Lean Improvement of the Fuzzy Overall Equipment Effectiveness for the Half-Bearing Production Processes using the System Dynamics Simulation

Sirang Klankamsorn*
Department of Industrial Engineering, Faculty of Engineering at Sriracha, Kasetsart University, Sriracha Campus, Si Racha, Chonburi, 20230, Thailand.
***Corresponding Author E-mail:** sirang@eng.src.ku.ac.th

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Abstract

This research presents the problem of decreasing the production efficiency of the Half-bearing production process resulting in parts production quantities not meeting the target. The OEE is used as a production efficiency index, which measures availability rate, performance efficiency and quality rate. The characteristic of production data in practice is dynamic behaviour. The objectives of this research are to analyze problems of the half-bearing production process to make improvements using OEE assuming time and loss to be TFNs. The research method is to develop a system dynamics model to analyze %OEE, whereas %OEE before improvements ranges between 67–72%. The improvement operations are waste reduction, planned maintenance, system testing and tool change. The results found that the %OEE after improvement range between 70–77% and the %improvement range between 3–11%.

Keywords: Fuzzy Overall Equipment Effectiveness, Half-Bearing, System Dynamics Simulation, Lean Improvement

1. Introduction

Half-bearing is a semi-cylindrical machine element that is usually made from copper-based material. The half bearing is a component of automotive parts that supports the crankshaft, and brake parts of internal combustion engines or high-speed engines. The production process for half bearings begins by cutting bimetal to form a curved and semi-circular shape. Parts are then chamfered, drilled and notched to create lubrication grooves.

The problem with half-bearing production in this research is the decreasing production efficiency, resulting in parts production quantities not meeting the target. The main causes of production problems include incorrect sensor readings, incorrect drilling process from the ram, defective compressor, non-standard thickness measuring nails, and interrupted workpiece flow from falling on a conveyor belt. Overall equipment effectiveness (OEE) is a "best practices" metric in lean production towards Industry 4.0 and total productive maintenance (TPM) that measures the productivity effectiveness of equipment and manufacturing processes. The OEE considers the availability, performance and quality factors of the machine [1],[2]. Bearing manufacturers employ the principles of lean improvement by using OEE as an indicator of machine losses. The loss analysis method and fishbone diagram are then used to improve the production line.

The objective of this research is to determine the overall equipment effectiveness (OEE) of the half-bearing processes in which the component data has a fuzzy nature. The OEE includes the availability rate, performance efficiency and quality rate. The assumption of production processes is made that the data is triangular fuzzy number during the production time. The system dynamics model by using the Vensim software was developed to simulate the fuzzy OEE throughout the production time. Then, the lean improvement of half-bearing processes is proposed to increase the percentage of the OEE. In section 2, the related theories of OEE formulation and triangular fuzzy number are presented. Whereas section 3 proposes the research methodology, section 4 provides the simulation results and section 5 presents the conclusions.

2. Literature Reviews and Related Theories

2.1 Literature Reviews

In the machinery or automotive parts manufacturing industry, OEE is used to measure the effectiveness of the machine works and production systems. Six big losses are analyzed and eliminated by using tools such as fishbone diagrams or Pareto analysis in Total Productive Maintenance to improve OEE. Losses are found during production processes such as setup errors, machine slowdowns or stops, misfeeds, bottlenecks, obstructed product flow or material jams. After the improvement, OEE will show the status of production time, production cost reduction, product quality, production efficiency, and production efficiency increment [2],[3].

The following papers show the use of OEE as a performance measure in different types of manufacturing systems. The OEE was found to be related with the failure-free period. The OEE will be increased when the defects-free time is increased [4]. Using the OEE together with MTBF, MTTR, Uptime, and Downtime data can measure the reliability and effectiveness of the CNC cutting machine [5]. For the semiconductor company, after the critical machine and problematic functions of the machine are evaluated, then the OEE and the reliability principle are integrated to measure the maintenance effectiveness [6]. The OEE was used to evaluate the efficiency of metal formation production stages including loading time, preparing tasks, and machine usage [7].

System Dynamics (SD) is a computer-aided simulation approach used to model and analyse the performances of complex manufacturing problems. Such a system has characteristics of nonlinear or dynamic behaviour over time. The SD concept uses cause-and-effect analysis and stock and flow diagrams to visualize the variables and system under study. The research that used the SD involving the OEE in maintenance management was found as follows. In [8], An SD model was developed as a qualitative mapping tool to investigate the factors affecting maintenance operations' asset management function. The factors included in the model are OEE, breakdown, downtime, accumulated defects, and total cost. The SD model considering OEE in total productive maintenance (TPM) was also shown in [9],[10]. The models show that improving OEE can increase production rates and reduce average downtime. Additionally, the OEE is used to identify production losses, machine and equipment breakdown and product quality. As proposed by [11], the effectiveness of the equipment is a function of equipment availability rates and equipment performance rates, which affects the efficiency and profitability of maintenance outsourcing.

The SD concept in the presence of lean improvement was proposed in [12] in which a lean assessment model was developed for automotive battery manufacturing systems with a one-piece flow concept. The lean improvement has an impact on the overall service level, overall work-in-progress efficiency and overall equipment effectiveness. The integrated manufacturing process modelling for Industry 4.0 by using the SD method was presented in [13]. The results showed that the process capability depends on manufacturing system availability. The related availability elements are material, personnel, information, and energy and capital equipment. However, operational variables in manufacturing industries are uncertain and vary with time or other production factors. Therefore, there have been studies of Fuzzy systems combined with SD. As proposed in the research of [14], Fuzzy logic is used to solve vague and imprecise problems in the system dynamics model. The Fuzzy causal loop can investigate the behaviour of fuzzy relations and be described by linguistic variables.

The OEE is stochastic, so the manufacturer needs to determine the hidden losses from variations for potential corrective actions. The results of OEE data will be accurate and robust in lean manufacturing and total productive maintenance. Research that considers the uncertainty or fuzzy nature of OEE as real production line problems with various mathematical approaches has been found in the following papers. The OEE is estimated by [15],[16] as a stochastic random variable with a probability density function and Central Limit Theorem to identify the hidden losses of the availability, performance and quality performances.

Various approaches for fuzzy OEE's loss ratings are proposed by authors. The fuzzy theory is compiled in the OEE computation to reduce indecisiveness because of constant behavioural changes in plant performance [17]. The work of [18] extends the capabilities of the OEE to capture the day-to-day fluctuations of production processes. The losses are decomposed into elementary causes and modelled as LR fuzzy numbers. The Fuzzy Overall Equipment Effectiveness (FOEE) will be determined by using the fuzzy transformation model. The reason for combining the fuzzy set theory with the limitation of OEE analysis is explained by [19]. There are time-referenced vagueness and discrepancies in the classification of losses during the data collection process, the fuzzy theory is then required to determine the precise OEE. A temporal performance expression model for particular characterises the OEE was proposed by [20]. A fuzzy processing is described by the short-term reactive control based on instantaneous performance expression and the long-term reactive control based on predictive performance expressions.

2.2 Overall Equipment Effectiveness and Six Big Losses in Manufacturing

This section presents the contents of overall equipment effectiveness and six big losses [5],[14–20].

Overall equipment effectiveness (OEE) was proposed by Seiichi Nakajima in 1982. The OEE is a metric for production equipment efficiency integrated into the Total Productive Maintenance System, Lean Six Sigma's DMAIC (Define-Measure-Analyze-Improve-Control) and other approaches of production systems. Three components of OEE are availability, performance, and quality.

Availability as shown in Eq. (1) is the actual operating time compared to the planned operating time. The causes of availability losses are planned and unplanned stoppages such as machine breakdowns, setup, planned maintenance, etc.

Performance as shown in Eq. (2) is a metric measured by the production speed compared to the planned speed or actual run time compared to the ideal run time. Performance Loss is caused by minor stoppage, idling losses and machine speed losses.

Quality as shown in Eq. (3) is evaluated by the percentage of first-pass yield, which is the number of good units produced compared to the total production units. Quality losses and quality stops occur from errors (machines, operators, material, and process), defects, rework, etc.

The formulation of %OEE is shown in Eq. (4). A high value of %OEE means better machine effectiveness, while a lower OEE needs a process improvement to reach a process target.

$$\text{Availability rate} = \frac{\text{actual operating time} \times 100}{\text{planned production time}} = \frac{(\text{available time} - \text{downtime}) \times 100}{\text{planned production time}} \tag{1}$$

$$\text{Performance efficiency} = \frac{(\text{actual cycle time} \times \text{output}) \times 100}{\text{actual operating time}} \tag{2}$$

$$\text{Quality rate} = \frac{\text{good units produced} \times 100}{\text{actual output}} \tag{3}$$

$$\%\text{OEE} = \%\text{Availability} \times \%\text{Performance} \times \%\text{Quality} \tag{4}$$

Whereas, the six big losses are the category of losses related to the main components of OEE as follows.

1. Equipment failure (downtime loss)
2. Setup and adjustment (stoppage loss)
3. Idling and minor stoppages (speed loss)
4. Reduced speed (speed loss)
5. Defects in process or start-up rejection (quality loss)
6. Reduced yield or production rejects (quality loss)

2.3 Triangular Fuzzy Number (TFN)

Decision-making and problem analysis of production lines often require data that dynamically fluctuates from many factors. For this reason, fuzzy numbers based on fuzzy set theory are used to represent production data. Triangular fuzzy numbers consist of data with a modal value, a left spread, and a right spread. The data has an asymmetrical nature of fuzzy numbers. The weight of fuzzy numbers is in the range between 0 and 1 which can be a regular or real number. The triangular fuzzy number is presented by $\tilde{A} = (a, b, c)$, where $a < b < c$. **Figure 1** depicts the triangular fuzzy number and Eq. (5) presents the membership function of the triangular distribution [21],[22].

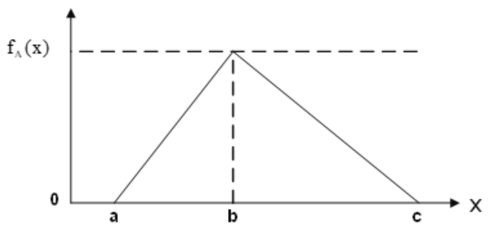


Figure 1 Triangular fuzzy number

$$f_A(x) = \begin{cases} 0, & x \le a \\ (x-a)/(b-a) & a < x \le b \\ 1, & x = b \\ (c-x)/(c-b) & b < x \le c \\ 0, x \ge c & x \ge c \end{cases} \tag{5}$$

3. Research Methodology

The research methodologies of this research are proposed as follows.

3.1 Problem Statements

This research presents the problems of a case study company, which is a manufacturer of half-bearing used in the automotive and machinery industries. The problem encountered in the production line is the occurrence of losses of the machines, resulting in the production quantity and workpiece quality not being as targeted. The case study company focused on the OEE, which is one of the productivity indicators affected by wasted time. The methodologies of OEE analysis of the case study company are shown in **Figure 2**.

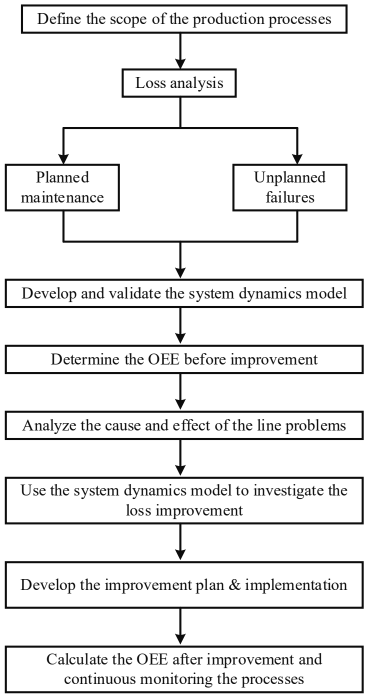


Figure 2 Methodologies of OEE analysis for half-bearing model

3.2 Production Processes of Half-Bearing

The half-bearing manufacturing process is shown in **Figure 3** with the following details.

Cutting: a process of cutting bimetal sheets or carbon steel blades into smaller sizes.

Blanking: a shearing process that feeds a bimetal workpiece into a punch and die.

Bending and forming: shear force is applied to the plane surface of a workpiece to form angular and semi-circular bends.

Face and chamfering: a process to remove the edges or sharp corners with a certain slope of a workpiece.

Hole piercing: holes on the workpiece are created using the drilling machine.

Nicking: a corner notcher is used to produce a smooth and sharp corner of the workpiece.

Oil grooving: small lubricant grooves in various parts of the bearing surface are made to be passageways to distribute lubricating oil.

Joint face: the process of making the joint is to place two pieces of workpieces together by setting the edges of the workpiece at an angle equal to 90 degrees.

Wall thickness checking: the measurement of the workpiece's thickness.

Plating: the finishing process of a micrometre-thin layer coating to the surface of the workpiece to protect from corrosion and enhance the surface quality and durability.

3.3 Loss analysis

The tools of loss analysis that are used in this research are presented as follows:

3.3.1 Fishbone diagram

The problem is the reduction of production efficiency. So, the losses are identified and visualized using a fishbone diagram or a cause-and-effect diagram. A causal analysis depicts the potential causes and sub-causes of losses for half-bearing production processes as shown in **Figure 4**.

3.3.2 Pareto chart

The data on losses is shown in **Table 1**. Then, the loss analysis is presented using a Pareto chart, which ranks the time value from highest to lowest as shown in **Figure 5**. The y-axis is the loss time in minutes of the 8-week data collection.

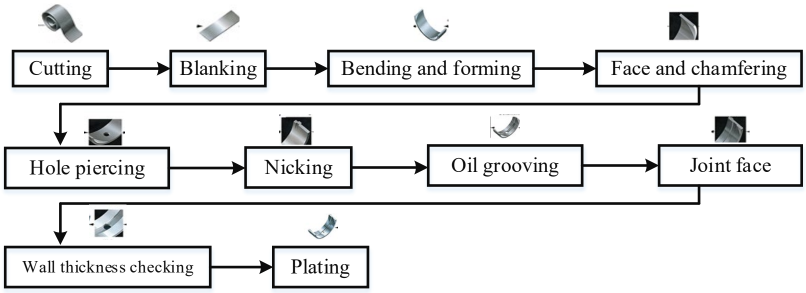


Figure 3 Production processes of half-bearing

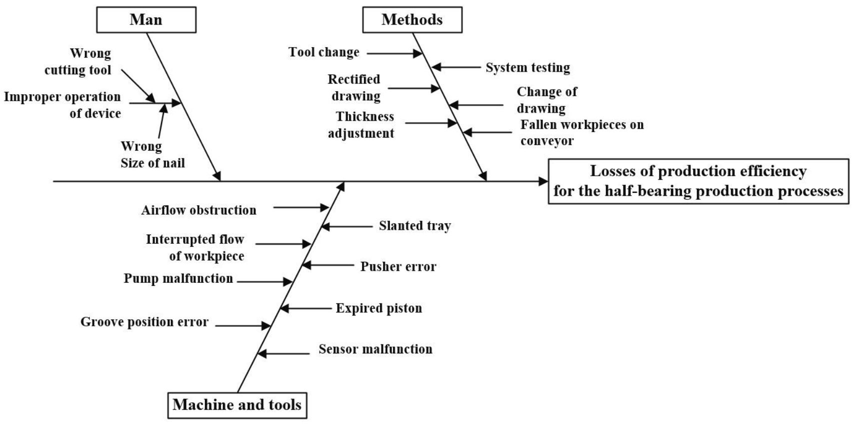


Figure 4 Fishbone diagram for losses of production efficiency of half-bearing production processes

Table 1 Loss analysis of the half-bearing production processes

Causes	Duration (Mins)	Percentage
Expired piston	2,128	15.53
Tool change	2,074	15.14
Thickness adjustment	1,896	13.84
Improper operation of the device	1,468	10.72
Fallen workpieces on the conveyor	1,467	10.71
Groove position error	1,063	7.76
Change/rectified of drawing	951	6.94
System testing	931	6.80
Pump malfunction	456	3.33
Airflow obstruction	341	2.49
Sensor malfunction	290	2.12
Slanted tray	240	1.75
Interrupted flow of workpiece	215	1.57
Pusher error	180	1.31
Total	**13,700**	**100**

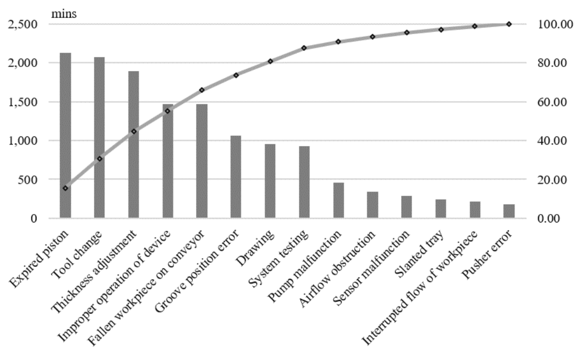


Figure 5 Pareto chart of losses for half-bearing production processes

3.4 System Dynamics Model of Overall Equipment Effectiveness of Half-Bearing Production Processes

This topic presents the system dynamics model for determining the OEE for half-bearing manufacturing. **Figure 6** shows a system dynamics model presenting the relationship between availability, performance, and quality rates that affect OEE by time variation. **Table 2** shows the equations involved in the OEE and its components. The availability rate is the ratio of operating time to planned production time. Performance rate is the ratio between production time and planned production time, where production time is the multiplication of production quantity and cycle time. The quality rate is a ratio between the quantity of good pieces produced and the total production quantity. In this research, Vensim software was used to develop a system dynamics model. The verification and validation methods are 1) the direct empirical structure tests and 2) the dimensional consistency test. All test results are correct.

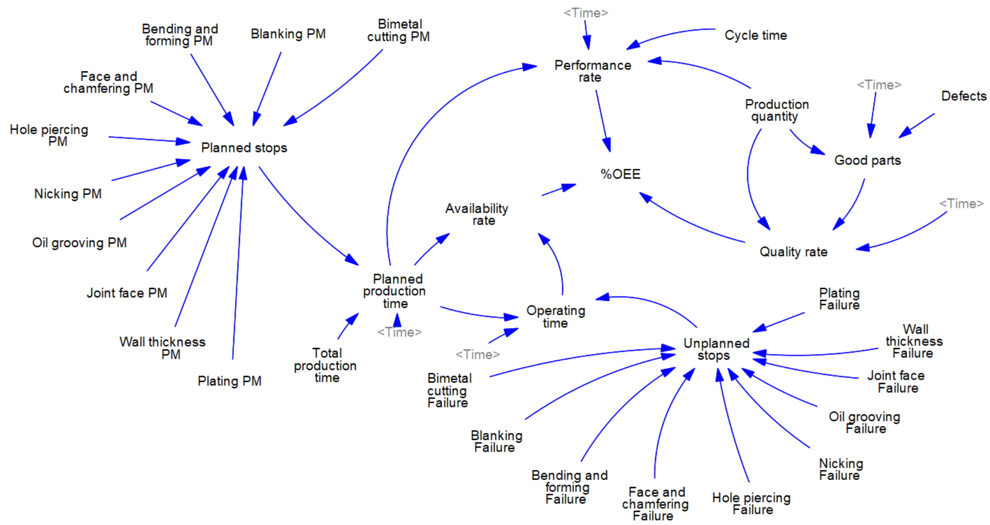


Figure 6 Stock and flow diagram of OEE analysis for half-bearing model

Table 2 Performance parameters of the half-bearing system dynamics model

No.	Parameters	Formula	Units
1	total production time	number of shift × working hours per shift	hours
2	planned production time	total production time - planned stops	hours
3	operating time	planned production time - unplanned stops	hours
4	Availability rate	operating time / planned production time × 100	%
5	Performance efficiency	(production quantity × cycle time) / planned production time × 100	%
6	Quality rate	(production quantity - defects) / production quantity × 100	%

3.5 Time and Losses of Half-Bearing Production Processes

There are the interdependencies and dynamics of lean manufacturing metrics. In real practice, production line loss time is a dynamic behaviour that is uncertain and depends on many factors. The fuzzy membership function is then applied to the lean manufacturing system. The time and losses of half-bearing production processes in this research are shown in **Figure 7**. The total production time is divided into two parts 1) planned production time and 2) planned stops, which are maintenance plans that are scheduled in advance. The planned production time consists of two periods, which are 1) operating time and 2) unplanned failure time that results in a decrease in machine production capacity. Examples of unplanned losses are machine failure, tool change, tool adjustment or miscellaneous losses. The net operating time is affected by the quality of workpieces, including productive time in which the production line can produce good quality workpieces and quality loss time in which defective workpieces are produced. The triangular fuzzy number data is used in systems dynamics models to simulate production line problems. **Table 3** shows the triangular fuzzy data before the improvement of half-bearing production processes. The parameters include the total production time, planned stop time, unplanned stop time, production quantity and number of defects.

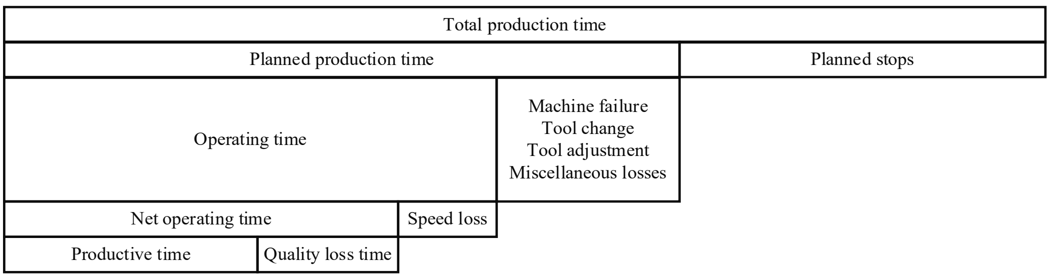


Figure 7 Time and losses of half-bearing production processes

Table 3 Triangular fuzzy data before improvement of half-bearing production processes

Week	Total production time (Hours)	Planned stops (Hours)	Unplanned stops (Hours)	Production quantity (Units)	Defects (Units)
1	(151.60,160.40,167.90)	(15.8,17.9,23.7)	(26.3,26.4,26.8)	(150,987/153,124/154,345)	(6,833/8,861/8,715)
2	(158.50,162.90,167.0)	(14.7,16.9,23.8)	(26.1,27.1,27.6)	(151,151/153,992/154,464)	(7,377/7,965/8,715)
3	(156.3,166.8,170)	(17,22.2,23.7)	(25.9,26.2,27.4)	(152,743/153,702/154,908)	(7,367/8,344/8,513)
4	(151,164.6,166.7)	(16.5,20.1,21.9)	(26.1,27.2,27.4)	(150,541/152,876/153,195)	(6,855/9,212/9,365)
5	(154.7,164.7,165.3)	(19,20.3,21.6)	(25.1,25.7,27.8)	(151,896/151,924/153,331)	(7,010/8,650/9,745)
6	(157,162.8,169.3)	(18,22.3,23.8)	(25,26.8,27.6)	(152,420/152,951/154,670)	(8,383/8,702/9,780)
7	(154.8,167.5,169.5)	(17.3,18.8,20.2)	(25.2,26.6,27.5)	(150,417/152,980/153,468)	(7,389/7,846/8,797)
8	(150.1,154.2,163)	(17,18.6,22)	(25,25.2,25.8)	(150,322/153,054/153,899d)	(8,566/9,733/9,770)

4. Simulation Results and Discussions

In analyzing production line problems, the waste time of workstations is considered, including face and chamfering, hole piercing, nicking, oil grooving, joint face, and wall thickness processes. The types of loss time are classified into planned maintenance and breakdown or failure, which are shown in **Table 4**. This table shows the improvement methods to increase the OEE value. Then the data will be collected after the improvement as shown in **Table 5**.

Table 4 Results of loss improvement of half-bearing production processes

Process	Types of loss time		Improvement methods
	Planned maintenance	Breakdown/failures	
Face and chamfering	system testing/ tool change	1) The workpiece falls on the conveyor 2) rectified by the drawing 3) slanted tray	1) install a sensor to detect and monitor the falling parts on the conveyor 2) set the preventive maintenance manual 3) considers precisely and continuously for mean time to failure of tools and equipment 4) check the drawing with the sample part before manufacturing 5) monitor the flow of raw materials and parts before starting the machine
Hole piercing	system testing/ tool change	1) pusher error 2) expired piston 3)the device is not operated properly 4) the workpiece falls on the conveyor 5) rectified by the drawing 6) change the drawing 7) airflow obstruction 8) pump malfunction 9) the flow of the workpiece is interrupted	
Nicking	system testing/ tool change	1) airflow obstruction	
Oil grooving	system testing/ tool change	1) groove position error 2)the device is not operated properly 3) the workpiece falls on the conveyor 4) rectified by the drawing 5) groove position error 6)the flow of the workpiece is interrupted 7) wrong cutting tool	
Joint face	system testing/ tool change	1) the device is not operated properly 2) the workpiece falls on the conveyor 3) rectified by the drawing 4) the flow of the workpiece is interrupted	
Wall thickness	system testing/ tool change	1) sensor malfunction 2) thickness adjustment 3) wrong size of nail 4) the flow of the workpiece is interrupted	

Table 5 Triangular fuzzy data after improvement of half-bearing production processes

Week	Total production time (Hours)	Planned stops (Hours)	Unplanned stops (Hours)	Production quantity (Units)	Defects (Units)
1	(153.3,159.7,165.8)	(9,9.4,9.9)	(15.3,15.4,16)	(83,289/100,950/109,123)	(6,224/6,278/6,354)
2	(151.6,154.9,165.3)	(9.5,9.7,10)	(15.5,15.7,15.8)	(151,225/152,062/153,011)	(4,732/5,986/6,216)
3	(150.9,158.5,169.1)	(8.8,9.3,9.9)	(15.4,15.5,15.7)	(150,293/150,454/150,808)	(4,996/6,231/6,243)
4	(156.6,162.8,163.8)	(9.5,9.6,10)	(15.1,15.5,15.7)	(153,475/154,668/154,844)	(5,611/5,647/6,876)
5	(152.5,155.8,158)	(8.8,8.9,10)	(15.5,15.7,15.8)	(154,334/154,902/154,938)	(4,798/4,958/6,400)
6	(150.4,157.5,160.5)	(8.1,8.4,9.5)	(15.2,15.3,15.7)	(150,278/151,388/151,675)	(4,902/6,178/6,423)
7	(153.8,167.5,170)	(8.3,8.7,9.7)	(15.4,15.6,16)	(150,815/151,420/153,130)	(4,556/5,732/6,660)
8	(153.5,162.9,168.2)	(8.4,8.7,9.4)	(15.1,15.7,15.9)	(160,406/161,863/162,714)	(4,976/5,942/6,627)

The main problems found in the half-bearing production processes are the workpiece falls on the conveyor, the lack of checking the workpiece dimension with the drawing, tool and equipment errors or malfunction, airflow interruption, position errors wrong cutting tool, etc. The improvements by using the lean methods are the installation of a sensor to detect and monitor the falling parts on the conveyor, the preparation of a preventive maintenance manual, the data collection of mean time to failure of tools and equipment and also mean time to repair, checking of drawing with the sample part before manufacturing and monitoring the flow of raw materials and parts before starting the machine. Whereas **Table 6** and **Figure 8** show the % availability rate, % performance rate, % quality rate and %OEE of half-bearing production processes before and after the improvement. The method of defuzzification of triangular fuzzy numbers is the graded mean integration [23]. The example of defuzzification of total production time of week 1 is shown as follows.

$\tilde{A} = (a_1, a_2, a_3)$, $d_F(\tilde{A}) = (a_1 + 4a_2 + a_3)/6$

Total production time

= (151.60, 160.40, 167.90)

= (151.60 + (4 × 160.40) + 167.90) / 6 = 160.2

The example of the calculation of %OEE via Vensim software of week 1 is shown below.

Planned production time

= total production time - planned stops

= 160.2 - 18.52 = 141.7 hours

Operating time

= planned production time - unplanned stops

= 141.7 - 26.5 = 115.2 hours

Availability rate (%)

= operating time/planned production time*100

= 115.2 / 141.7 × 100 = 81.33%

Production quantity

= 152,971 units

Defects

= 8,580 units

Good products

= production quantity – defects

= 152,971 - 8,580 = 144,392 units

Cycle time

= 0.00084 hours

Performance rate (%)

= (production quantity × cycle time)/ planned production time × 100

= (152,971 × 0.00084) / 141.7*100 = 90.88%

Quality rate (%)

= good products/ production quantity × 100

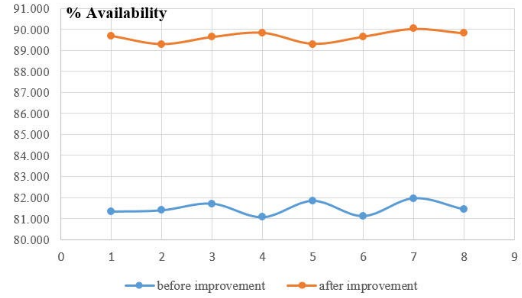
= 144,392/152,971 × 100 = 94.39%

%OEE

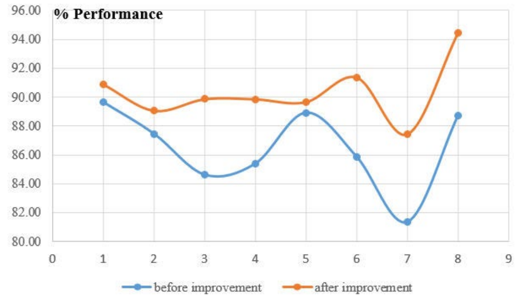
= 81.33% × 90.88 % × 94.39 % = 69.77%

Table 6 The %availability rate, %performance rate, %quality rate and %OEE of half-bearing production processes before and after the improvement

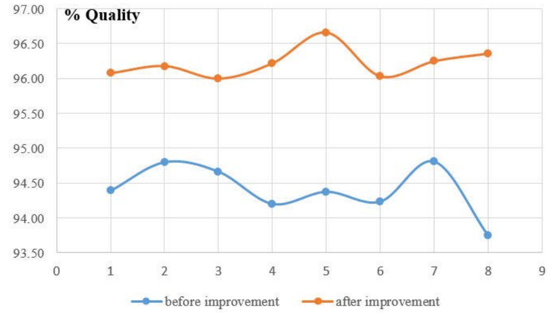
Week	%Availability		%Performance		%Quality		%OEE		%Improvement
	before	after	before	after	before	after	before	after	
1	81.329	89.694	90.88	89.64	94.39	96.07	69.77	77.24	10.71
2	81.389	89.285	89.05	87.45	94.80	96.18	68.71	75.10	9.30
3	81.701	89.634	89.86	84.62	94.66	95.99	69.50	72.81	4.76
4	81.068	89.843	89.86	85.39	94.20	96.22	68.62	73.82	7.57
5	81.832	89.298	89.66	88.91	94.37	96.66	69.24	76.74	10.84
6	81.122	89.648	91.36	85.85	94.24	96.03	69.84	73.91	5.82
7	81.953	90.032	87.43	81.36	94.81	96.25	67.93	70.50	3.78
8	81.433	89.812	94.47	88.73	93.75	96.36	72.12	76.78	6.46



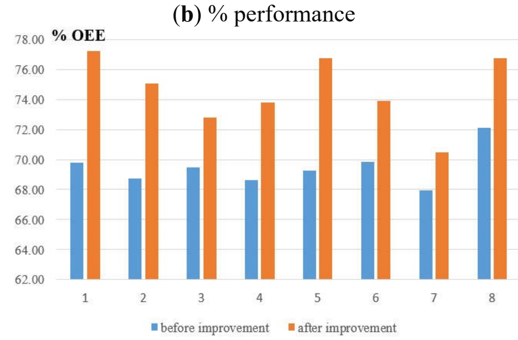
(**a**) % availability



(**b**) % performance



(**c**) % quality



(**d**) % OEE

Figure 8 Before and after improvement of the OEE of half-bearing production processes

The results show that after applying the lean improvement the %availability rate, %performance efficiency and %quality rate are increased leading to the increase of the %OEE during 8 weeks of the production schedule.

5. Discusison and Conclusion

This research proposed the application of system dynamics to determine time-varying OEE for a half-bearing production process. System dynamics simulation was found to be an efficient technique used in manufacturing. The variation of time or losses that affect the OEE can be simulated during the production time. The loss time can be determined by using triangular fuzzy numbers to make it realistic as in the production line. The most common problems encountered in half-bearing production lines are equipment failure, workpiece falling on the conveyor, airflow interruption, etc. The improvement of lean methods to increase the OEE are the use of sensors or other devices to detect errors, the data collection of failures, the preparation of preventive maintenance manual and continuous improvement of production processes. The results of improvement can increase %availability rate, %performance efficiency, %quality rate and %OEE between 3–10%. The contribution of this research is to provide knowledge about the application of SD and Fuzzy membership function to find %OEE where related factors are uncertain. The future research work is to extend other uncertain variables into the SD models that affect OEE such as the demand or spare part inventory fluctuation. The total cost of the system derived from those uncertainties also can be added to future research. The data of real practice has characteristics of some probability distribution, so the data should be correctly analyzed according to the probability distribution.

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