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Procedia CIRP 134 (2025) 331–336

www.elsevier.com/locate/procedia

Proceedings of the 58th CIRP Conference on Manufacturing Systems 2025

Environmental Impacts of Production Disturbances in Manufacturing from an OEE Perspective

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Abstract

Production Disturbances (PDs) negatively impact efficiency and productivity in manufacturing systems by consuming resources and causing losses. It is intuitive that production equipment maintenance, and thereby PDs handling, is tightly connected to sustainability by contributing to the extended longevity of technical systems. However, there is a lack of knowledge regarding how PDs impact Environmental Sustainability Indicators (ESIs). This missing connection makes it challenging for decision-makers to motivate green investments and to align work procedures to reduce environmental impacts. This study aims to bridge the gap between PDs and ESIs through a questionnaire-based survey to collect data and establish an integrated picture of PDs and ESIs in the context of Overall Equipment Effectiveness (OEE). The findings within our study indicated that quality and maintenance organizations should prioritize addressing defects, reduced yield and idling/minor stops to improve ESIs. Targeted strategies to reduce these PDs can lead to improvements in energy efficiency and waste reduction, ultimately contributing to net-zero emissions.

Keywords: Production Disturbances; Environmental Sustainability Indicators; Maintenace; OEE; Eficiency

1. Introduction

Following increasing concerns about environmental sustainability, businesses are attempting to integrate sustainability into their strategies and operations [1]. Reporting on significant sustainability aspects and indicators is a need for companies to show their transparency and accountability, build long-term sustainability, and foster stakeholder trust [2]. The manufacturing industry takes second place in terms of its contribution to greenhouse gas emissions in Europe [3] which highlights a serious challenge in environmental sustainability and climate change. The manufacturing industry is responsible for about 35% of CO_2 emissions and one-third of worldwide energy consumption, as indicated by a report published in 2015 by the International Energy Agency [4]. Thus, manufacturers must prioritize environmental impact reduction in their strategies. Based on the U.S. Department of Commerce definition, sustainable manufacturing is “the creation of manufactured products that use processes that minimize negative environmental impact, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [5]. Therefore, manufacturing should adopt an approach to their production process to take a balance between the dual goals of increasing operational efficiency and minimizing environmental impact. Prior studies showed the productivity and efficiency of production systems are directly impacted by production disturbances (PDs) arising from various causes such as equipment failure, human error, set-up, etc. [6,7]. These disturbances can lead to excessive consumption of resources, increased waste generation, emissions, and wastewater discharge that pose environmental issues. Overall Equipment Effectiveness (OEE) is one of the

10.1016/j.procir.2025.03.039

well-known metrics for assessing equipment performance and identifying losses caused by PDs [8]. However, the connection between PDs and ESIs has not been widely studied. This paper explores the effect of PDs on key ESIs to help organizations monitor and assess how production activities affect these indicators. It also provides insights into the environmental health state and supports decision-making processes to meet sustainable development targets. Considering the gap, two research questions have been formulated:

RQ1. How can PDs be prioritized in terms of their impacts on ESIs?

RQ2. Which indicator is most impacted by PDs?

2. Terminologies and concepts

This section provides the general concepts of the study.

- **PDs**: PDs are defined as undesirable or unplanned events that cause deviations from the normal situation of system performance in a way that results in losses [9]. PD is a complex issue as organizations have different definitions for that and there is a lack of consensus in the literature. Other terms such as disruptions, hazards, errors, failures, defects, waste, and losses are frequently applied to PD [10].
- **OEE**: OEE is provided as an important measure for manufacturing improvement, as it helps identify losses in production processes thereby contributing to environmental sustainability. For small and medium-sized enterprises (SMEs), OEE is a key component to assess performance and a valuable tool to facilitate the decision-making process across various disciplines. OEE is split into three components: availability, performance, and quality [11]:

$$OEE = Availability(A) * Performance(P) * Quality(Q) \quad (1)$$

$$A = Operating\ Time / Loading\ Time \quad (2)$$

$$P = (Theoretical\ Cycle\ time * Processed\ Amount) / Operating\ Time \quad (3)$$

$$Q = (Processed\ Amount - Defect\ Amount) / Processed\ Amount \quad (4)$$

OEE can be considered as the initial step in analyzing PDs [6]. Therefore, PDs as the causes of the losses can be categorized into three types: downtime, speed, and quality (defect) losses [12] (see Fig. 1).

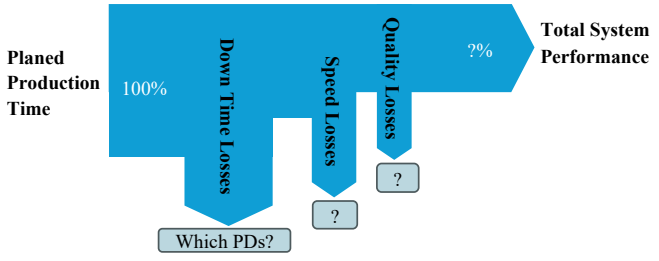

Fig. 1. OEE components [12]

Each component of OEE can be categorized into two subcategories, forming six big losses [11]. A brief description of each is outlined in Table 1.

Table 1. Six big losses of OEE [11]

OEE components	Six big losses	Description
Availability	Equipment failure	Losses arising from any unplanned stop or downtime
	Setup & adjustment	Losses due to stoppages during setup, changeovers, and adjustments
Performance	Reduced Speed	Losses arising from the difference between actual operating speeds and design speeds
	Idling & Minor stops	Losses due to occasional waiting, delay and stopping for minor checks that usually resolve quickly; Their frequency can cause significant capacity loss.
Quality	Process Defect	Losses due to defects and rework
	Reduced Yield	Losses due to defective parts produced from startup until stable production is reached, including scrapped parts as well as parts that can be reworked

- **ESIs**: Indicators are applied to explain a particular status. Thus, ESIs are valuable tools to aware organizations of potential harm to the ecosystem and assist them in gauging their operations and finding areas for improvement. The term *metrics* is another term that is often used interchangeably with indicators. However, there are no widely accepted definitions for metrics and indicators, and their usage often overlaps [13]. This study adopts the definitions provided in [13,14] where indicators represent broader sustainability objectives, such as energy consumption, while metrics are measurable quantities (absolute or relative) used to track these indicators, such as "kilowatt-hours per unit produced". Also, *Measures*, refer to the collected values. Given the broader scope of this study, the focus is on indicators.

3. Background

3.1. Production disturbances

All types of PDs should be identified to prevent material wastage and ensure product quality; therefore, it is important to classify PDs to manage their operational and environmental effects [9]. PDs can be classified based on various criteria. In a study, in Bangladesh's garment sector, by considering the frequency and correlation with causes, significant PDs proposed [15]. A research study in New Zealand involving 212 SMEs discovered typical PDs associated with these organizations. The researchers considered hazards as PDs and identified 20 distinct PDs based on their frequency and impact. [9]. A longitudinal survey was conducted to explore various PDs in the Swedish industry [6,7]. 21 different PDs are found in this study and the findings revealed differences between how individuals classify PDs and how they are registered in the companies' follow-up systems. In a separate study within the heavy equipment industry, PDs classified based on their characteristics such as source (internal, external), type (demand, raw material, machine and operator), severity, duration, impact, frequency and division [16]. PDs may be categorized both qualitatively and quantitatively according to their effects on production, safety, and business [10].

3.2. Overall Equipment effectiveness

The concept of OEE was introduced in 1988 for the first time [11]. However, recent advancements have extended its scope to incorporate sustainability dimensions. One such extension is Overall Environmental Equipment Effectiveness (OEEE) which shows the relationship between OEE and CO_2 [16]. Also, Overall Sustainable Equipment Effectiveness (OSEE), integrates ecological and social dimensions into the OEE framework, including indicators like resource efficiency, recycling share, emission and waste [17]. The literature provides evidence of connections between OEE and ESIs. A theoretical model that integrates productivity KPIs with energy consumption data is proposed in [18]. Further study has investigated the relationship between the various OEE loss categories and their effects on the system's energy efficiency [19]. The other research has shown that benchmarking energy consumption helps factories identify inefficiencies and implement best practices for energy management [20]. Findings from [21] showed that when improving OEE (by 37%), CO_2 emission per product can be significantly reduced (by 26%) while profitability increases (by 9%). Another case study [22] reported a 7% improvement in OEE due to the reduction of failures led to a 23% reduction in emission. In a more recent study, a data-driven approach is proposed that links OEE-related losses to energy demand [23]. Furthermore, implementing Industry 4.0 technologies to increase OEE can impact ESIs, such as energy and water consumption [24].

3.3. Environmental Sustainability Indicators

Environmental sustainability refers to the balance of source and sink functions which can be defined as "a set of constraints on the four major activities regulating the scale of the human economic subsystems: the use of renewable and non-renewable resources on the source side, and pollution and waste assimilation on the sink side" [25]. Sustainable production indicators are key components to improve organizational learning. By involving all staff in the measurement process, these indicators can help to boost awareness and skills in an organization. Therefore, the management team should consider environmental sustainability as a part of the organization's training program to achieve environmental targets [26]. Different aspects can influence the selection of appropriate indicators such as product, processes, reporting format, budget, time constraints, etc [5]. Raouf [26] emphasized ineffective maintenance negatively impacts the environment due to excesses in production, processing, inventory, transportation, defects, and waiting time. Also, this study suggested input indicators—such as material, energy, and water consumption—and output indicators, like air emissions, water pollution, and solid waste to be considered for environmental assessment. Based on Global Reporting Initiative (GRI) guidelines, Samuel et al. [27] categorized ESIs into emissions, energy, materials, water, products and services, effluent and waste, transport, environmental accounting and compliance. Gani et al. [28] applied different methods for identifying and categorizing the most important ESIs within the manufacturing sector. The researchers grouped ESIs into 7 categories including energy, water, waste and effluent, material, air emissions, R&D/compliance-related, and natural habitat, listed in descending order of rank. The National Institute of Standards and Technology (NIST) suggested five dimensions for sustainability: environmental, economic, social, technological advancement, and performance management. Based on NIST's categorization, ESIs were allocated to four main groups: emissions, resource consumption (water, energy, material, and land), pollution, and natural habitat conservation [5]. A literature study showed a lack of consensus in applying indicators. However, some of them are most consistently and frequently used for sustainability assessment like resources, emissions, and wastes for the environmental dimension [29]. In a study, ESIs were classified into three main groups. Evidence from the literature showed maintenance has a positive impact on ESIs [30]. EU taxonomy for sustainable activities defines six environmental objectives that companies are expected to meet: climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, protection, and restoration of biodiversity and ecosystems. All companies subject to the Corporate Sustainability Reporting Directive (CSRD) must report in accordance with the European Sustainability Reporting Standards (ESRS) [31].

Based on findings from the literature, this study focuses on six ESIs that provide insights into significant aspects of environmental performance:

- Raw Material Usage: refers to the volume of materials consumed.
- Water Consumption: refers to the volume of water used in the production process.
- Energy Consumption: refers to the amount of energy used during production.
- Air Emission: refers to the volume of pollutants released into the air during production.
- Wastewater Generation: refers to the volume of wastewater produced.
- Waste Generation refers to the volume of waste generated from production. (i.e. solid waste including defective products (all those need rework or discarded), hazardous substances, and other solid pollutants that are harmful to the environment)

The selected ESIs in this study are also aligned with the EU taxonomy, focusing on key areas such as waste indicator which is part of the circular economy topic and emphasizes waste prevention and the reduction of pollution resulting from waste. Additionally, the water consumption indicator, under the water and marine resources topic, addresses water consumption and its environmental impact.

4. Research Methodology

As a part of a broader research, this study adopts a qualitative approach to analyze the impacts of PDs on ESIs. Reducing the environmental impact of the production system requires knowledge about the material flow through the process, which

is usually represented by an input/output model. Raw materials, water, and energy are categorized as inputs to production processes and systems while products, waste, air emissions, and wastewater are considered as outputs [32]. A conceptual input/output model of a production system is visualized in Fig. 2 for the manufacturing or production system to show the framework of interrelated components. However, PDs interfere with this process, influencing both the efficiency and the environmental sustainability outcomes.

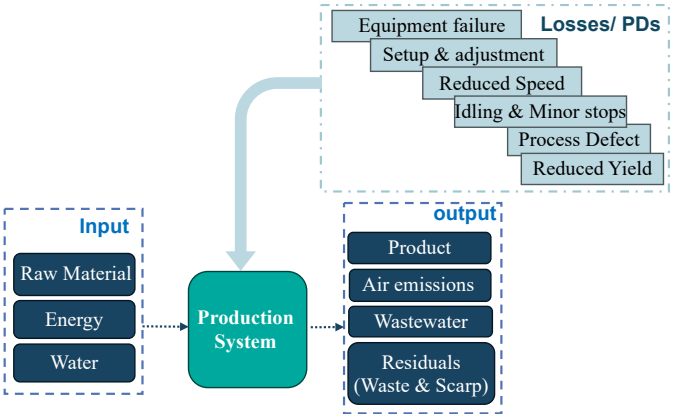

Fig. 2. Conceptual input/out Model of a production system

Considering the conceptual model in this study, a structured methodology for analyzing the impacts of PDs on ESIs is suggested to address RQ1 and RQ2. It follows a three-step framework to ensure a systematic and objective assessment of sustainability impacts.

Step 1: Identification of PDs and ESIs: industry-specific PDs are categorized according to OEE losses. The ESIs are selected from the literature. They can be adapted based on the EU Taxonomy, GRI, and others.

Step 2: Data Collection and Scoring: based on the defined input/output model, ESIs, and PDs, a questionnaire-based survey is designed, targeting practitioners in manufacturing from production, quality, maintenance and sustainability roles. The Fig. 3 illustrates the ranking system used in designing the questionnaire.

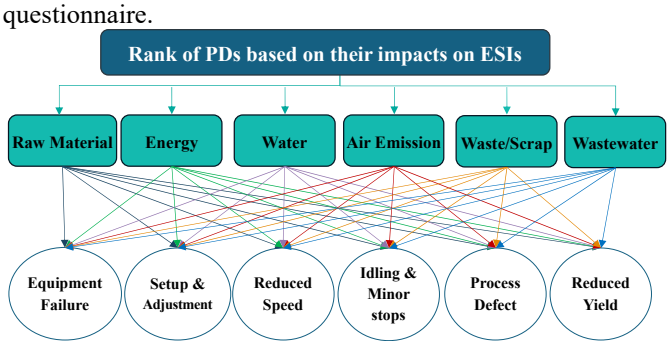

Fig. 3. Ranking system of PDs based on their impacts on ESIs

Step 3: Ranking and Prioritization: after data collection, the severity of each PD's effect on different ESIs is assessed using a mathematical ranking approach. The matrix **X** represents the severity of each PD's impact on various ESIs. Each array (X_{ij}) in the matrix indicates the experts' average impact score of PD_i (i=1,…, N=6), which corresponds to the six big losses, on the six selected ESI_j (j=1,…, M=6):

$$\boldsymbol{X} = \begin{matrix} ESI_1 & \dots & ESI_M \\ \begin{bmatrix} X_{1j} & \cdots & X_{1M} \\ \vdots & \ddots & \vdots \\ X_{N1} & \cdots & X_{NM} \end{bmatrix} & \begin{matrix} PD_1 \\ \vdots \\ PD_N \end{matrix} \end{matrix} \quad (5)$$

$$S(PD_i) = \frac{\sum_{j=1}^{M} X_{ij}}{M} \quad (6)$$

$$I\ (ESI_j) = \frac{\sum_{i=1}^{N} X_{ij}}{N} \quad (7)$$

$S(PD_i)$ is the impact score of PD_i on ESIs

$I(ESI_j)$ is the average impact of all PDs on ESI_j

A higher Impact score ($S(PD_i)$) indicates a greater negative impact on sustainability. Furthermore, the ESI most influenced by PDs is represented by the highest value of $I(ESI_j)$.

4.1. Data Collection

Data collection was conducted within the Swedish manufacturing industry, focusing on two case companies (Table 2). A panel of experts from these companies participated in a structured session, comprising five representatives from the production, quality, and sustainability departments. This panel provided a multi-faceted perspective on the topic and allowed for an in-depth exploration of insights within manufacturing operations.

Table 2. Description of companies and interviewee profiles

Company	Description	No. of employees	No. of interviewees	Positions in company
1	Advanced plastic products	200-250	4	Quality and Environmental Manager, Technical Manager, Team leader, Production Engineer
2	Metal industry	200-250	1	Quality and Sustainability Manager

It must be noted that the availability of experts and the ongoing production schedules, restricted the number of participants. The participants were carefully selected based on their roles ensuring that their inputs were highly relevant and informed. In the beginning, the research dimensions were presented and the process of completing the questionnaire was explained. Based on PDs and ESIs derived from the literature review, the participants then rated the importance of six types of PDs in terms of their impacts on ESIs using a Likert 5-point scale, with 1 indicating "very low" and 5 indicating "very high". Likert scale enables researchers to collect numeric data which can be used to visualize and analyze respondents' opinions (South et al., 2022). After the questionnaires were collected, a discussion followed to explore the experts' reasons behind their ratings and validate the results with them. Finally, the average scores for each type of PD, as well as the average impacts of PDs on a specific indicator were calculated. As mentioned, operational schedules in the participating companies posed challenges for conducting direct, open-ended interviews. To address this, the structured questionnaire was selected for its efficiency in collecting standardized data, ensuring consistency across responses. This approach facilitated the initial exploration of the PD-ESI relationship

while minimizing disruption to company operations. However, incorporating semi-structured interviews and focus groups could enhance qualitative insights.

5. Results

The results of the analysis are presented and explained in this section. Fig. 4 shows the average impact scores PDs on each ESI. The key findings from the analysis are as follows:

- Process defects ($S(PD_{Defect})=2,8$) and reduced yield ($S(PD_{Yield})=3,1$) showed the highest impact across most ESIs, particularly in waste generation.
- Energy consumption ($I(ESI_{Energy})=2,9$) was most affected by PDs, mainly by process defects ($X_{defect,Energy}=3,4$) and reduced yield ($X_{Yield,Energy}=3,5$)
- Air emission ($I(ESI_{Emission})=1,8$) was less impacted by PDs compared to other ESIs.

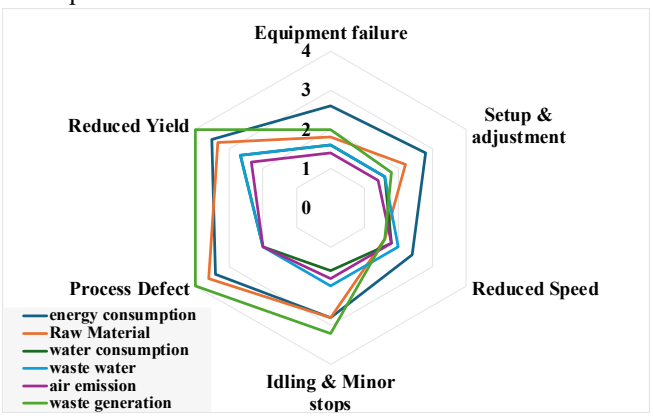

Fig. 4. Overall view of PDs' impacts on ESIs, indicating (X_{ij})

The results indicate that PDs, particularly reduced yield and process defects have significant negative impacts on ESIs, ranking as the top two PDs which show the need for targeting strategies to minimize these effects to improve both operational efficiency and environmental sustainability (Fig. 5).

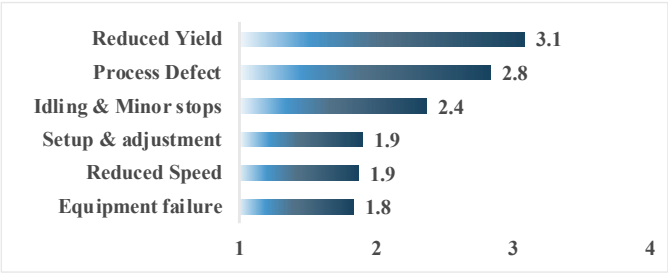

Fig. 5. Average score of PDs and their ranks

The highest average impact is observed on energy consumption and waste generation. The significant effects of PDs on energy consumption highlighted the importance of this indicator and necessitated attention from the manufacturers (Fig. 6). This result is aligned with the finding from [28]. The observed consistency with prior work shows that the relationships identified in this study may not be context-dependent but are instead indicative of broader patterns in manufacturing systems. However, Further research is needed to test this scalability by extending the study to other sectors and larger datasets.

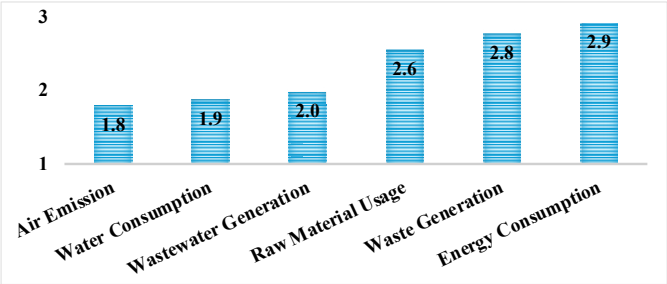

Fig. 6. Average PDs' impacts on ESIs

Air emissions show the least impact from PDs among the ESIs. In this study, clean energy usage plays a critical role in reducing the impact of PDs on air emission, with minimal impact observed across all types of PDs. Maintaining and expanding clean energy will continue to mitigate the environmental impact of inefficiencies in production. The low effect on water-related indicators, such as water consumption and wastewater generation, showed water is mainly utilized for cooling purposes in these cases, instead of being significantly consumed during the process itself. The overall environmental impact of PDs reveals that addressing quality-related disturbances (defects and yield) should be a priority for achieving sustainable production. By addressing these key PDs and aligning operational practices with environmental goals, industries can enhance their efficiency while contributing to sustainability targets. One of the key components of sustainable manufacturing can be the maintenance which is required to guarantee the availability, reliability, and safety of assets.

6. Limitations and future research

The current study relies on a small sample size, which might limit the broader applicability of the findings. While the insights gained are valuable for the studied case companies, they may not fully represent the diversity of manufacturing environments. It is important to emphasize that this was a targeted exploratory study designed to provide preliminary insights into the relationship between PDs and ESIs. These foundational findings offer a starting point for further research and refinement. Future work can focus on addressing these limitations by expanding the sample size and incorporating a more diverse range of manufacturing contexts and employing a mixed-methods approach to validate the findings and enhance reproducibility.

7. Conclusion

The dual analysis of ESIs and PDs highlights a critical connection between operational efficiency and environmental impact. To improve environmental sustainability in production systems, it is essential to focus on reducing process defects and improving yield efficiency. These two PDs are the main drivers of energy overconsumption, waste generation, and material usage. By addressing these inefficiencies, companies can significantly reduce their environmental impacts. In addition, efforts to minimize idling & minor stops will further contribute to reducing waste generation and energy consumption. Optimizing production processes through predictive

maintenance, lean manufacturing, and quality control will result in a more sustainable and resource-efficient production system. This study was conducted in the focused cases, which limits the generalizability of the findings. Including additional case studies can support the current results or provide new insights, leading to a broader understanding and validation of the findings across diverse organizational contexts.

Acknowledgements

The study was supported by the Swedish innovation agency VINNOVA under grant no. 2021-02478 (DFusion). The work was carried out within Chalmers' Area of Advanced Production whose support is greatly acknowledged.

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