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System-level Overall Equipment Effectiveness for improving Asset Management performance: a case study application

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Abstract. The discipline of Asset Management (AM), which focuses on the management of physical assets in an integrated and holistic way along their life cycle, can be adopted by companies to promote sustainability since it enhances asset reliability and availability for the whole duration of its usage. Within the manufacturing industry, a relevant AM-related performance indicator is the Overall Equipment Effectiveness (OEE), which measures the efficiency of equipment. However, traditionally OEE measures the performance of individual equipment only, while neglecting the system perspective, which is core in AM. Only few contributions propose an extension towards a system-level performance indicator. After the OEE-related system-level indicators from the scientific literature are reviewed, an application of one of them in an industrial case is presented, selected as the indicator best fitting the characteristics of the industrial case itself, which is a disconnected flow manufacturing line. The application of the system-level indicator allows comparing it with the traditional OEE. Results show that a system approach better supports AM since the information carried out by the indicator is more complete and adherent with the actual asset and system characteristics. In turn, the system-level perspective is assumed just as a first step towards a holistic performance improvement as it is required by AM. A step forward to fulfill the sustainable performance is the integration of measurements of other sustainability-related impacts leading to effective asset-related decisions.

Keywords: OEE, OFE, System-level Performance, Asset Management, Life Cycle, Disconnected Flow Line.

1 Introduction

Nowadays, due to the increasing pollution generation and scarcity of resources registered in the last decades, the entire society looks towards sustainable development [1]. Out of all sectors, manufacturing companies are considered among the major responsible sources of materials and energy usage, while undeniably leading also towards the increase in emission generations [2]. The discipline of Asset Management (AM), which focuses on the management of physical assets in an integrated and holistic way along their life cycle [3], could be adopted by companies to promote sustainability [4] since it enhances asset reliability and availability for the whole duration of its usage [2].

AM is defined as "the coordinated activities of an organization to realize value from assets" by ISO 55000 [5]. Despite originating in the context of Maintenance Management (MM), considering both the approaches of Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM), it goes beyond the traditional goals of MM. Instead of focusing mainly on the operational phase of an asset, it covers its whole life cycle, from the Beginning of Life (BoL) to the End of Life (EoL) [2]. Therefore, evaluating the performance of a production asset along its life constitutes the foundation for any improvement activity (corrective or preventive). Indeed, this is a relevant approach for the achievement of a sustainable performance.

Considering the improvement activity, since the late 1980s the Overall Equipment Effectiveness (OEE) has been recognized as a fundamental indicator for measuring the performance of production systems and it is now accepted as primary performance metric [6]. However, OEE presents a relevant limitation that should be taken into consideration and further investigated when thinking from an AM standpoint: it focuses on the individual equipment, therefore lacking a system-level perspective [7]. In fact, it is worth remarking that AM claims that *"an organization may choose to manage its assets as a group, rather than individually, according to its needs, and to achieve additional benefits"* (extract from ISO 55000 [5]). This leads to the need of building a management practice that looks at individual assets, systems of assets and multiple assets portfolio, for effective asset-related decisions.

The present work focuses on OEE and its limitations at system-level perspective. After a brief introduction on OEE, this research work addresses this limitation by reviewing extant system-level indicators developed in the scientific literature. The indicator that better fits the characteristics of a manufacturing company taken as industrial case is selected and applied. Finally, results as well as managerial implications are discussed.

2 Beyond OEE: review of existent system-level performance indicators

The OEE was proposed by Nakajima in 1988 as a supporting metric to Total Productive Maintenance (TPM) [8] and it has the dual purpose of discovering hidden losses in production systems and evaluating the effect of improvement actions [9,10].

Analytically, the OEE can be expressed as the product of three mutually exclusive components: Availability (A), Performance (P), and Quality (Q). Generally, it represents the ratio between what is actually manufactured and what could be ideally manufactured. The inefficiencies that cause the actual production to differ from the ideal production are classified into the so-called Six Big Losses [8]: failures, set up & adjustment, minor stoppages, reduced speed, defects, and reduced yield. Despite the broadly accepted relevance of OEE, [11] pointed out also some limitations. Indeed, the OEE is able to measure only the performance of individual equipment, whereas in a factory machines are usually not isolated, but operate jointly in a production line. Another limitation that is closely linked arises when the inefficiencies of a line cannot be easily classified in terms of the Six Big Losses because they are generated at a system-level [8]. This may lead to a misattribution of inefficiencies to the three components of the OEE.

Since the ultimate objective of any factory is to have a highly efficient integrated system and not brilliant individual equipment [9], it is important to take into consideration variables that are outside the perimeter of OEE, such as relationships between machines, material flows, logistics, queues, and the integration of information, decisions and actions across independent systems and subsystems [7].

In the literature there is no evidence of a standard method to measure the overall effectiveness at system or factory level [12], but several studies have tried to expand the application scope of OEE to overcome its main limitation.

Nachiappan and Anantharaman [13] propose the Overall Line Effectiveness (OLE), expressed in Eq. 1, as a metric for performance evaluation in a continuous manufacturing line.

$$\text{OLE}=\text{LA}\times\text{LPQP} \tag{1}$$

Where LA is Line Availability and LPQP is Line Production Quality Performance, a parameter that merges Line Quality and Line Performance in a single metric. The peculiar assumption at the base of this indicator is that only the good output of machine i (where $i = 1 \ldots n$, being n the last machine of the line) will be the input of machine i+1, defects and reworks will not reach the downstream process. LA is computed as the Operating Time of machine n (i.e., the last machine in the line) as a percentage of the Loading Time (i.e., the time the line is expected to operate). LPQP can be calculated as the amount of good production realized by machine n times the largest cycle time of the line (i.e., the bottleneck cycle time) over the operating time of the first machine.

Muthiah and Huang [6] develop the Overall Throughput Effectiveness (OTE) as an extension of the definition of OEE to the factory level by comparing the actual and the maximum attainable productivity of the line. The OTE is formulated in Eq. 2.

$$\text{OTE}=\frac{\text{Actual throughput (units) from factory in total time}}{\text{Theoretical throughput (units) from factory in total time}} \tag{2}$$

The OEE on which the OTE is based is a modified version of the conventional OEE developed by Nakajima and takes the name of Theoretical OEE. What changes is the Performance parameter: in the conventional OEE, P accounts for equipment idle time, which according to [7] can be attributed to poor factory operations such as material-handling problems or factory design flaws rather than the equipment itself. For this reason, it should be captured by factory-level metrics. The manufacturing line is decomposed in subsystems, which can be of four different types, namely series, parallel, assembly and expansion. OTE is computed for each subsystem. The process is repeated until the OTE of the factory (also designated as Overall Factory Effectiveness – OFE) is computed.

Braglia et al. [8] propose the Overall Equipment Effectiveness of a Manufacturing Line (OEEML), expressed by Eq. 3:

$$\mathrm{OEEML}=\frac{\mathrm{O_{LM}}}{\mathrm{LLT}/\mathrm{CT_{BN}}} \tag{3}$$

Where O_{LM} is the output of the last machine, CT_{BN} is the ideal cycle time of the bottleneck machine, and LLT is the Line Loading Time (i.e., Calendar Time minus Planned Stops). At the basis of this approach is a modification to the traditional structure of losses that characterizes the OEE, as it is important to separate the losses that can be directly ascribed to an equipment from the losses that are spread in the line. The former takes the name of Equipment Dependent Losses (EDL), the latter Equipment Independent Losses (EIL). Finally, this approach allows to express the OEEML as a function of efficiency reduction components, i.e., reductions due to the shifting of the bottleneck from theoretical to actual, minor inefficiencies upstream of the bottleneck machine, minor inefficiencies downstream of the bottleneck machine, and the quality rate of machines installed downstream from the constraining operation. These components provide additional information on what is actually lowering the performance of the line.

Raja et al. [12] propose the Overall Line Effectiveness (OLE) for continuous flow lines computed with the same logic of the OEE:

$$\mathrm{OLE}=\mathrm{A}\times\mathrm{P}\times\mathrm{Q} \tag{4}$$

Availability is computed on the basis of Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) and takes into account the relationships between machines (i.e., series and parallel); Performance is based on the number of products realized by the bottleneck machine; finally, Quality not only expresses the rate of good production over total production but also takes into account the number of parameters that are measured in the quality assessment process.

Finally, Roda and Macchi [7] develop the OFE (Overall Factory Effectiveness), which extends from the already mentioned OTE. The OFE is expressed in Eq. 5, where D is a coefficient accounting for deterministic losses, like scheduled maintenance, and TH_{system} is the theoretical throughput of the system. The other terms consider the product output from the factory and the simulation time since the OFE is based on the evaluation of system performance with multi-state machines.

$$\mathrm{OFE} = \mathrm{D} \times \frac{\text{actual product output from factory in simulation time}}{\mathrm{TH_{system}} \times \text{simulation length}} \tag{5}$$

3 System-level indicator applied in a case study

3.1 Case study introduction

The choice of the most suitable system-level indicator cannot disregard the characteristics of the case study whose performance it is supposed to measure. Therefore, a brief introduction of the case study is provided before comparing the metrics.

The system of interest could be classified as a disconnected flow line (see Fig. 1) according to the classification by Hopp and Spearman [14].

In a disconnected flow line, product batches are produced on a limited number of routings and individual stations within lines are not connected by paced material-handling systems, so that inventories can build up between stations.

Specifically, the manufacturing line under examination realizes components for gas turbines and is composed of five stations (see Fig. 1). Products are moved from a station to the next manually through the usage of various types of cranes.

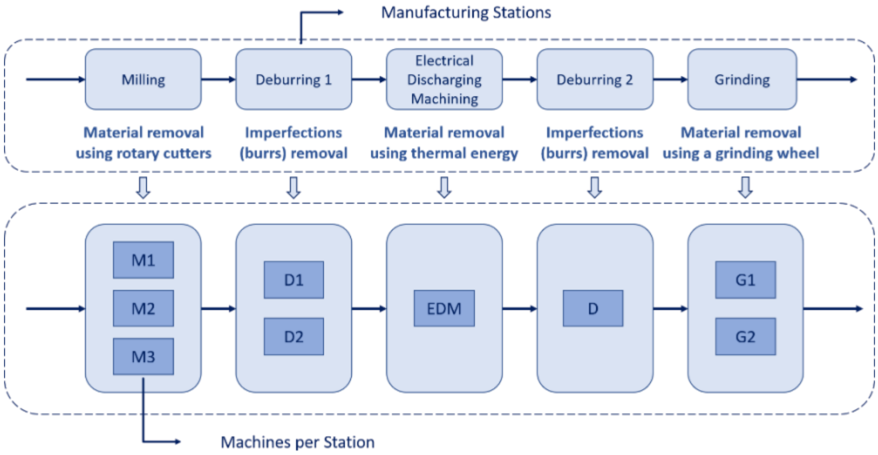

Fig. 1. Schematic representation of the case study manufacturing line.

3.2 Metric Selection

The screening process that is used to select the best fit for the case study can be broken down into two stages.

The first stage excludes the metrics that are not suitable for the line configuration (i.e., disconnected flow lines). OLE from [12] and OLE from [13] were discarded in this way, as they find application in connected flow lines. According to [14], in connected flow lines products are fabricated and assembled along a rigid routing connected by a paced material-handling system, which prevents building up inventories in between stations.

The second stage consists in an evaluation of the complexity of the metric. This can be defined by considering two functional aspects in relationship to the input and output information flows of the metric computation: on one hand, the amount and type of required input data in terms of availability and reliability; on the other hand, the usefulness and coverage of the output information the metric returns to the decision-maker. As for the latter aspect, all the remaining metrics appear as relevant indicators. In fact, OTE/OFE [7] allows to compute performance at system-level based on the type of connection between machines as well as identify inefficiencies down to subsystem-level. OEEML [8] allows to identify the location of inefficiencies regarding the position of the theoretical and actual bottlenecks. And finally, OFE [7], allows to operate an ex-ante system-level performance evaluation as opposed to all the other metrics that are ex-post. As for this last metric, it was discarded due to its intrinsic complexity, as it requires the building of the RBD (Reliability Block Diagram), the modeling of Markov chains and the execution of the simulation. As for the remaining two metrics, despite OEEML provides, to an extent, more specific information on inefficiencies, OTE/OFE is selected based on the aspect of availability of input data. While OTE/OFE only requires modifying the Performance component of OEE by taking into account losses that are directly attributable to the individual machine, OEEML requires a deeper adjustment of the structure of losses. This deeper adjustment is not judged feasible in the real case study.

3.3 Computation of OFE and results analysis

Fig. 2 summarizes the results of the computation of OEE for each machine and OTE for each subsystem for a given scenario relying on the formulae for the computation of OTE that are reported in [6].

The data required for the computations were provided by the company and were already organized into the items that typically characterize an OEE data collection, which are common to all the lines as regards this company. According to the type of data, some were automatically computed by the information systems, some were automatically retrieved by machines and some other were inserted manually by the operator.

Due to extensive maintenance interventions, the first machine of the milling phase and the EDM are characterized by the lowest OEE in the line. Considering the importance of maintenance interventions, the OEE takes into account the losses measured within the availability. In this work, Performance and Quality are instead both coefficients set to 1.

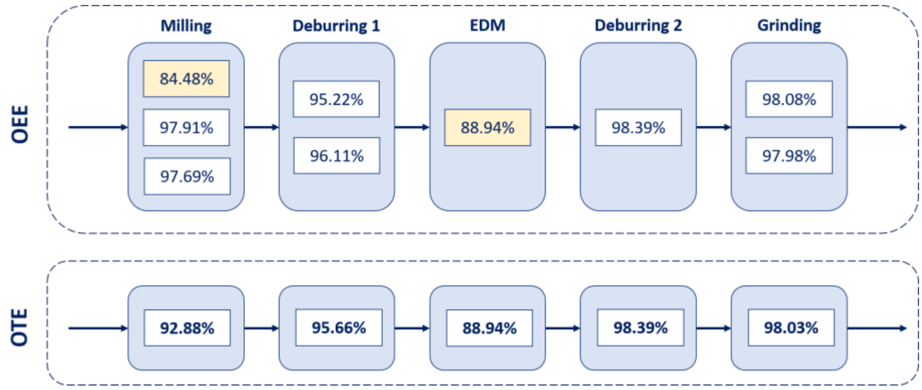

Fig. 2. Case study OEE and OTE computation.

The results allow making two main observations: the first one about the difference between the classic OEE and OTE; the second one about the difference between OFE (as previously said, the OTE of the entire line according to the designation of the authors [7]) and the OEE of the line computed as mathematical average, which is how the company used to compute system-level performances.

Regarding the first observation, according to the conventional OEE priority should be given to the first machine of the milling phase, as 84.48% is the lowest value in the line. However, its low efficiency is dampened by the parallel connection with the other two machines of the phase. This piece of information is taken into consideration by OTE, which is much greater (i.e., 92.88%) than the OEE of the first machine. Instead, the effort should be focused on the subsystem with the lowest efficiency (i.e., EDM – 88.94%), as the five subsystems are connected in series.

Regarding the second observation, not taking into account the connections between machines and between phases when computing system-level performances may result in their overestimation or underestimation. In this specific case, the mathematical average of all the OEE's amounts to 94.98%, which is 6.79% greater than the OFE (i.e., 88.94%). From a factory perspective, knowing the actual performance of a line would prove to be crucial when deciding where to invest and/or focus the effort. This line would probably go overlooked if decisions were made based on the overestimated value of the OEE, when, instead, the actual performance could be deemed as critical form an OFE point of view.

4 Conclusions

The discipline of AM is promising to support companies in pursuing sustainability-related goals given its holistic approach. To this end, a key enabler is having available the right set of indicators to measure the performance of assets comprehensively. This is the reason why it is appropriate to consider OEE but also to go beyond it, as the efficiency of individual equipment only is not sufficient, and a system-level perspective is missed. Despite the absence of a unique standard for measuring system-level performance, in the scientific literature different examples of system-level performance indicators are available, each trying to consider the complexity of the system. It is however not clear enough what is the proper system-level indicator to be used or recommended in a given production context.

Based on the characteristic of an industrial case study, an indicator from the literature is selected. The application helps highlight the differences between an actual system-level indicator, the OTE/OFE, and an indicator whose perimeter is limited to an individual equipment, the OEE. The non-negligible discrepancy of the results shows how important it is to rely on the right key performance indicators for the sake of taking decisions, especially when they entail choosing among different improvement options, considering both investments and operational decisions. By adopting system-level performance, it is possible for companies to focus the effort on the actual major causes of inefficiency and waste that damage the system of assets, rather than the individual assets.

It is evident that the system-level perspective herein discussed is a necessary step, but cannot be considered enough to achieve a holistic performance assessment and improvement as it is required by AM. The research direction to extend the current results, entails the integration of measures of other sustainability-related impacts and, moreover, their arrangement in an entire framework that consists of different levels including individual assets, systems of assets and multiple assets portfolio. It will be orienting to the requirements for the AM system as indicated in asset-related norms such as the ISO 55000. As a specific interest of the authors, there is a major insight on the energy efficiency at system level to cover this sustainability aspect; at the same time, it is relevant to evaluate the balance of cost and performance, thus looking at the total cost of ownership or similar economic-related indicators. In turn, these are just a few actions that will set in motion a process of continuous improvement towards a more sustainable production performance.

References

1. ECD. 2019. Global Material Resources Outlook to 2060. OECD. doi:10.1787/9789264307452-en.
2. Franciosi, C., Lambiase, A., Miranda, S.: Sustainable Maintenance: A Periodic Preventive Maintenance Model with Sustainable Spare Parts Management. IFAC-PapersOnLine 50(1). 13692–13697(2017). doi:10.1016/j.ifacol.2017.08.2536.
3. Roda, I., Macchi, M. A Framework to Embed Asset Management in Production Companies. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability 232 (4), 368–378 (2018). doi:10.1177/1748006X17753501.
4. Acerbi, F., Polenghi, A., Roda, I., Macchi, M.: Exploring Synergies Between Circular Economy and Asset Management. In: Lalic, B., Majstorovic, V., Marjanovic, U., Von Cieminski, G. RD, editor. IFIP Int. Conf. Adv. Prod. Manag. Syst. 2020, pp. 695–702. Springer, Cham (2020). https://doi.org/https://doi.org/10.1007/978-3-030-57997-5_80
5. ISO 55000. Asset management-Overview, principles and terminology. BSI Stand Publ 2014.
6. Muthiah, K. M. N., Huang, H.: Overall throughput effectiveness (OTE) metric for factory-level performance monitoring and bottleneck detection. International Journal of Production Research 45(20), 4753-4769 (2007).

7. Roda, I., Macchi M.: Factory-level performance evaluation of buffered multi-state production systems. Journal of Manufacturing Systems 50, 226-235 (2019).
8. Braglia, M., Frosolini, M., Zammori, F.: Overall equipment effectiveness of a manufacturing line (OEEML): an integrated approach to assess systems performance. Journal of Manufacturing Technology Management 20(1), 8-29 (2009).
9. Oechsner, R., Pfeffer, M., Pfitzner, L., Binder, H., Müller, E., Vonderstrass, T.: From overall equipment efficiency (OEE) to overall Fab effectiveness (OFE). Materials Science in Semiconductor Processing 5, 333-339 (2003).
10. Nakajima, S.: Introduction to TPM: Total Productive Maintenance. Productivity Pr, Cambridge, MA (1988).
11. Scott, D., Pisa, R.: Can overall Factory Effectiveness prolong Moore's Law? Solid State Technology 41(3), 75-82 (1998).
12. Raja, N., Kannan, S. M., Jeyabalan, V.: Overall line effectiveness – a performance evaluation index of a manufacturing system. International Journal of Productivity and Quality Management 5(1), 38-59 (2010).
13. Nachiappan, R. M., Anantharaman, N.: Evaluation of overall line effectiveness (OLE) in a continuous product line. Journal of Manufacturing Technology Management 17(7), 987-1008 (2006).
14. Hopp, W., J., Spearman, M., L.: Factory Physics: Foundation of Manufacturing Management. 2nd edn. Irwin/McGraw-Hill, New York, NY, (2000).