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Handling of production disturbances in the manufacturing industry

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Abstract

Purpose – A common understanding of what events to regard as production disturbances (PD) are essential for effective handling of PDs. Therefore, the purpose of this paper is to answer the two questions: how are individuals with production or maintenance management positions in industry classifying different PD factors? Which factors are being measured and registered as PDs in the companies monitoring systems?
Design/methodology/approach – A longitudinal approach using a repeated cross-sectional survey design was adopted. Empirical data were collected from 80 companies in 2001 using a paper-based questionnaire, and from 71 companies in 2014 using a web-based questionnaire.
Findings – A diverging view of 21 proposed PD factors is found between respondents in manufacturing industry, and there is also a lack of correspondence with existing literature. In particular, planned events are not classified and registered to the same extent as downtime losses. Moreover, the respondents are often prone to classify factors as PDs compared to what is actually registered. This diverging view has been consistent for over a decade, and hinders companies to develop systematic and effective strategies for handling of PDs.
Originality/value – There has been no in-depth investigation, especially not from a longitudinal perspective, of the personal interpretation of PDs from people who play a central role in achieving high reliability of production systems.
Keywords Manufacturing, Maintenance, Overall equipment effectiveness, Production disturbances
Paper type Research paper

1. Introduction

Today's production systems are required to deliver high productivity, resource efficiency, and flexibility, and these requirements will continue to rise in line with the realization of digital manufacturing. There is a strong commitment in production and maintenance personnel to exploit the full potential of current systems, but the complex and highly automated equipment in future digital factories are required to deliver even higher levels of performance. However, poor performance in terms of overall equipment effectiveness (OEE) has been reported for over a decade. Ahlmann (1993), Ericsson (1997), and Ljungberg (1998) present numbers between 55 and 60 per cent, and Ingemansson (2004) between 40 and 60 per cent. More recently, by collecting OEE data from 2006 to 2012 in over 90 companies, Ylipää *et al.* (forthcoming) present an average number of 51.5 per cent. Consequently, companies are beginning to worry about keeping track of the parameters that affect production performance (Kumar *et al.*, 2013).

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A production disturbance (PD) directly impedes production performance (Ylipää, 2000), and decreasing the amount of PDs contributes to more reliable production systems (Ingemansson, 2004). In fact, the most important factor that determines the magnitude of production losses is how much emphasis that is put on minimizing PDs (Ericsson, 1997). Modern production requires disturbance free operations in chosen equipment and more precise knowledge when and where to intervene in order to prevent PDs (Sandberg *et al.*, 2014). However, operational risks created by PDs receive less attention from both practitioners and academics, even though they are increasing due to greater uncertainty in today's market (Islam, 2008). Clearly, manufacturing companies are struggling with the handling of PDs.

Handling of PDs is crucial; PDs decrease productivity, increase product cost, and reduce profitability (Alsyouf, 2007). Moreover, PDs often result in direct safety risks for operators (Toulouse, 2002), and PDs may put entire organizations at financial risk (Islam, 2008). In fact, PDs can threaten a company's competitiveness both in stable production phases (Ericsson, 1997; Jonsson, 1999) and in changing conditions (Almgren, 1999), and handling of PDs is crucial in both high- and low-volume production (Bellgran and Aresu, 2003). However, despite the combination of increased demands on high performance of modern production systems and consistent reports of low-OEE figures, the Association of Swedish Engineering Industries (Teknikföretagen) (2014) maintains a vision of disturbance free production systems by 2030.

Originally, OEE was developed to reveal the losses from PDs (Nakajima, 1988), and has been widely used to measure equipment performance in industry (Kumar *et al.*, 2013). However, the handling of PDs must focus on individual factors and their underlying causes, not merely on addressing the symptoms of poor performance (Ericsson, 1997; Smith and Hawkins, 2004). By measuring individual PDs and the different components of the OEE figure, a production system's OEE can be increased (Ingemansson, 2004). In essence, a systematic monitoring of individual PDs provides a guide for continuous improvements (Smet *et al.*, 1997). Nevertheless, before something can be measured, it must be defined (Tsang *et al.*, 1999). Therefore, a prerequisite for effective handling of PDs is to determine what actually constitutes a "PD". However, not only does the definition of OEE vary between applications and authors (e.g. Nakajima, 1988; De Groote, 1995; Ericsson, 1997; Ingemansson, 2004), but the definition of a PD is also relatively ambiguous (Ingemansson, 2004). Extensive literature research, discussed in Ylipää *et al.* (2007), indicates a wide array of interpretations and definitions of the concept of PDs, and the topic is still being discussed (Golinska *et al.*, 2011). In fact, different views of PDs exist between academia, industry, and even within companies and their own organizations (Ljungberg, 1998; Harlin, 2000; Ylipää, 2000).

The bottom line is that effective handling of PDs is essential to achieve high reliability of production systems (Ingemansson, 2004), but a consequence of classifying PDs differently is that they will be resolved differently (Ylipää, 2000). Therefore, the aim of this paper is to answer the following two questions:

(1) How are individuals with production or maintenance management positions in industry classifying different PD factors?

(2) Which factors are being measured and registered as PDs in the companies monitoring systems?

The two questions are answered based on a repeated cross-sectional survey study carried out in 2001 and 2014, where longitudinal data are obtained in order to establish the view of PDs within Swedish manufacturing industry. By focussing on the individual PD factors in improvement work rather than solely achieving a high OEE percentage figure, companies can more systematically and effectively tackle the underlying reasons for PDs. However, to make a factor-based approach to handling of PDs effective from both a management and operative perspective, it is crucial to achieve an internal consensus of what factors that should be classified and registered as PDs.

2. Background and literature review

In this section, important aspects for the handling of PDs are presented, including the role of OEE and various interpretations of the concept of PDs.

2.1 PD in terms of OEE

OEE has been proposed as one way of measuring the losses from PD, and it has been used widely in industry (Kumar *et al.*, 2013). According to the original definition by Nakajima (1988), OEE is a bottom-up approach where an integrated workforce strives to achieve OEE by eliminating the six big losses: equipment failures/breakdowns, set-up/adjustments, idling and minor stoppages, reduced speed, reduced yield, and quality defects. These losses are measured in terms of OEE, which is a function of the three components availability, performance, and quality.

Following this, numerous alternative definitions and additional losses have been proposed. In fact, there has been a gradual expansion of the number of losses to be included in the OEE figure. The original six big losses have been expanded to eight (Ljungberg, 1998) and 11 major factors (Smith and Hawkins, 2004). In addition to the losses captured by OEE, numerous other losses related to labour effectiveness, resource consumption, and safety have been proposed as total preventive maintenance losses (Averill, 2011). Interestingly, a similar development can also be found within Lean, where up to 12 types of wastes have been proposed where in contrast to the original seven (Kyrö *et al.*, 2011). This expansion holds an emphasis on planned activities such as preventive maintenance, shortage of staff from breaks, meetings and education, etc. (Ljungberg, 1998; Jonsson and Lesshammar, 1999; Smith and Hawkins, 2004). In particular, Jonsson and Lesshammar (1999) argue that including planned activities in the production time creates a motive for improvement, e.g., by more efficient set-ups.

Unfortunately, the wide array of OEE definitions has caused misunderstanding and misuse (Williamson, 2006). In an attempt to solve this, the OEE Foundation (2014) has suggested an "OEE Industry Standard" with guidelines on how to define OEE in order to find all potential losses. They state that all losses need to be defined and visualized, and stress that set-ups, breaks, and maintenance are all potential losses to be reduced. In particular, reducing set-up losses through continuous improvements is the core of concepts like Single Minute Exchange of Die (SMED) (Shingo, 1985). Such improvements hold great potential for increasing productivity, made evident by, e.g., Ericsson's (1997) case studies where 24 per cent of the non-operative machine time consisted of set-ups. Nevertheless, the consistent reports of low-OEE figures illustrate that handling of PDs remains a crucial task at hand, and new OEE definitions and additional losses have not solved the problem. Moreover, despite the extensive use of OEE as a measurement for PDs, there remains a dissent in regard to the understanding of what actually constitutes a PD; in industry and in academia. Overall, this raises the need for a more holistic approach to defining, measuring, and handling of PDs.

2.2 Preventive maintenance as a PD

In terms of OEE, preventive maintenance has been a particularly popular subject of discussion. In Ericsson's (1997) studies, 39 per cent of non-operative time consisted of maintenance-related activities. Preventive maintenance is typically excluded from OEE as it is assumed you have to do it, you cannot reduce it, and you cannot eliminate it (Smith and Hawkins, 2004). It is also a sort of a paradox: it can cause disruption if carried out during production, even though it is aimed at avoiding failures. In some occasions, preventive maintenance is also a cause of failure due to the probability of introducing failures during the maintenance activity (Ylipää, 2000). In fact, poor scheduling of preventive maintenance also increases the risk of dramatically disturbing production (Wong *et al.*, 2013). Also, one-third of all maintenance costs have been found to be wasted due to unnecessary or improperly carried out maintenance (Mobley, 2002).

According to Katila (2000), the most effective way to reduce technical failures is to increase the amount of preventive maintenance. Therefore, many industrial companies are targeting an 80/20 relationship between preventive and corrective maintenance (Adolfsson and Dahlström, 2011; Wängberg and Larsson, 2013). Sandberg *et al.* (2014) specifically highlight a case where such a target was set within an organization. However, it was found that the corrective vs preventive ratio was difficult to affect due to several hindering factors, including, e.g., a perception amongst many company functions and employees that preventive maintenance is of no financial value. This issue is, e.g., tackled in reliability-centered maintenance, where a deeper analysis of specific failure modes dictates the chosen maintenance action (i.e. reactive, preventive, or predictive). It is stressed that a preventive maintenance activity should only be chosen if it is effective and applicable, i.e. being both cost-effective and able to detect, prevent, mitigate a failure or discover a hidden failure (Hinchcliffe and Smith, 2003).

Due to the both the high cost of maintenance and its impact on production efficiency, not only a shift towards increased predictive maintenance is emphasized (Hinchcliffe and Smith, 2003). The goal could also be to minimize the maintenance requirement throughout its life cycle by addressing maintainability and reliability at the earliest stage possible, preferably during the design phase of new equipment or machinery (Almgren, 1999; Jonsson, 1999; Ylipää, 2000; Wireman, 2000).

2.3 The use of OEE

Not only has the losses in OEE been widely discussed in literature, but the purpose of OEE has also been debated. It is, for example, argued inappropriate to use this as a plant-level measure or for benchmarking different assets or processes (Williamson, 2006), and more system-oriented versions have therefore been proposed, such as overall line effectiveness (Braglia *et al.*, 2008), and overall throughput effectiveness (Muthiah and Huang, 2007). Another flaw in the original OEE definition is that each of the three components is assumed to be equally important, resulting in a statistically invalid OEE percentage rating. To resolve this, a weighted OEE figure has been proposed (Raouf, 1994; Wudhikarn, 2010; Yuniawan *et al.*, 2013).

However, regardless of the OEE definition or the included losses, striving for maximizing the OEE percentage rating and manipulating calculations to obtain a favourable figure can cause sub-optimization and stimulate overproduction (Van Goubergen, 2010). Therefore, a general consensus exists that the fundamental purpose of OEE is to direct improvements by identifying and reducing specific losses (Nakajima, 1988; Ljungberg, 1998; Jonsson and Lesshammar, 1999; Bamber *et al.*, 2003; Williamson, 2006). Instead of purely focussing on increasing the OEE percentage rating without considering its impact on overall system performance, focus should be on the individual factors where root cause analysis is performed, improvements are identified, and specific losses are eliminated (Smith and Hawkins, 2004; Van Goubergen, 2010).

2.4 Mapping of PD factors

To support the handling of PDs, Ljungberg (1998) argues that it would be beneficial to shift from a narrow focus on down time losses and instead use a more comprehensive model of losses. Moreover, Smet *et al.* (1997) stress that a necessary condition for successful automation of registering of PDs is an appropriate model of PDs. However, due to the ambiguousness of the definition of a PD, Ingemansson (2004) highlights that the categories of PDs should be clearly distinguished from each other in order to reduce the risk of misconception. Moreover, Ingemansson (2004) believes there can be a debate on what should be regarded as a PD, both in the academic and industrial world. In real life however, it is more important to find a workable definition. Nonetheless, such a definition needs to be able to capture all losses, and PDs therefore need specific classifications for different fields (Smet *et al.*, 1997; Bellgran and Aresu, 2003). Bamber *et al.* (2003) argue that organizations should develop their own classification frameworks. Depending on the specific field of application, it is not necessarily important that such frameworks explicitly or definitively include the original six big losses in OEE.

Studies highlighting different PD factors have been presented, e.g. in SMEs in New Zealand, where a mapping of 14 operational disturbances that degrade business performance and environment was presented. The authors found that disturbance handling systems are weak and informal (Islam and Tedford, 2012). In another study, in Bangladesh, 11 proposed disturbance factors were mapped, and 27 root causes behind the disturbances were identified. The authors conclude that frequent changeovers in production is one of the most detrimental, and if an organization can systematically identify disturbances and their root causes, overall productivity can easily be improved (Islam *et al.*, 2012).

Another dimension of the handling of PDs is how the individuals who play a central role in achieving high reliability at their company view different PD factors, and how this relates to whether they are being measured or not. Some authors have touched upon this subject, e.g., Ljungberg (1998) who mentions that major time losses such as set-up and adjustments are not regarded as losses but as productive time. However, individual view on various PD factors has not been specifically addressed in literature. A prerequisite for measuring an event as a disturbance is naturally that is must be interpreted as one. Therefore, the fundamental basis for working with individual PD factors in improvement work is to first agree on what factors that should be regarded as PDs and treated as such.

With the assumption that the reader is reasonably well versed in the concept of PDs, the basis for discussion regarding PDs is the definition proposed by Ylipää (2000); "Production disturbances are discrete or decreasing, planned or unplanned, disruptions or change during planned production time, which might affect availability, operational performance, product quality, security, work conditions, environment, etc." This definition thus includes planned stoppages, as well as any measurable stop, regardless of time limit (in contrast to e.g. Golinska *et al.*, 2011 who define PDs as solely unexpected and unplanned events). The essence is that PDs should be measured as deviations from the normal, desirable conditions. However, this general definition do not explain in detail what constitutes a PD, and the aim of this study is therefore to provide a more detailed view of what factors that can be regarded as PDs within the manufacturing industry.

3. Methodology

This study was based on a descriptive survey research approach (Forza, 2002), with the intention of increasing available knowledge of a wide array of factors that could be regarded as PDs. Empirical data were collected from within the Swedish manufacturing industry on two occasions. The overall method used was a questionnaire survey, where a paper-based mail survey at 80 companies was carried out during 2001, and a web-based survey from 71 companies was carried out in 2014. For the reader to easily distinguish between the two surveys, the 2001 survey is referred to as "survey A", and the 2014 survey as "survey B".

Longitudinal studies can be defined as research in which data are collected for each item or variable for two or more distinct periods; the subjects or cases analysed are the same, or at least comparable, from one period to the next; the analysis involves comparison of data between or among periods. The longitudinal evidence in this study was constructed using a repeated cross-sectional design. If repeated with a high consistency in between questions, it enables the inclusion of a time trend into the analysis (Ruspini, 1999) and can provide good estimates about changes that have occurred between two surveys (Lynn, 2009). The drawback is the inability to resolve issues of casual order (Ruspini, 1999). However, the purpose of this study has primarily been to provide a description of how PDs are regarded within the Swedish manufacturing industry, not deliberately determining the cause for the individuals' views.

3.1 Distribution of the questionnaire

Survey A was carried out as part of a national multi-disciplinary co-operation research project called "TIME" during 2001-2004, with researchers from three universities and one industrial research institute (Gullander *et al.*, 2003). The data were collected during May 2001 to August 2001. Parts of the original questionnaire and an extended methodology have been reported in Ingemansson *et al.* (2002) and Ylipää *et al.* (2007). This chapter therefore focusses primarily on describing the methodology of survey B.

For survey B, the paper-based questionnaire was reconstructed to a web-based questionnaire, and held open for submission between March and April 2014. Invitation to the questionnaire was sent by e-mail to selected respondents, while an open invitation was listed publicly on the website of Sustainability Circle (SC), and included in an SC e-mail newsletter sent to their subscribers. SC is a non-governmental, maintenance-focussed organization with more than 50 member companies. The companies that participated in survey A received a prior notification call, and an invitation was sent if personal contact with an appropriate representative at the company could be established.

In order to facilitate a survey including different production contexts, a pre-study including five context descriptions of different production systems based on data from 24 respondents from 15 different companies was used to construct the questionnaire in survey A (Ylipää *et al.*, 2007). Due to the transformation from a paper to a web-based questionnaire, pre-testing was performed again. A pilot questionnaire was tested and evaluated by external researchers and industrial experts (Forza, 2002). In order to improve the questionnaire, unstructured telephone interviews followed after completion of the pilot version, and minor revisions were made before airing the final survey.

3.2 Structure of the questionnaire

The questionnaire included questions related to 21 main PD factors. These were originally derived from literature review and case studies performed in a longitudinal research project called CONSENSUS, where critical events and PDs were studied during the running-in of a new product (Harlin, 2000).

Data regarding the 21 PD factors were collected using "yes/no/do not know" alternatives. However, as seen in Tables AI and AII in Appendix, the classification of PDs was asked using a "yes/no" alternative in survey A, and a "yes/no/do not know" alternative in survey B. The registration of PDs was collected using "yes/no/do not know" in both surveys. This inconsistency was due to limitations of the web-based survey tool. As seen in the schematic example in Table I, the respondent first classified the 21 factors as PD or not PD based on personal opinion. Thereafter, they answered whether the factor was measured and registered as PD in the monitoring system at their company. These two questions were asked to gain knowledge about the practical perspective of the handling of PDs, as well as enabling analysis of similarities or differences between the individual views and the registration of PDs. Moreover, the possibility for the respondents to add other PD factors (beyond the 21 proposed factors) was suggested after the completion of survey A. This option was therefore included in survey B by means of an additional open-ended answer alternative.

The remaining parts of the questionnaire were used to explore further aspects concerning the handling of PDs, e.g., the use of engineering tools and methods. The questionnaire also included a final part regarding demographic information about the respondent and the participating company (Table II).

3.3 Selection of companies and respondents

A non-probabilistic judgement sample was chosen in both surveys (Forza, 2002). The intention was to indicate an expert view from a high-strategic level within maintenance or production management at the different companies. This selection was made as these

Table I. Schematic image of the questionnaire, which exemplifies five out of the 21 proposed PD factors to illustrate the structure

	Classified by You as a Production Disturbance?	Registered as a Production Disturbance in your company?
Equipment failure/breakdowns in machines or equipment	Yes	Yes
Human error	Yes	No
Failure of peripheral, e.g. external transport systems	Yes	No
Reprogramming	-- Please select -- ⇳	-- Please select -- ⇳
Planning error	-- Please select -- ⇳	-- Please select -- ⇳

Notes: A "yes/no/don't know" alternative is chosen from the "please select" drop-down menu, and the form is filled out for all 21 factors

Table II. Demographic information on participating respondents and companies

No. of employees	*n*	%	Capital turnover per year	*n*	%	Years of experience	*n*	%
10-99	16	21	< 105 M€	35	46	0-5 years	20	26
100-499	37	49	105-1,050 M€	17	22	6-15 years	25	33
500 or more	23	30	> 1,050 M€	16	21	> 16 years	31	41
			Missing answer	8	11			

Note: Data about respondents and participating companies in survey B respondents were considered to possess specific knowledge about the production area, and play a central role in achieving high reliability of the production system with respect to PDs.

The sample size of survey A was 80 responses, and the same number was therefore set as a goal for survey B. For survey B, 82 selected respondents received an invitation to answer the questionnaire, out of which 62 answered, resulting in a response rate of 75 per cent. In order in increase the response rate, non-respondents received monitoring phone calls and up to three e-mail reminders. The most common argument for non-response was lack of time. The open invitation resulted in 22 additional responses. Out of the total 84 submissions, the respondents who did not fulfil the criteria of having an expert view from high-strategic level were excluded, and the respondents with the highest management level were chosen at plant-level for each company.

The final selection consisted of 76 responses from 71 companies. The five duplicates represent individual respondents from different plants within the same company or corporate group, but separated geographically and operating with different management. In total, 62 per cent of the respondents can be regarded as maintenance department, 25 per cent production department, and 13 per cent as equally maintenance and production department.

3.4 Data about the respondents and participating companies

A description of the respondents and participating companies in survey A has been reported in Ingemansson *et al.* (2002). In Table II, the presented categories of company sizes, in terms of number of employees, follow EU classification for enterprise size (Pagell and Halperin, 2000). Turnover is based on 9.52 SEK per 1€. The data illustrate the number of employees, capital turnover per year, and the respondents' years of experience within production or maintenance. Moreover, regarding industry type, the majority of the respondents, 52 in total, represented discrete manufacturing companies. Thereafter, 11 respondents represented process industry companies, and 13 represented other types of companies, e.g., food, energy, pulp, etc. Several of the participating companies are large multi-national corporations acting on a global market, who may have an internally consistent approach to operations. This implies a possibility that the view of PDs amongst these respondents is also prevalent outside Swedish industry.

3.5 Analysis and presentation of data

In line with the descriptive research approach, the results are presented using descriptive statistics. This is a way of reducing the data to a manageable form (Faber, 2012) and allows for summarizing the results into numbers and graphs that are easy to interpret (Fisher and Marshall, 2009). Discussion of individual PD factors and highlighting of differences are therefore presented in terms of frequency of responses. In order to present the compiled data of the 21 PD factors in a comprehensible way, polar diagrams (also called radar charts, spider diagrams, etc.) are used. This is a graphical tool that allows for a better and more graspable display of multivariate data in comparison to bar charts or text (Saary, 2008).

4. Results

Results from the study cover how individuals classify the 21 proposed PD factors and whether they are measured and registered as PDs in the company's monitoring system. In addition, differences between the classification and registration are highlighted, as well as the development between the two surveys.

4.1 Classification of PDs

The polar diagram in Figure 1 (full data in Tables AI and AII in Appendix) displays how individuals in both surveys classify the 21 different PD factors. It shows that 90 per cent or more of the respondents classify the three factors "equipment failure", "failure in software in production equipment", and "media error" as PD, i.e. factors that result in clearly visual effects. Moreover, six other factors are classified as PD by 75 per cent or more in both surveys: "human error, "failure of peripheral", "subsequent stop in output flow", "speed loss", "waiting time for incoming material/product", and "scrap or quality problems". In contrast, it is observed that planned events such as "tool change" and "set-up/resetting", "preventive maintenance", "pauses or breaks", and "cleaning", are classified as PDs to a lower extent: by 50 per cent or less in both surveys. This indicates that unplanned events are classified as PDs at a higher degree than planned events.

Moreover, the possibility in survey B to add further PD factors resulted in that seven individuals reported that the following factors are classified and registered as PDs in their company: "errors in drawings", "OEE", "process waste", "delivery service", "minor stoppages", and "consumables". One respondent also classified the factor "negative employees" as a PD, but this was not registered as a PD. Also, one respondent commented that adjustments, set-ups and reprogramming are planned activities and therefore not regarded as PDs.

4.2 Comparing classification of PDs in surveys A and B

The similarity of the two data sets in Figure 1 indicates a general consistency in the classification of PD factors. Further, Table III shows the eight factors with the largest

Figure 1.
Classification of PD

difference between the two surveys. It indicates that "time for refilling/changing material" and "incidents/near misses" are to a greater extent classified as a PD by in survey B, indicated by a difference of 14 absolute per cent. Thereafter, six other factors display a difference of 7-8 absolute per cent. Moreover, by taking the mean value of all 21 factors (i.e. the mean of combining 97 per cent classification of equipment failure as PD, 85 per cent human error, 23 per cent pauses or breaks, etc.), a general mean value of 63 per cent and 65 per cent for the two surveys is found (Tables AI and AII in Appendix). This lends further support to a general consistency of the classification of PDs between the two surveys.

4.3 Registration of PDs

Figure 2 (full data in Tables AI and AII in Appendix) shows to what extent the proposed factors are registered as PDs in the company's monitoring system. In both surveys, the three factors "equipment failure", "failure in software in production equipment", and "media error", were registered as PDs in approximately 75 per cent or more of the companies. Moreover, four additional factors are registered by 50 per cent or more of the companies in both surveys: "human error", "failure or peripheral", "subsequent stop in output flow", and "scrap or quality problems" as PDs. Planned events are registered at a lower degree: "tool change" and "set-up/resetting" were registered as PDs according to less than 50 per cent of the respondents, and "pauses or breaks" according to less than 25 per cent. Overall, these results are consistent with the classification of PDs, i.e. that unplanned events are emphasized to a larger extent than planned events.

4.4 Comparing registration of PDs in surveys A and B

In contrast to the classification of PD factors, larger differences between the two surveys can be found for the registration of PDs. A general trend that companies in survey B register more of factors as PDs is observed, where in total 14 out of the 21 factors display a difference of 8 to 31 absolute per cent (Table IV). The largest differences are found for "preventive maintenance" and "incidents/near misses". The companies in survey B clearly register these two factors as PDs to a larger extent, indicated by a difference of 25 and 31 absolute per cent, respectively. Thereafter, "cleaning" and "scrap or quality problems" are also registered to a substantially higher degree in the survey B. The general mean values of which factors are registered as PDs are 45 and 56 per cent for the two surveys, respectively.

PD factor	Classified as PD Survey A (%)	Survey B (%)	Difference (%)
Time for refilling/changing of material	33	47	14
Incidents/near misses	55	69	14
Tool change	44	37	8
Failure of peripheral, e.g., external transport system	77	85	8
Set-up/resetting	42	50	8
Planning error	71	78	7
Scrap or quality problems of the product	77	85	7
Cleaning	32	39	7

Note: The 8 factors with the largest difference, presented in descending order

Table III. Comparing classification of PDs in surveys A and B

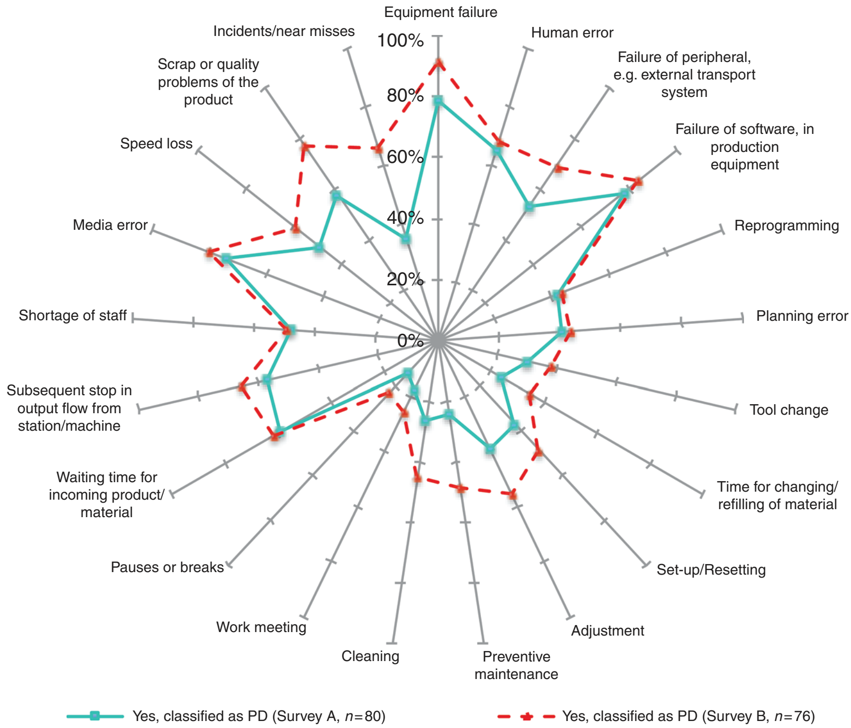

Figure 2.
Registration of PD

Table IV.
Comparing registration of PDs in surveys A and B

PD factor	Registered as PD Survey A (%)	Survey B (%)	Difference (%)
Incidents/near misses	35	66	31
Preventive maintenance	24	49	25
Cleaning	26	45	19
Scrap or quality problems of the product	58	77	19

Note: The four factors with the largest difference presented in descending order

4.5 Comparing classification and registration of PDs

A general tendency can be found regarding the difference between classifying and registering the factors as PDs. In both surveys, the individual experts are prone to classify more factors as PDs compared to what is being registered at their company. In survey A, all 21 factors are at a higher degree classified as PDs, and 13 factors display a difference of 18 absolute per cent or more (Table AI in Appendix). In survey B, ten factors have a difference of 13 absolute per cent or more (Table AII in Appendix). Moreover, when comparing the general mean value of classification and registration, there is a difference of 18 absolute per cent in survey A and 9 absolute per cent in survey B. The largest differences are illustrated in Tables V and VI. In survey A, "planning error" stands out with a difference of 30 absolute per cent. In survey B, the two largest differences are observed for "planning error" (34 absolute per cent) and "shortage of staff" (28 absolute per cent). Interestingly, the factor "preventive maintenance" goes

PD factor	Classified as PD (%)	Registered as PD (%)	Difference (%)
Planning error	71	41	30
Adjustment	66	39	27
Subsequent stop in output flow	83	57	26
Speed loss	75	49	26
Shortage of staff	74	48	26
Waiting time for incoming product/material	84	59	25
Failure of peripheral, e.g., external transport system	77	53	24
Human error	88	65	23

Note: The eight factors with the largest difference presented in descending order

Table V. Comparing classification and registration of PDs in survey A

PD factor	Classified as PD (%)	Registered as PD (%)	Difference (%)
Planning error	78	44	34
Shortage of staff	77	49	28
Waiting time for incoming product/material	80	62	18
Human error	85	68	17
Speed loss	77	60	17
Failure of peripheral, e.g., external transport system	85	69	16
Media error	96	80	16
Preventive maintenance	36	49	13

Note: The eight factors with the largest difference presented in descending order

Table VI. Comparing classification and registration of PDs in survey B

against the trend and is in survey B instead registered as a PD at a higher degree (with a difference of 13 absolute per cent). Overall, these results suggest that there is a gap between the classification and registration of PDs, where the respondents are more prone to classify the proposed factors as PDs compared to what is being registered.

5. Discussion

Effective handling of PDs is essential to achieve high reliability of production systems. The results from this study show how individuals with management positions in industry classify PD factors, and which factors that are being registered as PDs in the companies monitoring systems.

5.1 Interpretation of PD factors

OEE was originally developed to reveal the losses from PD (Nakajima, 1988), but the wide array of definitions have caused misunderstanding and misuse (Williamson, 2006). By measuring individual PDs and the different components of the OEE figure, the OEE can be increased (Ingemansson, 2004). However, a prerequisite for an event to be registered and measured as a PD is naturally that it is interpreted as one. The results from this study show that almost all respondents regard the factors "equipment failure", "failure of software", and "media error" as PDs (Figure 1). This goes in line with Ljungberg's (1998) conclusion that companies focus on down time losses and especially breakdowns. These three factors are also easy to detect due to the visual deviation from the normal state. Furthermore, over 75 per cent of the respondents in both surveys classified eight other factors as PDs. These factors relate to the production flow ("waiting time for incoming product/material", "subsequent stop in output flow", and "speed loss"), people ("human error", "planning error"), and quality ("scrap or quality problems").

Following Nakajima's (1988) definition, there has been an increase of the losses proposed for inclusion in OEE. Emphasis has been put on planned activities (Ljungberg, 1998; Jonsson and Lesshammar, 1999). Similarly, Ylipää (2000) includes any planned or unplanned event in his definition of a PD. However, the planned events "tool change" and "set-up/resetting" were regarded as PDs by 50 per cent or less in both surveys (Figure 1). This supports Ljungberg's (1998) notion that these are often not seen as losses but as productive time, even though frequent changeovers are highly detrimental (Islam *et al.*, 2012) and can make up large parts of a machines non-operative time (Ericsson, 1997). In fact, one respondent even clarified that adjustments, set-ups, and reprogramming are planned activities and therefore not regarded as PDs. Measuring these as losses creates an incentive for improvements, e.g., more efficient set-ups (Jonsson and Lesshammar, 1999). The rather low recognition of these two factors as PDs is noteworthy since they have been included in virtually all OEE definitions since its origin, and have been subjects of continuous improvement in, for example, SMED (Shingo, 1985).

Similarly, other planned events such as "time for changing/refilling of material", "cleaning", "work meeting", and "pauses or breaks" were regarded as PDs by less than 50 per cent of the respondents in both surveys (Figure 1). These events have also been included in OEE definitions (e.g. Ericsson, 1997; Ingemansson, 2004; Smith and Hawkins, 2004). In fact, OEE Foundation (2014) argues that all losses, including planned events, need to be defined and visualized. It shall be stressed that this low recognition of planned events as PDs is based on the view of individual experts with long experience of working at these companies; people within industry who one can expect to possess a high level of competence, knowledge and education within the subject area of PDs.

Due to the ambiguousness of the concept of a PD, Ingemansson (2004) argues that categories of PDs should be clearly distinguished from each other in order to reduce the risk of misconception. This ambiguousness is observed in this study, where, for example, "set-ups" are classified as a PD to a considerably lower extent than "adjustments" in both surveys (Table I). This is rather interesting and surprising since set-ups and adjustments are merged as one of Nakajima's (1988) original six big losses. An adjustment is however a correction from an unwanted to a satisfactory state, which could explain why this is more often regarded as a PD. In fact, several similar cases of ambiguity are found in this study. For example, whilst 26 per cent or less of the respondents in both surveys classified "pauses or breaks" and "work meetings" as PDs, the rather similar factor "shortage of staff" was classified as a PD by more than 70 per cent in both surveys. Moreover, the possibility of adding PD factors further highlighted how similar events could be classified as different PDs. For example, the additionally mentioned factor "process waste" could potentially be regarded as the proposed factor "scrap or quality problems". Further, "consumables" (i.e. lack of these) may be interpreted as "waiting time for incoming material", and "errors in drawings" might be described as a consequence of a "human error". These examples show how easily different views and multiple definitions and interpretations of PDs can arise.

5.2 *Classifying and registering PD factors*

From a longitudinal perspective, a general stability can be found regarding how individuals classify the proposed PD factors (Figure 1). The general mean value between the two surveys only differ by 2 absolute per cent, and 19 out of the 21 factors display a mere difference of 8 absolute per cent or less. These results indicate that the view of which factors the individual experts at the companies regard as being PDs have been consistent for over a decade. Interestingly however, the reported OEE figures during the past two decades have been consistently low (Ahlmann, 1993; Ericsson, 1997; Ljungberg, 1998; Ingemansson, 2004; Ylipää *et al.*, forthcoming). This raises the questions of what is actually required in order to achieve effective handling of PDs in industry.

Moreover, a gap between the classification and registration of PDs is found, where individual experts at companies are more prone to classify factors as PDs compared to what is being registered. In survey A, a difference of 18 absolute per cent of the general mean value could be found between classification and registration of PDs, and a difference of 9 absolute per cent was found in survey B. As seen in Tables V and VI, large differences are found for individual factors. These results illustrate how the individual view of managers does not always reflect what is really being measured and registered at the company. Fortunately, this gap seems to be decreasing since this study also observed a trend towards increased registration of PD factors (Figure 2). The general mean value for registration of PD factors is 45 per cent in survey A and 56 per cent in survey B, and individual factors display substantial increase (Table IV). This increase could possibly be an effect of advancements in information technology systems and computerized maintenance management systems. Overall, the results suggest that most companies have started to register various PD factors in their monitoring systems, but have not fully reached a state where all regarded factors are being measured.

5.3 *Preventive maintenance as a PD*

There has been much debate in literature regarding whether preventive maintenance should be viewed as a PD or not. Typically, it is excluded from OEE calculations as it is assumed you have to do it, you cannot reduce it, and you cannot eliminate it (Smith and Hawkins, 2004). Some authors exclude preventive maintenance from their definitions (Nakajima, 1988; Smet *et al.*, 1997), whilst other emphasize that it should be regarded as a PD and included in OEE (e.g. Ljungberg, 1998; Jonsson and Lesshammar, 1999). However, this study shows that a majority of respondents do not consider the factor "preventive maintenance" to be a PD. Only 32 and 36 per cent of the respondents classify it as a PD in surveys A and B, respectively (Figure 1). Surprisingly however, a positive trend towards increased registration of "preventive maintenance" as a PD is indicated (Figure 2).

In terms of PDs, preventive maintenance is paradoxical in several aspects. First, preventive maintenance is a paradox in itself: even though it is fundamentally aimed at avoiding failures, it can be a disruption if it is carried out during production, and it can also introduce new failures (Ylipää, 2000). Moreover, increasing the amount of preventive maintenance is, according to some authors, the most effective way of preventing technical failures (Katila, 2000). Many industrial companies are also striving to achieve an 80/20 relationship between preventive and corrective maintenance (Adolfsson and Dahlström, 2011; Wängberg and Larsson, 2013). These could be contributing reasons for the increased registration of preventive maintenance as a PD as seen in this study. However, poor scheduling of preventive maintenance can dramatically disturb production (Wong *et al.*, 2013), so the aim of increased preventive maintenance is also a paradox in terms of PDs: reducing potential downtime from failures by increasing preventive maintenance could increase potential downtime from preventive maintenance itself. Also, no studies have shown that 80/20 would be an optimal distribution, and other studies have shown that the corrective vs preventive ratio can be very hard to affect (Sandberg *et al.*, 2014).

Undoubtedly, the complex problems with preventive maintenance are not easy to solve. It is however of great importance, especially since it has been indicated that one-third of total maintenance costs are wasted due to unnecessary or improperly carried out maintenance (Mobley, 2002). This is particularly hard to tackle if preventive maintenance is not even regarded as a PD that could be reduced, an attitude shown to be prevalent according to the data in this study. Clearly, one cannot simply strive to increase preventive maintenance, and in some companies it is not even perceived as financially valuable (Sandberg *et al.*, 2014). It is first when one can collect data about individual PDs and use this as guidance for focussed analysis down to specific failure modes that decisions can be made as to whether preventive maintenance should be increased or not. A systematic framework for classifying, measuring, and registering specific PDs could however help in this work. For example, instead of simply increasing preventive maintenance, there could be a focus on "better" maintenance (e.g. predictive maintenance) or striving to minimize the maintenance requirement by addressing maintainability and reliability during the design phase (Almgren, 1999; Jonsson, 1999; Ylipää, 2000; Wireman, 2000).

5.4 The effect of different views of PDs

The original OEE percentage rating is questioned by, e.g., Liker, Raouf (1994), Wudhikarn (2010), and Yuniawan *et al.* (2013). However, OEE can be seen as the starting point for identifying PDs and directing further analysis and improvement work, instead of being used as the final measure. In essence, a systematic monitoring of PDs provides a guide for continuous improvements (Smet *et al.*, 1997). However, this study has shown that several of the proposed factors are not regarded as PDs, which arguably omits them from being improved. Within literature, there is support for conflicting views of the concept of PDs between industry, academia, and even within companies and their own organizations (Ljungberg, 1998; Harlin, 2000; Ylipää, 2000). This study has presented further empirical evidence that suggests this scenario to be prevalent, and seems to have been consistent for over a decade. Individuals within industry interpret and classify various PD factors differently, and their views do not always correspond with existing literature. Moreover, the personal view of experienced maintenance and production experts does not always resemble what is being measured and registered.

The combination of consistent reports of low-OEE figures for over two decades, the increasing number of OEE definitions and proposed losses, and the differences in the view of PDs shown in this study, clearly highlight the need for more detailed and structured frameworks for handling of PDs. The consequence of classifying PDs differently is that they will be resolved differently (Ylipää, 2000), and this is the fundamental practical issue to overcome from a managerial perspective. Therefore, organization must establish a common, internal understanding of what events that should be regarded as PDs and treated as such. This understanding should constitute the basis for developing their own classification framework that corresponds to the specific field of business (Bellgran and Aresu, 2003; Bamber *et al.*, 2003). By doing so, an organization can systematically identify PDs and their associated root causes, and overall productivity can thus be improved (Islam *et al.*, 2012).

Finally, the urgency of this matter will increase in line with the development towards digital manufacturing. In the digital factories of the future, companies will be able to collect enormous amounts of data regarding potential PDs, and analyses of such data will be the primary means for identifying, reducing, and eliminating PDs. Since a necessary condition for successful automation of registering of PDs is an appropriate model of PDs (Smet *et al.*, 1997), industrial managers must work towards achieving an internal consensus of what events that should be classified and registered as PDs.

5.5 Methodology discussion

Naturally, the potential PD factors included in this study are not exhaustive. In fact, the additional comments in survey B illustrated that other factors can absolutely be considered as PDs. Nonetheless, the list of 21 factors is seen as being a list of key PDs factors in the manufacturing industry, which should be completed in relation to specific industrial or individual contexts.

This longitudinal study involves a fairly large sample including both SMEs and large multi-national corporations based on a non-random sampling strategy, which limits the overall generalizability of the results. Moreover, the targeted sample for the open invitation could not be quantified, thus prohibiting the possibility of establishing a definitive response rate. These responses could also potentially be influenced by self-selection bias (Forza, 2002). However, the fact that responses from individuals not having an expert view were excluded ensured that the open invitation resulted in relevant data. Further, the responses are based on an expert view on a high-strategic level, a group that is often hard to obtain in questionnaire studies. Therefore, the authors are convinced that this study provides valuable empirical data that contribute to an increased understanding of how various PDs are classified and registered in industry. Moreover, the intention of the study has not been to establish any exact numbers of any PD factors. Instead, it aims at achieving a descriptive picture of how PDs are regarded in Swedish industry.

5.6 Suggestions for further research

One aspect to consider is the potential differences in the view of PDs between organizational levels. This study was based on the views of maintenance or production experts at high level. If there are such widespread views amongst management, there are likely to be even larger differences at operational level. If OEE, or handling of PDs in general, is to be the bottom-up approach that it intends to be, a shared view of what factors should be regarded as PDs needs to be established throughout the organization. Therefore, a suggestion would be to replicate this study with a sample of shop floor workers.

In order to fully operationalize the concept of PDs and a factor-based approach to handling them, further research towards data-driven analysis on an individual PD level is needed. These analyses could be used for immediate maintenance actions as well as input to engineering activities aimed at a reduction of production losses. This also requires further development of monitoring systems that are based on established PD classification frameworks. Furthermore, a fundamental prerequisite for using collection and analysis of production data as a mean for identifying, reducing, and eliminating PDs, is the development of systematic approaches that ensures the quality of production data.

6. Conclusions

The evaluation of how PDs are classified and registered in Swedish industry based on a repeated cross-sectional survey study carried out between 2001 and 2014 illustrates a diverging view of 21 proposed PD factors. By studying this subject from a longitudinal perspective, this diverging view is found to have been consistent for over a decade. During the same time span, reports of low-OEE figures have also been consistent.

This study contributes with empirical data that answers the following two questions:

(1) How are individuals with production or maintenance management positions in industry classifying different PD factors?

Most individuals regard events that cause clearly visual downtime as PDs, where the three factors "equipment failure", "failure in software", and "media error" were classified at the highest degree. In contrast, planned events are regarded as PDs to a much lower extent, where the two factors "pauses or breaks" and "work meetings" were classified as PDs at the lowest degree. A general consistency of this interpretation of PDs is found between the two surveys. However, a lack of correspondence between the respondents' view and existing literature is identified, particularly in regard to planned events. For example, "set-up/resetting" and "tool change", which have been included in OEE definitions since its origin, were only regarded as PDs by around half of the respondents in both surveys, and "preventive maintenance" was regarded as a PD by less than one-fourth. This lack of recognition of planned events as PDs is a source of lost potential. Classifying planned events as losses creates a motive for improvements beyond the confines of the unexpected, which in turn can result in increased productivity:

(2) Which factors are being measured and registered as PDs in the companies monitoring systems?

Factors causing visual downtime are also registered as PDs at a higher degree than planned events. Naturally, avoiding registration of planned events as PDs further limit companies' possibility to improve productivity. Moreover, a gap between the classification and registration of PDs is found, where the maintenance or production experts with long experience at the companies are more prone to classify a majority of the proposed factors as PDs compared to what is being registered. However, this gap appears to be shrinking due to a trend towards increased registration of PD factors during the past decade. These results suggest that most companies have started to register various PD factors in their monitoring systems, but have not fully reached a state where all regarded factors are being measured.

Overall, a diverging view of PDs has been found between respondents in the manufacturing industry. This diverging view, in turn, hinders the possibility for companies to develop systematic and effective strategies for handling of PDs; these strategies are dependent on an internal consensus of what events that should be classified and registered as PDs. Further, to exploit the full potential of the production systems in future digital factories, deciding what PDs to measure will become even more important. Finally, the handling of PDs must radically improve and become much more effective in order to realize digital manufacturing.

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Appendix

Proposed PD factors	Classified as PD ($n = 80$) Yes	No	Yes (%)	n/a	Registered as PD ($n = 80$) Yes	No	Yes (%)	?	n/a
Equipment failure	76	1	99	3	61	13	79	2	1
Human error	67	9	88	4	50	25	65	1	2
Failure of peripheral, e.g., external transport system	57	17	77	6	39	30	53	5	2
Failure of software in production equipment	74	3	96	3	60	14	78	2	1
Reprogramming	39	36	52	5	31	36	42	6	1
Planning error	54	22	71	4	29	35	41	9	1
Tool change	28	36	44	16	22	39	30	3	3
Time for changing/refilling of material	24	48	33	8	18	48	24	4	2
Set-up/resetting	30	41	42	9	28	42	37	2	2
Adjustment	48	25	66	7	30	40	39	2	1
Preventive maintenance	24	52	32	4	19	55	24	1	1
Cleaning	24	50	32	6	20	51	26	2	1
Work meeting	18	55	25	7	14	56	18	2	1
Pauses or breaks	15	58	21	7	11	58	14	3	1
Waiting time for incoming product/material	62	12	84	6	44	25	59	4	1
Subsequent stop in output flow from station/machine	60	12	83	8	39	23	57	9	2
Shortage of staff	55	19	74	6	36	33	48	4	1
Media error	73	3	96	4	57	15	74	2	1
Speed loss	59	19	79	5	37	33	49	4	1
Scrap or quality problems of the product	56	17	77	7	42	28	58	3	4
Incidents/near misses	40	33	55	7	24	40	35	9	3
μ			63				45		

Notes: μ – general mean value, ? – do not know, n/a – missing answer

Table AI. Classification and registration of PDs in survey A

Proposed PD factors	Classified as PD ($n = 76$) Yes	No	Yes (%)	?	n/a	Registered as PD ($n = 76$) Yes	No	Yes (%)	?	n/a
Equipment failure	73	2	97	0	1	67	6	92	0	3
Human error	63	9	88	2	2	51	17	75	7	1
Failure of peripheral, e.g., external transport system	63	8	89	3	2	51	20	72	3	2
Failure of software in production equipment	69	3	96	3	1	62	8	89	4	2
Reprogramming	36	35	51	4	1	32	35	48	7	2
Planning error	58	16	78	0	2	32	37	46	4	3
Tool change	26	43	38	2	5	27	39	41	5	5
Time for changing/refilling of material	34	35	49	3	4	25	43	37	4	4
Set-up/resetting	36	36	50	0	4	35	36	49	1	4
Adjustment	49	21	70	2	4	41	26	59	4	2
Preventive maintenance	27	48	36	0	1	36	36	50	2	2
Cleaning	29	45	39	0	2	33	38	46	2	3
Work meeting	17	54	24	2	3	19	51	27	3	3
Pauses or breaks	17	56	23	1	2	17	52	25	4	3
Waiting time for incoming product/material	59	14	81	1	2	45	25	64	3	3
Subsequent stop in output flow from station/machine	57	14	80	1	4	48	23	68	2	3
Shortage of staff	57	17	77	0	2	36	34	51	3	3
Media error	70	3	96	0	3	57	10	85	4	5
Speed loss	55	13	81	3	5	43	26	62	3	4
Scrap or quality problems of the product	61	9	87	2	4	55	15	79	1	5
Incidents/near misses	51	22	70	1	2	48	19	72	6	3
μ			67					59		

Notes: μ – general mean value, ? – do not know, n/a – missing answer

Table AII. Classification and registration of PDs in survey B

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