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Uncovering hidden capacity in overall equipment effectiveness management

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A B S T R A C T

An ongoing challenge in manufacturing management is to maximize the output volume from limited production capacity. Total productive maintenance (TPM) is a promising strategy to enhance machinery efficiency in factories by reducing downtime, speed, and quality losses. The associated metric of TPM is overall equipment effectiveness (OEE), which comprises three components, namely availability, performance, and quality, that measure the various aspects of production losses. However, output is restricted by the design cycle time in OEE, so purely improving OEE could only yield limited output increase. We argue that excess motion and processing in the ideal design cycle lead to design cycle losses. If these non-value-added activities as hidden capacity could be eliminated, production output would have considerable increment without extra investment. Adopting the input distance function approach, we show that the improvements gained from enhancing overall equipment availability and performance are different from the capacity unleashed by eliminating the design cycle losses. Accordingly, we propose value-added overall equipment effectiveness (VAOEE) as a novel metric to measure all the identified losses in search of hidden capacity. We provide three examples to demonstrate application of our novel productivity improvement approach in both semi-automatic and manual production in a non-continuous based plant.

1. Introduction

The problem of achieving the output target level in a given period is crucial for production executives, especially for those working on the shop floor, because capacity disruption due to slow cycles or machine failures leading to production suspension could cause late deliveries and even missing sales. In order to keep production running in an uncertain environment, manufacturers often install spare machinery or work overtime to ensure that the planned output volume is met. Evidently, taking precautionary measures to sustain production efficiency will incur cost. Advocating that effective equipment maintenance is imperative for factory management to reduce production downtime by maximizing equipment availability, Pintelon and Gelders (1992) stressed that maintenance management should be supported by an effective system to control the high maintenance cost. Compared with reactive maintenance, Meller and Kim (1996) found that preventive maintenance could reduce the system cost and output level variations. Despite having measures to keep equipment and workers fully occupied, the operating efficiency problem still causes production capacity losses because it is hard to continuously run equipment at the full speed due to minor stoppages that exist (Nakajima, 1988). Hence, how does a plant significantly boost production volume without increasing the associated capacity cost is a challenge for any production manager in today's highly competitive and rapidly changing market environment.

A common approach to increasing equipment availability and efficiency is to pursue total productive maintenance (TPM). A promising strategy, TPM addresses not only the equipment maintenance issue, but also eliminates different production losses, resulting in increases in saleable output quantity. TPM provides manufacturers with a proactive and aggressive method, rather than reactive and fire-fighting measures, for equipment maintenance (Swanson, 2001). Also known as the Toyota Production System (TPS), TPM is a problem-solving approach that adopts an uncompromising attitude towards reducing cost and increasing output from limited production capacity. In essence, TPM seeks to identify and solve different issues concerning production losses in a plant by increasing the production uptime of high-level processes (Nakajima, 1988).

TPM initially identifies the "six big losses" (BSL) and their causes in

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production, namely downtime losses due to equipment failure and setup/adjustment, speed losses caused by idling/minor stoppages and reduced speed, and defect losses arising from process defects and reduced yield. The associated metric of TPM is overall equipment effectiveness (OEE), which rates the real capability of machinery in production by comparing it with the optimal capacity, ideal cycle time, and zero-defect quality (Nakajima 1988). Shirose and Goto (1989) observed that the breakdowns caused by hidden defects are commonly treated as "normal state" in factories. They pointed out that OEE allows hidden losses and unnoticed equipment defects to be exposed. So OEE drives managers to reduce all the production losses by attaining defect-free output produced at a rate close to the ideal or design cycle time. However, TPM often faces the issue as to whether the output volume can be further raised by shortening the design cycle time.

The outcomes of TPM, OEE, and the "six big losses" are significant and impactful. One of their functions is that they can avoid cognitive bias in decision-making (Purushothaman and Seadon, 2021). A cognitive bias is an observed error in the span of making a decision or forming a judgement (Bendoly et al., 2010). It is a result of people's brain attempting to overcome bounded rationality (Eckerd and Bendoly, 2015). The behavioural operations literature also finds that operations managers are subjected to various cognitive biases. In fact, a study of six cognitive biases in operations management found that more than 50% of the respondents made biased decisions (AIKhars et al., 2019). Gino and Pisano (2008) explained that during the operation management process, different biases or heuristics, such as confirmation bias (favouring information that conforms to one's existing beliefs and devaluing unfavoured information) and availability heuristics (using the information that comes up first) might interfere with managers decoding their acquired information. Heuristic is a common approach in problem-solving because it is a mental shortcut to help people make decisions and form judgements quickly with less effort (Dale, 2015).

Floor managers in the stage of "inattentional blindness" might easily ignore issues related to facilities and production lines. Shirose (1989) lamented that so many losses in the workplace are neglected due to some engineers merely focusing on certain details. Mack and Rock (1998) observed in their perception and attention experiments that the subjects without cognitive deficits might fail to attend to the stimulus but instead were attending to something else. They coined the term "inattentional blindness" to describe this psychological phenomenon. This inability to perceive a flaw is due to the attentional mechanism having already been occupied to focus on the efficiency of the limited processing capacity to handle the most important information relevant to the ongoing operation (Pashler et al., 2001). Furthermore, chronic losses caused by hidden defects in machinery or equipment could be incurred by the "change blindness" of managers. Change blindness is another failure in noticing change in visual awareness because the original appearance is unavailable for comparison. Hence, even people pay visual attention to abnormal performance in a production process, they may not be aware of the existence of improper appearance that should be taken care of (Lamme, 2003). Essentially, OEE provides a framework for managers to examine whether hidden issues causing production efficiency losses still exist to avoid making biased decisions. It is a potent conventional tool to overcome production deficiencies and operational performance constraints (Gupta and Vardhan, 2016). However, we argue that the assumed ideal cycle time in OEE may give rise to heuristics and bias in the decision-maker, leading them to ignore the hidden losses even in the lean production context.

The purpose of studying OEE is to maximize the output volume, not just to improve equipment efficiency to reach world-class performance. Considerable capacity, however, might be concealed in the design cycle of any process, which the extant literature has not fully explored. In this paper we challenge the assumption that the design cycle time is the shortest. We apply the input distance function to analyze production efficiency, and study the relationship between the equipment availability and performance measures. We assume that the ideal cycle contains significant undetected production losses as hidden capacity caused by cognitive biases that exist in the decision-maker at the time when they devise an ideal cycle design and process set up. We propose a novel metric that captures all the identified losses in the non-continuous manufacturing environment, providing a new avenue for productivity improvement. This new tool is especially suitable for manual assembly systems and automated lines that require manual feeding of raw materials or parts to the machinery.

We organize the rest of the paper as follows: In Section 2 we review the basic concept and assumptions of TPM. In Section 3 we review the past studies on OEE and cycle time. In Section 4 we apply the unit distance function approach to address the issues of efficiency and losses in the design cycle. We then propose value-added overall equipment effectiveness (VAOEE) as a novel metric to measure all the identified losses in search of hidden capacity. In Section 5 we provide three examples to demonstrate application of our novel productivity improvement approach in real practice. Finally, in Section 6, we conclude the paper and suggest topics for future research.

2. Total productive maintenance

Japan Institute of Plant Engineers (JIPE) proposed TPM in 1971 to maximize equipment effectiveness by involving everyone in a company to build a productive maintenance system. The system covers the entire life cycle of equipment and all the equipment-related areas (Tsuchiya, 1992). The idea of TPM stems from the concepts of "preventive maintenance" and "productive maintenance" in the fields of reliability and maintenance initially practiced in the United States. Preventive maintenance is a daily maintenance plan to prevent failure and to reduce the repair time of equipment. Incidentally, productive maintenance extends the concept of preventive maintenance to "maintenance prevention", which is considerable during the equipment design stage to prevent machinery failure, and to "maintainability improvement", which facilitates ease of maintenance. These concepts were introduced to Japan in the 1950's (Nakajima, 1988; McKone and Weiss, 1998).

Before 1991, the classical TPM focused on the equipment itself. The word "total" in TPM has triple meanings. First, it is the total effectiveness in pursuing profitability. Second, it is a total maintenance system. Third, it is the total participation of all the employees. The last "total" emphasizes that maintenance is not the responsibility of the maintenance department but should rely on everyone in pursuing autonomous maintenance (Nakajima, 1988).

In the early stage of promoting TPM, JIPE emphasized the elimination of the "six big losses" mentioned in Section 1 to "achieve overall equipment effectiveness by maximizing output while minimizing the input, for instance, the life cycle cost of equipment" (Nakajima, 1988). In order to prevent such big losses, JIPE recommended that Japanese companies pursue autonomous maintenance, scheduled maintenance, and preliminary equipment management, and pay attention to safety and sanitation in their plants. In addition, employees should seek individual improvement through proper training. These form the five pillars of TPM (Nakajima, 1988; Nakamura, 2016). In fact, the basic objectives of TPM should be achieved by using appropriate tools, such as life-cycle cost analysis, failure mode effects and criticality analysis (FMECA), and maintenance task analysis, which enable visualization of hidden or potential problems (Blanchard, 1997). Moreover, employee motivation and morale also play an important role in TPM. Konecny and Thun, 2011 studied how human resource-related practices become a supportive base for both TPM and total quality management (TQM). They found that human resources management is a driving force of TPM and TQM, and affects all the performance criteria of TPM.

Unfortunately, TPM is sometimes treated as equivalent to maintenance management in the literature, see, e.g., Sahin and Polatoglu (1996), Alsyouf (2007), and Muchiri et al. (2011). But the maintenance objectives defined by Muchiri et al. (2011) of ensuring plant life and functionality, plant safety and environment, maintenance cost and resources effectiveness are quite different from the objectives of TPM that are promoted by JIPE. Labib (1999) commented that TPM, as an activity-centred management theory, just blends maintenance and production together by exchanging skills and taking actions within a small group. He suspected that TPM is not a result-driven approach. Indeed, TPM not only contributes to maintenance programmes but also improves the cost, quality, and delivery of a plant (McKone et al., 2001). Furthermore, Brah and Chong (2004) showed that TPM is positively correlated with business performance. They found that the financial, managerial, and operational management performance of TPM firms is remarkably better than non-TPM firms. On the other hand, pursuing TPM yields intangible benefits such as recognition and acceptance of individual responsibility for equipment, development of the "can-do" attitude and ownership for autonomous maintenance members, establishing a sense of importance for maintaining basic equipment conditions, and development of problem-solving skills for team members (Chan et al., 2005).

Subsequently, JIPE has extended the context of TPM since 1991 to eight pillars by adding quality maintenance, development management, and indirect department involvement to the original five pillars. JIPE has also identified 16 major losses, grouped into six categories, in a company, as shown in Table 1 (Nakamura, 2016).

Evidently, this extension of TPM covers the whole company, spanning administration, safety, environmental management, quality maintenance, product development, customer service, and logistics. It also provides a means of aligning improvement beyond the production shop floor and across the supply chain (McCarthy and Rich, 2015). Plants could also improve performance by pursuing TPM regardless of their sizes (Wang and Lee, 2001).

Therefore, the management concept of TPM has evolved from the production floor to company-wide TPM and further to supply-chain-based TPM, seeking to maximize output from limited input. TPM initiatives are executed in both manufacturing and non-manufacturing streaming processes and operations to enhance the overall performance of a company and raise profitability. In spite of its evolution, TPM can still benefit firms' various priorities and goals such as increasing productivity, improving output quality, reducing cost, quickening delivery, enhancing safety/environment, and raising morale (Ahuja and Khamba, 2008).

The classical TPM has developed the OEE metric to measure the availability, performance, and quality of the equipment in use. We discuss the use of OEE and its limitations, and propose incorporating the value-added concept into OEE in the next section.

Table 1
The 16 major losses in TPM.

Category	Major Loss	Example
Planned: Scheduled equipment loading time losses	Shutdown losses	Planned periodic inspection of equipment
Availability: Downtime losses	Failure losses	Function of equipment drops
	Setup and adjustment losses	Changeovers
	Cutting tool replacement losses	Changing cutting blade
	Startup losses	Production processing before stabilization
Performance: Speed losses	Minor stops and idling losses	Equipment temporarily stops or idles due to sensor actuation or jamming of work
	Speed losses	Equipment actual operating speed not up to designed speed
Quality: Defect losses	Scrap and rework losses	Output defects
Manpower: Inefficiency losses	Management losses	Waiting for materials, tools, instructions or equipment breakdown repairing
	Motion losses	Additional motion due to different skills prolonging the design cycle
	Line organization losses	Idle time due to line balancing
	Distribution losses	Man-hour losses due to moving materials, WIP, and products
	Measurement and adjustment losses	Frequent measurement and adjustment for preventing defects
Resource: Consumption losses	Energy losses	Ineffective utilization of input energy
	Yield losses	Materials losses in the process
	Consumable losses	Financial losses of repairing or replacing dyes, jigs, and tools due to abnormal aging

3. Overall equipment effectiveness and cycle time

Process efficiency assessment plays a crucial role in the strategic performance measurement of a firm, in addition to evaluating the values received from suppliers and employees, and the values provided to the stakeholders (Atkinson et al., 1997). OEE is a quantitative tool to evaluate equipment effectiveness by identifying different production losses for process improvement. It is composed of three components, namely availability, performance, and quality, that evaluate the famous "six big losses". Accordingly, OEE provides a yardstick to assess the effectiveness of the equipment and production system, enabling productivity improvement by reducing the downtime, speed, and defect losses that are of critical concern to TPM. Specifically, Nakajima (1988) gave the following definitions:

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

and

$$Availability = \frac{Operation\ time}{Loading\ time} = \alpha, \tag{2}$$

where loading time refers to the net availability of equipment during a given period, excluding the planned downtime and unscheduled production, and operation time is the loading time deducting the machine breakdowns, setups, and adjustments, retooling, and brief stoppages (unexpected small stops).

In addition,

$$Performance = \frac{Processed\ amount\ \times\ Design\ cycle\ time}{Operation\ time} = \beta. \tag{3}$$

where design cycle time assumes that the machine is being operated at the full design speed. Hence speed losses and minor stoppages are captured in Eq. (3).

Furthermore,

$$\begin{aligned} Quality &= \frac{Processed\ amount - \ Defect\ amount}{Processed\ amount} \\ &= \frac{Good\ qulaity\ amount}{Processed\ amount} = \gamma. \end{aligned} \tag{4}$$

Therefore,

$$OEE = \alpha \times \beta \times \gamma = \frac{Good\ quality\ amount\ \times\ Design\ cycle\ time}{Loading\ time}. \tag{5}$$

Widely accepted by productivity management researchers and practitioners, Eqs. (1)–(5) provide good insights for frontline managers to identify improvement areas in production. Rita et al. (2017) compared four different approaches to assess OEE for a single piece of equipment. They found that the approaches are suitable for job shops, manual assembly lines, or workstations, which commonly integrate manual and automatic machinery. Sage Clarity Systems (2019) reported that, based on a study of over 100 global manufacturing operations worldwide, the best of the best in the study reached an OEE value of 96.9%, while the laggard only got 31.2%. The best-in-class that were within the top 25% of the firms in the survey attained an OEE value 2.6 times more than the bottom 25% of the firms. The results imply that most firms still have room for efficiency improvement.

In the literature, there are studies that propose alternative approaches to practise OEE management (De Ron and Rooda, 2005, 2006; Rita et al., 2017). Moreover, some researchers consider extending the OEE metric to cover the entire manufacturing process or factory (Garza-Reyes, 2015). For example, Huang et al. (2003), and Muthiah and Huang (2007) developed the overall throughout effectiveness (OTE) metric to detect bottlenecks and hidden capacity at the factory level. Nevertheless, all the losses that are identified by different models could be grouped into the "six big losses" or "16 major losses". There is hardly any breakthrough in this approach that can increase the output from the limited production capacity. On the other hand, Munoz-Villamizar et al. (2018) suggested that both OEE and profit be maximized by optimizing quality, performance, and availability in that order.

Zammori et al. (2011) argued that the main drawback of OEE management is the variability of a manufacturing process that cannot be captured. Treating the OEE metric as a random variable and based on the Central Limit Theorem, they worked out the stochastic OEE metric. Consequently, both the mean and standard deviation are involved in computing the stochastic OEE value. They found that when there is a sufficient difference between the cycle time and Takt time, it is better to reduce the OEE variability than the OEE mean value. Wudhikarn (2012) pointed out that different conclusions might emerge from using different monetary values for cost of quality to calculate the equipment losses. He proposed an improved model that combines OEE and quality cost to overcome this weakness of OEE.

In the late 1990's, Ivancic proposed the new term of total equipment effectiveness performance (TEEP). The difference between OEE and TEEP is the utilization rate, which provides an insight into the true capacity of manufacturing. TEEP recognizes schedule losses in capacity utilization that are generated by the plant that is occupied and production that is not scheduled. These two losses have therefore been added to the "six big losses" to become the "eight big losses" (Muchiri and Pintelon, 2008). Similarly, Alsyouf (2006) proposed that company performance be measured by multiplying OEE by a planning indicator to compute the total overall equipment effectiveness (TOEE). The planning indicator is the ratio of the planned downtime to the theoretical production time. Therefore,

$$TEEP = Utilization \times OEE, \tag{6}$$

where

$$Utilization = \frac{Loading\ time}{All\ time} \tag{7}$$

and all time is the maximum capacity time including the unscheduled capacity.

On the other hand, our discussion so far does not fit continuous production. In the early 1990's, JIPM considered the overall plant effectiveness (OPE) metric, which is similar to OEE, but for the process industry. Accordingly, JIPM identified eight major losses in the process industry, which is different from the fabrication and assembly industries. The eight major losses are shutdown, production adjustment, equipment failure, process failure, normal production loss, abnormal production loss, quality defects, and reprocessing. Suzuki (1994) pointed out that these losses often prevent any factory in the process industry from reaching its maximum effectiveness. Specifically, similar to OEE, JIPM defined OPE as follows:

$$OPE = Availability \times Performance\ rate \times Quality\ rate. \tag{8}$$

Evidently, similar to TEEP, OPE measures the overall equipment effectiveness relative to the calendar time, but it is suitable for different kinds of manufacturing processes (Ahuja and Khamba, 2008). Since our focus is on OEE for non-continuous manufacturing processes, OPE is outside our study scope. So, in this paper, we extend the scope of OEE to cover any manual or equipment-free production process.

In the 1980's, Nakajima (1988) suggested that a manufacturer that reaches an OEE value of 85% made up of 90% of availability, 95% of performance, and 99% of quality should be considered as world class. However, a quality rating of 99% only yields a process capability index C_{pk} of 0.78, which is unlikely to be accepted in almost any industry in the contemporary setting. Yet, boosting the C_{pk} value to over 0.8 does not have any significant implication for OEE (Garza-Reyes et al., 2010).

On the other hand, equipment breakdown is highly visible and could easily draw senior management's attention, which compels the floor manager to address the issue. Hence, among the three components of OEE, performance might need more reinforcement. In fact, Ljungberg (1998) emphasized that performance losses are an influential factor in the OEE metric. He found that performance in general was as low as 68%, while availability was 80% and quality was 99% on average in his sample. Zennaro et al. (2018) reported that 57% of inefficiency was caused by small process failures in their bottling lines study. In case those unfavourable performance measures are subjected to some cognitive biases, improvement in performance might have a stronger impact than quality on OEE.

From Eq. (3), we see that the design or ideal cycle time dominates the performance measure, which is determined using the best speed rate, given the size of the product (Hansen, 2001). Indeed, the theoretical cycle time is based on the design equipment capacity (Nakajima, 1988). Nevertheless, the ideal cycle time has not been considered for reduction, rendering it a key limitation of OEE. Since a fixed cycle time regulates the maximum output rate, Andersson and Bellgran (2015) pointed out that OEE could not be proactively used for productivity improvement as for capacity improvement. They argued that even OEE is decreased due to a reduced ideal cycle time by modifying the process, productivity could be improved due to the shortened cycle time. We emphasize that the opportunity for such improvement arises from the existing non-value-added activities in the ideal cycle. With the possibility of inattentional blindness or other biases, unnecessary motion or processing could be ignored by the process designer. However, there is a lack of research on ways to reduce the design cycle time.

Hung et al. (2009) stated that on examining the components of a production function, only positive/negative value-added processes and non-value-added processes, and no waste, could be identified. They divided value-added work into "positive value-added work", which is work that creates value as perceived by customers, and "negative value-added-work", which reduces the accumulated value of a process due to being defective. Each piece of non-value-added work is associated with one or more hindrances. They also emphasized that non-value-added work is necessarily carried out to cope with hindrances and maintain the accumulated value of a process. Therefore, the ideal cycle time could be further reduced if some hindrances in the non-value-added motions or processes are eliminated. But this should not be the case for solving the problems of decreasing the rework of defective items and scrap items so as to reduce the actual cycle time (Flynn et al., 1995, 1997). Indeed, the design cycle time will remain unchanged after taking such an approach for quality enhancement.

In the next section we propose a new metric for productivity improvement that explicitly considers the losses in the design cycle of OEE.

4. A new metric for productivity improvement

We follow TEEP to consider capacity utilization from the perspective of production. Let a production function $P : \Re^n_+ \rightarrow \Re_+$ produce output $q \in \Re_+$, where $P(0) = 0$. Denote the variable inputs by the vector $x = (x_1, x_2, \cdots, x_n) \in \Re^n_+$. The input requirement set is $V(q) = \{x \in \Re^n_+ : (x, q) \in Q\}$, where Q is the production possibility set of a productive process. The input requirement set is the set of all the input bundles that produce at least q units of output. The production function P is continuous, strictly increasing, and strictly quasi-concave on $\Re_+^n$ and $V(q)$ is a convex set (Chambers, 1988).

Suppose that there are $t = 1, \cdots, T$ periods. We denote the capital input by the vector $K = (K_{n+1}, \cdots K_{n+m})$ and $\theta \in \Re_+$ as the time required for producing q. Given the production function $P : \Re_+^n \rightarrow \Re_+$ with $x = (x_1, x_2, \cdots x_n) \in \Re_+^n$ to produce output $q \in \Re_+$, we have

$$q^t = P(x^t, K^t, \theta),\ K^t \leq K,\ t = 1, \cdots, T, \tag{9}$$

Note that P is defined by the isoquant

$$I(q) = \{x : x \in V(q) \text{ and } \lambda x \notin V(q) \text{ if } 0 \leq \lambda < 1\}. \tag{10}$$

In other words, if a firm employs x^t variable inputs and uses K^t capital inputs with the isoquant $I(q)$ playing the role as the boundary of the input requirement set, it will produce a level of output q^t in period t with the required production time θ. K is the size of the plant, which is associated with capacity $h(K)$ and cannot be exceeded, regardless of the amount of variable inputs used (Panzar, 1976). Therefore, the rated capacity of a plant is defined as $h(K) = \max_{x^t} P(x^t, K)$, which is the same as the full utilization capacity in TEEP. OEE considers the total output to be produced from $h(K)$ after reducing the schedule losses such as non-saleable capacity, scheduled holidays and maintenance, unscheduled material events, labour shortages etc. If a process has OEE = 100%, then the maximum output is $q_m \in \Re_+$, which is associated with the ideal or design cycle time $c \in \Re_+$ of each unit output. Hence, $q_m = \frac{h(K)}{c}$. Therefore, output $q^t \leq q_m$ in period t is determined by c and OEE. However, c depends on the input vector x. Moreover, the handling time in producing each unit of output is also included in c according to this argument. Obviously, the OEE measure assumes that the design cycle time c is fully productive, so it is the shortest. However, the effectiveness of a piece of equipment or a production process depends on factors other than c, such as downtime, speed, and defect losses (Nakajima, 1988).

In short, we illustrate both the availability and performance measures of OEE in Eqs. (2) and (3), respectively, by constructing a unit input-orientated measure in Fig. 1, which is the same as the expression of productive efficiency in Farrell (1957). This is an isoquant graph for a single unit output being produced with two inputs. The unit input isoquant is represented by the curve VV', which is the fully availability isoquant as shown in Eq. (10). However, a plant usually uses quantities of inputs above VV', defined by the point E, to produce a unit of output since idle and break downtimes accumulate. Hence, the input $x(q_0)$ is represented by the distance OE, which is the required production time. The isoquant VV' is indeed the actual cycle time per unit in production. WW' is the slope of VV' at D' that measures the rate of change of the two input factors and is joined with point C, in which OC is the design cycle time. The actual cycle time OD could be longer than the known design cycle time OC due to speed losses. For the case where such losses could be reduced completely, point D will move forward to D', the fully performance point. Hence, availability is

$$\alpha = \frac{OD}{OE} \tag{11}$$

and performance is

$$\beta = \frac{OC}{OD}. \tag{12}$$

So equipment efficiency per output unit is

$$\frac{OD}{OE} \times \frac{OC}{OD} = \frac{OC}{OE}. \tag{13}$$

Since the inspection result $Q(y)$ of each output unit is either pass or rejection, we have

$$Q(y) = \begin{cases} 1 & \text{qualified goods;} \\ 0 & \text{otherwise;} \end{cases} \tag{14}$$

such that equipment efficiency per unit after inspection is

$$\begin{cases} \dfrac{OC}{OE} & \text{salesable/marketed goods,} \\ 0 & \text{otherwise.} \end{cases} \tag{15}$$

Suppose the production lot has an inspection passing rate γ, then OEE $= \frac{OC}{OE} \times \gamma = \alpha \times \beta \times \gamma$, which is the same as Eq. (5).

Nevertheless, we argue that the vector $x = (x_1, x_2, \cdots, x_n) \in \Re_+^n$ includes both value-added and non-value-added work (Hung et al., 2009). Therefore, if some of the non-value-added work such as excess motion or excess processing in x could be eliminated by re-designing machinery/worker operations and production processes, the new design cycle time becomes $c' < c$, or it could not be accepted. Hence, the original isoquant VV' will shift down to $I_0(q)$, as SS' at a lower level in Fig. 2. Assume that point A in Fig. 2 is the new design cycle time, where $OA = c'$, associated with $I_0(q)$ is the boundary of a new input requirement set $V_0(q_0) = \{x \in R_+^n : (x, q) \in Q\}$ Therefore, the distance AC is equivalent to the time of the eliminated non-value-added activities in the original design cycle. The length of OA should be shorter than that of OC, or the new design cycle will be rejected. The isoquant SS' has its own efficient point at B'. Hence, point $B' \neq D'$ since $I_0(q) \neq I(q)$. Nevertheless, the time saving as shown by AC is unlikely coming from availability or performance improvement in OEE but from reduction in the original

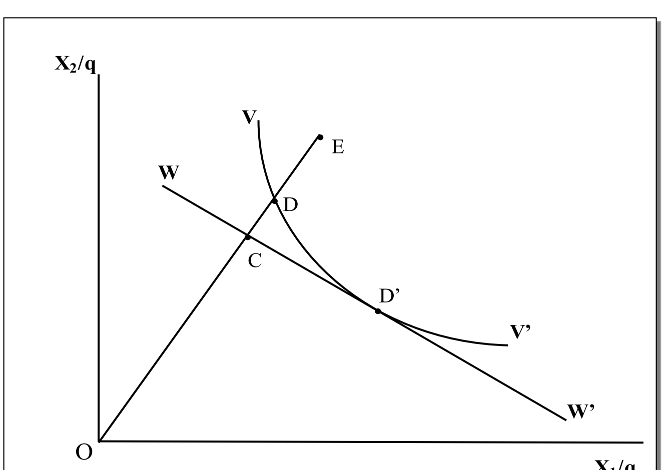

Fig. 1. Unit input-orientated measure by using the distance function.

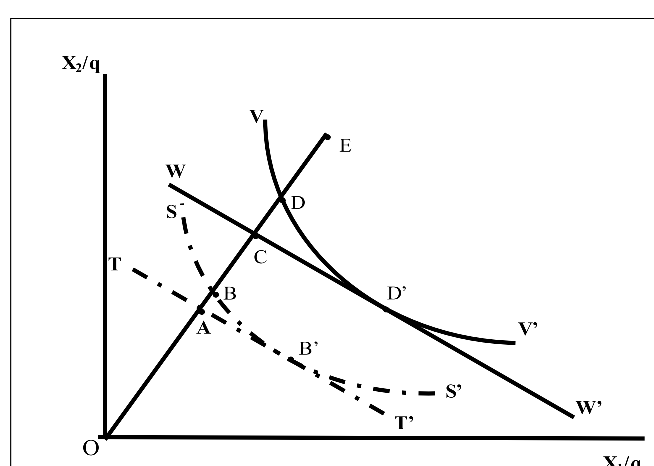

Fig. 2. Shifted isoquant after reducing the original design cycle time.

design cycle. Moreover, BD is the diminution of the actual cycle time after implementing the new production method. The length of BD could reflect the degree of improvement for the case where the ideal cycle time is hard to work out. However, AC might not be exactly equal to BD due to different performance measures in OEE that may be experienced. Consequently, the output will increase at the same capacity $h(K)$ by reducing the design losses such that $q_m < \frac{h(K)}{c'}$.

Accordingly, we suggest that design losses should be included in the OEE metric to become value-added OEE (VAOEE) for productivity management. Hence,

$$VAOEE = Availability \times Performance \times Quality \times Design. \tag{16}$$

We use a similar approach of OEE to define the design measure as

$$Design = \frac{Value - added\ time\ in\ a\ design\ cycle}{Design\ cycle\ time} = \delta. \tag{17}$$

So

$$VAOEE = OEE \times \frac{Value - added\ time\ in\ a\ design\ cycle}{Design\ cycle\ time}$$
$$= \frac{Good\ quality\ amount \times (Value - added\ time\ in\ a\ design\ cycle)}{Loading\ time} = \alpha \times \beta \times \gamma \times \delta. \tag{18}$$

We can also include the design measure in TEEP to become value-added-TEEP (VATEEP) as follows:

$$VATEEP = Utilization \times Availability \times Performance \times Quality \times Design = Utilization \times VAOEE. \tag{19}$$

From (7) and (18), we have

$$VATEEP = \frac{Good\ qulaity\ amount\ \times (Value - added\ time\ in\ a\ design\ cycle)}{All\ time}. \tag{20}$$

Therefore, in addition to reducing the losses in availability, performance, quality, and utilization, practitioners could reduce two extra big losses, namely "excess motion" and "excess processing", in processes and/or equipment to improve both output quantity and production efficiency. We show that our new metric of VAOEE can provide an unprecedented direction and avenue for factories to increase production output volume from the same manufacturing scale if the factory manager has an opportunity to determine the cycle time. In the next section we present three real-life examples to demonstrate the relationship between the original OEE and our developed VAOEE.

5. Illustrative cases and discussion

We present three real-life cases to illustrate applying OEE and VAOEE to make productivity improvement. In the first case, the OEE approach is initially adopted to enhance productivity, followed by using the VAOEE concept for productivity improvement. In the second case, the design cycle time is initially reduced, followed by removing the minor stoppages in line with the traditional OEE approach. The third case shows how a design cycle of CNC machining is shortened to gain improvement beyond 100% OEE. As the three cases contain proprietary information and data, we only provide limited quantitative information about the three case firms, and merely report the final OEE and VAOEE values in the third case.

5.1. Argument between maximizing machinery speed and output volume

This case shows an improvement process starting with OEE and later being extended to VAOEE. W.L. Gore & Associates, Inc. (Gore) invents Gore-Tex® material made of waterproof, windproof, and breathable fabric and markets it. Customers convert the material into different end products such as outerwear, footwear, gloves, and hats. Gore also provides equipment, tapes, and technical support to ensure that the end products are completely impermeable to water by appropriate style design and by adopting a special tape to cover the stitching seams. All the factories that produce Gore-Tex® apparel should follow the seam sealing quality specification established by Gore. This seam sealing process is one of our examples of productivity improvement.

The main equipment to be used in seam sealing is a kind of hot air machine that looks like sewing machinery. It provides hot air to stick a dedicated tape on a sewing seam by melting over the adhesive on the back of the tape. Then the tape is pressed on top of the seam by two working rollers immediately to enhance the waterproof function. The speed of the roller is equivalent to the velocity of machine running. Gore defines various scopes of the hot air temperature and different ranges of the roller speed for particular fabrics accordingly. In addition to preventative maintenance, Gore also introduces autonomous maintenance in the factories by helping operators to develop a procedure of cleaning and adjusting all the parameters of the equipment every morning to prevent quality issues and to avoid declining operating efficiency. Moreover, Gore also identifies that the durability of the waterproof function may be affected if a stop-start occurs when sealing a seam. Otherwise, an additional operation of fixing the quality issue of insufficient heat energy to be absorbed by the tape at any stop-start point is required. From the perspective of quality management, this extra operation is a remedy. Gore, however, encourages operators to avoid any stop-start in their daily work.

The case originated from an argument between Gore and one of its customers regarding the roller speed. The production floor of a certain customer requested Gore to increase the velocity of the hot air machine because it believed a faster machine would produce more output. This requirement triggered a global study of operating efficiency for this process within Gore.

At the beginning of the efficiency study, the project team determined that availability in OEE would not be included because it should be dealt with by each workshop manager. The team just wanted to improve the performance measure without compromising the output quality.

After collecting production data from good-performance factories across Asia, Europe, and America, a production site in Europe was identified to be the best player. By learning the production practice in this factory, the team discovered that output would not be maximized by a higher speed but by an optimal one. Even the speed used in this factory was much lower than the speed adopted in Asia, they achieved higher productivity. At the end of the study, the team concluded that operators hardly controlled a machine that was running beyond a certain speed limit. Thus one or more stop-starts would appear to prolong its actual cycle time when the rollers were running at an uncontrolled speed for a longer tape. Therefore, stop-starts were a hurdle to the output rate and affected product quality. Furthermore, machinery speed was not a critical issue for most tapes since in a jacket they were as short as 200 mm or less. In the new setting based on the finding, the output volumes of the complaining factory and others increased by reducing the machinery velocity and averting the stop-starts. This is a typical example of performance improvement by eliminating minor stoppages in TPM, even when the focus is not on the equipment but on the operators to attain their full speeds. Moreover, quality could be satisfied by removing the start-stops in production. This study resulted in a win-win outcome where both performance and quality in OEE were achieved at a higher level.

Nevertheless, the project did not stop at this point. The team further explored room for productivity improvement in the seam sealing process. They discovered that the ideal cycle time included both value-added and non-value-added activities. As a matter of fact, the running time of a machine was defined as the value-added time while the rest of the operation was non-value-added time in their study. Shortly, the team was really shocked to discover that the value-added time accounted for only 20% of the total normal production time, in which all the unavailable times, such as breakdowns, waiting for materials, and operator taking rest were excluded.

The motion of the operator was then analyzed. The team revealed that some necessary motions and movements of the operator were due to the design of the hot air machine and the production setup. The cycle time was therefore shortened by re-designing the equipment and production method to eradicate some of the non-value-added procedures in the current process. Output volume then increased substantially without requiring any additional equipment or overtime work. In addition, this case also demonstrates how to reduce cost and increase production amount from limited resources by taking an uncompromising attitude as learned from TPM and TPS.

5.2. Packing productivity increased in double

The second case concerns re-designing the working cycle for operators without involving equipment. Tana Netting Co., Ltd. (TNCL) is a leading manufacturer and distributor of mosquito netting and other products for public health, travel, and personal protection, as well as for use at home and in gardens. Their clients include administrators of malaria control projects, United Nations (UN) agencies, international non-governmental organizations (NGOs), businesses, the military, travelers, hotels and resorts, and home-owners worldwide. Their production facility is located in Chonburi, Thailand. Having been introduced the concept of eliminating non-value-added activities in the design cycle by one of the authors, TNCL applied the approach to their production line with a view to improving process productivity.

The production flow is quite simple in the netting business in comparison with those in other sewing industries. First, the fabric is sent to the cutting room after inspection of the incoming material, and then the sewing room makes the product. If the product does not require any further treatment, then it will be directly sent to the packing room. If the product requires further treatment, e.g., addition of a specific chemical, then the product will go through further processing prior to packaging (Fig. 3).

The management team selected the packing department as the first unit to undergo the cycle re-designing exercise by decreasing the non-value-added work in the process, since the labour cost of this department was 40.48% of the total direct labour cost, a very high percentage. After applying the new design cycle in a couple of months, the department stably achieved substantial improvement. Given that TNCL was reluctant to share their entire experience, we only highlight the results and the extent of their success. All of the figures in this example are therefore the results from just one production line, and not the total output of TNCL. We also assume for the purpose of this exercise that the production line only deals with one product at all times. Nevertheless, the entire packing department has indeed benefited from the process improvement exercise, resulting in considerable saving in resources.

The main cycle time reduction resulted from a change in the sitting position of the packing workers. Prior to that, the workers adopted the traditional practice of sitting on the floor to carry out the packaging operation. TNCL classified the packaging process into value-added and non-value-added activities. Upon reviewing some of the non-value-added activities, they identified workers' sitting position as the root cause of the hindrance. As a result of this observation, the packaging activities were subsequently carried out by workers sitting at a table, which reduced the actual cycle time by more than half immediately from day one of the change, since the new process eliminated some of the required movements when workers were sitting on the floor. However, we did not adopt the design cycle time but the actual cycle time in this study because the variance exhibited among the workers would reduce the accuracy of the time measurements. Therefore, as discussed in Section 4, only improvement in the actual cycle time was observed.

After a few months of practice, the actual cycle time reached a stable level. In the second stage of the improvement exercise, the focus was on improving workers' efficiency by incorporating a "trainer" in the line and using the continuous-flow process concept. In other words, the second stage focused on removing the minor stoppages and speed losses. But there was a high turnover during that period of time, which required some effort to train the new staff. For this reason, a longer period of time was required for the actual cycle time to become stable.

Table 2 shows that the improvement result in this period was significant. The actual cycle time for each net was reduced from 7.56 to 3.50 s in the packaging process. The second stage was pursued one year later, during which the actual cycle time was further reduced to 3.25 s. The daily capacity of the production line therefore increased from 3333 to 7200 pieces of netting in the first stage, and then to 7759 pieces of

Table 2
Increase in labor productivity in the packing department of TNCL.

Item	Prior to process improvement	After 8 months	After 20 months
Capacity per day	3333 nets	7200 nets	7759 nets
Actual cycle time per net	7.56 s	3.50 s	3.25 s
Labour productivity change	–	+116.02%	+132.79%

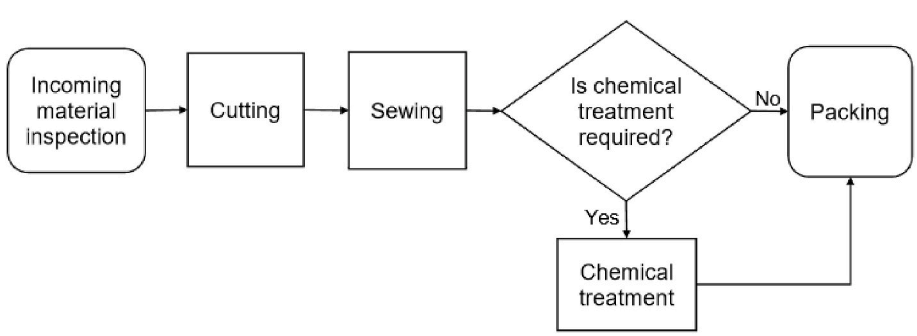

Fig. 3. Production process at TNCL.

netting in the second stage. Hence, labour productivity increased by 132.79% overall. The crucial point is that the value-added time of each output did not change before or after the improvement process was carried out. If the available capacity remained at the same level, the proportion of value-added capacity would increase because some non-value-added activities were eliminated.

Even though these figures reflect the results over a period of 20 months, it should be noted that the results were already evident after the concept was first introduced to TNCL, which was able to benefit directly from the improved process. However, a longer period of time for this study also shows that the results sustained over time and the process improvement continued.

This example shows that OEE can also be adopted from Eqs. (1)–(5) for equipment-independent operations. But the challenge is that a stable measurement is required, which is hardly obtainable. Hence, an observation period should be long enough to gather reliable data. By comparing with historical figures, the management of TNCL believes that without a change in the sitting position of the packing workers, there is no way they could gain such significant productivity improvement in their factory.

5.3. CNC machining productivity improvement

The third case demonstrates how an outstanding OEE performer makes a breakthrough in the constraint of the traditional OEE to obtain further improvement. ABB Jiangjin Turbo Systems Co. Ltd, China is a joint venture between ABB, a leading global technology company and a local Chinese company. Their headquarters and factory in Chongqing, China have 350 employees. It is a sourcing hub for ABB turbocharging and the centre of excellence for the production of ABB turbochargers for the Chinese market.

One of the core production processes in ABB Jiangjin Turbo Systems uses the computer numerical controlled (CNC) machine, an automated metalworking tool that controls a range of complex machinery, such as grinders, lathes, and turning mills, to create the required complicated parts. Exhibition 1 shows one of the blanks before CNC machining and Exhibition 2 shows the finished product that we discuss in this case.

The flow of the CNC machine is usually of high concern in the factory because it is a bottleneck of the whole production process. In a study of the sales order of 42 pieces of the product that was delivered in December 2020, the production team found out that its OEE was only

Exhibition 1. A piece of blank before CNC machining.

Exhibition 2. A finished output of the CNC machine.

78.72%. However, the quality passing rate of this particular order was as high as 100% and the performance rate was 98.4%. Therefore, the team focused on improving the availability rate of the process by adopting the "single-minute exchange of die" (SMED) approach to reduce the set-up time (Shingo, 1985). The team streamlined the production preparation procedure from eight to six steps in the first stage of the improvement exercise. However, they later discovered that three of these steps could be performed offline to increase the availability of the CNC machine. Moreover, they also modified the method of data input into the CNC machine that saved 75% of the input time during the production set-up period. Therefore, the availability rate was raised from 80% to 92.22%. Hence the improved OEE jumped to 90.7% after the radical redesign of the set-up process. The team was satisfied with the result and believed the process had reached the ceiling of OEE. Unfortunately, even the team had achieved such excellent OEE performance, the CNC production process was still the bottleneck of the production line.

After the concept of VAOEE was introduced to ABB Jiangjin Turbo Systems, the managers revealed that the design cycle was an area that they had never considered in any productivity improvement exercise. The team then listed all the activities in the design cycle of the CNC machining process and classified them into either value-added or non-value-added steps. They found that among the eleven activities in the design cycle, five of them were non-value-added procedures. Then they used "5-why" to explore what the hindrance behind each of them was. Their aim was to eliminate some of those hindrances they discovered to shorten the cycle time by removing certain excess steps and redesigning the whole process.

Eventually, the team successfully reduced the design cycle time from 123 min to 88 min, in which both the original and improved cycles contained 62 min of value-added activities. By Eq. (17), the original $\delta =$ 50.41% and the improved $\delta' =$ 70.45%. Therefore, by Eq. (18), VAOEE increased from 45.72% to 63.9%. Meanwhile, the output volume increased remarkably by 39.77% even the rates of availability, performance, and quality were not changed. This wonderful result not only eased the production flow but also motivated the team to seek further improvement by eliminating the non-value-added activities in other areas as much as possible. The factory management admitted that VAOEE was an innovative concept that helped them craft a clear path for their continuous improvement journey.

5.4. Discussion

Obviously, the cycle time reductions in all the cases do not involve any of the 16 major losses in Table 1. They are realized from the original design cycles and are not part of the OEE improvement. Meanwhile, the design cycle time reduction does not incite any conflict with OEE. In fact, they could be combined as VAOEE. Factories could start their improvement journeys either with OEE improvement or design cycle time reduction as illustrated in the three cases. We stress that OEE not only focuses on equipment effectiveness but also increases output volume. Our approach of reducing the non-value-added activities in the cycle time is a powerful tool to uncover hidden capacity in the firm because it provides a methodical scheme based on sound principles to identify areas for improvement without resorting to heuristics. For example, in the TNCL case, more than 100% improvement resulted from changing the sitting position of the packing workers, and the production team of ABB attained an extra 39.77% of output volume by redesigning the production process. Both outcomes can hardly be achieved by increasing the OEE rate.

Our cases also reflect that the application of our new concept fits both semi-automatic and manual production in the non-continuous manufacturing environment, provided that the factory personnel are involved in establishing the cycle time. Therefore, a production line could manifest breakthrough output volume without incurring the associated capacity cost in this manner. Indeed, both excess motion and excess processing in the process to be eliminated in the ideal cycle could be included in the “six big losses” of OEE to become the “eight big losses” of VAOEE. By the same token, these two types of losses could also be combined with the eight big losses in TEEP to become the ten big losses of VATEEP.

Therefore, our contribution is not merely a theoretical framework, but also a practical methodology that manufacturing firms can adopt to unlock the hidden capacity in their production lines. Consequently, elimination of the non-value-added time in the design cycle might herald a new avenue for practitioners to surpass their own productivity.

6. Conclusions

The purpose of OEE management is to maximize the salable output from the available capacity and output the ideal cycle time by diminishing downtime, speed, and defect losses. We suggest that design cycle time reduction is an additional productivity improvement opportunity apart from those available from the components of the OEE metric. We challenge the assumption that the ideal or design cycle time is the shortest, in view of the fact that excess motion and excess processing existing in the design cycle are two big losses. The design cycle time could be shortened if some of its non-value-added activities are eliminated. Adopting the unit distance function, we show that any production time saved from the design cycle is different from the improvement of OEE, especially availability and performance efficiency enhancements. We further propose the notion of incorporating cycle time reduction into OEE to become VAOEE. We use three real-life cases to explain the difference between OEE and cycle time improvement. The cases also demonstrate that OEE could be applied beyond equipment to a manual production line to detect the hidden capacity in the ideal process cycle. This finding also encourages practitioners to preclude some non-value-added motions during the equipment design stage to prevent design losses.

Our new concept makes a considerable contribution to both the literature and industry. Specifically, VAOEE provides firms with a new metric for increasing output volume without requiring additional capacity in their pursuit of profitability enhancement. However, our approach is limited to one piece of equipment and one process type. Future studies should extend our work to consider the entire production plant and the whole firm. It is also interesting to determine whether local minimization of losses in VAOEE could also be global minimization of the whole plant. Moreover, unequal weights might be assigned to the four components in VAOEE or the five components in VATEEP to reflect the genuine equipment efficiency. Thus managers can make most of their capacity on hand to increase their firms’ competitiveness in the market.

References

Ahuja, I.P.S., Khamba, J.S., 2008. Total productive maintenance: literature review and directions. Int. J. Qual. Reliab. Manag. 25 (7), 709–756.

AlKhars, M., Evangelopoulos, N., Pavur, R., Kulkarni, S., 2019. Cognitive biases resulting from the representativeness heuristic in operations management: an experimental investigation. Psychol. Res. Behav. Manag. 12, 263–276.

Alsyouf, I., 2006. Measuring maintenance performance using a balanced scorecard approach. J. Qual. Mainten. Eng. 12 (2), 133–149.

Alsyouf, I., 2007. The role of maintenance in improving companies’ productivity and profitability. Int. J. Prod. Econ. 105, 70–78.

Andersson, C., Bellgran, M., 2015. On the complexity of using performance measures: enhancing sustained production improvement capability by combining OEE and productivity. J. Manuf. Syst. 35, 144–154.

Atkinson, A.A., Waterhouse, J.H., Wells, R.B., 1997. A stakeholder approach to strategic performance measurement. Sloan Management Review, Spring 25–37, 1997.

Bendoly, E., Croson, R., Goncalves, P., Schultz, K., 2010. Bodies of knowledge for research in behavioral operations. Prod. Oper. Manag. 19 (4), 434–452.

Blanchard, B., 1997. An enhanced approach for implementing total productive maintenance in the manufacturing environment. J. Qual. Mainten. Eng. 3 (2), 69–80.

Brah, S.A., Chong, W.K., 2004. Relationship between total productive maintenance and performance. Int. J. Prod. Res. 42 (12), 2383–2401.

Chambers, R.G., 1988. Applied Production Analysis: A Dual Approach. Cambridge University Press, Cambridge, England.

Chan, F.T.S., Lau, H.C.W., Ip, R.W.L., Chan, H.K., Kong, S., 2005. Implementation of total productive maintenance: a case study. Int. J. Prod. Econ. 95, 71–94.

Dale, S., 2015. Heuristics and biases: the science of decision-making. Bus. Inf. Rev. 32 (2), 93–99.

De Ron, A.J., Rooda, J.E., 2005. Equipment effectiveness: OEE revisited. IEEE Trans. Semicond. Manuf. 18 (1), 190–196.

De Ron, A.J., Rooda, J.E., 2006. OEE and equipment effectiveness: an evaluation. Int. J. Prod. Res. 44 (23), 4987–5003.

Eckerd, S., Bendoly, E., 2015. The study of behavioral operations. In: Bendoly, E., Van Wezel, W., Bachrach, D.G. (Eds.), The Handbook of Behavioral Operations Management: Social and Psychological Dynamics in Production and Service Settings. Oxford University Press, New York, USA.

Farrell, M.J., 1957. The measurement of productive efficiency. J. Roy. Stat. Soc. 120 (3), 253–281.

Flynn, B.B., Sakakibara, S., Schroeder, R.G., 1995. Relationship between JIT and TQM: practices and performance. Acad. Manag. J. 38 (5), 1325–1360.

Flynn, B.B., Schroeder, R.G., Flynn, E.J., Sakakibara, S., Bates, K.A., 1997. World-class manufacturing project: overview and selected results. Int. J. Oper. Prod. Manag. 17 (7), 671–685.

Garza-Reyes, J.A., 2015. From measuring overall equipment effectiveness (OEE) to overall resource effectiveness (ORE). J. Qual. Mainten. Eng. 21 (4), 506–527.

Garza-Reyes, J.A., Eldridge, S., Barber, K.D., Soriano-Meier, H., 2010. Overall equipment effectiveness (OEE) and process capability (PC) measures: a relationship analysis. Int. J. Qual. Reliab. Manag. 27 (1), 48–62.

Gino, F., Pisano, G., 2008. Toward a theory of behavioral operations. Manuf. Serv. Oper. Manag. 10 (4), 676–691.

Gupta, P., Vardhan, S., 2016. Optimizing OEE, productivity and production cost for improving sales volume in an automobile industry through TPM: a case study. Int. J. Prod. Res. 54 (10), 2976–2988.

Hansen, R.C., 2001. Overall Equipment Effectiveness: A Powerful Production/ Maintenance Tool for Increased Profits. Industrial Press Inc., New York, USA.

Huang, S.H., Dismukes, J.P., Shi, J., Su, Q.I., Razzak, M.A., Bodhale, R., Robinson, D.E., 2003. Manufacturing productivity improvement using effectiveness metrics and simulation analysis. Int. J. Prod. Res. 41 (3), 513–527.

Hung, Y.-H., Li, L.Y.O., Cheng, T.C.E., 2009. A new look at waste and value-added work in the toyota production system. In: Proceedings of the First POMS-Hong Kong International Conference, Hong Kong, pp. 44–50.

Konecny, P.A., Thun, J.-H., 2011. Do it separately or simultaneously – an empirical analysis of a conjoint implementation of TQM and TPM on plant performance. Int. J. Prod. Econ. 133, 496–507.

Labib, A.W., 1999. A framework for benchmarking appropriate productive maintenance. Manag. Decis. 37 (10), 792–799.

Lamme, V.A.F., 2003. Why visual attention and awareness are different. Trends Cognit. Sci. 7 (1), 12–18.

Ljungberg, Õ., 1998. Measurement of overall equipment effectiveness as a basis for TPM activities. Int. J. Oper. Prod. Manag. 18 (5), 495–507.

Mack, A., Rock, I., 1998. Inattentional Blindness. MIT Press, Cambridge, USA.

McCarthy, D., Rich, N., 2015. Lean TPM: A Blueprint for Change, *second ed.* Butterworth-Heinemann, Oxford, England.

McKone, K.E., Weiss, E.N., 1998. TPM: planned and autonomous maintenance: bridging the gap between practice and research. Prod. Oper. Manag. 7 (4), 335–351.

McKone, K.E., Schroeder, R.G., Cua, K.O., 2001. The impact of total productive maintenance practices on manufacturing performance. J. Oper. Manag. 19, 39–58.

Meller, R.D., Kim, D.S., 1996. The impact of preventive maintenance on system cost and buffer size. Eur. J. Oper. Res. 95, 577–591.

Muchiri, P., Pintelon, L., 2008. Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. Int. J. Prod. Res. 46 (13), 3517–3535.

Muchiri, P., Pintelon, L., Gelders, L., Martin, H., 2011. Development of maintenance function performance measurement framework and indicators. Int. J. Prod. Econ. 131, 295–302.
Munoz-Villamizar, A., Santos, J., Montoya-Torres, J.R., Jaca, C., 2018. Using OEE to evaluate the effectiveness of urban freight transportation systems: a case study. Int. J. Prod. Econ. 197, 232–242.
Muthiah, K.M.N., Huang, S.H., 2007. Overall throughput effectiveness (OTE) metric for factory-level performance monitoring and bottleneck detection. Int. J. Prod. Res. 45 (20), 4753–4769.
Nakajima, S., 1988. Introduction to TPM: Total Productive Maintenance. Productivity Press, Massachusetts, USA.
Nakamura, T., 2016. History of TPM and JIPM: the TPM awards from the Japan Institute of plant maintenance (JIPM). In: Baroncelli, C., Ballerio, N. (Eds.), World Class Operations Management: Why You Need More than Lean. Springer, Switzerland, pp. 169–172.
Panzar, J.C., 1976. A neoclassical approach to peak load pricing. Bell J. Econ. 7 (2), 521–530.
Pashler, H., Johnston, J.C., Ruthruff, E., 2001. Attention and performance. Annu. Rev. Psychol. 52 (1), 629–651.
Pintelon, L.M., Gelders, L.F., 1992. Maintenance management decision making. Eur. J. Oper. Res. 58, 301–317.
Purushothaman, M.B., Seadon, J., 2021. A Relationship between Bias, Lean Tools and Waste. International Journal of Lean Six Sigma. Advance online publication. https://doi.org/10.1108/IJLSS-03-2021-0045.
Rita, G., Luca, G., Francesco, L., Bianca, R., 2017. On the analysis of effectiveness in a manufacturing cell: a critical implementation of existing approaches. Procedia Manuf. 11, 1882–1891.
Sage Clarity Systems, 2019. 2018 OEE benchmark study. Available at: https://sageclarity.com/articles-oee-benchmark-study/. (Accessed 13 August 2019).
Sahin, I., Polatoglu, H., 1996. Manufacturing quality, reliability and preventive maintenance. Prod. Oper. Manag. 5 (2), 132–147.
Shingo, S., 1985. A Revolution in Manufacturing: the SMED System. Productivity Press, Cambridge, USA.
Shirose, K., 1989. Equipment effectiveness, chronic losses, and other TPM improvement concepts. In: Nakajima, S. (Ed.), TPM Development Program: Implementing Total Productive Maintenance. Productivity Press, Oregon, USA.
Shirose, K., Goto, F., 1989. Eliminating the six big losses. In: Nakajima, S. (Ed.), TPM Development Program: Implementing Total Productive Maintenance. Productivity Press, Oregon, USA.
Suzuki, T., 1994. TPM in Process Industries. Productivity Press, Oregon, USA.
Swanson, L., 2001. Linking maintenance strategies to performance. Int. J. Prod. Econ. 70, 237–244.
Tsuchiya, S., 1992. Quality Maintenance: Zero Defects through Equipment Management. Productivity Press, Oregon, USA.
Wang, F.K., Lee, W., 2001. Learning curve analysis in total productive maintenance. Omega 29, 491–499.
Wudhikarn, R., 2012. Improving overall equipment cost loss adding cost of quality. Int. J. Prod. Res. 50 (12), 3434–3449.
Zammori, F., Braglia, M., Frosolini, M., 2011. Stochastic overall equipment effectiveness. Int. J. Prod. Res. 49 (21), 6469–6490.
Zennaro, I., Battini, D., Sgarbossa, F., Persona, A., De Marchi, R., 2018. Micro downtime: data collection, analysis and impact on OEE in bottling lines the San Benedetto case study. Int. J. Qual. Reliab. Manag. 35 (4), 965–995.