implementing total productive maintenance Evaluating the Efficiency of Implementing Total Productive Maintenance," *Total Qual. Manag. Bus. Excell.*, no. February 2012, pp. 37-41, 2007.

[13] J. Teknologi, E.T. Prasetio, and R.A. Oktora, "Evaluation of The Effectiveness of Die Casting Machines Using Overall Equipment Effectiveness (OEE)," vol. 1, no. September 2021, pp. 99-106, 2024, doi: 10.52330/jtm.v22i1.239.

[14] D. Shetty, A. Ali, and J. J. Chapdelaine, "A model for the total productive manufacturing assessment and implementation Implementing Total Productive Manufacturing (TPM) is a time consuming effort that requires dedicated resources and focused planning in order to be successful. This implementat," *J. Adv. Manuf. Syst.*, vol. 8, no. 2, pp. 117-136, 2009.

[15] J. Jeon, C. Kim, and H. Lee, "Measuring efficiency of total

productive maintenance (TPM): A three-stage data envelopment analysis (DEA) approach," *Total Qual. Manag. Bus. Excell.*, vol. 22, no. 8, pp. 911-924, 2011, doi: 10.1080/14783363.2011.593865.

[16] P. Nunes, J. Santos, and E. Rocha, "Challenges in predictive maintenance – A review," *CIRP J. Manuf. Sci. Technol.*, vol. 40, pp. 53-67, 2023, doi: 10.1016/j.cirpj.2022.11.004.

[17] R. McAdam and F. McGeough, "Implementing total productive maintenance in multi-union manufacturing organizations: Overcoming job demarcation," *Total Qual. Manag. Bus. Excell.*, vol. 11, no. 2, pp. 187-197, 2000, doi: 10.1080/0954412006928.

[18] G. Lanza, J. Stoll, N. Stricker, S. Peters, and C. Lorenz, "Measuring global production effectiveness," *Procedia CIRP*, vol. 7, pp. 31-36, 2013, doi: 10.1016/j.procir.2013.05.006.

[19] A. Jain, R. Bhatti, and H. Singh, *Total productive maintenance (TPM) implementation practice: a literature review and directions*, vol. 5, no. 3. 2014. doi: 10.1108/IJLSS-06-2013-0032.

[20] I.S. Muthalib, M. Rusman, and G.L. Griseldis, "Overall Equipment Effectiveness (OEE) analysis and Failure Mode and Effect Analysis (FMEA) on Packer Machines for minimizing the Six Big Losses-A cement industry case," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 885, no. 1, 2020, doi: 10.1088/1757-899X/885/1/012061.

[21] L. Castro-Mercado, J.C. Osorio-Gómez, and J.J. Bravo-Bastidas, *Production Analysis of the Beekeeping Chain in Vichada, Colombia. A System Dynamics Approach*, vol. 966. 2021. doi: 10.1007/978-3-030-71115-3_5.

[22] F. Anvari, R. Edwards, and A. Starr, "Methodology and theory evaluation of overall equipment effectiveness based on market," *J. Qual. Maint. Eng.*, vol. 16, no. 3, pp. 256-270, 2010, doi: 10.1108/13552511011072907.

[23] D. Yuniawan, T. Ito, and M.E. Bin, "Calculation of overall equipment effectiveness weight by Taguchi method with simulation," *Concurr. Eng. Res. Appl.*, vol. 21, no. 4, pp. 296-306, 2013, doi: 10.1177/1063293X13507938.

[24] L. Van De Ginste, E.H. Aghezzaf, and J. Cottyn, "The role of equipment flexibility in Overall Equipment Effectiveness (OEE)-driven process improvement," *Procedia CIRP*, vol. 107, pp. 289-294, 2022, doi: 10.1016/j.procir.2022.04.047.

[25] D. Yandriyani, M.L. Sitanggang, and I. Masri, "The effect of low oveerall equipment effectiveness (OEE) on working hours and production costs of supplement products," *J. Info Sains Inform. dan Sains*, vol. 14, no. 01, pp. 529-538, 2024, doi: 10.54209/infosains.v14i01.

[26] A. R. A. P. V. Nova and M.E. Fontana, "Integrative conceptual framework to support decisions on warehousing operations in forward and reverse flow," *Int. J. Logist. Syst. Manag.*, vol. 42, no. 1, pp. 53-74, 2022, doi: 10.1504/IJLSM.2022.123520.

[27] J. Mooren, J. De Mast, and R. J. M. M. Does, "Quality quandaries *: The case of premature drill wear out," *Qual. Eng.*, vol. 24, no. 2, pp. 354-359, 2012, doi: 10.1080/08982112.2011.652584.

[28] S. Mihretu and M. Gopal, "Effect of Work Environment on Organizational Performance: A Comparative Study on Arjo Dedessa and Finchaa Sugar Factory," *Int. J. Ind. Eng. Prod. Res.*, vol. 32, no. 4, pp. 1-9, 2021, doi: 10.22068/ijiepr.32.4.3.

[29] S. Khawarita, S. Khalida, R. M. S. Anizar, R. Indah, and M.T. Mangara, "Effectiveness of compressor machine by using overall equipment effectiveness (OEE) method," *E3S Web Conf.*, vol. 73, no. February 2017, 2018, doi: 10.1051/e3sconf/20187305007.

[30] B. Dal, P. Tugwell, and R. Greatbanks, "Overall equipment effectiveness as a measure of operational improvement – A practical analysis," *Int. J. Oper. Prod. Manag.*, vol. 20, no. 12, pp. 1488-1502, 2000, doi: 10.1108/01443570010355750.

[31] C. EL Mazgualdi, T. Masrour, I. El Hassani, and A. Khdoudi, "Machine learning for KPIs prediction: a case study of the overall equipment effectiveness within the automotive industry," *Soft Comput.*, vol. 25, no. 4, pp. 2891-2909, 2021, doi: 10.1007/s00500-020-05348-y.

[32] A.S. Badiger and R. Gandhinathan, "A proposal: Evaluation of OEE and impact of six big losses on equipment earning capacity," *Int. J. Process Manag. Benchmarking*, vol. 2, no. 3, pp. 234-248, 2008, doi: 10.1504/IJPMB.2008.017962.

[33] Y. Parikh and P. Mahamuni, "Total productive maintenance," *SAE Tech. Pap.*, no. February 2015, 1998, doi: 10.4271/982092.

[34] M.B. Ramzan, H. Jamshaid, I. Usman, and R. Mishra, "Development and Evaluation of Overall Equipment Effectiveness of Knitting Machines Using Statistical Tools," *SAGE Open*, vol. 12, no. 2, 2022, doi: 10.1177/21582440221091249.

[35] M. Caterino *et al.*, "Simulation techniques for production lines performance control," *Procedia Manuf.*, vol. 42, no. 2019, pp. 91-96, 2020, doi: 10.1016/j.promfg.2020.02.027.

[36] I. Doyer and W.L.L. Bean, "As easy as OEE: enabling productivity improvement in schools by using overall equipment effectiveness as framework for classroom data analysis," *Int. J. Lean Six Sigma*, 2023, doi: 10.1108/IJLSS-03-2022-0057.

[37] K.P.B. Sathler, K. Salonitis, and A. Kolios, "Overall Equipment Effectiveness as a Metric for Assessing Operational Losses in Wind Farms: A Critical Review of Literature," *Int. J. Sustain. Energy*, vol. 42, no. 1, pp. 374-396, 2023, doi: 10.1080/14786451.2023.2189490.

[38] F.A. Tonny, A. Maliha, M.I. Chayan, and M.D. Xames, "Optimization of overall equipment effectiveness (OEE) factors: Case study of a vegetable oil manufacturing company," *Manag. Sci. Lett.*, vol. 13, no. 2, pp. 124-135, 2023, doi: 10.5267/j.msl.2022.12.002.

[39] S. Singh, J.S. Khamba, and D. Singh, "Study of energy-efficient attributes of overall equipment effectiveness in Indian sugar mill industries through analytical hierarchy process (AHP)," *Int. J. Syst. Assur. Eng. Manag.*, no. 0123456789, 2023, doi: 10.1007/s13198-023-01865-9.

[40] M.M. Schiraldi and M. Varisco, "Overall Equipment Effectiveness: consistency of ISO standard with literature," *Comput. Ind. Eng.*, vol. 145, no. May, p. 106518, 2020, doi: 10.1016/j.cie.2020.106518.

[41] I. Kustiyawan, M.R. Roestan, and C. Riani, "Automated Packaging Machine Analysis with The Overall Equipment Efficiency Method," *Int. J. Ind. Eng. Manag. Prod. Res.*, vol. 34, no. 4, pp. 1-14, 2023, doi: 10.22068/ijiepr.34.4.14.

[42] S.H. Huang *et al.*, "Manufacturing system modeling for productivity improvement," *J. Manuf. Syst.*, vol. 21, no. 6, p. 488, 2002, doi: 10.1016/s0278-6125(02)80143-1.

[43] P. Antônio Mendonça, R. da Piedade Francisco, and D. de Souza Rabelo, "OEE approach applied to additive manufacturing systems in distributed manufacturing networks," *Comput. Ind. Eng.*, vol. 171, no. June, pp. 1-17, 2022, doi: 10.1016/j.cie.2022.108359.

[44] P. Muchiri and L. Pintelon, "Performance measurement using overall equipment effectiveness (OEE): Literature review and practical application discussion," *Int. J. Prod. Res.*, vol. 46, no. 13, pp. 3517-3535, 2008, doi: 10.1080/00207540601142645.

[45] S. Basak, M. Baumers, M. Holweg, R. Hague, and C. Tuck, "Reducing production losses in additive manufacturing using overall equipment effectiveness," *Addit. Manuf.*, vol. 56, no. January, p. 102904, 2022, doi:

10.1016/j.addma.2022.102904.

[46] S. Nakajima, "Introduction to TPM: Total Productive Maintenance.pdf," *Productivity Press, Cambridge*. p. MA, 1988. http://www.plant-maintenance.com/articles/tpm_intro.shtml.

[47] F. Saleem, S. Nisar, M.A. Khan, S.Z. Khan, and M.A. Sheikh, "Overall equipment effectiveness of tyre curing press: A case study," *J. Qual. Maint. Eng.*, vol. 23, no. 1, pp. 39-56, 2017, doi: 10.1108/JQME-06-2015-0021.

[48] S. Fam, H. Yanto, U.N. Semarang, and D. Prastyo, "Lean manufacturing and overall equipment efficiency (OEE) in paper manufacturing and paper products industry Lean Manufacturing and overall equipment efficiency (OEE) in paper manufacturing and paper products industry int r odu ction The process of gl," *J. Adv. Manuf. Technol.*, vol. 12, no. 1, pp. 461-474, 2018.

[49] H. Pozo, O. Roque da Silva, and T. Tachizawa, "The influence of performance objectives on the implementation of lean manufacturing practices: An analysis based on strategic groups," *Cogent Bus. Manag.*, vol. 4, no. 1, pp. 1-18, 2017, doi: 10.1080/23311975.2017.1405718.

[50] M.A. Habib, R. Rizvan, and S. Ahmed, "Implementing lean manufacturing for improvement of operational performance in a labeling and packaging plant: A case study in Bangladesh," *Results Eng.*, vol. 17, no. 100818, 2022, doi: 10.1016/j.rineng.2022.100818.

[51] G. Anand and R. Kodali, "Analysis of lean manufacturing frameworks," *J. Adv. Manuf. Syst.*, vol. 9, no. 1, pp. 1-30, 2010, doi: 10.1142/S0219686710001776.

[52] G. Ariadi, Surachman, Sumiati, and F. Rohman, "The effect of lean and agile supply chain strategy on financial performance with mediating of strategic supplier integration & strategic customer integration: Evidence from bottled drinking-water industry in Indonesia," *Cogent Bus. Manag.*, vol. 8, no. 1, pp. 1-19, 2021, doi: 10.1080/23311975.2021.1930500.

[53] N. Garcia-Buendia, J. Moyano-Fuentes, and J.M. Maqueira-Marín, "Lean supply chain management and performance relationships: what has been done and what is left to do," *CIRP J. Manuf. Sci. Technol.*, vol. 32, pp. 405-423, 2021, doi: 10.1016/j.cirpj.2021.01.016.

[54] A. A.P, A. E.K, I. N.M, and I. E.E, "Lean management and performance of telecommunication firms: The mediating role of workplace structure," *Cogent Bus. Manag.*, vol. 7, no. 1, 2020, doi: 10.1080/23311975.2020.1761637.

[55] A. da Silva, A. Dionísio, and L. Coelho, "Flexible-lean processes optimization: A case study in stone sector," *Results Eng.*, vol. 6, no. January, p. 100129, 2020, doi: 10.1016/j.rineng.2020.100129.

[56] M.S. Bin Abd Rahman, E. Mohamad, and A.A. Bin Abdul Rahman, "Development of IoT – enabled data analytics enhance decision support system for lean manufacturing process improvement," *Concurr. Eng. Res. Appl.*, vol. 29, no. 3, pp. 208-220, 2021, doi: 10.1177/1063293X20987911.

[57] M. Zubair *et al.*, "Manufacturing productivity analysis by applying overall equipment effectiveness metric in a pharmaceutical industry," *Cogent Eng.*, vol. 8, no. 1, 2021, doi: 10.1080/23311916.2021.1953681.

[58] T. Haddad, B.W. Shaheen, and I. Németh, "Improving Overall Equipment Effectiveness (OEE) of Extrusion Machine Using Lean Manufacturing Approach Improving Overall Equipment Effectiveness (OEE) of Extrusion Machine Using Lean Manufacturing Approach," *Manuf. Technol.*, vol. 21, no. 1, 2021, doi: 10.21062/mft.2021.006.

[59] E.J. Clements, V. Sonwaney, and R.K. Singh, "Measurement of overall equipment effectiveness to improve operational efficiency," *Int. J. Process Manag. Benchmarking*, vol. 8, no. 2, p. 246, 2018, doi: 10.1504/ijpmb.2018.10010267.

[60] L. Foulloy, V. Clivillé, and L. Berrah, "A fuzzy temporal approach to the Overall Equipment Effectiveness measurement," *Comput. Ind. Eng.*, vol. 127, no. November 2018, pp. 103-115, 2019, doi: 10.1016/j.cie.2018.11.043.

[61] M. Braglia, M. Frosolini, and F. Zammori, "Overall equipment effectiveness of a manufacturing line (OEEML): An integrated approach to assess systems performance," *J. Manuf. Technol. Manag.*, vol. 20, no. 1, pp. 8-29, 2008, doi: 10.1108/17410380910925389.

[62] M. Baghbani, S. Iranzadeh, and M. Bagherzadeh khajeh, "Investigating the relationship between RPN parameters in fuzzy PFMEA and OEE in a sugar factory," *J. Loss Prev. Process Ind.*, vol. 60, no. January, pp. 221-232, 2019, doi: 10.1016/j.jlp.2019.05.003.

[63] L. Ouyang and Y. Nie, "An improved FMEA model considering information quality in a multi-granularity probability linguistic environment," *Qual. Eng.*, vol. 35, no. 2, pp. 207-221, 2022, doi: 10.1080/08982112.2022.2106438.

[64] H.-C. Liu, J.-X. You, X.-F. Ding, Su, and Qiang, "Improving risk evaluation in FMEA with a hybrid multiple criteria decision making method," *nternational J. Qual. Reliab. Manag.*, 2015, doi: 10.1108/MBE-09-2016-0047.

[65] H. Akbarzade Khorshidi, I. Gunawan, and M.Y. Ibrahim, "Applying UGF Concept to Enhance the Assessment Capability of FMEA," *Qual. Reliab. Eng. Int.*, vol. 32, no. 3, pp. 1085-1093, 2016, doi: 10.1002/qre.1817.

[66] R. Sharma, "Overall equipment effectiveness measurement of TPM manager model machines in flexible manufacturing environment: A case study of automobile sector," *Int. J. Product. Qual. Manag.*, vol. 26, no. 2, pp. 206-222, 2019, doi: 10.1504/IJPQM.2019.097767.

[67] A.P. Puvanasvaran, C.Z. Mei, and V.A. Alagendran, "Overall equipment efficiency improvement using time study in an aerospace industry," *Procedia Eng.*, vol. 68, pp. 271-277, 2013, doi: 10.1016/j.proeng.2013.12.179.

[68] A. Azizi, "Evaluation Improvement of Production Productivity Performance using Statistical Process Control, Overall Equipment Efficiency, and Autonomous Maintenance," *Procedia Manuf.*, vol. 2, no. February, pp. 186-190, 2015, doi: 10.1016/j.promfg.2015.07.032.

[69] H. Fourie, "Improvement in the overall efficiency of mining equipment: A case study," *J. South. African Inst. Min. Metall.*, vol. 116, no. 3, pp. 275-281, 2016, doi: 10.17159/2411-9717/2016/v116n3a9.

[70] K.M. Abdelbar, D. Bouami, and S. Elfezazi, "New approach towards formulation of the overall equipment effectiveness," *J. Qual. Maint. Eng.*, vol. 25, no. 1, pp. 90-127, 2019, doi: 10.1108/JQME-07-2017-0046.

[71] A. Sohal, J. Olhager, P. O'Neill, and D. Prajogo, "Implementation of OEE – Issues and challenges," *Proc. APMS 2010 – Int. Conf. Adv. Prod. Manag. Syst.*, no. August, 2010.

[72] Z.T. Xiang and C.J. Feng, "Implementing total productive maintenance in a manufacturing small or medium-sized enterprise," *J. Ind. Eng. Manag.*, vol. 14, no. 2, pp. 152-175, 2021, doi: 10.3926/jiem.3286.

[73] P.G. Yazdi, A. Azizi, and M. Hashemipour, "An empirical investigation of the relationship between overall equipment efficiency (OEE) and manufacturing sustainability in industry 4.0 with time study approach," *Sustain.*, vol. 10, no. 9, 2018, doi: 10.3390/su10093031.

[74] J. García-Arca, J.C. Prado-Prado, and A.J. Fernández-González, "Integrating KPIs for improving efficiency in road

transport," *Int. J. Phys. Distrib. Logist. Manag.*, vol. 48, no. 9, pp. 931-951, 2018, doi: 10.1108/IJPDLM-05-2017-0199.
[75] F. Zammori, "Fuzzy Overall Equipment Effectiveness (FOEE): Capturing performance fluctuations through LR Fuzzy numbers," *Prod. Plan. Control*, vol. 26, no. 6, pp. 451-466, 2015, doi: 10.1080/09537287.2014.920545.
[76] M. Fekri Sari and S. Avakh Darestani, "Fuzzy overall equipment effectiveness and line performance measurement using artificial neural network," *J. Qual. Maint. Eng.*, vol. 25, no. 2, pp. 340-354, 2019, doi: 10.1108/JQME-12-2017-0085.
[77] H. Tang, "A new method of bottleneck analysis for manufacturing systems," *Manuf. Lett.*, vol. 19, pp. 21-24, 2019, doi: 10.1016/j.mfglet.2019.01.003.
[78] C.C. Mathematics, S. Sunadi, H.H. Purba, U.M. Buana, and E. Paulina, "Overall Equipment Effectiveness to Increase Productivity of Injection Molding Machine: A Case Study in Plastic Manufacturing Industry," *ComTech*, no. June, pp. 53-64, 2021, doi: 10.21512/comtech.v12i1.6706.
[79] S. Nallusamy, "Enhancement of productivity and efficiency of CNC machines in a small scale industry using total productive maintenance," *Int. J. Eng. Res. Africa*, vol. 25, no. August, pp. 119-126, 2016, doi: 10.4028/www.scientific.net/JERA.25.119.
[80] H. Soltanali, A. Rohani, M. Tabasizadeh, M. Hossein Abbaspour-Fard, A. Parida, and P.D. Student, "Improving the performance measurement using overall equipment effectiveness in an automotive industry," *Int. J. Automot. Eng.*, vol. 8, no. 3, pp. 2781-2791, 2018, doi: 10.22068/ijae.8.3.2781.
[81] S. Muthukumar and M. Thiruchitrambalam, "Performance augmentation of machining centers by improving the overall equipment effectiveness in subsystems," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 993, no. 1, 2020, doi: 10.1088/1757-899X/993/1/012024.
[82] Z.A. Fadhlurrahman, Yuniaristanto, M. Hisjam, and R. Zakaria, "Supply Chain Performance Analysis Using Hybrid Overall Equipment Effectiveness and Discrete Event Simulation (Case Study: Futura Energy Nusantara)," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 943, no. 1, 2020, doi: 10.1088/1757-899X/943/1/012050.
[83] S. Phogat and A.K. Gupta, "Identification of problems in maintenance operations and comparison with manufacturing operations: A review," *J. Qual. Maint. Eng.*, vol. 23, no. 2, pp. 226-238, 2017, doi: 10.1108/JQME-06-2016-0027.
[84] R. Oliveira, S.A. Taki, S. Sousa, and M.A. Salimi, "Global process effectiveness: When overall equipment effectiveness meets adherence to schedule," *Procedia Manuf.*, vol. 38, no. 2019, pp. 1615-1622, 2019, doi: 10.1016/j.promfg.2020.01.123.
[85] A. Zuashkiani, H. Rahmandad, and A.K.S. Jardine, "Mapping the dynamics of overall equipment effectiveness to enhance asset management practices," *J. Qual. Maint. Eng.*, vol. 17, no. 1, pp. 74-92, 2011, doi: 10.1108/13552511111116268.
[86] A.H.C. Tsang and P.K. Chan, "TPM implementation in China: A case study," *Int. J. Qual. Reliab. Manag.*, vol. 17, no. 2, pp. 144-157, 2000, doi: 10.1108/02656710010304555.
[87] J.J. Rojas-Reyes, J.R. Montoya-Torres, and E.L. Solano-Charris, "A decision support system for the multi-client storage location assignment problem," *Int. J. Logist. Syst. Manag.*, vol. 42, no. 1, pp. 89-116, 2022, doi: 10.1504/IJLSM.2022.123528.
[88] T. Sasaki, N. Koga, K. Shirai, Y. Kobayashi, and A. Toyoshima, "Experimental study on ejection forces of injection molding," *Precis. Eng.*, vol. 24, no. 3, pp. 270-273, 2000, doi: 10.1016/S0141-6359(99)00039-2.
[89] F. Kimura, S. Kadoya, and Y. Kajihara, "Effects of molding conditions on injection molded direct joining using a metal with nano-structured surface," *Precis. Eng.*, vol. 45, pp. 203-208, 2016, doi: 10.1016/j.precisioneng.2016.02.013.
[90] A.M. Abed, A. Alarjani, L.F. Seddek, and S. Elattar, "Modify the Injection Machine Mechanism to Enhance the Recycling of Plastic Waste Mixed with MHD Nanoparticles," pp. 1-36, 2023.
[91] A. Kuiper, M. Van Raalte, and R. J. M. M. Does, "Quality quandaries: Improving the overall equipment effectiveness at a pharmaceutical company," *Qual. Eng.*, vol. 26, no. 4, pp. 478-483, 2014, doi: 10.1080/08982112.2014.936457.
[92] A.P. Puvanasvaran, S.S. Yoong, and C.C. Tay, "Effect of hidden wastes in overall equipment effectiveness calculation," *ARPN J. Eng. Appl. Sci.*, vol. 12, no. 22, pp. 6443-6448, 2017.
[93] H. Chen *et al.*, "Measurement of overall equipment effectiveness as a basis for TPM activities Õrjan Ljungberg"Expanding the concept of requirements traceability: The role of electronic records ma," *Int. J. Oper. Prod. Manag.*, vol. 18, no. 37, pp. 510–528, 2011, http://dx.doi.org/10.1108/01443579810206334

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