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Operating Equipment Effectiveness with a Reliability Indicator

Carl D. Hays III

Abstract**—**The purpose of this theory paper is to add a reliability indicator to Operating Equipment Effectiveness (OpEE) which is used to evaluate the productivity of machines and equipment with wheels and tracks. OpEE is a derivative of Overall Equipment Effectiveness (OEE) which has been widely used for many decades in factories that manufacture products. OEE has three variables, Availability Rate, Work Rate, and Quality Rate. When OpEE was converted from OEE, the Quality Rate variable was replaced with Travel Rate. Travel Rate is essentially utilization which is a common performance indicator in machines and equipment. OpEE was designed for machines operated in remote locations such as forests, roads, fields, and farms. This theory paper intends to add the Quality Rate variable back to OpEE by including a reliability indicator in the dashboard view. This paper will suggest that the OEE quality variable can be used with a reliability metric and combined with the OpEE score. With this dashboard view of both performance metrics and reliability, fleet managers will have a more complete understanding of equipment productivity and reliability. This view will provide both leading and lagging indicators of performance in machines and equipment. The lagging indicators will indicate the trends and the leading indicators will provide an overall performance score to manage.

Keywords**—**Operating Equipment Effectiveness, Operating Equipment Effectiveness, IoT, Contamination Monitoring.

I. Introduction

OEE is the gold standard for monitoring performance in manufacturing products. OEE is a simple key performance indicator to determine how a manufacturing operation is performing. The primary variables within OEE are Availability Rate, Work Rate, and Quality Rate. These variables are multiplied together to provide the OEE score. The standards of excellence and benchmarks for OEE have been well established since it was introduced by Nakajima in 1988 [11]. The majority of research papers written on OEE have been done in the last 7 years indicating a sustained and increasing interest in its application [9]. In fact, there are a number of derivatives that have been created from the use of OEE [9]. Lisbeth reviewed modifications to OEE from its introduction in 1988 through 2019 and found that OEE “was modified to solve gaps in various issues, such as sustainability, human factor, transport, manufacturing system, mining, cost, port and resources” [9]. In 2021, OEE was transferred to machine and equipment using the acronym Operating Equipment Effectiveness, OpEE [6].

Hays [6] demonstrated that OEE could be transferred in part to equipment, or machines with wheels and tracks, by using Availability, Work Rate, and Utilization. In mobile equipment utilization alone has become the standard for measuring equipment performance. Utilization is a ratio of two inputs, one that tracks engine hours, or the total time a machine’s engine is on, divided into the total number of idle hours a machine has accumulated. Utilization is typically used with trucks that transport cargo from point A to point B because it indicates when a truck is on and moving cargo. This form of measuring productivity was inadequate for applications where work was not transporting cargo. When equipment is performing work that is not moving cargo from point A to point B such as a street sweeper, see Fig. 1, the work rate is dependent on the broom actively sweeping the street.

Fig. 1 Front Boom Sweeper [4]

Hays [6] indicated that utilization alone did not adequately capture down time where a machine was not being used or was inoperable due to a breakdown. OpEE addressed this down-time gap by adding the availability variable in OEE [6]. Availability accounts for the time that a machine is both on and off. This provides an indicator of how often a piece of equipment is either broken down or not being used in a calendar year. OpEE is very similar to OEE, however, it replaced the quality variable in OEE with travel time because there is not a readily transferable variable for the quality rate that was used in OEE, see Fig. 2. Travel time, in effect, is the same variable as utilization. Because of this, OpEE did not adequately address the notion of quality found in OEE. OpEE provides a complete picture for when a machine is being productive, but it does not provide a good measurement of quality that OEE offers.

This paper intends to provide a more complete version of the OpEE score through adding a reliability indicator to it. This

Carl D. Hays III is a doctoral student at George Fox University, 414 N Meridian St, Newberg, OR 97132 USA (phone: 805-801-0643; e-mail: chays21@ georgefox.edu).

addition will provide a better transfer of the OEE score to use cases outside of manufacturing, see Fig. 3. This theory will provide managers with a simple tool to evaluate both the performance and reliability of equipment within their organization. This theory is both relevant and important because there are not very good indicators for this kind of information today in mobile equipment, or the indicators are inadequate and do not provide the kind of performance story that OEE is able to. This story tells managers a more complete version of productivity and also provides an indicator for equipment reliability.

This paper will start with the origins and foundation of quality in manufacturing and from there discusses how reliability and reliability engineering are virtually synonymous with this measure. With this background, OEE will be reviewed in manufacturing as a performance indicator. From here this discussion will explain how OpEE was created from OEE, and review how quality was dropped from the measure and replaced with travel time (utilization). From there it will discuss how reliability may be added back into the solution. With this foundation, this paper will propose a dashboard view that includes OpEE and a reliability indicator. This paper will then present a reliability example using a hydraulic contamination sensor made by Tan Delta Sensors [19]. This view will provide a more complete picture of equipment performance because it combines productivity and equipment health. After laying out and discussing the proposition, we will move to the implications of using this and suggest future research using machine learning to test and validate this theory.

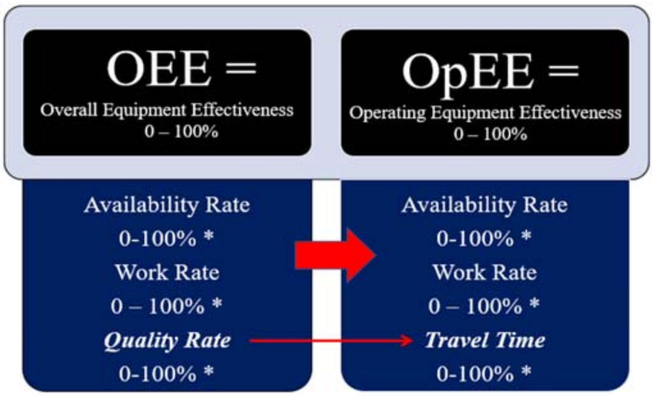

Fig. 2 Concept Map OEE and OpEE
Note: This was conversion of OEE to OpEE by Hays [6]

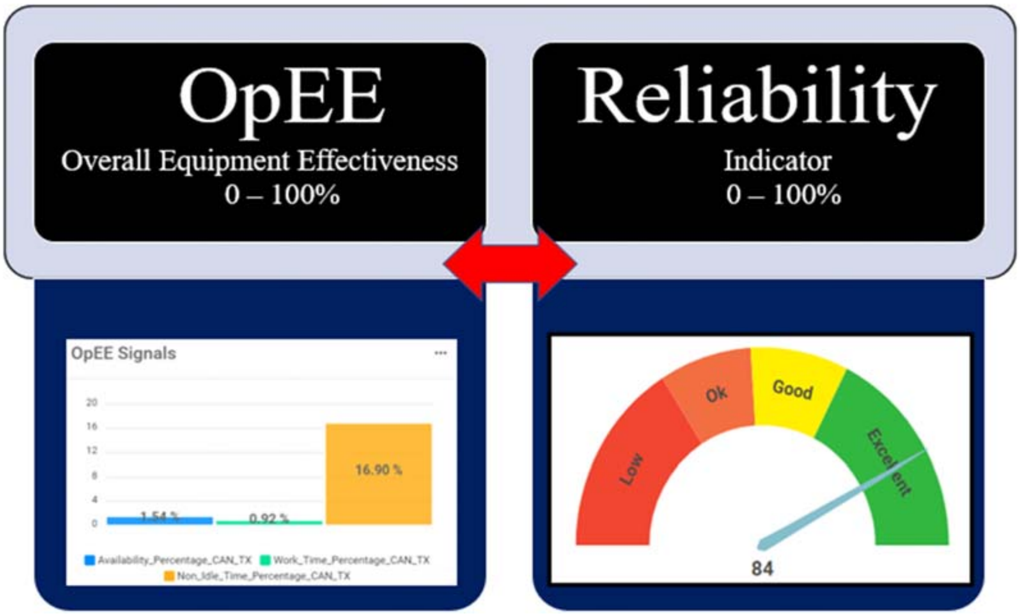

Fig. 3 Concept Map of Proposed Theory
Note: This is the theory adding Quality to OpEE

II. Literature Review

A. Quality in Manufacturing

The notion of using statistical methods to define quality in mass production was framed by Walter Shewhart in the 1920's and 30's [18]. He suggested that there were three steps for controlling quality. The first step was defining the specification for what was wanted [18]. The second step was producing the thing defined in the specification [18]. The third step was inspecting what was made to determine whether it met the specification [18]. For this last step, Shewhart suggested the use of statistical methods to determine how closely the product matched its specification [18]. Within this work Shewhart developed the notion of control over the manufacturing process and sampling to evaluate a population of manufactured products.

Zairi characterized Shewhart's work as the foundation for analyzing variability through monitoring, measuring and controlling production [21]. From Shewhart's seminal work [18], quality has been referred to in nearly every industry in some capacity or another with a literature survey done by

Kamarkar and Pitbladdo [8] identifying its use in manufacturing, engineering, economics, management, and process. In engineering and manufacturing, they explain that quality is typically referred to as conformance to specification where a product has characteristics and attributes within its design [8]. When manufacturing this product, "firms produce a population of product units that have a probability distribution on the vector of the product characteristics" [8]. They further indicated that there are several research papers on quality that associate it with some form of reliability and dependability [8].

Wu summarized quality to cover two separate dimensions, design and conformance [20]. Sauter and Montgomery [19] point out that historically quality has been more of a measure for how closely something matches its specification [9]. This specification matching concept of quality is referred to as conformance quality [4]. Wu suggests conformance quality is when something is produced to closely match its design [18].

To properly understand what quality measures in manufacturing today it is important to expand on the concept of failure. Smith and Mobley [15] define failure as an event where equipment fails to meet its functional specification. Key performance indicators provide this performance objective benchmark and let managers know how the equipment is performing in addition to when it is beginning to fail [15]. This notion of failure as an indicator of quality led to the birth of reliability and reliability engineering as a means of reducing it.

B. Reliability in Manufacturing

Smith and Mobley [15] define reliability in two parts, the first is "the probability or duration of failure-free performance under stated conditions" and the second is "the ability of an item to perform a required function under a stated set of conditions for a stated period of time." They further unpack this definition by explaining that failure is when equipment is operating outside of its required function which is defined by a specification. A specification is a "detailed precise presentation of that which is required" [16]. Reliability, therefore, is the ability of a piece of equipment to operate within its specification, for a specific period of time, without failure. With this current definition in mind, let us move to understand how reliability and reliability engineering developed to its current state.

The concept of Reliability has a humble origin first referenced by Coleridge in a poem to his friend where he writes "He inflicts none of those small pains and discomforts which irregular men scatter about them and which in the aggregate so often become formidable obstacles both to happiness and utility; while on the contrary he bestows all the pleasures, and inspires all that ease of mind on those around him or connected with him, with perfect consistency, and (if such a word might be framed) absolute reliability" [2]. While Coleridge was not thinking about engineering when he wrote this, his concept of reliability has become a standard bearer in equipment design.

For the concept of reliability to really take off, two other pioneers were crucial to this success, Blaise Pascal and Pierre de Fermat who through a series of letters in 1654 established the foundation for probability and statistics [14]. This statistics foundation led to the notion of sampling in manufacturing and provided theoretical criteria for mass production of interchangeable parts [16]. Mass production was ushered in by Springfield armory who produced three hundred thousand rifles for the union army in 1863 and then by Henry Ford and the Model T [15]. Mass production, due to its high volume production achievements, required the concept of quality control, a method for measuring it, and the discipline of reliability engineering for doing it.

The underpinnings of reliability engineering as a discipline, came with the invention of the vacuum tube by Lee Dee Forest [16]. The vacuum tube was a key component in radios, radar, and was instrumental for the Allied forces winning WWII [16]. The main issue with the vacuum tube was it frequently failed at a rate of 5 times all other equipment [16]. Because of this issue, the US department of defense began to study these failures and their root cause which gave birth to reliability engineering [16]. Reliability engineering required further techniques to truly evolve and provide value to manufacturing.

As with the origin of quality, Walter Shewhart in the 1920's to 30's used applied statistical methods at Bell Laboratories to define quality control and is considered a seminal author in the field of reliability. The use of statistical methods in manufacturing was further codified as a discipline in the 1950's, post WWII as reliability engineering [16]. In 1952, AGREE (Advisory Group on Reliability of Electronic Equipment) was formed between the American electronics industry and the DOD (Department of Defense) to "recommend measures that would result in more reliable equipment, help implement reliability programs in government and civilian agencies, and disseminate a better education on reliability" [16]. The establishment of AGREE led to Navy funded contracts with ARINC (Aeronautical Radio Inc) focused on providing feedback to manufacturers related to vacuum tube failures [16].

ARINC contributed in both the application of statistical methods in addition to defining terms. Reliability engineering as a discipline, model, and approach developed over the next few decades in both research, standards, and specializations [16]. During the 1950's when reliability engineering was just starting to take off post World War II, George Smith traveled to Japan to introduce Preventative Maintenance which ultimately became Total Productive Maintenance (TPM) and led to OEE a key performance indicator that measured how successful manufacturers were at implementing TPM [12]. Key performance indicators provided this performance objective benchmark and let managers know how the equipment is performing in addition to when it is beginning to fail [15].

C. OEE in Manufacturing

OEE is a productivity performance indicator for factories. Performance indicators such as OEE, "are a set of quantifiable metrics used by companies to assess their performance according to established strategic and operational goals" [3]. A Key Performance Indicator is simply a performance indicator that has been identified as critical to the success of the organization [15]. "When identified and aligned properly, key performance indicators (KPIs) can save a plant, a job, a career. If management truly understood the power of KPIs, things would change quickly." In fact, managing without KPIs gives one the feeling of being lost with no hope [15]. The strategic goal of OEE is to monitor productivity consisting of three ratios; Availability Rate, Performance Rate, and Quality Rate [15]. These ratios allow plant managers to measure performance and make both business and technical decisions to improve performance.

OEE began with Preventative Maintenance (PM) which was introduced to Japan in 1958 by George Smith [11]. The objective of PM was to develop maintenance functions for equipment to prevent failure and preserve the life of the machine. The concept of PM is plain and simple: by taking care of machines, failure can be prevented. PM strategies are still in place today and include operator's manuals with specific maintenance plans and protocols from changing fluids and filters to identifying wear-and-tear components that require replacement over time.

PM was also expanded to Total Preventative Maintenance (TPM). The basic premise of TPM was to develop a maintenance culture that is trained at the lowest level to clean, repair, and maintain the equipment and the facility with the goal of creating an "immaculately" clean manufacturing environment by focusing on the 6 categories: organization, tidiness, purity, cleanliness, discipline, and trying hard [11]. Nippoldensco Company was the first company to be awarded the Distinguished Plant Prize for its achievements in TPM [11]. These awards started the standards of excellence for benchmarking the performance of future companies [12].

The key to adopting a TPM strategy was having a reliable measurement for performance from which to evaluate how to improve it. This need for a performance indicator to determine whether a company had a successful TPM strategy was the introduction of OEE. The earliest version of OEE consisted of metrics measuring Plant Scheduled Time, Plant Run Time, and Count of Quality Parts versus defects. This measurement begins with the ideal manufacturing state, where the plant would be scheduled 365 days of the year to run and would actually run all of those days, 24 hours each day, and during that time every part made would be to specification without defect. OEE is a key performance indicator measuring the productivity of a manufacturing plant through three key variables: Availability, Performance Rate, and Quality Rate. These three ratios are multiplied together to generate a score between 1-100% where 100% indicates a plant is operating 100% of the time at 100% capacity making only good parts 100% of the time [15].

In the absence of a metric like this, the source for evaluating plant performance relied heavily on total production of good parts in addition to general accounting indicators as determined by the company's financial performance [11]. To make improvements on the OEE score, 6 categories of loss were developed. Through these categories of loss, plant managers were able to identify the sources and factors reducing the overall score and a lagging Key Performance Indicator.

In order to establish a leading and lagging KPI, it is paramount to have a system or process in place, with inputs and outputs for both, that can be tracked and recorded. These data may then be aggregated on a time basis to produce both lagging and leading KPI. With the data stream in place, the last part of the puzzle is to establish a benchmark, objective, or standard to evaluate the KPI against. Without the benchmark, it would be really difficult to determine where production was at any point of time. The elegance of OEE is in its ability to establish objective standards in addition to what needs to be measured to get there.

Simplified, the OEE formula is: Time * Speed * Quality. To convert this to the mobile equipment formula OpEE, Hays [6] had to determine how best to calculate Time. In this formula, Time was calculated from a count of the total Operating Days in a calendar year e.g. between 0 and 365. For Speed, the variable "Work Time" was used for when machine was performing its function and for Quality the variable "travel time," or when the machine is moving from point A to point B to perform work, see Fig. 2 which illustrates the variables used in OEE. An important variable used in the OEE formula that requires further explanation is quality. In OEE, Quality does not have its own definition and references what is commonly understood as defect rate. Because of this ambiguity, there may be an opportunity to substitute other measurements besides the defect rate such as focusing on reliability.

D. OpEE in Machines

For machines, nothing really matches OEE which is why the industry standard for performance has been utilization. Hays [6] demonstrated that machines may be treated like mobile factories, or machines like tractors, pumps, and excavators. OpEE was developed to measure their performance in the same way OpEE provides a KPI to plant managers.

OpEE: A derivative of OEE for mobile equipment applications comprises of three leading indicators; Availability, Work Time, Travel Time, and provides a lagging indicator as a score between 0-100%. A score of 100% indicates that the equipment was available to work 100% of the time, during that time it worked 100%, and have 0% travel from point A to point B to perform work. Travel time is calculated from the engine RPM. For an engine in an idle state is determined by a set point defined by the manufacturer. For example, when we turn our car on, it idles at 1000 rpm until we press on the gas and put the engine under load which increases the rpm. The time that an engine is in its Non-Idle state is calculated and divided by the total engine hours and the output is a ratio = 25/50 = 50% [6].

The OpEE score combines Availability, Work, and Travel as its three components to determine the performance of a piece of equipment. Availability matches *Availability* in OEE, Work Time and Travel matches *Performance Rate*, however, there is not a variable that matches Quality Rate. What OpEE does not do well is predict future performance such as a machine breaking down, or it does not do a very good job of establishing machine health.

By adding a reliability indicator, we are able to better predict failure in addition to providing a leading indicator for productivity. Predicting and monitoring equipment failure is a function of reliability. Reliability theory covers the ideas, definitions and best practices for maintaining equipment and keeping it in its optimal state for maximum performance [15].

III. Theory Proposal

The primary definitions of quality used in manufacturing were absorbed in the discipline of reliability engineering. Reliability engineering was brought to Japanese manufacturing in the 1950's by Smith and developed performance indicators to measure success, one of which was OEE. OEE was a very useful tool but did not translate well to machines and equipment which is why Hays [6] developed OpEE. This new score replaced the quality indicator in OEE with Utilization (Travel Time) because utilization was used in the cargo transportation industry and machines and equipment do not make widgets. This theory paper proposes adding a reliability indicator to the OpEE score in order to accomplish both indicators that OEE did.

OEE has been used successfully for many decades to measure productivity and" performance in manufacturing. Measuring productivity in mobile equipment has typically been done with Utilization which is not a measure for work performed by equipment other than trucks transporting cargo. OEE is a better measure of productivity than Utilization because it adds the element of work time and availability.

OpEE incorporated the theory of utilization with some of the variables of OEE, specifically Availability, and Work Time. Travel Time, which is essentially Utilization, replaced the quality rate variable in OEE. This removal of quality rate created a gap in the application of OEE for machines and equipment in multiple industries. This paper presented an addition to OpEE with adding a reliability indicator to the score. The combination of these two measurements provides a more complete picture of equipment performance and machine reliability. One such reliability measure could be the contamination monitoring of hydraulic fluids.

Hydraulic fluids first emerged when Bramah used water as a source to transfer power [7]. From water, the need for anti-rust fluids translated to the use of mineral oil, which in turn created a need for anti-flammable material for use as a lubricant and in the 1960's led to the modern development of hydraulic fluids we use today [7]. Oil contamination is the process of exposure to environmental materials over time that leads to the breakdown of the oil and its protective and lubricative properties.

Chaplin [1] studied the relationship between fluid cleanliness and vehicle failure as measured by the mean time before failure (MTBF). Chaplin argued that "improved vehicle productivity results from increased reliability, and overall system reliability is affected by the reliability of the hydraulic system" [1]. Therefore, a rationale for determining fluid cleanliness by selecting a target MTBF should have a positive effect on vehicle productivity [1]. Ng et al. [12] reviewed excavator performance when using an in-line sensor to monitor contamination. Ng et al. [13] found that contamination monitoring was insufficient to predict future failure, but oil sensors need to detect specific metals, Cu and Fe, respectively because of their overall negative impact on the hydraulic system. Zhang et al. [22] pointed out "that hydraulic oil contamination results in 60%-80% failures of aviation hydraulic system." They go on to say that managing hydraulic oil contamination can significantly remove water, gas, and solid contaminants [22]. They concluded that monitoring oil contamination in real time was key to achieving the appropriate level of cleanliness to prevent hydraulic component failures [22]. As an example of this, the use of a Tan Delta oil contamination sensor [19] could provide a useful quality indicator, see Fig. 4. Tan Delta has developed a sensor that "detects all and any wear and contamination: water, acid, fuel, viscosity, different oil types, carbon, particles, etc." [19]. Because of the advancement of sensor technology, it is more feasible to add monitoring sensors and because of this feasible to use this score in addition to the OpEE score to provide fleet managers with a productivity and reliability indicator.

- Proposition Statement: OpEE with a reliability indicator will allow fleet managers to improve not only productivity but also equipment reliability on machine equipment.

Fig. 4 Tan Delta Hydraulic Oil Contamination Sensor [19]
Note: this sensor measures hydraulic fluid contamination on a scale of 0 - 100%. 100% indicates that the oil has recently been changed

IV. Implications

The purpose of OpEE is to provide business and fleet managers a simple key performance indicator to evaluate productivity of their fleet. Without this measure, fleet managers have either used Utilization or nothing at all. By combining OpEE with a quality indicator, fleet managers get more of the benefits of OEE. Using OpEE fleet managers can determine to what extent the equipment is being allocated to work during a calendar year. Changes in this score could mean that the organization owns too many pieces of equipment for that class of work. It could mean that there is a shift in demand for services within the industry. It could also indicate when equipment is breaking down during planned operation too frequently or for longer than typical periods of time.

Using a reliability indicator, like a hydraulic fluid sensor, can optimize the replacement of hydraulic oil in the machine. As this indicator drops, a threshold may be selected to determine the correct time to change it. This quality indicator can affect machine performance, reliability and overall health [15]. In fact, reliability is so important that a CEO who focused on it over the course of two years with a dedicated team of 50 people provided the biggest return over the longest period of time [15]. While this is an easier target for companies maintaining equipment in a single location within a manufacturing facility, it is much more elusive for companies that own equipment and deploy them to different parts of their city, state, country and world. Furthermore, by separating the quality indicator from the OpEE score, this allows for different kinds of indicators other than hydraulic fluid health. Fleet managers would be able to select the best indicator for their application. For example, vibration monitoring could be added to determine when a piece of equipment is beginning to break down. Vibration monitors specific frequencies and when equipment is out of frequency it can indicate performance degradation. For electric applications, temperature can be an indicator of performance degradation. Providing a quality indicator focused on time under temperature could provide an indicator for future reliability. In short, offering a quality variable apart from the OpEE score allows for flexibility in selecting the best measure of equipment reliability. This view of both productivity and reliability would have a significant impact on organizational operations, and overall profitability.

V. Future Research

The theory of adding a reliability indicator to OpEE presented in this paper needs to be validated in a real application. This would provide an indicator of the usefulness of both measures working together. Additionally, using a condition-based monitoring (CBM) solution could provide an alert for when the measurements are following below acceptable performance levels. CBM would allow for alerts to be sent to fleet managers when either of the parameters are trending in a direction that is not favorable to the equipment, in terms of either performance or reliability. This could initiate a level of automation to the overall solution and allow fleet managers to focus on other things than monitoring these scores.

Automation could also be achieved by incorporating machine learning into the system. Machine learning could provide a reinforcement learning algorithm dedicated to determining what the optimum fleet performance could be. This optimization would be a benchmark to determine when equipment is performing at, below, or above this benchmark. From reinforcement learning, unsupervised machine learning could be added. Unsupervised learning would provide anomaly detection to determine when a piece of equipment is outside of specification. This could be especially useful for the quality indicator and when the optimum parameters are unknown such as in a research and development environment.

Finally, a supervised machine learning model could provide a management solution to track and categorize fleet performance. By tracking and categorizing equipment recommendations for improvement can be made by the system. This would provide a data-driven improvement approach to managing fleet operations and support innovations in logistics, maintenance, and overall operations.

VI. Conclusion

Building on the previous work of Hays [6] which laid the foundation and theory for transferring part of OEE to a new KPI OEE, this paper presented an addition to this score using a reliability indicator. Reliability has a long history as a measure for defects in part and component manufacturing such as vacuum tubes. Because OEE defines quality as a defect rate, reliability is a natural substitute. Using a reliability measure in addition to OpEE provides a more complete view of the health and performance of machine equipment. This theory provides a new means of measuring asset health and reliability with an example of using a hydraulic oil sensor. Hydraulic oil sensors determine the level of contamination as the oil breaks down over time. This is just one reliability indicator that could be paired with OpEE. If this OpEE score successfully provides a score that can be translated into health and ultimately reliability, it could provide fleet managers a simple and very low cost, key performance indicator to manage their fleets and make business decisions with a lasting impact to their bottom line.

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