Implementing the Overall Equipment Effectiveness Metric in an Industrial Manufacturing Environment

Alexandr M. Sokolov, Niamat Ullah Ibne Hossain, Aaron Storms, and Brian Merrill
Engineering Management and Construction Management
College of Engineering and Computer Science, Arkansas State University
State University, AR 72467, USA
asokolov@astate.edu, nibnehossain@astate.edu, Aaron.Storms@smail.astate.edu, brian.merrill1@smail.astate.edu

Abstract

Manufacturing shops that utilize Computer Numerical Control (CNC) machines often need a way to measure the performance of the manufacturing process. Overall Equipment Effectiveness (OEE) is the standard measurement used and this paper will explore the steps required to implement the OEE metric as well as ways to improve the performance of a machine shop utilizing the metric. It will explain the metric itself, the various formulae that comprise it, and some the technologies available to implement it. Example data will be used to present a before and after scenario that shows the usefulness of the OEE metric and how it considers quality, performance, and availability of a single machine, or an entire machine shop. Expected results of this study are a quantitative review that show how a machine shop can increase its performance by focusing on specific aspects that make up the OEE number. As OEE gets closer to 100%, the machine shop should be shown to create more good quality parts faster than it had at a previously lower number. Automation of the calculations will also be discussed, as well as the logic that determines what state a machine is in during the manufacturing process.

Keywords
Overall Equipment Effectiveness, OEE, Utilization, Quality, Machine State, CNC

1. Introduction
The OEE calculation "a three-part analysis tool for equipment performance based on its availability, performance, and quality rate of the output" (Muchiri & Pintelon 2008). A 100% OEE means that a machine shop only produces good parts, with no stop times, and that all machines are utilized during the available machining hours. The number can be calculated for single or multiple shifts, or it can be measured across a 24-hour time if the machine shop is expected to be producing nonstop. The most common practice is to measure across the shifts being used by the manufacturing company in question.

The main components of the OEE calculation are availability, performance, and quality. They are multiplied together to produce overall equipment effectiveness as shown in equation 1.

$$OEE = Availability * Performance * Quality \tag{1}$$

Availability refers to the amount of production time that a machine has during working hours to make parts or product. "All planned shutdown and maintenance activities reduce equipment availability" (Tsarouhas 2019) and therefore, maintenance should be tracked and reduced as much as possible to increase production time and OEE. Performance is the measurement of the ideal production rate of parts over a period. Idle time, reduced speeds, increased setup times and other delays during production are accounted for in the performance number. Quality refers to the number of good parts and bad parts made during production. Higher quantities of bad quality parts increase the amount of rework or scrap, costing the manufacturer money and time. By factoring in the ratio for quality, OEE can measure whether a manufacturing process is within statistical control.

These three individual pieces are all useful on their own and keeping track of them should be a common business practice, but they also do not allow an engineer or engineering manager to see the entire picture when it comes to managing a machine shop. By combining them into a single metric, a goal can be set those accounts for quality, performance, and availability all at once. When the goal isn't being met, breaking down the OEE metric into its individual parts makes it easier to focus on the correct area to get the most improvement. Increasing availability from 95% to 98% percent may increase production, but instead increasing quality from 75% to 90% would make more significant increase to OEE and therefore overall production.

OEE is also flexible in that the standards used to measure it can be tightened once an appropriate measurement is reached. If a shop is happy with its OEE number (for example 90% to 95% is excellent) then the performance standards by which the company measures the ideal production rate can be evaluated to determine if they should be capable of producing more parts in a smaller amount of time. Similarly, an organization's definition of quality can be altered to be more stringent and allow less defects to make it into a finished product. These changes would decrease the OEE number, but it would also give the engineers on staff the opportunity to investigate further into the manufacturing process to increase its efficiency even more.

1.1 Objectives

The objectives of this study is to institute a practical method for measuring performance and effectiveness within a Computer Numerical Control (CNC) manufacturing facility. Overall Equipment Effectiveness (OEE) is a key performance indicator (KPI) that measures how effectively equipment and/or machines within a manufacturing facility performs. The OEE model utilizes the following data inputs:

- Quality: The ratio of completed units that has successfully passed a quality inspection.
- Availability: The ratio of how much time your equipment was running during a duration of time.
- Performance: The ratio of how many units were produced during a duration of time.

These inputs are calculated by utilization of specific formulae. The statistical values of these inputs are presented as a percentage and this value displays the manufacturing facilities overall equipment efficiency. Evidence will be introduced that represents previous and subsequential scenarios that depict the usefulness of such KPI's. The anticipated results of this study will display that it is possible for a Computer Numerical Control (CNC) manufacturing facility to increase its performance by concentrating on distinct elements of the OEE model.

2. Literature Review

OEE is a well-documented metric used by many engineering managers and manufacturing engineers around the world. Case studies are often performed with specific production lines in mind to give instructions to engineers who to implement OEE in their own relevant work areas. This paper will reference these case studies and use industry examples from an aircraft manufacturer to demonstrate the usefulness of OEE in a way that is agnostic to more specific production lines.

The purpose of the OEE metric is to have a single measurement that can be indicative of a variety of process capabilities. Corelating many metrics together can be labor intensive, making "OEE is a simple and clear overall metric, and managers appreciate such an aggregated metric instead of many detailed metrics" (De Ron & Rooda 2006). Since OEE is easily scalable "OEE is an effective way of analyzing the efficiency of a single machine and also an integrated machinery system" (Ljungberg 1998). Being able to drill down from a top level all the way to individual work center or machines gives valuable insights to engineers trying to determine where to focus their efforts. However, it is not enough to just ask for an OEE number. Standards on measurement are industry wide and deviating from the standards could skew the OEE metric, and therefore make it useless. "Commitment and understanding from the company should exist for the OEE practice in order to be transmitted in all employees and make them a fundamental part of their work" (Tsarouhas 2020). Often, many organizations overestimate their efficiency and believe their OEE number to be in the realm of 70%-80%, when actually "It is a well-known fact that the initial measurement of OEE at the start… is normally less than 40%" (Gupta & Vardhan 2016).

This is not to be blamed on the employees of the production line however, as this initial measurement is always used as a baseline for improvements. Involving the employees and getting feedback from them is one of the most valuable sources of information for a manufacturing engineer that doesn't spend every hour of the day using and listening to the machines in question. Punishing workers for lower-than-expected results in the OEE measurement process can make them reluctant to process changes and sharing issues that and engineering manager may want to address.

It can be a common mistake by engineering managers to focus to much on raising an already high OEE metric. Oftentimes when an engineering project team has successfully completed a few projects that raise the OEE number to around 80%, managers can become to focuses on that last 20%. However, unless a machine shop is perfect and never experiences any quality issues from their suppliers or any machine downtime, a 100% OEE is unachievable. In a study done on 23 different companies that produce different kind of products "The overall median OEE of all 23 companies is 70%" (), which is high and indicative of those companies already attempting to improve their availability, performance, and quality. An organization that is only just now starting to implement this metric is usually looking to make process improvements and can be expected to have a low or average OEE.

OEE should also not be considered the only metric of importance to an organization. Though many different factors are considered by the metric, it should not be forgotten that a "limitation of the measure provided by OEE is related to the lack of consideration of other factors of the production environment" (Garza-Reyes 2015) such as "labour management and utilisation, raw materials' quality, cost, among others" (Garza-Reyes 2015). With these limitations in mind, OEE is still seen as one of the more consequential metrics for machine shops and production lines, and the benefits of OEE are "reduction in the expenditure of over timing, deferment of investments of larger capital, reduction in downtime/idle time, and improvement in the performance of the operator" (Yazdi et al. 2018).

Implementing OEE requires an engineering team to factor in 3 key pieces of information: availability, performance, and quality. While these will be discussed further in this paper, it is important to note that maximizing output in these areas allows for "cooperation between maintenance and production… for an improvement in the efficiency of even heavily used machinery and a significant reduction in hazards such as machinery breakdown, or unplanned downtime" (Korski et al. 2017). Availability and quality are simple numbers to calculate since they are just ratios of time spent or defects found. With performance though the "relationships between variables for its calculation is more complex than in the previous cases" (Cercós et al. 2019). Performance is more complicated because it has to do with the in-process cycle times, and factors in speed of the manufacturing operation to compare against a theoretical top speed that a machine or process should be operating at. Performance is usually much more difficult to measure in discrete manufacturing environments due to the differences in part runs on a given machine, but even larger production line with little variation can suffer from unexpected performance issues. A study of the Toshiba manufacturing facility found that the "biggest factors that caused losses [in OEE] were Reduced Speed Loss" (Dewi et al. 2020). This paper will explore the specifics of these calculations in the next section.

3. Methods

The OEE metric is calculated using equation 1 above. In this equation there are three smaller calculations that will be discussed in this section. These calculations are availability, performance, and quality of a production area. Collecting data directly from a machine about its activities can be done automatically, and many machines support data egress into a manufacturing execution system (MES) or a facilities management system via the use of standardized data protocols. One of the most common protocols used is MTConnect. Because MTConnect is a nonproprietary standard "MTConnect specification provides an open and extensible channel of communication for interconnectivity between devices, equipment, and systems" (Edrington, Zhao, Hansel, Mori, & Fujishima 2014). Besides MTConnect, there are other standard protocols commonly used to export data automatically from CNC machines and programmable logic controllers (PLCs). They are OPCUA, Modbus, Ethernet/IP, and more. Any one of these communication protocols can be made to communicate with a data historian that will store and export data to other programs that calculate metrics such as OEE.

4. Data Collection

Of the three key metrics that comprise OEE, availability is usually the first and one of the easiest to calculate. Availability is defined as the ratio of actual working time to the total production time and will be calculated using equation 2.

$$\text{Availability} = (\text{Production Time} - \text{Downtime}) / \text{Production Time} \quad (2)$$

Where production time is the amount of time across all shifts minus the breaks and lunches of the operators. Usually, the maintenance of the machines is scheduled during non-production time, so downtime for equation 2 is any unplanned stoppages or setup times where the machine is not actively producing during the scheduled production time. Clearing chips, tool breakages, crashes, and other examples of unplanned stoppages are common in many machine shops and production lines, but programmers and industrial engineers should be constantly trying to improve programs and processes to minimize these delays and maximize availability.

The next step to OEE should be to calculate the performance metric. During the time in which the machines are producing parts, performance measures the ideal rate of production against the actual rate. This allows reduction of ideal cycle times to be noted and studied by an engineering team or programmers. Calculating performance is defined as equation 3.

$$\text{Performance} = (\text{Ideal Cycle Time} * \text{Parts Produced}) / \text{Actual Run Time} \tag{3}$$

Where the ideal cycle time is the fastest possible time that a machine can produce parts. Multiplying the ideal cycle time and parts produced gives the shortest possible time that a batch or group of parts can be made. Dividing this number by the actual run time for the same subset of parts produces a ratio that measures how well the machines are being utilized during actual production time and make slowdowns and reduced speeds stand out when trying to understand how well a machine shop is performing.
Quality is the final piece of OEE and considers the number of parts produced and the number of defective parts. It can be calculated using equation 4.

$$\text{Quality} = (\text{Total Parts} - \text{Defective Parts}) / \text{Total Parts} \tag{4}$$

Where total parts are the number of parts finished in each time-period and defective parts are the total number of parts in that set that are not considered good. This ratio allows the engineers and engineering managers to scrutinize their processes for quality mistakes or to corelate poor quality parts with specific batches of raw materials. It should be clear to anyone working in the manufacturing space that reducing quality errors is one of the most important tasks, and entire methodologies such as lean manufacturing and six sigma have been developed as a way to do just that.

Analysis

To show the impact of OEE on a manufacturing space, an example organization will be used to calculate the metrics discussed in the above section. In this case, Toshiba had available data form 2019 where it ran a study against one of its CNC machines to determine if it met the Japan Institute of Pant Maintenance (JIPM) standards for OEE. These standards are outlined in Table 1.

Table 1. JIPM Standards for World Class OEE

Metric	Standard Requirements
Availability	90%
Performance	95%
Quality	99%
OEE	85%

These are stringent and difficult to achieve numbers, especially across a multi-faceted manufacturing landscape such as Toshiba. Many other industries also fail to meet the JIPM standards but strive to improve their process and machine operations because certification from the JIMP means that a company's manufacturing facilities are among the most efficient in the world. The results of the study taken from January to December of 2019 are shown in Table 2 where A is availability, P is performance, and Q is quality.

Table 2. Overall Equipment Effectiveness of Toshiba CNC Machine. (Dewi et al. 2020)

Month	A	P	Q	*OEE (%)*
1	90.59%	80.36%	100.00%	72.80%
2	89.81%	82.54%	100.00%	74.13%
3	88.37%	82.62%	100.00%	73.01%
4	90.58%	86.79%	100.00%	78.62%

5	88.73%	62.24%	100.00%	55.22%
6	89.56%	77.25%	100.00%	69.19%
7	89.63%	77.45%	100.00%	69.42%
8	89.16%	80.48%	100.00%	71.76%
9	90.17%	87.19%	100.00%	78.62%
10	85.81%	83.16%	100.00%	71.35%
11	88.10%	68.59%	100.00%	60.43%
12	66.61%	75.08%	100.00%	50.01%
Average	87.26%	78.64%	100.00%	68.63%

It is clear from the data that the quality of this machines output is excellent and does not appear to need any adjustments. It would be recommended though to pay close attention to any changes in quality as it could indicate problems in the program or the operator's ability to manage the machine. Availability is also quite high until month 12, with a total average of 87.26%. This is a high availability and should still be improved but could prove difficult to obtain that last 13%. The lowest metric that accounts for OEE was performance, which was consistently less than availability, and would be the best candidate for an engineering improvement project. An overall OEE number of 68.63% seems low, and by the standards of the Japan Institute of Pant Maintenance, it needs to be an overall 85% to be acceptable, but this OEE metric is respectable and isn't far off from most industry averages. It leaves room to improve without indicating that there are serious manufacturing process issues, and some recommendations for Toshiba can be found in the next section.

5.3 Proposed Improvements

For Toshiba, the recommendation for this single machine is to iron out performance. Reduced speeds are the most likely culprit for the lower than desired performance numbers, and it could be that extra training for the operator and the programmer could bring the actual cycle time closer to the ideal cycle time for that machine. Availability was high, but to meet the world class standard of the JIMP it will need to be brought up even higher, and setup times and idle time would be one of the best places to start. Waiting for work on the machine or having to leave it idle because the raw materials required additional set up is a waste of production hours. It could also mean that tooling or unexpected maintenance was needed, which should be tracked and minimized to non-production hours only. Another study at a cement company stated that the "biggest factors that cause the low achievement of OEE values on [their] machines were Reduced Speed Loss, Idling and Minor Stoppages, and Equipment Failure" (Muthalib et al. 2020) and this is usually the case occross most manufacturing indistries.

One of the best ways to improve a machine shop or manufacturing facility is to impliment OEE, and to track it at scale across the organization.CNC macines are not the only benefactors of this kind of information. Production lines, material handling machines, and other types of industrial automation all have quality, performance, and availability metrics that should be tracked to ensure that a company is getting as close as possible to its peak efficiency. And companies with already consistently high OEE metrics should re-evaluate how they are measuring the 3 pieces of OEE. Quality standards can be made more stringent, ideal cycle times can be improved up with updated equipment, and production schedules can be extended or changed to allow for more potential availability. These recommendations may decrease the OEE number for an organization, but it will also shed light on where other potential improvments can be made so that engineering project teams can continue to improve upon existing processes or come up with new solutions.

5.4 Validation

OEE is a simplified metric that provides a lot of information and can help a manager "focus on improving the performance of machinery and associated processes by identifying those performance opportunities that will have the greatest impact to the bottom line" (Jain, Bhatti, & Singh 2015). Backing up a project proposal requires hard data and being able to give expected results on improved OEE can be easily calculated into monetary terms that the accounting department and higher management can take to their investors. Similarly, projects that aim to improve the quality of the Toshiba CNC machine should be rejected in favor of projects that will have an actual impact on manufacturing operations. Though it seems obvious, being able to choose the right projects at the right time and have actual returns on investment can be one of the most difficult parts about being a manager, and OEE is just one metric that can help with that.

6. Conclusions

Proper implementation of OEE can provide a consistent metric that encompasses a wide range of measurements applicable to engineering managers and higher management of an organization. By having a single number that incorporates the availability, the performance efficiency, and the quality of output of a machine, engineers will have the tools they need to choose projects based on the best returns. Managers and senior leadership can easily understand the metric and use it as a snapshot over a period to determine how their machine shop is performing.

As seen in the above example of the Toshiba CNC machine measurements, small changes in any of the three key measurements can have large impacts on the final OEE number. Even with 100% in quality, the machine did not meet JIPM standards for world class OEE and this can be attributed to the slight underperformance in availability and the severely lacking performance metric. However, just because the standards weren't met doesn't mean that the OEE for that machine was necessarily bad, and many organizations would struggle to achieve the OEE numbers that Toshiba already has. The point of OEE is not to grade on a pass or fail, but to continuously improve upon the standards and processes already in place. Toshiba could even adjust their definition of quality to be more stringent, therefore lowering their overall quality and OEE number, but allowing them to be even more competitive in the manufacturing industry if they were able to improve upon what is currently considered 100% good quality products. With technological improvements happening at a quicker rate than ever before, the "industry moves faster, the period of change or innovation is shorter, the decision must be made in less time, that is why tools should be used to help identify losses caused during a production process" (Ng Corrales et al.2021). OEE is one of these tools that allows for faster communication of problems withing a machine shop, as well as identifying the specific area that needs to be addressed to solve these problems.

References

Cercós, M. P., Calvo, L. M., & Domingo, R., An exploratory study on the relationship of overall equipment effectiveness (OEE) variables and CO2 emissions. *Procedia Manufacturing,* 41, p224-232, 2019.

De Ron, A. J., Rooda, J. E., OEE and equipment effectiveness: an evaluation. *International Journal of Production Research*, 44(23), 4987-5003, 2006.

Dewi, S., Alhilman, J., & Tatas Dwi Atmaji, F., Evaluation of effectiveness and cost of machine losses using overall equipment effectiveness (OEE) and overall equipment cost loss (OECL) methods, a case study on toshiba CNC machine. *IOP Conference Series. Materials Science and Engineering, 847*(1), 12020.

Edrington, B., Zhao, B., Hansel, A., Mori, M., & Fujishima, M., Machine monitoring system based on MTConnect technology. *Procedia CIRP, 22*, 92-97, 2014.

Garza-Reyes, J., From measuring overall equipment effectiveness (OEE) to overall resource effectiveness (ORE). *Journal of Quality in Maintenance Engineering,* 2015.

Gupta, P., Vardhan, S., Optimizing OEE, productivity and production cost for improving sales volume in an automobile industry through TPM: a case study. *International journal of production research,* 54(10), 2976-2988, 2016.

Jain, A., Bhatti, R. S., & Singh, H., OEE enhancement in SMEs through mobile maintenance: A TPM concept. *The International Journal of Quality & Reliability Management, 32*(5), 503-516, 2015.

Korski, J., Tobór-Osadnik, K., & Wyganowska, M., Mining machines effectiveness and OEE indicator. *IOP Conference Series.Materials Science and Engineering*, 2017.

Ljungberg, Õ., Measurement of overall equipment effectiveness as a basis for TPM activities. *International Journal of Operations & Production Management*, 18(5), 495-507, 1998.

Muchiri, P., & Pintelon, L., Performance measurement using overall equipment effectiveness (OEE): Literature review and practical application discussion. *International Journal of Production Research, 46*(13), 3517-3535, 2008.

Muthalib, I. S., Rusman, M., & Griseldis, G. L., 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 Conference Series. Materials Science and Engineering, 885*(1), 12061, 2020.

Ng Corrales, ,L.C., Lambán, ,M.P., Royo, J. A., & Hernández, ,M.E., Productivity tool for automated guided vehicles: OEE indicator perspective. *IOP Conference Series.Materials Science and Engineering, 1193*(1), 2021.

Richard H., Mukund S., Peter A., Analysis of Critical Factors for Automatic Measurement of OEE. *Procedia CIRP*, 57, 128-133, 2016.

Tsarouhas, P., Improving operation of the croissant production line through overall equipment effectiveness (OEE): A case study. *International Journal of Productivity and Performance Management*, 68(1), 88-108, 2019.

Tsarouhas, P. (2020). Overall equipment effectiveness (OEE) evaluation for an automated ice cream production line: A case study. *International Journal of Productivity and Performance Management*, 69(5), 1009-1032.

Yazdi, P. G., Azizi, A., & Hashemipour, M., An empirical investigation of the relationship between overall equipment efficiency (OEE) and manufacturing sustainability in industry 4.0 with time study approach. *Sustainability*, 10(9), 303, 2018.

Biographies

Alexandr M. Sokolov, Ph.D., is a faculty in the Engineering Management Department of the College of Engineering and Computer Science at A-STATE. He holds a B.S., where he focused on Bioinformatics from the University of Tennessee Knoxville, an M.B.A., in Finance from Lincoln Memorial University, and a Ph.D., in Industrial Systems Engineering, Engineering Management from the University of Tennessee Space Institute. Alexandr has over 15 years of infield and teaching experience. His teaching experience includes multiple institutions dealing with Engineering, Management, and Technology disciplines. He is focusing on research dealing with Engineering Management, Performance Management, and Interdisciplinary Studies.

Niamat Ullah Ibne Hossain, PhD., is an assistant professor in the Department of Engineering Management at Arkansas State University. Dr. Hossain received his PhD in Industrial and Systems Engineering in 2020 from Mississippi State University (MSU), Starkville, MS. He obtained his bachelor's degree in Mechanical Engineering in 2010 from Khulna University of Engineering and Technology (KUET) and his MBA in Management Information Systems in 2013 from the University of Dhaka, both in Bangladesh. His main research interests include systems engineering, systems model-based systems engineering/SysML, Systems thinking, Systems resilience, & sustainability management, System dynamics, and systems simulation.

Aaron Storms is a graduate student in the Management Department of the College of Engineering and Computer Science at Arkansas State and currently pursuing the Master's in Engineering Management. He is an automation engineer for General Atomics Aeronautical Systems Incorporated. He holds a Bachelor of Science in Computer Science from Cal State San Marcos.

Brian Merrill is a graduate student in the Management Department of the College of Engineering and Computer Science at Arkansas State and currently pursuing the Master's in Engineering Management. He is an Electro-Mechanical Engineer at a Pharmaceutical Manufacturing Facility located in North Las Vegas, Nevada. Holds a B.S., in Electrical Engineering from Nevada State College, with minors in Mechanical Engineering, and Biomedical Engineering and a certificate in Engineering Management from the universities engineering department.