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Machine Failures' Consequences – A Classification Model Considering Ultra-Efficiency Criteria

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Abstract

To strive for a sustainable production, maintenance has to evaluate possible machine failure consequences not just economically but also holistically. Approaches such as the ultra-efficiency factory consider energy, material, human/staff, emission, and organization as optimization dimensions. These ultra-efficiency dimensions can be considered for analyzing not only the respective machine failure but also the effects on the entire production system holistically. This paper presents an easy to use method, based on a questionnaire, for assessing the failure consequences of a machine malfunction in a production system considering the ultra-efficiency dimensions. The method was validated in a battery production.

Keywords: Mainteance; Sustainability

1. Introduction

The worldwide sustainability development goals of the United Nations and efforts to limit climate change are becoming more and more concrete on a political level. Also, more and more factories recognize ecological and social aspects competition relevant. This results in objectives for the improvement of resource efficiency and effectiveness optimizing the usage of material, energy, machines, and equipment. [1] On a social level, developments such as the skilled workers shortage or an aging workforce complement the technologically more complex machines and equipment and need to be addressed. Existing approaches that include sustainability aspects of machines and equipment, focus either the planning and investment phase or energy consumption and emissions in the operation phase. Examples for approaches in the planning and investment phase are Life Cycle Assessment (LCA), Life Cycle Costing (LCC) or Total Cost of Ownership (TCO). Carbon footprint or emission calculation are approaches used during operation phase and often part of a product's carbon footprint calculation.

Unplanned failures or breakdowns but also too early changes of components reduce machine and equipment efficiency. Especially, consequences of unplanned breakdowns for following production processes typically add extra emissions on a product's footprint. Here, maintenance is one of the key enabler to improve the sustainability of a factory since its overall objective is to safeguard its operability. [2]

Traditionally, the main optimization goal of maintenance activities is reducing costs. Deciding on a maintenance strategy for machinery and equipment is one of the major steps, influencing all following planning and operational activities [3]. Those in charge are more and more confronted with sustainability objectives coming from the management, but the implementation requires a lot of time and effort. Thus, there is a need for new, fast, and easy-to use methods for a first systematic classification leading to holistic maintenance strategy selection approaches considering the traditional cost-driven maintenance as well as ecological and social aspects.

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This paper presents a machine failure consequence classification considering ultra-efficiency dimensions being the key enabler for a holistic maintenance strategy selection.

2. Related Work

Against this background, Fraunhofer developed the concept of the ultra-efficiency factory. It is defined as a completely loss-free factor, that contributes positively to its immediate environment and implies a factory that operates in symbiosis with the environment [4]. Further, this concept includes the conventional paradigms – efficiency and effectiveness. Ideally, resources are managed in closed loops using regenerative, sustainable energy sources. In order to enable a holistic view, five fields of action, namely material, energy, emission, human/staff, and organization, were defined making the ultra-efficient factory concept unique and giving it an extended sustainability framework [5]. Previous research established industry-specific benchmarks and guiding principles in order to enable a comparison of companies and, thus, the identification of potential improvement actions [6,7]. The aim is to achieve ultra-efficiency in all five fields of action.[5,8]

Machine failure consequence classification methods for maintenance strategy selection can be clustered in KPI-based approaches, risk-based approaches and approaches considering the entire value stream of a production. KPI-based approaches use KPIs such as the Mean Time Between Failure (MTBF) or the Mean Time to Repair (MTTR) the availability and Overall Equipment Effectiveness (OEE) to identify improvement potentials and assign in a following step the maintenance policy/strategy. Other common approaches used for selecting a maintenance strategy are to calculate the failure cost [9–12] or Reliability Centered Maintenance (RCM II) [13]. Risk-based approaches such as risk graph [14], Quantified Risk Analysis (QRA) [15], Risk Based Maintenance (RBM) [16] or Failure Mode Effects and Criticality Analysis (FMECA) [17] consider the occurrence and severity of failures. Holistic approaches take a production's entire value stream into account, e.g., weak point and potential analysis [18], system reliability analysis [12], or lean maintenance system [19]. The SUPREME risk assessment method [20] considers failures on machine level as well as on production system level. However, existing approaches for machine and failure consequence classification either consume much time and effort and are domain-agnostic or they don't directly address sustainability aspects.

3. Failure Consequence Classification

The task of operational maintenance is to ensure that production machines are technically available to produce the planned products. The primary aim is to avoid unplanned downtime and to schedule planned downtime for maintenance, either during non-production periods, or to keep them as short as possible. To define where the operational maintenance has the greatest leverage in the production system, the individual machines have so far only been (if at all) evaluated according to their economic value contributions to production in order to define suitable maintenance strategies, initiate optimization measures, or prioritize short-term work.

Against the background of the proposed holistic view, the economic focus needs to be expanded to include other fields of action and ultra-efficiency criteria. In order to ascertain holistically which machines and equipment of production system maintenance investments are most worthwhile the influences of maintenance on the production system must consider the influence on energy, material, personnel, emissions, and the organization. Only by taking the holistic view on the fields of action the scarce resources of operational maintenance, either investment capital or available manpower, can be allocated to the right machines and equipment.

To enable a fast and easy-to-use prioritization of production machines and equipment according to all criteria of ultra-efficiency, proven methods of machine prioritization by maintenance are used [20,21]. A questionnaire-based approach was chosen with a group of employees evaluating various production machines to get a first impression which machines should be included in a more detailed analysis. With the help of targeted questions, the importance of each machine for the production system can be determined and the consequences of a machine failure can be ascertained. The importance and the consequences of failure are then mapped in a scatter plot and the individual machines are sorted graphically. Thus, the importance of a machine can be determined over the respective position.

The advantages of the existing approach, the simple applicability, the fast solution finding and the simple interpretation are employed for the evaluation of the machines and equipment according to the ultra-efficiency fields of action. For each of the five fields, the importance of the machine or equipment compared to the average of the production system is determined with up to three questions per fields of action. In the same way, the failure consequence per field is recorded with up to three questions compared to the failure consequences of the average machine. The questions are posed to a group of employees for each machine by a moderator and the group estimates for each case how important the individual machine is and whether a failure of the respective machine would have more or less bad consequences for the production system than the average. The ordinal scaled response options: much less, less, average, more, and much more are assigned values from 0 to 1 in increments of 0.25. An average important machine with a much greater failure consequence than the average has values of 0.5 for importance and 1 for failure consequence. The answers for importance and consequence from each field of action can either be weighted company individually or just averaged. The values obtained in this way for each field of action are transferred to a scatter plot in which the importance of the machine is shown on the horizontal axis and the consequence of a failure is shown on the vertical axis as shown in figure 1. Values close to or at zero meaning much fewer consequences and much less importance are placed at the bottom left, and the most important machines with the greatest failure consequences are placed at the top right. In these five scatter plots for all fields of action of ultra-efficiency, all machines and equipment are included so that prioritization can be done per field by placement in the plots.

The individual questions can be adapted to the specific needs of each company. However, when developing the

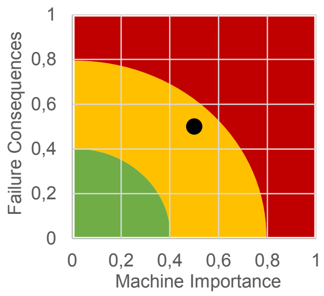

Fig. 1. Visualization of the machine classification considering ultra-efficiency criteria.

questions, care must be taken to ensure that they can be answered by a small group of employees without extensive data research in order to retain the advantages of the approach and to enable fast and uncomplicated prioritization of the machines. For this reason, a maximum of three questions per dimension and field of action was agreed upon, presented in the following. For each question, the individual machine is compared to the average of the production system.

3.1. Organization

All aspects related to the maintenance organization and general information related to the production system structure are clustered in this category.

- Machine-related aspects
  - How high is the machine hour rate?
  - How high is the meantime between failures (MTBF)?
  - How high is the overall equipment efficiency (OEE)?
- Consequences for the production system
  - Is there more or less technical and capacitive redundancy in the production system?
  - Is the maximum system downtime until next production step shutdown higher or lower?
  - What is the maximum system downtime until supply chain interruption to the customer?

3.2. Energy

This category addresses all aspects of the machine directly related to energy (electricity, compressed air, heat and cold).

- Machine-related aspects
  - How high is the overall energy consumption of the machine?
  - How high is the standby energy consumption w.r.t to normal operation?
- Consequences on the production system
  - How high is the standby energy consumption of dependent processes, affected by a machine failure?

3.3. Emission

This category includes all questions related to solid, liquid, and gaseous emissions in normal operation as well as in cases of a machine failure and its consequences for the production system.

- Machine-related aspects
  - How high is the amount of hazardous emissions and waste (solid, liquid, gas)?
- Consequences for the production system
  - How high is the hazard potential w.r.t. environment?
  - How much additional emissions in the production system are produced due to failure of this machine?

3.4. Material

The questions in this category address the material resource efficiency and product quality, with respect to both production material and consumable material.

- Machine-related aspects
  - How high is the amount of overall material consumption?
  - How high is the amount of waste w.r.t. raw material?
  - How high is the amount of recyclable waste w.r.t. raw material?
- Consequences on the production system
  - How many scrappy products are produced because of this machine's break downs?
  - How high is the standby material consumption of dependent processes?

3.5. Human

This category comprises aspects related to the required number of employees, the qualification level, and the hazard potential with respect to health and safety.

- Machine-related aspects
  - How many employees does the machine require?
  - How high is the qualification level?
  - How high is the hazard potential w.r.t. health and employee's safety?
- Consequences for the production system
  - How many employees are affected in case of a machine breakdown?
  - How many machine processes can be substituted by manual labor?

3.6. Normalized field of action value

To represent all five fields of action (FoA) for a single machine, the importance of the machine (Imp_{FoA}) and the failure consequence (Con_{FoA}) are used to determine a characteristic value for the respective fields of action by using the distance from zero in the scatter plot, normalized to one. The formula to ascertain the field's individual value is shown in (1).

$$S_{FoA} = \frac{\sqrt{{Imp_{FoA}}^2 + {Con_{FoA}}^2}}{\sqrt{2}} \quad (1)$$

This results in one key figure per field of action per machine which can then be displayed in a network diagram as shown in figure 2 to give a quick overview of each machine. The five scatter plots can then be used to select field-specific machines in order to define suitable maintenance strategies, initiate optimization measures, or prioritize short-term work. The machine-specific network diagrams can be used to determine which fields of action can be worked on at the respective machine and how the individual areas relate to each other.

3.7. Weighted averages of normalized field of action values

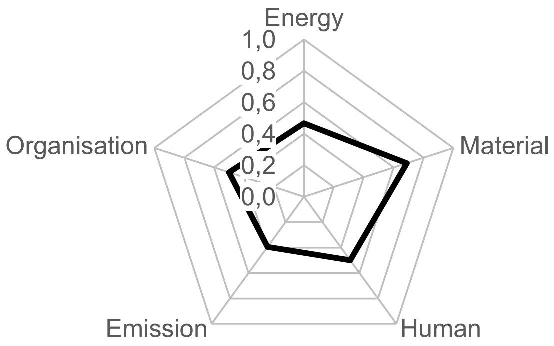

Fig. 2. Normalized machine maintenance classification ultra-efficiency criteria (exemplary machine visualization).

To arrive at an overall prioritization of the machines from the evaluations of the individual fields of action, a weighted average can be taken over the calculated values per field. Through weighting it is possible for the company to set priorities in one of the fields and thus prioritize machines that show the most potential in the respective focus. Using the weighted average of the fields, a priority list of the plants can be created in which the plants with the most important machines and the greatest consequences in the event of a failure are weighted and sorted according to the interests of the company.

4. Validation

To validate the holistic assessment of the possible downtime of a production line against the ultra-efficiency criteria, the assessment was validated on a production line of a battery manufacturer. The line produces disposable batteries for consumers and operates continuously, except for certain holidays. Cycle-dependent maintenance shifts are currently performed to carry out predictive maintenance measures. For this purpose, the closely linked production line is completely shut down to be able to carry out all tasks on all machines at once. The line consists of eight different machines types, most of them working in parallel in multiple versions in order to achieve the high number of products per shift of the line. Since the multiple versions of a machine are each set up parallel to one another in the line and are technically identical, only one system per work step was included in the evaluation. The individual systems are mostly proprietary developments of the battery manufacturer, precisely matched to existing requirements and thus representing special machine construction. There is no retooling of the machines during production, only recipes changes or different battery cups are supplied to cover special variants.

The assessment of the machines of the production system is shown in figure 3. On the first machine (machine_1), the mineral mass of the later batteries is pressed into rings. In parallel with this step, the battery cups are taken from an

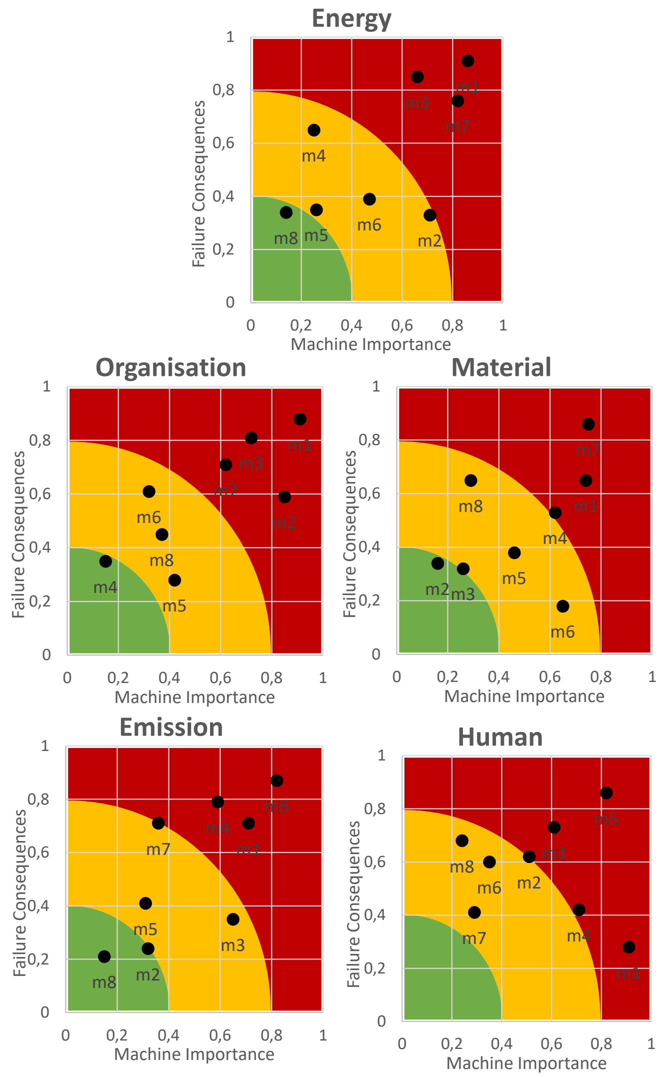

Fig. 3. Visualization of the machine classification considering ultra-efficiency criteria of the battery production line.

unsorted collection container in machine_2 and transferred to the line in correct positions. In the next machine group (machine_3), the mineral mass rings and the battery cups are brought together and the rings are pressed into the cups. In machine_4, the battery cell is wetted from the inside with a special liquid and the combination of cup and ring is inserted into a special tool carrier and the batteries then pass through the remaining production steps unsorted. The next machine group (machine_5) inserts the separator layer into the cell so that the electrolyte and after that a gel can be introduced on machine_6. In machine_7 two different tasks are carried out, first the battery cell is sealed and at the second step in this machine group, the cell is removed from the tool carrier to transfer the individual cells in machine_8 into boxes and which are then stacked on pallets for further processing. The assessment of the eight individual machine types of the line was carried out with a group of employees from the production company. The group has competences in maintenance and production as well as in environmental management tasks. The individual questions for the various fields of action were posed by the moderator and briefly discussed. Since the evaluation always considered the machine in comparison to the average of the entire line, the group was also allowed to change individual evaluations of machines already assessed, if it was determined in the discussion that previous evaluations had not taken details into account. The evaluation of the eight machine types and the preparation of the results took the group an hour, but the subsequent discussions about what action should now be taken took considerably longer. The prioritized list of the machine, shown in table 1, was recognized by the group and their superiors. The feedback of the employees was consistently positive, both in terms of how the evaluation was carried out and in terms of the result. Thus, the decisions regarding possible failures of machines now no longer only take economic interests into account but also create a basis for taking a holistic view.

Table 1. Prioritized list of machines by ultra-efficient criteria.

Machine name	Weighted average	normalized field of action values				
		Energy	Material	Human	Emission	Organisation
m1	**0,77**	0,89	0,70	0,67	0,71	0,90
m7	**0,64**	0,79	0,81	0,36	0,56	0,67
m3	**0,60**	0,76	0,29	0,67	0,52	0,77
m6	**0,55**	0,43	0,48	0,49	0,85	0,49
m4	**0,52**	0,49	0,58	0,58	0,70	0,27
m2	**0,48**	0,55	0,27	0,57	0,28	0,73
m5	**0,46**	0,31	0,42	0,84	0,36	0,36
m8	**0,37**	0,26	0,50	0,51	0,18	0,41

5. Conclusion and Outlook

This paper presents a classification approach for an evaluation of machine failures' consequences considering ultra-efficiency criteria for a holistic maintenance strategy decision. The inclusion of the fields of action: energy, material, human, emission, and organization by employing a questionnaire and workshops makes the approach suitable for various situations. This simple approach can address company-specific requirements without major changes. In addition, different prioritization options offer a wide individualization potential to reflect the respective focus. The evaluation of a specific machine and the possible consequences of its failures to the average of the production system allows for a first classification of the machines based on the experience of the experts and employees without the trouble of gathering and processing too much data. The face validation in a battery production showed the beneficial, practice-oriented, and fast application. Further research activities focus on an automated proposal and assignment of maintenance strategies for which this classification method provides a good foundation.

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