International Journal of Productivity and Performance Management

Identification of maintenance improvement potential using OEE assessment

Torbjörn Ylipää Anders Skoogh Jon Bokrantz Maheshwaran Gopalakrishnan

Received 28 January 2016
Accepted 22 April 2016

Identification of maintenance improvement potential using OEE assessment

Torbjörn Ylipää, Anders Skoogh, Jon Bokrantz and Maheshwaran Gopalakrishnan
Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Abstract

Purpose – The purpose of this paper is to identify maintenance improvement potentials using an overall equipment effectiveness (OEE) assessment within the manufacturing industry.

Design/methodology/approach – The paper assesses empirical OEE data gathered from 98 Swedish companies between 2006 and 2012. Further analysis using Monte-Carlo simulations were performed in order to study how each OEE component impacts the overall OEE.

Findings – The paper quantifies the various equipment losses in OEE, as well as the factors availability, utilization, speed, quality, and planned stop time. From the empirical findings, operational efficiency losses are found to have the largest impact on OEE followed by availability losses. Based on the results, improvement potentials and future trends for maintenance are identified, including a systems view and an extended scope of maintenance.

Originality/value – The paper provides detailed insights about the state of equipment effectiveness in terms of OEE in the manufacturing industry. Further, the results show how individual OEE components impact overall productivity and efficiency of the production system. This paper contributes with the identification of improvement potentials that are necessary for both practitioners and academics to understand the new direction in which maintenance needs to move. The authors argue for a service-oriented organization.

Keywords Manufacturing, Overall equipment effectiveness, Maintenance, Production service and maintenance systems

Paper type Research paper

1. Introduction

Current productivity and equipment utilization are generally low within the manufacturing industry. As an indicator, the average overall equipment effectiveness (OEE) has earlier been reported to be around 50 per cent (Ingemansson, 2004; GoodSolutions, 2012) while world-class figures are widely argued to be around 85 per cent, (e.g. Blanchard, 1997). In fact, Parida *et al.* (2014) argue that the largest problem that exists in industry today is low OEE, being 15-25 per cent below the targeted level. Direct machine failures are naturally a major reason, but on a production systems level the rippling effects (e.g. blocked and idle states) are substantial. It is easy to see the related economic losses, but the negative impacts on ecologic sustainability cannot be neglected. In fact, studies have shown that 30 per cent of the energy consumption in industry is wasted on machines in repair, idle, and stand-by states (Skoogh *et al.*, 2011).

Maintenance departments play an important role in increasing efficiency because they have the hands on technical knowhow, and their efforts make a substantial impact on equipment uptime and effectiveness. In fact, maintenance staff should be even more involved, and share their knowledge along the entire lifecycles of product and production systems. Examples of important contributions are found in: machine purchase, downtime reduction in running production, safety analysis, and expertise in repairing, renovating, or replacing equipment close to end-of-life.

Takata *et al.* (2004) claim that in the view of sustainable manufacturing, we should redefine the role of maintenance as a prime method for life cycle management. However, it is difficult to distribute maintenance efforts between reactive, preventive, and improving

International Journal of Productivity and Performance Management
Vol. 66 No. 1, 2017
pp. 126-143
© Emerald Publishing Limited
1741-0401
DOI 10.1108/IJPPM-01-2016-0028

activities in a strategic way. As an example, companies are struggling to switch focus from reactive maintenance to preventive and proactive efforts. A study in the aerospace industry resulted in the exposure of counteracting factors hindering the case company from turning a ratio of approximately 70 per cent reactive efforts and 30 per cent preventive efforts into the opposite proportion or preferably even better (Sandberg *et al.*, 2014).

Hence, there are several challenges in maintenance. One problem is to map the current state of equipment losses and relate them to existing maintenance activities. In fact, few studies are available showing the industrial averages of these losses (Ljungberg, 1998), and there is a lack of effort aimed at identifying key aspects for improvement. Another problem is that current definitions of maintenance focus on retaining and restoring equipment rather than reaching beyond an initial state. This is assumed to draw a line between maintenance and other departments such as production, engineering, and purchasing within organizations.

Therefore, the aim of this paper is to describe the need of maintenance evolutions in the manufacturing industry using an extensive set of OEE data to quantify the losses and identify the main factors that hinder OEE figures to reach world-class levels. Further, the study aims to show how much effort is invested in preventive compared to reactive maintenance activities at present. This information will serve as a guideline for future research and industrial development within maintenance organizations and their collaboration with other support functions.

First, the paper reviews important literature on OEE measurements as well as maintenance evaluations, concepts, and practices. Thereafter, the methodology for collecting and analyzing an extensive set of OEE measurements is described, followed by the empirical results. The last part of the paper discusses the results and reaches a conclusion on current maintenance role and future needs for increasing productivity and meeting upcoming challenges in manufacturing.

2. Frame of reference

The theoretical frameworks within maintenance and OEE and how this is related to productivity and production system efficiency are presented in this chapter.

2.1 Maintenance evolution

Maintenance in industry is an important area when securing equipment reliability. It is generally divided into two main categories, i.e. unplanned maintenance and planned maintenance. First, reactive maintenance action cannot be planned and occurs when we do not want it to. Second, preventive maintenance action aims to control the level of failures. Of these two types, it is preventive maintenance, and especially when to perform it, that has been the object of most of the academic interest in the past. According to the European Standard WI 319-003, maintenance is defined in as:

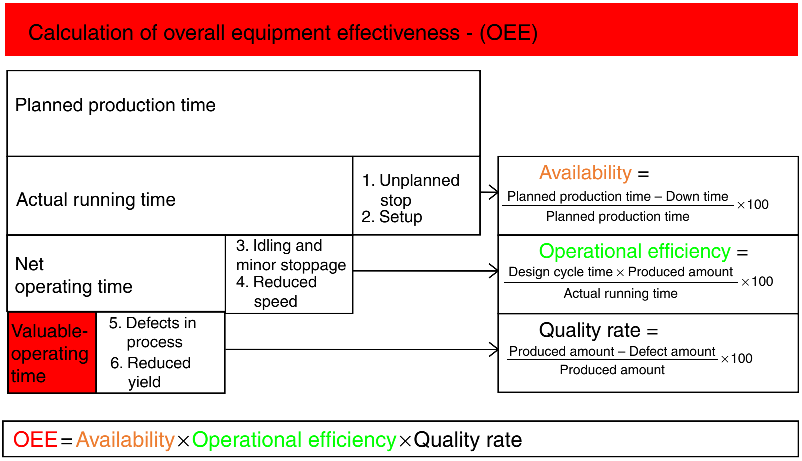
> A combination of all technical, administrative and managerial actions during the life-cycle of an item, and intended to remain it in, or restore it to a state in which it can perform the required function.

Moubray (1997) describes how the evolution of maintenance has passed through three generations of development from reactive maintenance towards predictive maintenance. Alsyouf (2007) also describes this development and adds a fourth holistic process oriented step. Dunn (1998) claims that the fourth generation of maintenance has more focus on safety, a greater integration between functional requirements, equipment design and maintenance, as well as a much greater use of information technology to detect, predict, and diagnose equipment failures. Pintelon and Parodi-Herz (2008) also discuss the evolution of different generations of maintenance concepts such as total productive maintenance (TPM), reliability centred maintenance (RCM), etc.

Even though there have been great developments within maintenance, service on the other hand has a broader scope. Service has initially laid more emphasis on consumer service (Ojasalo, 2007). During the last decade however, integration of manufactured products and service has become a fast growing business area in the manufacturing industry. A commonly used term is industrial product-service system (IPSS), defined as customer life cycle-oriented combinations of product and service (Mont, 2002). In this sense, service exceeds traditional maintenance and includes other services like planning, processing, and training (Alonso-Rasgado *et al.*, 2004). Takata *et al.* (2004) presents a view of maintenance activities from a service perspective, stemming from the outlook that the role of maintenance is currently changing within the area of life-cycle management. They provide a description on how gaps between the required function and the realized function are generated by changes during the life cycle, either due to deterioration or changes in the needs of customers or society. Maintenance is in turn executed to compensate for these gaps by means of reactive, preventive, improvement, and upgrade activities.

In an industrial environment, the best result that can be achieved within the confines of the narrow maintenance definition is clearly established in literature: reactive and preventive maintenance activities can only restore an asset to its inherent reliability – it cannot go beyond it (Moubray, 1997; Dunn, 1998; Coetzee, 2002; Mobley *et al.*, 2008). Following this, numerous authors elaborated on how most root causes of equipment reliability problems originate outside the maintenance department, and are uninfluenced by maintenance activities. For example, Mobley *et al.* (2008) presents a long list of causes of reliability problems in sales, production, procurement, plant engineering, and management. When accepting this limitation of maintenance activities, the next step is naturally to suggest ways in which this can be solved. Throughout history, various maintenance concepts such as TPM (Nakajima, 1988), terotechnology (Sherwin, 2000) and total quality maintenance (TQMain) (Al-Najjar, 1996) have expressed a view that to enlarge maintenance from the classical role of fix something when it is broken or prevent so it is not broken, to a more holistic company-wide approach to solving equipment-related problems, is more productive. Ahmed *et al.* (2005) even argue that TPM can go beyond maintenance and bring about such improvements in terms of reduction of manufacturing cycle time, size of inventory, and customer complaints. Other authors such as Sandberg *et al.* (2014) also argue for an enlarged maintenance function that assumes responsibilities far beyond the confines of traditional maintenance in the use-phase. Likewise, in his conceptual paper on fourth generation maintenance, Dunn (1998) stresses that future maintenance managers will require an expansion beyond traditional maintenance into, e.g. equipment selection and design. Widening the scope of maintenance from an economic perspective has also been a well-discussed topic, where several authors have presented models to calculate how maintenance influences profitability (e.g. Haarman and Delahaye, 2004; Alsyouf, 2007). On this topic, Ahlmann (2002) argues that maintenance must be managed as a process instead of by the out-dated maintenance department, and evaluated from a much wider perspective than the narrow and insufficient basis of costs and internal efficiency.

However, maintenance departments in many industrial organizations are still perceived as the sole supplier of equipment dependability, despite the narrow influence and actual control the maintenance function has on most equipment problems. At the same time, deficient maintenance practices are often seen as one of the main reasons for poor productivity and profitability. For example, this is shown by how OEE is still used by many companies as a maintenance performance indicator (Kumar *et al.*, 2013), despite the situation being that traditional maintenance activities (i.e. reactive and preventive) mainly affect two of the six main losses (Figure 1), i.e. planned and unplanned downtime. From this, the main point is clear: the act of maintenance cannot solve all reliability problems, and traditional maintenance departments cannot deliver sufficient production efficiency and effectiveness



Source: Based on Nakajima (1988)

Figure 1.
OEE and losses

when standing alone. Therefore, the vast majority of practitioners and academics can agree on the following: in order to achieve failure elimination and high production performance, all organizational functions influencing equipment must communicate, collaborate, and be integrated in addressing equipment problems.

This have been stressed in most concepts, where, e.g. TPM focus on the interface between engineering and maintenance through early equipment management and maintenance prevention (Gotoh, 1991), and between operations, quality, and maintenance through autonomous maintenance and focussed improvements of OEE (Nakajima, 1988). Terotechnology (Sherwin, 2000) highlights the collaboration with engineering as well as equipment OEM's using feedback loops. TQMain (Al-Najjar, 1996) strives to integrate various functions such as engineering, quality, and operations in a combined predictive maintenance data system, a suggestion also made by Mobley *et al.* (2008). In fact, Amadi-Echendu (2004) explains how concepts such as TPM and RCM only appear to be effective when the legacies of organizational barriers are de-emphasized. The realization of this inter-disciplinary nature of managing equipment is largely captured in the development of the discipline of asset management (AM), which by now has spawned through PAS55 into the release of the much-anticipated ISO55000 standard (numerous definitions and interpretations of AM exist, but a proposed AM framework is available in El-Akruti and Dwight, 2013). Nonetheless, what is shared among these examples is that they propose communication, collaboration, and integration between organizational functions, whilst preserving the structure where each function is designated in separate departments. Nonetheless, alternative solutions to the same fundamental problem can also be found, where for example Peng (2000) explains the situation at Intel where the maintenance department vanished through upstream integration with engineering, finally resulting in a consolidated ownership of all asset life cycle activities into a platform-based equipment management structure.

2.2 OEE

OEE is a key measurement in TPM introduced by Nakajima (1988). Today the OEE measurement is becoming increasingly popular, even outside the TPM concept, and used as a standalone key performance measurement tool for productivity improvements. Originally the OEE metric consisted of six major' losses, i.e. equipment failures, setup and adjustments, idling and minor stoppages, reduced speed, defects in process, and reduced yield (Nakajima, 1988).

More recently, a number of other planned stoppage factors, such as preventive maintenance, shortage of staff, etc., have been proposed to be included in the OEE calculation (Blanchard, 1997; Ericsson, 1997; Haarman and Delahay, 2004; Hansen, 2002; Ingemansson, 2004; Ljungberg, 1998; Sekine and Arai, 1998; Smith and Hawkins, 2004). According to Mikler *et al.* (1999) it can be questioned what factors should be regarded as losses. For example, it is debatable if a planned stoppage such as setups should be seen as a loss or not. The authors claim that it is logical to consider resetting as a loss, as it does not add any value to the product (Mikler *et al.*, 1999). Preventive maintenance is another kind of planned stoppage that can be questioned. This factor, however, is aimed to prevent failures from occurring, but it can still hinder products from being manufactured. For an in-depth discussion about this see Bokrantz *et al.* (2016).

The industrial application of OEE varies from one company to another and several different concepts have been developed. Muchiri and Pintelon (2008) present a literature review of the different concepts such as overall process effectiveness (OPE), overall throughput effectiveness (OTE), and total overall process effectiveness (TOPE). While OEE is about achieving excellence in individual equipment, the other measures (i.e. OPE, OTE, TOPE) also cover the relationships among different machines and processes, i.e. a line or an entire production system.

A study by Ljungberg (1998) reported data covering the six major losses from 23 different bottleneck machines (Table I). These figures can directly be compared with the results in this study performed about two decades later. An interesting result in Ljungberg's (1998) study was that the OEE for new processes (45 per cent) was much lower than for older processes (65 per cent), i.e. new machines are suffering from more production disturbances.

However, it is not always a straightforward task to measure some of these losses. Ljungberg (1998) found cases of positive cycle time losses, i.e. the process is run at a shorter cycle time/higher speed than nominal, as well as losses from other parts of the production system than the bottleneck influencing the losses measured at the bottleneck machine. Furthermore, minor stoppages are also hard to measure and can also influence, for example the availability, cycle time losses and reduced yield.

2.3 Planning of maintenance activities

Planning of maintenance activities is essential to production system efficiency. The objective of maintenance planning is to effectively utilize maintenance staff and minimize the impact of downtime on the production capacity of the whole plant (Mobley, 2004). Therefore, possessing a good knowledge of the equipment criticality would help in focusing maintenance resources on the most important equipment. To establish equipment criticality, manufacturing companies in Sweden predominantly use an ABC-type classification

Table I.
OEE results

OEE components (%)	Average
Planned stop	5
Availability	80
Unplanned stop	12
Setup losses	8
Operational efficiency	68
Utilization	77
Speed rate	91
Quality rate	99
OEE	55

Source: Ljungberg (1998)

(Gopalakrishnan *et al.*, 2015). However, such classifications differ between companies, and traditional ABC-classifications utilize a variety of factors such as environment, reliability, and availability to establish equipment criticality (Márquez, 2007). In fact, it is crucial to understand how machine level reliability affects the system level efficiency, i.e. productivity. Unfortunately, typical ABC-classifications cannot identify equipment criticality in terms of overall system performance. To improve the performance of the entire system, the focus must lie on throughput-critical machines (Ni and Jin, 2012). It has been shown that prioritizing maintenance activities to throughput-critical machines (i.e. bottlenecks) increases the throughput of the whole system (Gopalakrishnan *et al.*, 2013). However, the system may change over time due to random events occurring in the various machines, which result in that bottlenecks may shift from one machine to another over time (Roser *et al.*, 2002). Therefore, real-time bottleneck detection using live data are necessary to obtain continuous production improvement (Li *et al.*, 2009), and such approaches may be particularly valuable for maintenance planning purposes.

3. Methodology

The empirical findings presented in this paper were based on OEE data collected from 98 different companies in over 50 industrial workshops in Sweden between 2006 and 2012. The participants were first educated and trained in how to collect data and perform an OEE assessment. Then the participants were asked to select the bottleneck in their production system and perform an OEE assessment based on a data collection time ranging from one to five weeks. A total of 124 OEE calculations were made originally. However, certain calculations lacked data on all OEE components. For example, one OEE calculation did not have data on utilization but directly presented the operational efficiency data. Therefore, the OEE calculations which had data on all components alone were considered. After discarding this poor data, a total of 94 OEE calculations were finally selected for analysis.

The companies were a mixture of discrete and process industries and of different sizes concerning turnovers, personnel, etc. Additionally, company sizes range from small to large scale, including supplier companies and multi-national companies. The OEE data were compiled in an Excel sheet and further analyzed using Monte-Carlo simulations (@-Risk software was used) to find out the relative importance of the factors in OEE. The OEE assessments were performed according to Nakajima's (1988) six major losses (Figure 1).

In order to better understand the OEE results, it is important to elaborate on the calculations behind the "availability" part of the OEE value. Availability was calculated by considering the planned production time, not the total available production time. Figure 2 represents the distribution of different production times from which the calculations are made. The total available production time is the scheduled time for production without any interruption whatsoever. For example, the total available production time for one day with one eight-hour shift is eight hours and then the planned production time for this day with one hour planned production stoppage is seven hours. Further on, if the downtime for the day is one hour, composing of unplanned stop time and set-up time, then the "actual production time" (see Figure 2) would be six hours. Therefore, it is to be noted that apart from planned stops, all other OEE components are calculated with respect to the planned production time. Therefore the planned stop percentage cannot be equated with the percentage values of any other components of the OEE.

4. Results

The results chapter presents the gathered OEE data from 98 companies and also quantifies the various components used for the calculation of OEE. Additionally, Monte-Carlo simulation results are presented identifying the level of impact of components on OEE.

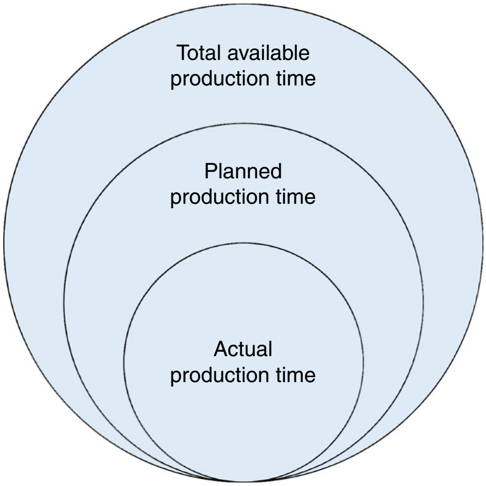


Figure 2.
Pictorial representation of production time

4.1 OEE data

The collected data includes planned stop time, unplanned stop time, set-up time, utilization, speed loss, and quality rate. Using these data, the availability, operational efficiency, quality rate, and the OEE for each machine is calculated. The overall results of the OEE data are summarized by the average values of the collected and calculated OEE components and are presented in Table II. Please note that the planned stop percentage (6.6 per cent) is calculated from the total available production time (Figure 2). This shows that average OEE is still 51.5 per cent, despite the fact that an average of 6.6 per cent of the possible production time was not considered for the OEE calculation. This means that if planned stoppages were to be included in OEE calculations (as proposed by many scholars), the already low figures would be hampered even further. A detailed analysis of the OEE values and the other components are further described in this section.

In order to analyze the distribution of the OEE values, the total set of 94 OEE values were used to plot a histogram (Figure 3) that shows the frequency of the OEE percentage rating. It can be observed that the highest frequency of OEE lies between 60 and 70 per cent, followed by between 20 and 30 per cent (both more than 15 values each). Even though the average OEE was 51.5 per cent, values are more or less evenly distributed between 20 and 80 per cent.

Further, in order to predict the OEE values based the collected empirical data, Monte-Carlo simulation software was used. The simulation run was carried out with 10,000 iterations, and the results are shown in Figure 4. The simulated OEE was based on fitted statistical

Table II.
Summary of the gathered OEE results

OEE components (%)	Average
Planned stop	6.6
Availability	78.9
Unplanned stop	9.6
Setup losses	11.5
Operational efficiency	67.1
Utilization	80.2
Speed rate	86.1
Quality rate	96.9
OEE	51.5

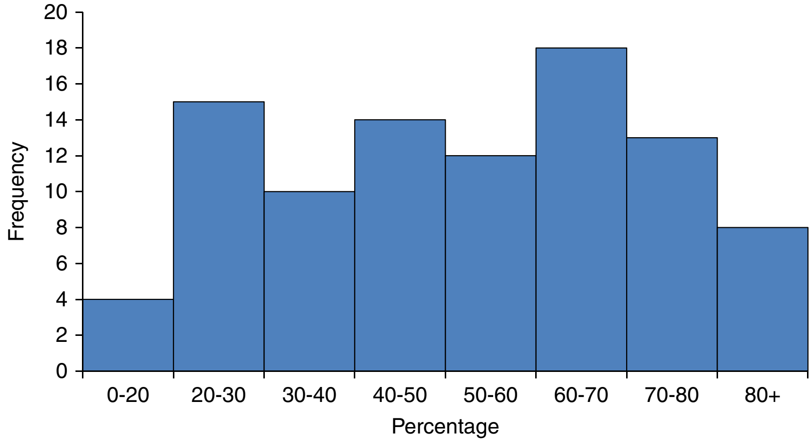


Figure 3.
Histogram of the percentage frequency of OEE

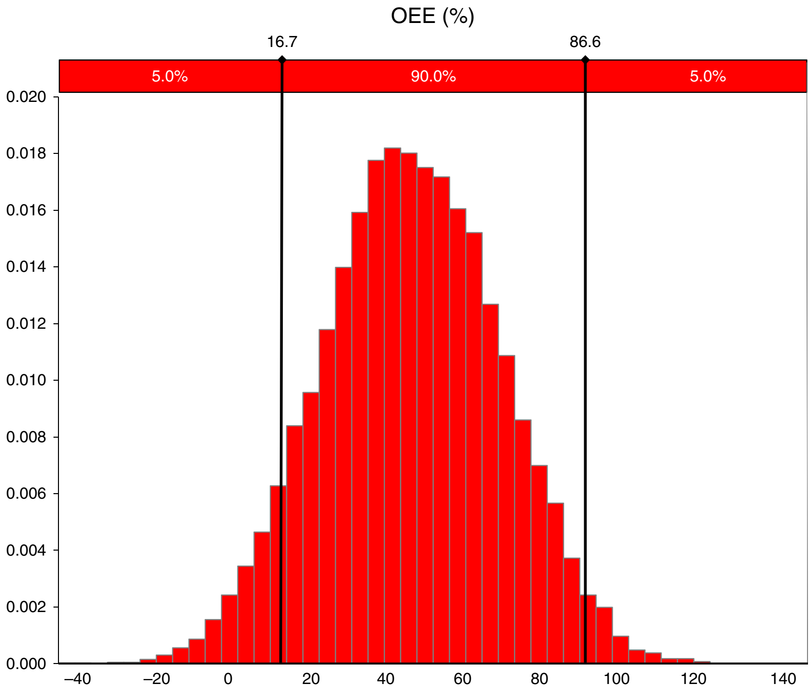


Figure 4.
Monte-Carlo simulated OEE results

distributions of availability, operational efficiency, and quality rate. From the simulated results, it can be observed that the average OEE values are normally distributed with an average of 51.9 per cent and a standard deviation of 21.20 per cent. Further, Figure 4 shows that with a probability of 90 per cent, the OEE percentage rating lies between 17 and 87 per cent, which is rather similar to the distribution fit of the actual empirical OEE results (Figure 3).

Moreover, the OEE component (availability, operational efficiency, or quality rate) that impacts the overall OEE the most, was identified. From a tornado analysis of the simulation result (Figure 5), it is observed that operational efficiency has the biggest impact on the OEE, followed by availability. The quality rate has the least impact on the OEE. For the existing average values of availability and quality rate, a low operational efficiency percentage of a machine may result in an OEE of as little as 17 per cent. In contrast, high operational efficiency could improve the OEE up to 82 per cent. Considering the existing average operational efficiency and quality rate, the availability percentage of the machines can cause the OEE to vary between 32 and 65 per cent. Finally, the quality rate of machines can make the OEE vary between 48 and 54 per cent, if the existing average values of availability and operational efficiency are considered.

4.2 Availability

The average availability of the machines from the empirical data are 78.9 per cent, with a minimum of 33.1 per cent and a maximum of 98 per cent. This suggests that the bottleneck machines are not used to their full planned capacity. In order to analyze the distribution of availability percentage across machines, a histogram was plotted (Figure 6).

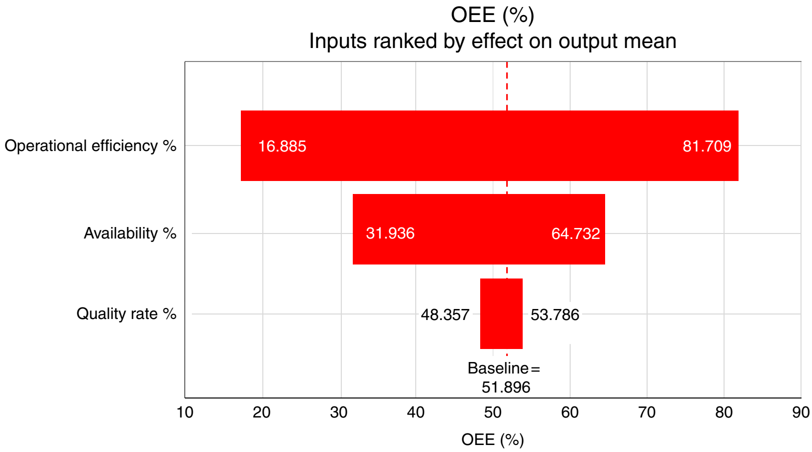


Figure 5.
Effects of individual components on OEE

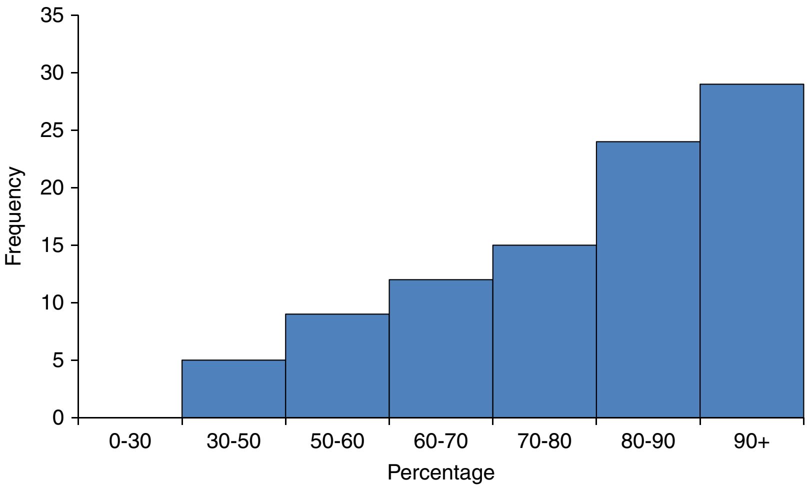


Figure 6.
Histogram of the percentage frequency of machine availability

The distribution of availability values increases from 30 to 50 per cent all the way to above 90 per cent. It can be observed that there are no availability values below 30 per cent.

The availability is the time remaining after subtracting the unplanned and setup time losses of the machines. Therefore, it is important to take a detailed view of the unplanned and set-up time losses of machines. First, the unplanned losses are analyzed. The average unplanned stop time is 9.63 per cent, with a minimum of 0.16 per cent and a maximum of 34.99 per cent. In order to analyze the distribution of unplanned losses, a histogram was plotted (Figure 7). Despite an average of 9.63 per cent, the majority of the unplanned losses lines lie between 0 and 5 per cent in the histogram, and there are no values over 40 per cent.

Second, the setup losses are analyzed (Figure 8), these following a similar distribution to that of unplanned losses (Figure 7). It can be seen that most losses lies between 0 and 5 per cent, followed by a steady decrease towards negligible values after 40 per cent. The average setup time is 11.54 per cent, with a minimum of 0.28 per cent and a maximum of 64.7 per cent.

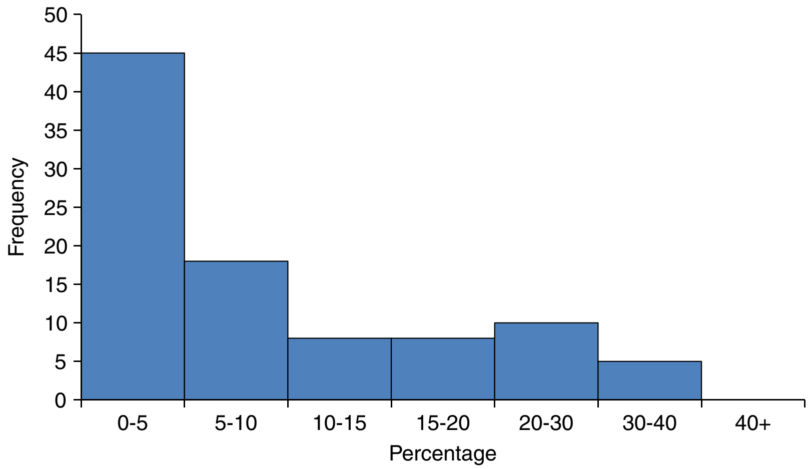


Figure 7.
Histogram of the percentage frequency of unplanned losses

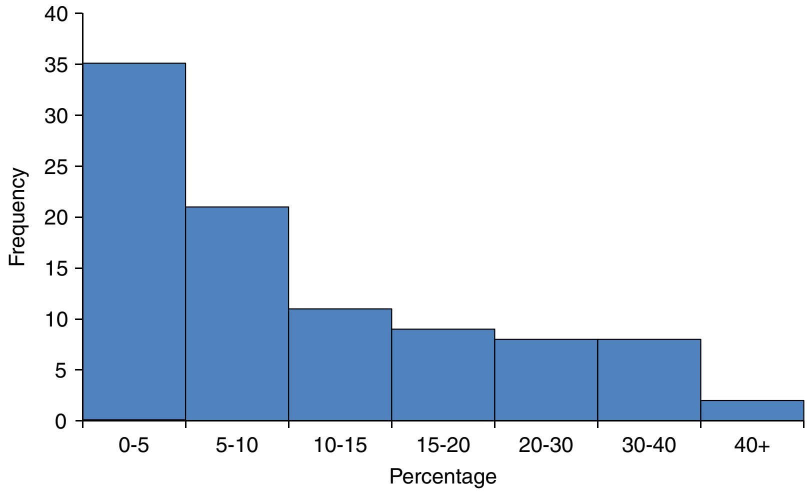


Figure 8.
Histogram of the percentage frequency of machine setup losses

4.3 Operational efficiency

The second OEE component is operation efficiency. From the calculated operational efficiency data, the average values obtained were 67.1 per cent, with a minimum of 4.8 per cent and maximum of 124 per cent (Table II). It can be seen that operational efficiency varied between companies. Figure 9 shows the frequency of distribution of the operational efficiency percentages. It can be seen that the frequency peaks in the 80-90 per cent range, and that there are consistently ten or more values in each section from 40 per cent and upwards.

The varied distributions of the operational efficiency were due to the utilization and speed rate percentages used to calculate the same. The average utilization from the data were 80.2 per cent, with a minimum of 4.8 per cent and a maximum of 129 per cent, whereas the average speed rate was 86.1 per cent with a minimum of 25 per cent and a maximum of 124 per cent. In particular, the utilization percentages of machines are calculated from machine availability. Therefore, the losses in utilization (difference between availability and utilization) are primarily ripple effects (idle and blocked times) in the production system. This suggests that system losses have a substantial impact on the OEE.

4.4 Quality rate

The last component used to calculate OEE is the quality rate. From the empirical data, it is observed that the quality rate of machines is generally high, with an average of 96.9 per cent, a minimum of 65 per cent, and a maximum of 100 per cent. The distribution fit for quality rate was not performed, since the majority of the machines had more than a 90 per cent quality rate.

4.5 Planned stop losses

In line with the original OEE definition, the OEE calculations in this study separated planned losses from planned production time (see Section 4.1). However, empirical data for the planned losses were collected, in which the average planned stop time is 6.63 per cent with a minimum of 0 per cent and a maximum of 31.58 per cent of the total available

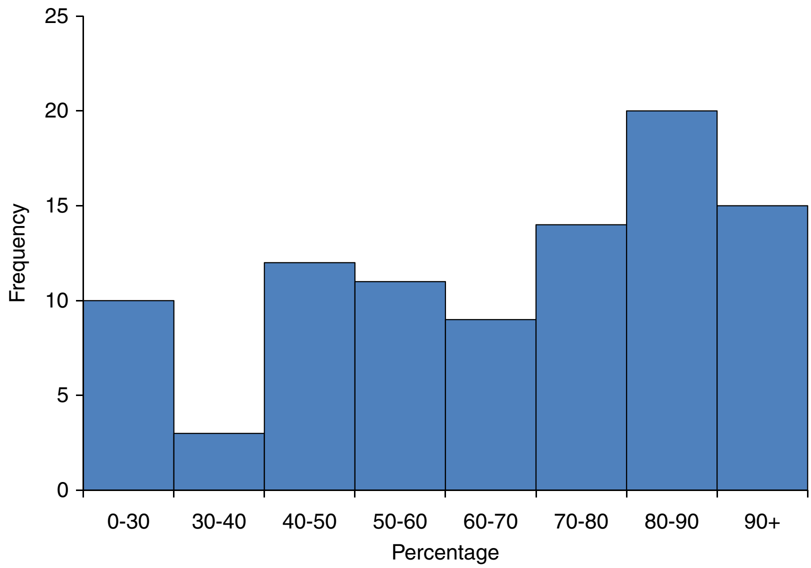


Figure 9.
Histogram of the percentage frequency of operational efficiency

production time. The histogram in Figure 10 shows the distribution of frequency of the planned stop time percentages of machines. It can be observed that the majority of the planned stop time values lie between 0 and 5 per cent, and decreases gradually down to 40 per cent. There are no values of planned stop time above 40 per cent.

5. Discussion

The discussion chapter presents the mapping of empirical OEE findings compared with industrial maintenance practices and the identified maintenance improvement potentials based on quantified OEE values and various production losses.

5.1 Mapping of OEE compared with industrial maintenance practices

The authors have examined empirical OEE data collected from 94 bottleneck machines in the Swedish manufacturing industry. The average OEE value of 51.5 per cent indicates there is a large improvement potential for the industry to raise their production efficiency. Moreover, compared with the study reported by Ljungberg (1998) almost two decades ago, the average OEE value has not improved, but rather decreased. An interesting result, presented in Table II, is that the time companies spend on preventive maintenance is, on average 6.6 per cent, which is the planned stop time. These results are similar to Ljungberg's (1998), but he also included other losses, such breaks in production schedule, precautionary resting time and daily shop floor meetings, in the planned stop time. This means that in the worst case, the results of this study may indicate that no time at all is spent on preventive maintenance, and many maintenance organizations are thus solely conducting repairs. These results lend further support to the difficulty in shifting from a reactive to a preventive mind-set (Sandberg *et al.*, 2014).

Further, the unplanned stoppage time is on average 9.6 per cent (slightly lower than Ljungberg's, 1998), which includes reactive activities. Moreover, the companies did not collect specific data regarding small stoppages. Therefore, these stoppages could be reflected in the utilization losses, or be part of the unplanned stoppages. Thus, based on the empirical findings, the industrial (or TPM) goal of "zero ups" is still far away. However, shifting from reactive to preventive is not the only solution, as studies have shown that working effectively with reactive maintenance can lead to increased production efficiency (Gopalakrishnan *et al.*, 2013; Li *et al.*, 2009).

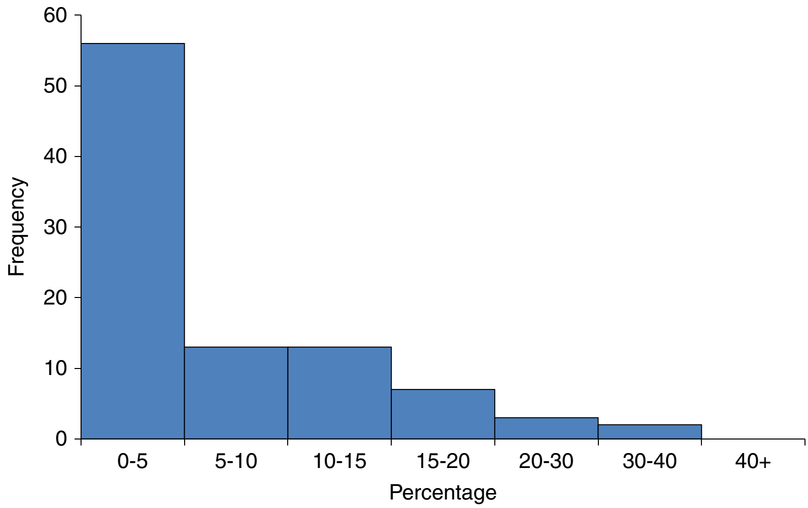


Figure 10. Histogram of the percentage frequency of machine planned losses

The biggest loss of the availability component was due to the setup times, with an average of 11.5 per cent, which is slightly higher than the numbers reported by Ljungberg (1998). Since traditional maintenance activities do not directly contribute to a reduction in set-up losses, improvement work on production and maintenance personnel collaboration is necessary. However, a major cause of system efficiency reduction is the operation efficiency of machines. In tightly coupled production systems with limited buffers, the rippling effects (blocked and idle states) will, of course, affect all efficiency at production system level (Skoogh *et al.*, 2011). Such losses are reflected in the operational efficiency component in this study, and the results show an average of around 67 per cent (Table II). This component also has the highest impact on the OEE (Figure 5). Therefore, a more system-oriented version of OEE, that covers the relationships among different machines and processes, is to be advised (Muchiri and Pintelon, 2008), and more effort should be directed towards the throughput-critical machines that impede overall system performance (Ni and Jin, 2012).

The last main factor in the OEE calculation is the quality rate. The empirical results illustrating high quality rate (average of approximately 97 per cent) is consistent with that of Ljungberg (1998), and the simulation results indicate that the quality rate has the lowest impact on the OEE (Figure 5). However, Nakajima's (1988) original OEE definition treats all three components at equal weights, and since product quality problems may directly affect the end customer, they can be seen as more serious than other internal losses. Nonetheless, upholding this high quality rate within the manufacturing industry is essential, and could be further improved through quality improvement work such as six sigma.

To conclude this mapping of OEE compared with maintenance practices, there are several losses that hinder production efficiency, and some of these losses are outside the area of traditional maintenance. Therefore, two courses of action are necessary. First, in order to utilize the existing maintenance practices effectively, a new view on maintenance is needed. Second, a wider scope of maintenance activities is needed.

5.2 A system view on maintenance

Maintenance has a tradition of practicing single-loop learning. The focus is on repairing broken technical equipment to make this work in accordance with specifications, or oftentimes just "as it is used to be". This mindset is also reflected in common maintenance KPIs, e.g. MTBF and MTTR. Such KPIs are usually measured on an individual equipment level and do not give much valuable information in terms of directing maintenance efforts based on a systems perspective. There are so many other parameters besides the direct downtime that determines what is constraining the system performance at a given point in time.

Further, in line with the previous paragraph, there is currently a focus on minimizing direct downtime, despite research studies and empirical data from this study actually showing that the major productivity losses are more related to their rippling effects (i.e. the blocked and idle machine states) (Skoogh *et al.*, 2011). Therefore, it is desirable that future decision support systems and planning principles focus on providing prioritized reactive and preventive maintenance as well as improvement activities directed towards the machines that constrain the system at any given point in time. However, such throughput-critical machines (i.e. bottlenecks) are difficult to track manually and have a tendency to move dynamically through the system (Roser *et al.*, 2002). Therefore, data-driven or simulation-based bottleneck techniques are desirable (Li *et al.*, 2009), and could be of great value for maintenance planning. To further support the differentiation of maintenance efforts to the most important parts of the system, establishing equipment criticality through criticality classification methods is of great value. However, the limitation of typical ABC-classifications used in industry in terms of detecting throughput-critical machines (Márquez, 2007; Gopalakrishnan *et al.*, 2015) calls for further development of equipment criticality classification methods. Based on the discussion above, maintenance planning needs to be more selective and fact-based compared to present situation. Acoustic planning, i.e. the loudest operator gets help first (humoristic reflection from an employee at one of the authors' partner companies) should be avoided, and instead replaced by modern methods for production data analysis where the system constraint is prioritized on a real-time basis (Li *et al.*, 2009).

5.3 Production service and maintenance systems

Based on the findings that current OEE figures are low and the fact that insufficient operational efficiency and availability are the two main reasons for this (Table II), there is a need for change in the maintenance function in the manufacturing industry. Equipment failures and their rippling effects on a systems level need to be more effectively handled in future production. This required change is even more important because of the expected implementation of digital production concepts such as Industrie 4.0 (In English: Industry 4.0). Digital production increases the level of complexity of production equipment and requires high availability and robustness to enable autonomous and highly automated production systems.

Therefore, current definitions of maintenance and the way companies organize this function is too narrow for future challenges (Takata *et al.*, 2004). Current maintenance needs to evolve from only retaining and restoring equipment back to a designed level (see Section 2.1) to taking a wider responsibility, including improvements and upgrades for extended equipment life-cycles (Figure 11). Organizational-wide communication, collaboration, and integration are essential as maintenance organizations cannot solve all problems related to OEE themselves (Mobley *et al.*, 2008) and the effect of reactive and preventive maintenance activities are limited to inherent reliability (Moubray, 1997; Dunn, 1998; Coetzee, 2002). Furthermore, there is currently a general lack of analysis capability and facts-based decision support because maintenance organizations are mainly experience-driven.

Based on these challenges, the authors foresee that the maintenance function will follow the development of IPSS (Mont, 2002; Alonso-Rasgado *et al.*, 2004) and become increasingly service oriented. Eventually, maintenance turns into a production service and maintenance system (PSMS). A PSMS aims to retain, restore, and improve (Figure 12) production systems' relative inherent or agreed specifications during their entire life cycles. Reactive and preventive maintenance as well as improving activities are applied to increase economical, ecological, and social sustainability. PSMS focuses more on a systems level compared to the traditional view of maintenance, in which the overall performance of a production flow or plant is of major importance.

In line with this, it is expected that the out-dated view of the maintenance department (Ahlmann, 2002) will become legacy, and the maintenance function will take on a wider

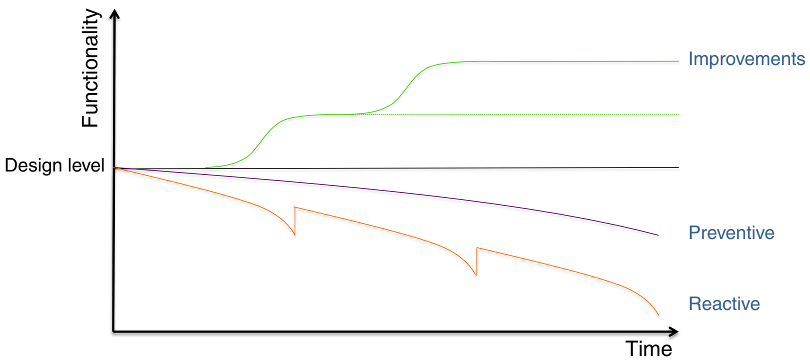


Figure 11. The impact of reactive, preventive and improvement activities on production system functionality

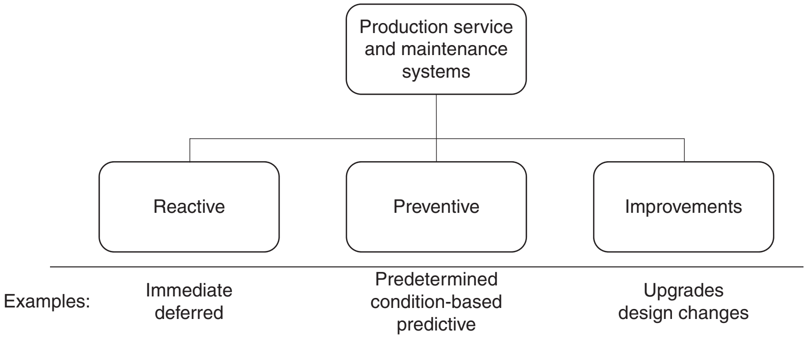


Figure 12.
Production service and maintenance systems

responsibility (Sandberg *et al.*, 2014) and integrate with other functions (e.g. purchase, engineering, and operations) to an even higher extent than what is proposed in concepts like TPM (Nakajima, 1988), TQMain (Al-Najjar, 1996) and AM (El-Akruti and Dwight, 2013). In fact, it is likely that a further step beyond communication, collaboration, and integration, is that companies in the future reorganize to turn the functional organization into a completely integrated, service-oriented organization (e.g. Peng, 2000). In such an organization, resources from the departments that currently influence equipment, form a team responsible for a delimited part of the production system over its entire life-cycle, from purchase through implementation, production, maintenance, upgrades, and end-of-life. Production is delivered as a service.

Such a modern view of designing, maintaining, and upgrading functionality over entire life-cycles is expected to improve the status of current maintenance workers. This will, in turn, facilitate the recruitment of talented and motivated personnel. The final result is increased capabilities of analyzing big data sets and preparing facts-based decision support. The bottom line is that PSMS will enable more robust and resource efficient production systems.

5.4 Methodology discussion

The strength of OEE measurements is that they provide comprehensive information, are well-known within the manufacturing industry, and are rather simple to calculate. In this study, one challenge with the OEE data were that they were collected as secondary data. The authors did not collect the data directly from the shop-floor, but were deeply involved in educating the industrial participants in established work procedures. The experience from the workshops is that the collection worked well and that the data are reliable. Another aspect to discuss is the timing of the data collection. Data were gathered from 2006 to 2012 with both ups and downs in the global economy. This wide time-span is of course positive when presenting average values, but it is still difficult to quantify to what extent good compared to bad (e.g. 2007 and 2008) years affected the OEE values. The time for which the data were collected at each company varied from one to five weeks. Around one month of data collection would of course have been preferable at all companies, but this was not possible due to limitation in time and data availability.

6. Conclusions

This study analyzed 94 empirical data sets from the manufacturing industry between 2006 and 2012 and found the average OEE to be 51.5 per cent. This means that the utilization of current production resources is low, which in turn leads to insufficient productivity and resource efficiency. These facts are problematic for current production in terms of economic and ecologic sustainability. In addition, low OEE figures are challenging for the expected increase of digitalization in production, where factories will be substantially more autonomous that today (compare concepts such as Industrie 4.0).

Further, the OEE assessment showed that operational efficiency and availability are the two main contributors in terms of losses. Average operational efficiency was 67.1 per cent and the average availability was 78.9 per cent. The fact that operational efficiency (including, e.g. blocked and idle machine states) is the category with highest impact shows that a systems perspective is important, also in maintenance. Components such as holistic performance measures, dynamic criticality analysis, and priority-based scheduling are needed. Direct unplanned downtime (included in availability figures) is naturally important, but the rippling effects have an even higher impact on the OEE.

Another interesting finding was that the distribution of preventive maintenance activities compared to reactive repairs is still not satisfactory. This is shown in the 9.6 per cent unplanned stops and 6.3 per cent planned stops in the data. It should also be mentioned that even more reactive stops can be hidden in the utilization category as minor stoppages.

The bottom line is that the current handling of production disturbance within the manufacturing industry is not effective. The OEE figures have not increased over the last decades, rather slightly decreased, and maintenance workers are mostly working with repairs instead of preventive activities. It is obvious that changes are needed. The authors argue for an increased systems view on maintenance, extended scope and responsibilities, and integration with other functions such as purchase and production engineering. The new, completely integrated organization, referred to as PSMS, will take responsibility over entire product life-cycles and deliver production as a service.

7. Future research

Maintenance organizations in the manufacturing industry will face several major challenges during the coming decades, especially in relation to increased digitalization in manufacturing. This paper highlights the problem that the traditional maintenance field has not developed and delivered improvements for a long time. OEE figures are the same as almost two decades ago. In addition to that, it can be assumed that the production environment will progress even faster in a near future because of the introduction of cyber-physical systems. Therefore it is crucial for future research activities to assist maintenance and manufacturing organizations to achieve a higher overall productivity and efficiency of the production system. The following fields need to develop rapidly:

- identification and definition of production service improvement activities;
- manufacturing data management for production service and maintenance purposes – collecting, analyzing, storing, and sharing the right amount of data;
- real-time analysis of big data sets for production service and maintenance purposes;
- data-driven criticality analysis to make sure that the constraining equipment, from a systems perspective, is always available; and
- safe and inspiring work-places attracting knowledge to production service and maintenance organizations.

References

Ahlmann, H. (2002), "From traditional practice to the new understanding: the significance of life cycle profit concept in the management of industrial enterprises", *IFRIM Conference*, *Växjö, 6-8 May*.

Ahmed, S., Hassan, M.H. and Taha, Z. (2005), "TPM can go beyond maintenance: excerpt from a case implementation", *Journal of Quality in Maintenance Engineering*, Vol. 11 No. 1, pp. 19-42.

Al-Najjar, B. (1996), "Total quality maintenance", *Journal of Quality in Maintenance Engineering*, Vol. 2 No. 3, pp. 4-20.

Alonso-Rasgado, T.A., Thompson, G. and Elfström, B.O. (2004), "The design of functional (total care) products", *Journal of Engineering Design*, Vol. 15 No. 6, pp. 515-540.

Alsyouf, I. (2007), "The role of maintenance in improving companies' productivity and profitability", *International Journal of Production Economics*, Vol. 105 No. 1, pp. 70-78.

Amadi-Echendu, J.E. (2004), "Managing physical assets is a paradigm shift from maintenance", *Proceedings of Engineering Management Conference, IEEE International*, Vol. 3, pp. 1156-1160.

Blanchard, B.S. (1997), "An enhanced approach for implementing total productive maintenance in the manufacturing environment", *Journal of Quality in Maintenance Engineering*, Vol. 3 No. 2, pp. 69-80.

Bokrantz, J., Ylipää, T., Skoogh, A. and Stahre, J. (2016), "Handling of production disturbances – classification and registration in the manufacturing industry", *Journal of Manufacturing Technology Management*, Vol. 27 No. 8, pp. 1054-1075.

Coetzee, J.L. (2002), "An optimised instrument for designing a maintenance plan", PhD thesis, Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Pretoria.

Dunn, S. (1998), "Re-inventing the maintenance process – towards zero downtime", *Maintenance Conference Queensland, Queensland, 1-5 May*.

El-Akruti, K. and Dwight, R. (2013), "A framework for the engineering asset management system", *Journal of Quality in Maintenance Engineering*, Vol. 19 No. 4, pp. 398-412.

Ericsson, J. (1997), "Störningsanalys av tillverkningssystem: ett viktigt verktyg inom lean production", PhD thesis, Lund University, Lund (in Swedish).

GoodSolutions, A.B. (2012), "Good Solutions customer survey", *Presented at the FFI Production Research Conference (In Swedish): Mötesplats för framtidens framgångsrika verkstäder, Katrineholm, 22-24 May*.

Gopalakrishnan, M., Bokrantz, J., Ylipää, T. and Skoogh, A. (2015), "Planning of maintenance activities – a current state mapping in industry", *Procedia CIRP*, Vol. 30, pp. 480-485.

Gopalakrishnan, M., Skoogh, A. and Laroque, C. (2013), "Simulation-based planning of maintenance activities in the automotive industry", *Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World, IEEE Press, Washington, DC*, pp. 2610-2621.

Gotoh, F. (1991), *Equipment Planning for TPM – Maintenance Prevention Design*, Productivity Press, Cambridge, MA.

Haarman, M. and Delahay, G. (2004), *Value Driven Maintenance – New Faith in Maintenance: Mainnovation*, Mainnoviation, Dordrecht.

Hansen, R.C. (2002), *Overall Equipment Effectiveness: A Powerful Production/Maintenance Tool for Increased Profits*, 1st ed., Industrial Press, Inc, New York, NY.

Ingemansson, A. (2004), "On reduction of production disturbances in manufacturing systems based on discrete-event simulation", PhD thesis, Department of Mechanical Engineering, Lund University, Lund.

Kumar, U., Galar, D., Parida, A., Stenström, C. and Beges, L. (2013), "Maintenance performance metrics: a state-of-the-art review", *Journal of Quality in Maintenance Engineering*, Vol. 19 No. 3, pp. 33-77.

Li, L., Chang, Q., Ni, J. and Biller, S. (2009), "Real time production improvement through bottleneck control", *International Journal of Production Research*, Vol. 47 No. 21, pp. 6145-6158.

Ljungberg, Ö. (1998), "Measurement of overall equipment effectiveness as a basis for TPM activities", *International Journal of Operations and Production Management*, Vol. 18 No. 5, pp. 495-507.

Márquez, A.C. (2007), *The Maintenance Management Framework*, Springer, London.

Mikler, J., Hådeby, H., Kjellberg, J. and Sohlenius, G. (1999), "Towards profitable persistent manufacturing. Human factors in overcoming disturbances in production systems", *International Journal of Advanced Manufacturing Technology*, Vol. 15 No. 10, pp. 749-756.

Mobley, R.K., Higgins, L.R. and Wikoff, D.J. (2008), *Maintenance Engineering Handbook*, 7th ed., McGraw-Hill, New York, NY.

Mobley, R.K. (2004), *Maintenance Fundamentals*, 2nd ed., Butterworth-Heinemann, Oxford.

Mont, O.K. (2002), "Clarifying the concept of product-service system", *Journal of Cleaner Production*, Vol. 10 No. 3, pp. 237-245.

Moubray, J. (1997), *Reliability-Centered Maintenance*, Butterwort-Heinemann, Burlington, MA.

Muchiri, P. and Pintelon, L. (2008), "Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion", *International Journal of Production Research*, Vol. 46 No. 13, pp. 3517-3535.

Nakajima, S. (1988), *Introduction to TPM,* Productivity Press, Cambridge, MA.

Ni, J. and Jin, X. (2012), "Decision support systems for effective maintenance operations", *CIRP Annals - Manufacturing Technology*, Vol. 61 No. 1, pp. 411-414.

Ojasalo, K. (2007), "Developing industrial services – an empirical study", *The Business Review, Cambridge*, Vol. 7 No. 1, pp. 58-62.

Parida, A., Kumar, U., Galar, D. and Stenström, C. (2014), "Performance measurement and management for maintenance: a literature review", *Journal of Quality in Maintenance Engineering*, Vol. 21 No. 1, pp. 2-33.

Peng, K. (2000), "The post-maintenance era of complex equipment management in the semiconductor industry – the case of Intel Corporation", PhD thesis, Golden Gate University, CA.

Pintelon, L. and Parodi-Herz, A. (2008), "Maintenance: an evolutionary perspective", in Kobbacy, K.A.H. and Murthy, D.N.P. (Eds), *Complex System Maintenance Handbook*, Springer, London, pp. 21-48.

Roser, C., Nakano, M. and Tanaka, M. (2002), "Shifting bottleneck detection", *Proceedings of the Winter Simulation Conference, Vol. 2, IEEE Press*, pp. 1079-1086.

Sandberg, U., Ylipää, T., Skoogh, A., Isacsson, M., Stieger, J., Wall, H., Andersson, M., Johansson, H., Nilsson, N., Agardtsson, J., Vikström, S. and Nyström, M. (2014), "Working with forces promoting or hindering implementation of strategies for maintenance – experiences from Swedish industry", *Proceedings of Swedish Production Symposium, Gothenburg, 16-18 September*.

Sekine, K. and Arai, K. (1998), *TPM for the Lean Factory*, Productivity, Inc, Portland.

Sherwin, D. (2000), "A review of overall models for maintenance management", *Journal of Quality in Maintenance Engineering*, Vol. 6 No. 3, pp. 138-164.

Skoogh, A., Johansson, B. and Hansson, L. (2011), "Data requirements and representation for simulation of energy consumption in production systems", *Proceedings of the 44th CIRP Conference on Manufacturing Systems, Madison, WI, 1-3 June*.

Smith, R. and Hawkins, B. (2004), *Lean Maintenance: Reduce Costs, Improve Quality, and Increase Market Share*, Elsevier Butterwort-Heinemann, New York, NY.

Takata, S., Kimura, F., van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ceglarek, D. and Lee, J. (2004), "Maintenance: changing role in life cycle management", *CIRP Annals – Manufacturing Technology*, Vol. 53 No. 2, pp. 643-655.

Further reading

Nakajima, S. and Yamashina, H. (Eds) (1994), *Human Factors in AMT Maintenance*, John Wiley & Sons, New York, NY.

Corresponding author
Torbjörn Ylipää can be contacted at: torbjorn.ylipaa@chalmers.se