

Implementation of Overall Equipment Effectiveness (OEE)

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Abstract: This project presents the implementation of overall equipment effectiveness (OEE) at a small enterprise finishing product specifications according to customer specifications in the developing country of India. This company had never established any performance measurement before. Therefore, an appropriate indicator was elaborately selected for the case study and OEE was chosen. OEE is employed as a simple indicator, but it is still an effective method for analyzing the efficiency of a single machine and an integrated machinery system. The case study of OEE was carried out from set-up stage to full implementation. Several processes were carried out to establish the OEE indicator. OEE helped the company identify the primary problems concerning the availability rate and performance efficiency. The management made the decisions by relying on OEE results and its details and mandated the elimination of the root causes of breakdown losses and speed losses. Finally, after full implementation, OEE performances improved by over 75 percentages, since availability rate and performance efficiency were improved over 79 percentages and quality rate was maintained at the same level.

Key words: Company had never established • Integrated machinery system • After full implementation

INTRODUCTION

Equipment is a major concern of any manufacturing company. Every product has three main properties to be considered such as quality, price and delivery time [1] and equipment affect all these three criteria. Equipment breakdown, repair, quality defects are daily problems that arise in manufacturing industry and can affect quality, cost and delivery time. Equipment is always designed to operate in an optimal condition. Oakland [2], states, “The best equipment will not work satisfactorily unless it is cared for”. Therefore, maintenance activity is important to optimize equipment usage. In explaining the concept of TQM, according to Antero [3], Lillrank highlighted that “Maintenance activities should be executed according to total productive maintenance philosophy”. Equipment maintenance is even more critical with the advancement of automation in industry. TPM emphasizes on total employee involvement and improving the efficiency of the total organization, not just the manufacturing capability. TPM involves every employee in an organization and aims to maximize equipment effectiveness. Based on TPM,

maintenance and production operators must work in a team in conducting maintenance activities. Employees will have new roles, better job function and responsibilities in TPM environment.

The term ‘overall equipment effectiveness’ is one that is often used as a jargon term, which few people fully understand, but it is an effective tool that is often used within the process of lean manufacturing as a ‘key performance indicator’ and allows success to be measured by comparing manufacturing units in different industries.

In brief OEE measures how effective the equipment used for manufacturing actually is in practice, as opposed to in theory. It is a useful tool because it provides a very good, all round and comprehensive measurement of how a machine performs; it is in effect a 3 dimensional picture of performance.

OEE is comprised of 6 metrics, often referred to as the ‘hierarchy of metrics’ which are:

- This is the OEE itself, which is a method of measuring how well a unit performs when it is operational, in comparison to how it ought to perform.

- TEEP is the second metric and this is the total effective equipment performance, which measures the OEE set against time, in other words, 24 hours a day, over 365 days.
- Loading: This is the part of the TEEP representing the amount of time that units are actually operational.
- Availability: this can be defined as uptime, i.e. when the equipment is available to operate.
- Performance: this is the speed at which the manufacturing unit operates as a % term of the capacity of the unit.
- Quality: This is often referred to as being FPY, which is the First Pass Yield and is the number of good i.e. perfect items that are produced with no defects.

Oee in Action: OEE takes a manufacturing unit and then breaks down its performance into 3 different components: namely:

- Availability,
- Performance,
- Quality.

Each of these will highlight any specific aspect of the manufacturing process where improvements can be made or where output is poor or not up to standard.

OEE is not, however, a programme that seeks to ensure that all equipment operates to 100% efficiency. This is not a realistic aim, with most companies aiming to achieve a level of 85% efficiency. This is a realistic figure that can be achieved, whereas anything higher could lead to failure to meet the challenge.

Benefits of Oee: The most obvious benefit of OEE is that it provides such a comprehensive view of how machinery operates. But it actually goes deeper than this because it forces an organisation to look at individual items of equipment and make sure that the maximum benefits are being obtained from the equipment.

Because it places the manufacturing unit or item of equipment under a (virtual) microscope, it allows real in depth analysis of how the unit performs. This means that a number of parameters can be examined, such as the shift or the specific part numbers involved. This means that all different aspects of the performance are assessed, instead of having to rely on verbal data from operators.

Literature Review: The role of top management's commitment and leadership has been frequently

emphasized in many literatures to have the decisive influence over successful TPM implementation. TPM requires a drastic change in the traditional mindset of work culture and maintenance approaches. However at the present moment, high resistance is often encountered from the shop floor operators and as well as the maintenance personnel. To this extent, active top management support is crucial to overcome such resistance, especially during the transition period that the major obstacle in implementing TPM was the lack of top management commitment to follow through which resulted in many organizations to struggle when attempting to implement TPM. An organization must be led by top management that must support the understanding and get committed to various kinds of TPM activities. Top management has the primary responsibility of preparing a suitable and supportive environment before the official kick-off of TPM within their organization. This may include resources allocation and training and education provided to the middle management level as well as the production floor operators. The top management's primary responsibility is to establish a favorable environment where the work environment can support autonomous activities. Human-oriented strategy in general involves strategies that actively involve human administrative application of management methods in achieving high extent of TPM. Three important aspects that are often discussed as the core of Human-oriented strategy that are top management commitment, total employee involvement and training and education.

Rung Chant *et al.* [4] tells that by implementing autonomous maintenance by operators reduces unplanned down time. Both qualitative and quantitative methods were used to evaluate the current maintenance program.

Chan *et al.* [5] tells the importance of OEE, a tool which helps to increase the productivity of existing equipment. OEE is basically a multiplication of three component efficiency percentages of availability, performance and quality. He showed that even if a tool is available almost 100% of the time and is utilized almost 100% of the time, its OEE could be extremely low due to the tool's performance or to the tool's quality of output. There are six major losses associated in OEE calculation Breakdowns, set up and adjustments, small stops, reduced speed, startup rejects and production rejects. Performance. Availability and Quality are the parameters taken into consideration. Total effectiveness indicates

TPM's pursuit of economic efficiency and profitability. Total maintenance system includes Maintenance Prevention and Maintainability Improvement as well as PM. Basically, this refers to "maintenance-free" design through the incorporation of reliability, maintainability supportability characteristics into the equipment design. Total participation of all employees includes Autonomous Maintenance (AM) by operators through small group activities. Essentially, maintenance is accomplished through a 'team' effort, with the operator being held responsible for the ultimate care of his/her equipment.

Ravi Shankar *et al.* [6] reveals the cost effective manufacturing. The output of the factory is not purely the sum of discrete steps in production process but an integrated function of the discrete process.

Maggard *et al.* [7] implemented TPM as a team approach and the use of performance management will increase the state of maintenance, improve product quality, reduce waste, improve productivity and achieve desired cultural change.

Hans Lofsten [8] reveals that firm should maximize its maintenance productivity in economic terms to produce output at minimum maintenance cost. Expected changes in the prices of outputs and of current inputs would be built in the partial productivity model.

Robert W. Freck, [9] emphasized on equipment reliability involving the workforce in equipment care, improve the maintenance function and improve overall cleanliness and Safety.

Stefan Schmidt [10] introduces Change over reduction engineering, using new software which takes SMED to new dimension. The heart of TPM implementation lies in maximizing equipment effectiveness, eliminating six major losses and proper training should be given to the operators.

Kathleen, [11] investigated the relationship between Total Productive maintenance and manufacturing performance through Structural equation Modeling and found that total productive maintenance has a positive and significant relationship with low cost high levels of quality and strong delivery performance.

Steps Involved in Industry

The Hub Synchronizer: The Hub Synchronizer is one such component that is manufactured in M/s. Sundaram Fasteners using the above powder metallurgy process. The component is shown below with the specification in which it is made in M/s. Sundaram Fasteners.



Fig. 5.1: Hub Synchroniser

Synchroniser Hub for Transmissions: Used in manual gear transmissions. Have the capabilities to make multilevel parts to near net shape, resulting in improved quality levels and considerable cost savings. These parts find application in passenger car and multi utility vehicles.

The component is manufactured using Powder Metallurgy process in M/s. Sundaram Fasteners in Hosur. The semi finished components are then sent to M/s. Arun Engineering Equipments for machining and finishing process. The process involved in the manufacturing of Hub synchronizers using Powder Metallurgy are explained below in detail.

Powder Metal Parts: The Powder Metallurgy unit was set up in the year 1982 with technology from Sintermetallwerk Krebssoege GmbH, Germany and is today one of the leading manufacturers of powder metallurgy parts in India.

Operational Excellence: Pursuit of excellence, over the years, has meant acquiring in-depth expertise in metal forming, machining, heat treatment and assembly; operator- assured quality; and customer-oriented design and development. As the business has grown with an expanding global customer base, the Company has steadily invested in creating additional capacities at multiple locations.

M/s. Sundram Fasteners was the first Indian manufacturing company to be ISO 9000 certified; the first to obtain a large, single sourced auto component order from a global OEM customer – the radiator caps business from General Motors, USA; the first to set up a Just In Time (JIT) supply chain from India to the US, including a JIT warehouse in the US; the first Indian company to win the global "Supplier of the Year" award for several years from General Motors; among the first to adopt and get recognized for Total Productive Maintenance (TPM) practices in India; and so on.

Uses of Hub Synchroniser:

- Power transmission.
- Shifting of gear.

Quality Objective:

- To obtain customer satisfaction 100%.
- On time delivery of products.
- Reduce internal rejection level.

Metal Powder: The chief raw materials used in the production of powder metallurgy components are the metal powders. These consist of fine, high purity metal powders produced by processes such as atomization, pulverization, chemical reduction, electrolytic techniques or mechanical alloying. Of these processes, atomization is the most popular technique.

Lubricants: Lubricants are added to the metal powders to reduce friction between powders and pressing dies, which in turn reduces pressure gradients.

Forming Processes: The raw materials are formed into shapes using pressure based techniques such as:

- Cold uniaxial pressing
- Metal injection moulding
- Cold isostatic pressing
- Hot isostatic pressing
- Hot forging

The latter 2 processes also combine the forming and sintering processes together.

Compaction of the raw materials at high pressures forms a “green shape”, where the particles bond together by mechanical interlocking and cold welding. Pressing at sufficiently high pressures gives the green shape enough strength to be handled and machined.

The amount of compression experienced by the powder during the forming process will dictate its green density. This in turn will control the amount of shrinkage/growth the powder compact will undergo during the sintering process. It will also influence the physical properties of the final component.

Sintering: Sintering is a high temperature process used to develop the final properties of the component. It involves heating to temperatures below the melting point of the major constituent in an inert atmosphere to protect

against oxidation. Typically temperatures of approximately 80% of the melting point are used.

During the sintering process, adjacent particles bond together by solid state diffusion processes. As mentioned earlier, processes such as hot isostatic pressing and hot forging combine the sintering and forming process into a single stage.

Secondary Operations: Sometimes secondary operations are used to improve surface finish or make sure components fall within required tolerances. Such operations may include, drilling, grinding, repressing. Density and strength can also be increased by a secondary sintering and depressing operation.

Sometimes porous metal components are deliberately produced so that they can be infiltrated with secondary materials. Further they are produced such that have interconnected pores, or capillary pores. These can be infiltrated with oil or other lower melting point metals. For this to work properly, oxide free pores are required, again requiring processing in an inert atmosphere.

An example of a metal infiltrated metal matrix is iron alloys infiltrated with alloys such as bronze brass or copper.

Heat Treatments: Due to the capillary porosity and the potential for future bleed out, powder metallurgy parts should not be liquid cyanide hardened or heat treated in liquid salt baths.

Processes such as gas carburizing, carbonitriding and black oxide steam treatments are suitable methods for heat treating components manufactured by powder metallurgy. The latter process can also be used as an effective method of closing pores in iron based parts.

Plant Layout: The industry consists of 3 shop floors:

1st shop floor carries the following process:

- Facing
- Grooving
- Chamfering
- Radius
- Quality Control department

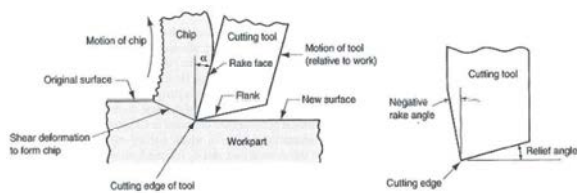
2nd shop floor carries the following machining process:

- Drilling
- De burring
- Buffing

3rd shop floor carries quality checks on the components.

- Visual inspection.

Overview of Machining Technology: Machining is not just one process; it is a group of processes. The common feature is the use of a cutting tool to form a chip that is removed from the work part, called swarf. To perform the operation, relative motion is required between the tool and work. This relative motion is achieved in most machining operation by means of a primary motion, called cutting speed and a secondary motion called feed [12]. The shape of the tool and its penetration into the work surface, combined with these motions, produce the desired shape of the resulting work surface.



Three Important Elements: In order to get an efficient process and beautiful surface at the lathe machining, it is important to adjust a rotating speed, a cutting depth and a sending speed. Please note that the important elements can not decide easily, because these suitable values are quite different by materials, size and shapes of the part [13].

Rotating Speed: It expresses with the number of rotations (rpm) of the chuck of a lathe. When the rotating speed is high, processing speed becomes quick and a processing surface is finely finished. However, since a little operation mistakes may lead to the serious accident, it is better to set low rotating speed at the first stage [14].

Cutting Depth: The cutting depth of the tool affects to the processing speed and the roughness of surface. When the cutting depth is big, the processing speed becomes quick, but the surface temperature becomes high and it has rough surface. Moreover, a life of byte also becomes short. If you do not know a suitable cutting depth, it is better to set to small value [15].

Sending Speed: The sending speed of the tool also affects to the processing speed and the roughness of surface. When the sending speed is high, the processing speed becomes quick. When the sending speed is low, the surface is finished beautiful. There are 'manual sending' which turns and operates a handle and

'automatic sending' which advances a byte automatically. A beginner must use the manual sending. Because serious accidents may be caused, such as touching the rotating chuck around the byte in automatic sending [16].

Tool Used for Material Removal: Insert type carbide tipped single point cutting tool is used to perform the material removal process involved on the component. Carbide, ceramics (such as cubic boron nitride) and diamond, having higher hardness than HSS, all allow faster material removal than HSS in most cases. Because these materials are more expensive and brittle than steel, typically the body of the cutting tool is made of steel and a small cutting edge made of the harder material is attached. The cutting edge is usually either screwed on (in this case it is called an insert), or brazed on to a steel shank (this is usually only done for carbide) [17].

Methodolog

Operations Performed on the Component

Facing: Facing is a lathe operation in which the cutting tool removes metal from the end of the work piece or a shoulder. Facing is a machine operation where the work is rotated against a single point tool. A workpiece may be held in a 3, 4, or 6 jaw chucks, collets or a faceplate [18].



Turning: Turning is a lathe operation in which the cutting tool removes metal from the outside diameter of a workpiece. A single point tool is used for turning. A workpiece may be held in a 3, 4, or 6 jaw chuck, collets or may also be held between centers.



Grooving: Grooving is like parting, except that grooves are cut to a specific depth by a form tool instead of severing a completed/part-complete component from the stock. Grooving can be performed on internal and external surfaces, as well as on the face of the part (face grooving or trepanning).

Chamfering: A chamfer is a beveled edge connecting two surfaces. If the surfaces are at right angles, the chamfer will typically be symmetrical at 45 degrees.

Radius: A rounding of an exterior corner is called a "round" or a "radius".

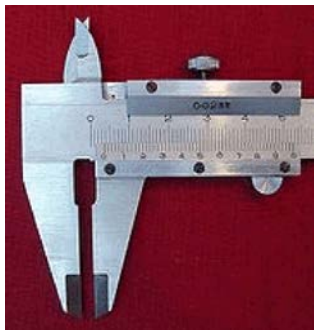
Quality Control Instruments Used

Calliper: A caliper (British spelling also calliper) is a device used to measure the distance between two symmetrically opposing sides. A caliper can be as simple as a compass with inward or outward-facing points. The tips of the caliper are adjusted to fit across the points to be measured, the caliper is then removed and the distance read by measuring between the tips with a measuring tool, such as a ruler.

Vernier Calliper: A variation to the more traditional caliper is the inclusion of a vernier scale; this makes it possible to directly obtain a more precise measurement. Vernier calipers can measure internal dimensions (using the uppermost jaws in the picture at right), external dimensions using the pictured lower jaws and depending on the manufacturer, depth measurements by the use of a probe that is attached to the movable head and slides along the centre of the body. This probe is slender and can get into deep grooves that may prove difficult for other measuring tools.

The vernier scales may include both metric and inch measurements on the upper and lower part of the scale. Vernier calipers commonly used in industry provide a precision to a hundredth of a millimeter (10 micrometers), or one thousandth of an inch.

A more precise instrument used for the same purpose is the micrometer.



Height Gauge: A height gauge is a measuring device used either for determining the height of something, or for repetitious marking of items to be worked on. The former type of height gauge is often used in doctor's surgeries to find the height of people.

These measuring tools are used in metalworking or metrology to either set or measure vertical distances; the pointer is sharpened to allow it to act as a scribe and assist in marking out work pieces.



The left height gauge has the vernier scale, while the right one is an electronic height gauge with a digital readout.

GO-NO Go Gauge: A Go-No Go gauge (or Go/no go) refers to an inspection tool used to check a work piece against its allowed tolerances. Its name derives from its use: the gauge itself has two tests; the check involves the work piece's having to pass one test (Go) and 'fail' the other (No Go). It is an integral part of the quality process that is used in the manufacturing industry to ensure interchangeability of parts between processes, or even between different manufacturers.

A Go No Go gauge is a measuring tool that does not return a size in the conventional sense, but instead returns a state. The state is either acceptable (the part is within tolerance and may be used) or it is unacceptable (and must be rejected).

Plug Gauge: These gauges are referred to as plug gauges; they are used in the manner of a plug. They are generally assembled from standard parts where the gauge portion is interchangeable with other gauge pieces (obtained from a set of pin type gauge blocks) and a body that uses the collet principle to hold the gauges firmly. To use this style of gauge, one end is inserted into the part first and depending on the result of that test, the other end is tried.

Magnetic V Block: 'V' Blocks are required for Quality Control, Tool Room and Standard Room. "Crystal" Brand Magnetic 'V' Blocks have high magnetic pull hence they



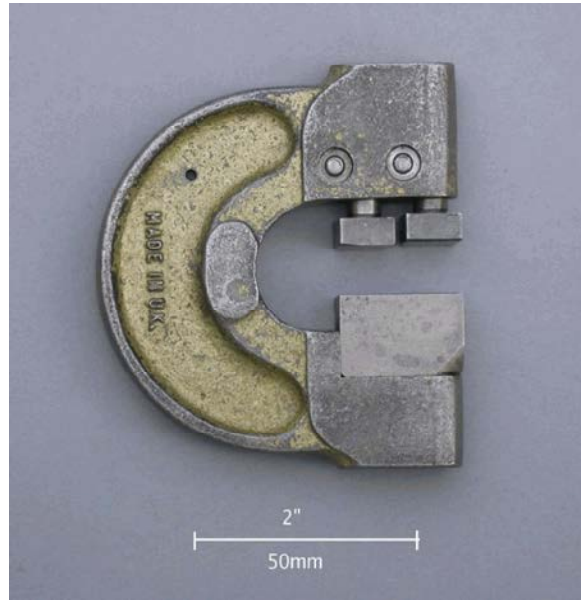
can be used for drilling and grinding (both wet and dry) and even for light milling work. The 'V' Block has a total three magnetic surfaces. Top and Bottom with 90° V angle and end surface opposite to each other. All three magnetic surfaces and the two sides are carefully ground. Their accuracy for flatness, parallelism and squareness is within 0.005 mm for 2", 3", 4" & 6" 'V' Blocks.

When turned "ON" all three magnetic surfaces are activated simultaneously. The permanent magnet holds the work firmly in the 'V' and if the block rests on a magnetically conductive surface, it is held firmly to this surface. The magnetic pull is constant and will not decrease even after long use. The magnetic system being shielded from penetration of moisture, cannot be damaged by coolants or:

Snap Gauge: These images illustrate an alternative type of gauge. The snap gauge has four anvils or jaws, the first one or pair (outermost) are set using the upper limit (tolerance) of the part and the inner set adjusted to the lower limit of the part.

The usage of this gauge may be more intuitive than the plug type. A correctly machined part will pass the first set of jaws and stop at the second — end of test. In this

manner a part may be checked in one action, unlike the plug gauge that needs to be used in the correct sequence and flipped to access the second gauge. The left image is a plain snap gauge used to measure outside distances (diameters); the right hand image shows two views of a thread snap gauge. Snap gauges are useful for mass production.



Drilling: Two holes are to be drilled on a specific place of the component. In order to increase the productivity the change over time is decreased by performing the drilling operation for 10 components fixed on a fixture.

There is a pair of jigs when one loaded with 10 components is undergoing the machining operation the other fixture is manually loaded by the operator. Thus the changeover time is reduced.

Poka Yoke: Since the drilling operation had to be done on a specific location the components when loaded on the fixture follows a fool proofing concept. That is it can be fixed only through a guiding rod thus facilitating the drilling operation.

Polishing and Buffing: Polishing and buffing are finishing processes for smoothing a work piece's surface using an abrasive and a work wheel. Technically polishing refers to processes that use an abrasive that is glued to the work wheel, while buffing uses a loose abrasive applied to the work wheel. Polishing is a more aggressive process while buffing is less harsh, which leads to a smoother, brighter finish. A common misconception is that a polished surface has a mirror bright finish, however

most mirror bright finishes are actually buffed. Polishing is often used to enhance the looks of an item, prevent contamination of medical instruments, remove oxidation, create a reflective surface, or prevent corrosion in pipes.

Buffing may be done by hand with a stationary polisher or die grinder, or it may be automated using specialized equipment. When buffing there are two types of buffing motions: the cut motion and the color motion. The cut motion is designed to give a uniform, smooth, semi-bright surface finish. This is achieved by moving the work piece against the rotation of the buffing wheel, while using medium to hard pressure. The color motion gives a clean, bright, shiny surface finish. This is achieved by moving the work piece with the rotation of the buffing wheel, while using medium to light pressure.

Deburring: A burr refers to the raised edge on a metal part. It may be present in the form of a fine wire on the edge of a freshly sharpened tool or as a raised portion on a surface, after being struck a blow from an equally hard or heavy object. More specifically, burrs are generally unwanted material remaining after a machining operation such as grinding, drilling, milling, or turning. When these burrs are removed it is called de burring.

Dispatching: Finally the component is dispatched to M/s. Sunderam Fasteners where it is Induction Hardened and makes the component to serve its purpose. Before dispatching the component undergoes visual inspection in the Shop floor 3.

Some of the other components that are taken by M/s. Arun Engineering works for Job order are.

- Inner Gear
- Spider

Oee Calculation: Overall equipment effectiveness (OEE) is a hierarchy of metrics created by Seiichi Nakajima in 1960's which evaluates and indicates how effectively a manufacturing operation is utilized. The results are stated in a generic form which allows comparison between manufacturing units in differing industries. It is not however an absolute measure and is best used to identify scope for process performance improvement and how to get the improvement. If for example the cycle time is reduced, the OEE can also reduce, even though more product is produced for less resource. Another example is if one enterprise serves a high volume, low variety market and another enterprise serves a low volume, high variety market. More changeovers (set-ups) will lower the OEE in

comparison, but if the product is sold at a premium, there could be more margin with a lower OEE.

OEE measurement is also commonly used as a key performance indicator (KPI) in conjunction with lean manufacturing efforts to provide an indicator of success.

Problem Definition:

Working hours 8 hours
Short break 15 min @ 2 intervals
Lunch break 30 min
Ideal run rate 2 pieces/min.
Down time 54 min
Total pieces 650 pieces
Reject pieces 10 pieces

Calculation of Oee: OEE Factors introduces Availability, Performance and Quality...the metrics that you will use to measure your plant's efficiency and effectiveness. We provide a visual overview of the key productivity losses that occur in the typical manufacturing environment. We start with Plant Operating Time and end up at Fully Productive Time, showing the sources of productivity loss that occur in between.

Availability = Operating Time / Planned Production time
Performance = (Total Pieces / Operating Time) / Ideal Run Rate

Quality = Good Pieces / Total Piece

Steps to Increase Oee: There are a number of ways to improve OEE. Preventive maintenance should be carried out regularly So that DOWNTIME can be reduced thus increasing the overall OEE. Let's see some of the importance of Preventive maintenance.

Preventive Maintenance -Definition: Preventive maintenance is defined as "the maintenance" of a system in which components are repaired or replaced periodically regardless of the system's current operational condition.

- Regular inspection of the roof system .
- Removal of all debris from the roof surface
- Cleaning of drains, gutters and waterways
- Filling of pitch pans
- Minor flashing and field repair
- Providing the commitment of time, funding and personnel to follow a regular program.

Improved Oee Calculation: The possible ways to improve OEE are as follows:

Working hours 8 hours
Short break 15 min @ 2 intervals
Lunch break 30 min
Ideal run rate 2 pieces/min.
Down time 47 min. (Down time reduced from 54 min)
Total pieces 675 pieces. (Increase in Total no. of pieces)
Reject pieces 10 pieces.

Calculation:

Availability = Operating Time / Planned Production time
Performance = (Total Pieces / Operating Time) / Ideal Run Rate
Quality = Good Pieces / Total Piece
OEE = Availability X Performance X Quality.

RESULTS AND DISCUSSIONS

As mentioned in problem definition the OEE of CNC machine was found to be 75% in order to increase OEE Down time Reduced through Preventive Maintenance Say from 54 minutes to 47 minutes which would automatically increase the productivity Or Total pieces produced would be 675.

From the observation it's clear that when the demand should be met with in short span SINGLE PASS is preferred compared to the double pass. Single pass refers to the flow of job or part one way i.e., meeting the job specification right at the first time. For performing the single pass operation proper knowledge should be installed in the mind of the operators and the operators should be aware of the things happening around him. Double pass takes 28 seconds to complete job specifications while Single pass takes around 24 seconds, this difference of 4 seconds has a great impact on the production process.

CONCLUSION

By reducing the downtime, OEE can be increased from 75% to 79% and Preventive Maintenance should be carried out at regular intervals.

- Proper knowledge should be installed to the operators
- OEE is useful as a heuristic, but can break down in several circumstances. For example, it may be far more costly to run a facility at certain times. Performance and quality may not be independent of each other or of availability and loading. Experience may develop over time.

- OEE has properties of a geometric mean. As such it punishes variability among its subcomponents. For example $20\% * 80\% = 16\%$, whereas $50\% * 50\% = 25\%$. When there are asymmetric costs associated with one or more of the components, then the model may become less appropriate.
- Consider a system where the cost of error is exceptionally high. In such a condition, higher quality may be far more important in a proper evaluation of effectiveness than performance or availability. OEE also to some extent assumes a closed system and a potentially static one. If one can bring in additional resources (or lease out unused resources to other projects or business units) then it may be more appropriate for example to use an expected net present value analysis.

REFERENCES

1. Tucker, A.L., 2004. The impact of operational failures on hospital nurses and their patients, *Journal of Operations Management*, 22(2): 151-169.
2. Sahney, V.K. and S.K. Kachhal, 2001. Health service, in Maynard's *Industrial Engineering Handbook*, K.B. Zandin, Ed. New York: McGraw-Hill, pp: 15, 43-15.64.
3. Peters, R.W., 2001. Maintenance management and control, in *Handbook of Industrial Engineering: Technology and Operation Management*, G. Salvendy, Ed. New York: John Wiley & Sons, Inc., pp: 1585-1623.
4. Blanchard, B.S., 1997. An enhanced approach for implementing total productive maintenance in the manufacturing environment, *Journal of Quality in Maintenance Engineering*, 3(2): 69-80.
5. Chan, F.T.S., *et al.*, 2005. Implementation of total productive maintenance: a case study, *International Journal of Production Economics*, 95: 71-94.
6. Eti, M.C., *et al.*, 2004. Implementing total productive maintenance in Nigerian manufacturing industries, *Applied Energy*, 79: 385-401.
7. Hartmann, E.H. and H.L. Charles, 2001. Total productive maintenance, in Maynard's *Industrial Engineering Handbook*, K.B. Zandin, Ed. New York: McGraw-Hill, pp: 16.57-16.77.
8. Ireland, F. and B.G. Dale, 2001. A study of total productive maintenance implementation, *Journal of Quality in Maintenance Engineering*, 7(3): 183-191.
9. Tsarouhas, P., 2007. Implementation of total productive maintenance in food industry: a case study, *Journal of Quality in Maintenance Engineering*, 13(1): 5-18.

10. Alsyouf, I., 2006. Measuring maintenance performance using a balanced scorecard approach, *Journal of Quality in Maintenance Engineering*, 12(2): 133-149.
11. Parida, A. and U. Kumar, 2006. Maintenance performance measurement (MPM): issues and challenges, *Journal of Quality in Maintenance Engineering*, 12(3): 239-251.
12. Pintelon, L. and G. Waeyenbergh, Pintelon, A practical approach to maintenance modeling, in: J. Ashayeri, W.G. Sullivan, M.M. Ahmad (Eds.), *Flexible Automation and Intelligent Manufacturing*, Begell House Inc., New York 1999, pp: 1109-1119.
13. Klein, M.R. and L.B. Methlie, 1995. *Knowledge-Based Decision Support Systems*, Wiley, New York.
14. Lenaerts, H., 1998. *Optimalisatie van het Onderhoud m.b.v. Onderhoudsconcepten*, Master Thesis, KULeuven.
15. De Smet, R., L. Gelders and L. Pintelon, 1997. Case studies on disturbance registrations for continuous improvement, *Journal of Quality in Maintenance Engineering*, 3: 91-108.
16. Pintelon, L., L. Gelders and F. Van Puyvelde, 1997. *Maintenance management*, Acco, Leuven/Amersfoort.
17. Jonsson, P., 1999. *The Impact of Maintenance on the Production Process – Achieving High Performance*, Lund University, Lund.
18. Geraerds, W.M.J., 1972. *Towards a Theory of Maintenance*, the English University Press, London, pp: 297-329.