Upcoming Role of Condition Monitoring in Risk-Based Asset Management for the Power Sector

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Abstract The electrical power sector is stimulated to evolve under the pressures of the energy transition, the deregulation of electricity markets and the introduction of intelligent grids. In general, engineers believe that technologies such as monitoring, control and diagnostic devices, can realize this evolvement smoothly. Unfortunately, the contributions of these emerging technologies to business strategies remain difficult to quantify in straightforward metrics. Consequently, decisions to invest on these technologies are still taken in an ad-hoc manner. This is far from the risk-based approach commonly recommended for asset management (AM). The paper introduces risk-based management as a guiding principle for maintenance management. Then, the triple-level AM model (strategic, tactical and operational) as the foundation to define risk-based AM is described. Afterwards, two categories of risks, one triggered by technical stimuli and the other by non-technical stimuli are introduced. It is shown that the main challenge of managing risks with technical stimuli is to have the ability to understand the technical cause of failures, which is located at the operational level within the triple-level AM model. One method to quantitatively understand the technical cause of failures is by means of condition diagnostic and monitoring technologies. Therefore, the aim of this paper is to clarify the potential contribution of condition diagnostic and monitoring technologies to risk-based decision making for the power sector. This paper shows that, in practice, the implementation of condition diagnostic and monitoring technologies is mainly driven by purely technical asset based considerations without evaluating the contribution to, for instance, risks. This paper provides a list of aspects in which condition diagnostic and monitoring may contribute to risk evaluation with technical stimuli. The listed aspects (which are: (1) asset specific condition data, (2) timely condition data and (3) predictive condition data) can be regarded as input for the probability of failure and as influencing input for the consequence of failure, hence benefiting quantitative risk studies and AM activities (such as condition assessment/ maintenance or replacement). Finally, these benefits can be evaluated afterwards in a risk-based AM planning stage, so that asset managers can justify investments on necessary technical improvements of condition monitoring systems.

Keywords asset management, maintenance, risk management, condition monitoring, electricity networks

1 Introduction

The restructuring and deregulation of the electricity industry has brought about a complete change and presented immense challenges to the electricity distribution network operators (DNO's), regarding their asset and financial portfolios. To meet these challenges, asset management (AM) needs to evolve. In general, DNO's are no longer able to make decisions which are merely technically justified. Examples of decisions that only rely on technical justified reasons could be e.g. "expand the network up to its technical constraints", or "enhance the reliability and redundancy with all available budgets". As a result, DNO's are exposed to two categories of risks, which are:

1. Risks with technical triggers that have economical and societal impacts: *these risks are related to assets*
2. Risks with economical and societal triggers that have technical impacts: *these risks are related to stakeholders*

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In table 1, the above mentioned risks are listed.

Table 1: Two categories of risks to which power delivery companies are exposed

Risks with technical triggers that have economical and societal impacts: *asset related risks*	Risks with economical and societal triggers that have technical impacts: *stakeholder related risks*
• Reliability needs to be maintained for the long-term continuity of the DNO • The age of components within the network is approaching their design lifetime • New components (e.g. power electronics) are widely installed, but their influence on the existing network is insufficiently understood • Decentralized generators (e.g. wind turbines) and appliances (e.g. electric vehicles) introduce different load profiles, which require a network of higher capacity or smart used of the existing network to carry them (e.g. dynamic loading)	• Investors and creditors expect profitability of the DNO • Due to large-scale retirement of employees born in the post-World War II baby boom, a vast loss of expertise is taking place • Consumers and the regulator are attempting to control the tariffs of DNO's • Concerns on safety, environment and other public values add to the costs of expansion, reinforcement, maintenance and failure of the network

Fortunately, it is expected that the evolvement of AM will provide DNO's with capabilities to deal with these risks. As an initial stage of such evolvement, it is seen that DNO's are improving themselves in both business and technology related areas. Firstly, at business level, operation in an electricity market suggests that risk management is one of the key processes for AM decision making for DNO's [1]. Correspondingly, risk management departments and business processes have been established within many DNO's for the purpose of identifying, quantifying, classifying and prioritizing possible risks. Lastly, in the technology area, a revolution is taking place in maintenance strategies, generally speaking, and especially in condition based management methods. The latter is being introduced as a countermeasure to, especially address, the "risks with technical triggers" as can be seen in table 1.

Preferably, the two above mentioned developments should come about in a related framework, which is commonly regarded as risk-based management (RBM) [2]. However, in the power delivery sector, the situation is that the roadmap to establish this framework is unknown. As a result, it is often encountered that the success of technological developments requires clear links with business level processes. Therefore, in this article, we aim to clarify the potential contribution of condition based technologies (such as condition monitoring, diagnostics, etc.) to risk-based management in DNO's.

The article is organized in the following way: In section 2, firstly, risk-based management and the role of maintenance are described. Lastly, the triple-level asset management model is described in which the position of risk management is given. In section 3, the role of diagnostics and condition monitoring in risk-based management is described. Finally, as a result, several AM activities in a risk-based regime which can benefit from the application of condition monitoring systems are described to justify investments on condition monitoring technologies. The article comes to a close in section 4 with a number of conclusions.

2 Risk Management in Asset Management – focus on maintenance

In today's DNO's, risk-based management (RBM) is seen as a guiding principle within AM strategies [3]. The focus of this section will be on maintenance management as a subsection of AM, and its roadmap towards the link with the risk-based regime.

2.1 Risk management as guiding principle for maintenance management

In contrast to what we have seen in the past years, where maintenance management was commonly translated in financial values such as lifecycle costs and total cost of ownership, currently, a trend in the coming years is seen where the value of maintenance will increasingly be quantified in terms of risks. In order to understand this, maintenance organisations will have to evolve towards a certain level of maturity regarding their maintenance regime [5]. From our point of view, the evolvement of maintenance strategies contains the following stages as shown in figure 1.

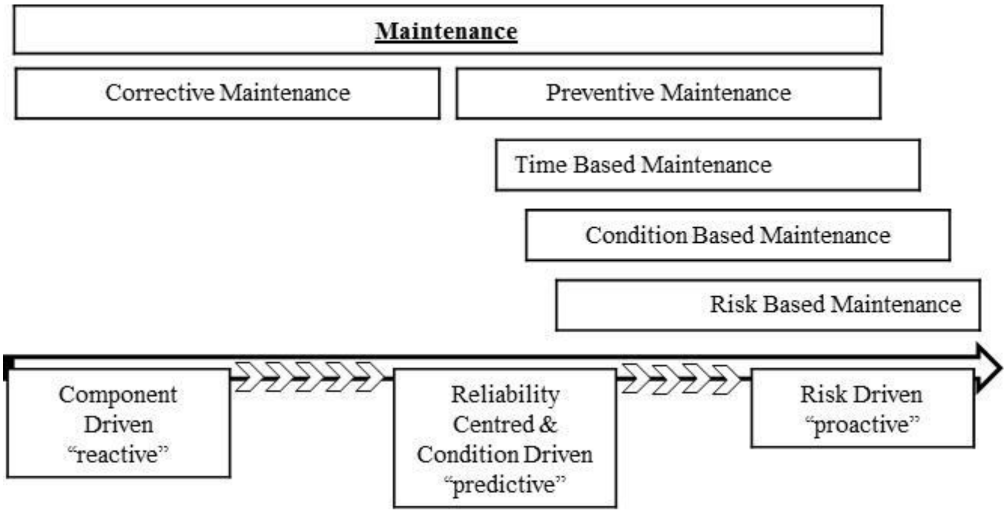

Figure 1: Evolvement of maintenance management in the last decades from reactive through predictive to finally proactive strategies

Figure 1 is briefly explained here:

- *Corrective Maintenance*: Corrective maintenance is essentially leaving all assets running till failure, and then replacing them. During the time corrective maintenance is being scheduled and performed (usually referred to "break-in", because they "break-in" to the schedule prepared) the asset is inactive [4]. As a general rule [4], a breakdown is often ten times more expensive compared to the situation that the failure can be identified and corrected (or prevented) in a planned and scheduled manner. Until now, the majority of components in distribution networks remains correctively maintained. However, with the adoption of AM, utilities are becoming aware of the changing requirements for maintenance.

- *Preventive Maintenance*: The primary upgrade from corrective maintenance to preventive maintenance is by means of maintenance plans and schedules (usually, preventive based on time (Time Based Maintenance), see figure 1). Broadly speaking, preventive maintenance plans describe the methods of inspections and maintenance tasks which can efficiently improve the reliability of physical assets. A shift from corrective to preventive maintenance will, inevitably, require some initial investment; however, it will eventually result in moderation of the total volume of planned work and will allow for control of maintenance hours and workload. When preventive maintenance is applied on an asset item it is called a preventive task. Subsequently, the timeline of the preventive task in an asset population is called the preventive schedule. This is why preventive scheduling will, eventually, result in arranging maintenance resources in advance, which, in turn, will considerably accelerate maintenance delivery and reduce operational costs (note, however, that an initial, increased, investment in the transition period is possible, but will decrease once in a controlled period).

  - *Time Based Maintenance*: as briefly mentioned earlier, traditionally, preventive maintenance is scheduled with predetermined interval, hence the name Time Based Maintenance. The time intervals are decided according to asset type and fixed for the whole lifecycle (usually with reference to manufacturer instructions and updated with historic operational and failure behaviour).
  - *Condition Based Maintenance*: Basically, condition-based maintenance differs from time-based maintenance in the sense that a shift is made in scheduling methods, namely, from an "intermediately" predictive method to a "fully" predictive method. Being predictive refers to estimating the probability of failures on assets. With condition-based maintenance, an early indication of an impending failure (by applying condition monitoring, diagnostics or inspection methods) can be detected and the consequences of an unexpected failure can be avoided.
  - *Risk Based Maintenance*: The state of the art maintenance regime is the risk-based version, which is guided by the principles of risk management. A risk is composed of a stimulus (i.e. the root cause) and its consequences. The risk-based approach refers to the quantitative assessments of (1) the probability of stimulus (event), and (2) on business values (Key Performance Indicators, KPI) evaluated consequences. In the planning, the stimuli are the failure modes for risk-based maintenance, which brings the term failure mode and effect analysis (FMEA). In scheduling of risk-based maintenance, the potential failures on asset items are the stimuli. The probabilities of

these stimuli are highly recommended to be derived from condition diagnosis (hence, the importance of the upcoming role of condition monitoring in a risk-based management regime). However, in practice, FMEA is mainly based on failure statistics if not expert judgements. The consequences of failure modes and potential failures are, if at all possible, measured with a number of key performance indicators (KPI's), such as customer minute loss, financial loss, safety etc. These KPI's connect the operational-level maintenance tasks with high-level corporate business values. In practice, this link of consequences and failure modes through a certain KPI framework is not yet straightforward, however this is beyond the scope of this article. Decisions on preventive maintenance plans or schedules are based on the risk register of failure modes or potential failures. Risk register is a process to rank the expected value of risks, while the expected value is the multiplying product of probability and consequence.

From the above review, it can be learned that: the risk-based approach for maintenance is based on five domains of knowledge, which are introduced in different stages of developments. These are:

1. Knowledge of the possibility of failure occurrence (failure modes in preventive maintenance)
2. Knowledge of the measures to prevent a possible failure occurrence (preventive maintenance plan)
3. Knowledge of the approach to predict the probability of a possible failure occurrence (failure statistics or condition diagnosis)
4. Knowledge of the consequences of a possible failure occurrence as well as a KPI system to benchmark this numerically (failure effect in risk-based maintenance)
5. Knowledge of the risk level of a possible failure occurrence (risk assessment methodology, such as risk register)

In the risk-based approach for maintenance, with the five domains of knowledge, two different types of risks can be distinguished of which the first one is with technical stimuli, especially asset failures. This is very familiar to maintenance management. The second type of risk is with financial and societal stimuli e.g. resistance of the public to new substations. The latter risk category initially started to be considered when maintenance management is extended to an organisation-wide asset management approach [5]. In section 2.2 we introduce how these two categories of risk (risk with technical trigger and non-technical risks) are handled in AM.

2.2 Risk management regime in the triple-level asset management model

Asset management is widely accepted and frequently implemented in a triple-level regime. The levels are named *strategic*, *tactic* and *operational* level from the management side to the technical side. Generally speaking, higher levels are concerning wider ranges of assets as a whole, in a longer frame, regarding larger amount of financial investment and consequences. See [3] for a definition for AM for utility companies. The technical and non-technical risk categories can be described for each level (triple-level) of the AM system.

I. The technical risks triggered by failures. These risks are the traditional target of investigation in maintenance management. Additionally, these risks can be studied scientifically and quantified with probabilities and consequences. Consequently, this allows the classic way to implement risk management and optimize by means of probabilistic data analysis and assess the condition of assets with appropriate technologies (such as condition monitoring tools). In the following, we discuss each level of AM from a technically triggered risk viewpoint.

- At the *operational level*, the hazards of asset failures are investigated, diagnosed and prevented, as the stimuli of "risks".
    - Condition diagnoses are performed to detect failure hazards.
    - The timetable to coordinate preventive maintenance with operation, inventory, human resource, safety measures and other civil works is called maintenance schedule.
- At the *tactical level*, the "risks of asset system failures" are investigated. Accordingly, replacements are scheduled and maintenance plans are decided.
    - The failures of asset systems, rather than assets, are investigated as stimuli of "risks". The term "failure mode" refers to the sequence of aging factor, asset deterioration, asset failure and asset system failure.
    - The consequences of failures are evaluated in several "business values". A business value reflects a KPI of asset portfolio which can be analysed quantitatively and financially.

    - Control of these "technically stimulated risks" is realized through proposal of replacements and decisions on preventive maintenance plans.
    - A preventive maintenance plan specifies
        - which maintenance strategy should be applied on which specific asset, and
        - the diagnosis procedure to be applied on an asset, if it is maintained on-condition.
        - how diagnostic outputs should decide the maintenance schedule.
    - Replacements of long-living assets (typically primary-side high-voltage components) are decided based on a fixed schedule rather than decided risk-based.

- At the *strategic level*, the full spectrum of risks should be managed and controlled.
    - Update the KPI system and review the financially summed risks of asset portfolio.

It is important to stress that from our experience, the main challenge of managing risks with technical stimuli is trying to understand their technical cause (trigger) of failure and the proper diagnosis (predictive) method to understand the condition of assets. This will have to be brought back to a risk-based approach, which will ultimately help to improve maintenance solutions. The left triangle in figure 2 represents the management of risks with technical stimuli. It has a larger area at the operational level (shown as O1), which indicates that the main effort will be made to understand the technical causes of failures. The future trend will more and more require contribution of diagnoses methods, condition monitoring technologies and statistical life data analysis to risk-based maintenance in this area (O1). In this contribution, we will further elaborate on this area within risk-based maintenance and what the role of condition monitoring technologies can be in risk management.

II. The non-technical risk (i.e. societal aspects, such as the development of sustainable energy and the public resistance to power installations). These risks are not considered in the relatively technical maintenance management, but considered by strategy specialists and policy analysers. Additionally, these risks are normally for long-term, so their probabilities and consequences are difficult to predict (e.g. the case that Germany abandoned nuclear power). Consequently, asset managers can only contribute to control these risks through providing innovative technical design of assets/asset systems. In the following, we discuss each level of AM from a non-technically triggered risk viewpoint.

- At the *strategic level*,
    - Analyse future networks, determine risks with commercial or societal stimuli.
        - The solutions to these risks are frequently not optimised in standard risk management system such as risk register. Since they are long-term and difficult to quantify (i.e. unlikely to be included in a KPI system), the asset portfolio should simply be redundant, robust or flexible enough to survive in each scenario.
        - Such robustness or flexibility can be interpreted technically as hard requirement on asset systems. These requirements are called strategic requirements.

- At the *tactical level*, an equally important task is to design new/replaced/refurbished asset systems, as well as their preventive maintenance plans, so that they can cope with strategic requirements.

- The *operational level* should investigate ways to operate and maintain new components and environments introduced by strategic requirements.

The right triangle in figure 2 represents the management of risks with non-technical stimuli. It has a larger area at the strategic level (S2), because the diversity (different specialities) and long term characteristic of these types of risks require a wider human resource (knowledge of overall system) to study.

As mentioned earlier, the technically triggered risk associated with assessing the asset condition will be further elaborated in this contribution. International trends in future maintenance regimes indicate two main developments [6].

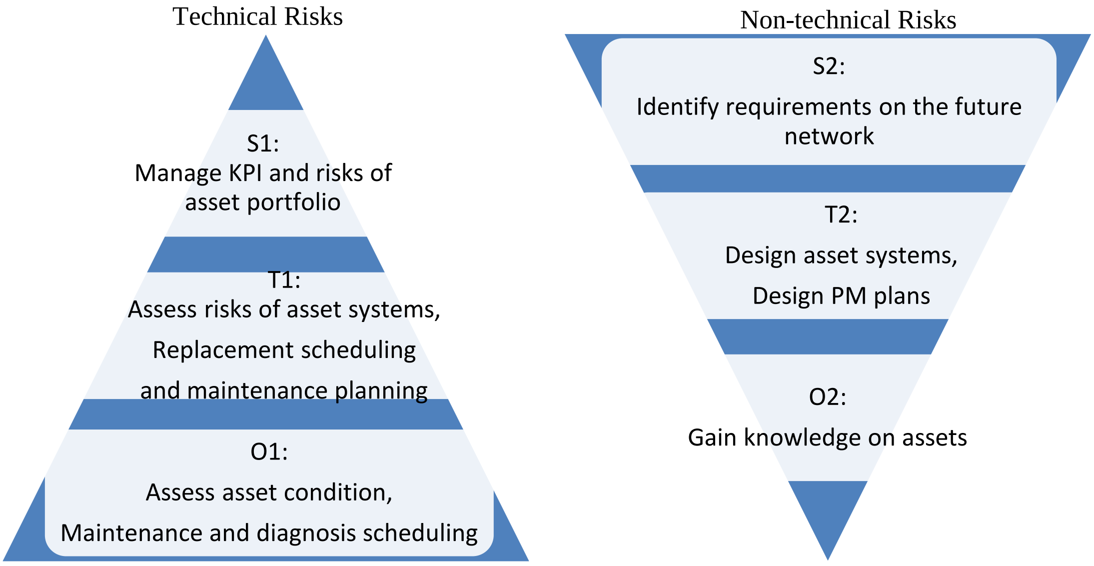

Figure 2: Represents two categories of risks. The left triangle summarizes the technically triggered risks for the three levels of AM (strategic, tactical and operational). The emphasis of this contribution is on area O1. The right triangle summarizes the non-technically triggered risks for the same three levels of AM.

Firstly, there is consensus among asset managers that a risk-based approach for maintenance will form the guiding principle in the future. Secondly, the developments in the area of sensor technology and data analysis are rapidly evolving. It is expected in future, that decisions are made based on these facts and figures coming from more asset specific condition assessments rather than on average (degradation) ageing curves. By applying condition monitoring technologies, asset specific risks can be assessed and “moving” risks (the condition of assets vary with time) can be controlled. Yet, in practice, the implementation of wide scale condition monitoring systems are carefully rolled out and usually still as innovation (pilot) projects. Typically, the reason behind this is because it is often unclear on strategic level what the added value of condition monitoring technologies might be. In section 3, we describe the role of condition monitoring in a risk-based management era, and elaborate on the technically triggered risk area O1 (as shown in figure 2).

3 Role of Condition Monitoring in Risk-Based Management

In order to incorporate more predictive technologies into risk-based maintenance as a part of an AM strategy, it is vital to demonstrate the value of condition monitoring. To introduce condition monitoring requires sufficient financial investments (stemming mainly from the purchase of condition monitoring systems, employing and training monitoring personnel). To evaluate the added value of implementing condition monitoring, we need to know in which AM activities and at which AM level (e.g. effective maintenance activities based on monitored condition and on operational level) condition monitoring can improve performance or control risks. Therefore, in this section these activities are discussed.

3.1 General contribution of condition monitoring

Condition diagnostics and monitoring techniques have been applied in the past and gained the interest, especially, at management level [1]. Despite this interest, we see in practice that condition monitoring is occasionally introduced, usually as innovation/pilot project or other reasons such as stakeholder satisfaction after major failures in critical areas. In general, condition monitoring in the power industry has been applied as a method to gather information for the following reasons [1]:

- To manage life expenditures and to ensure that equipment ratings are not exceeded, by monitoring loads and stresses on equipment
- To detect and locate defects or failures. Also, to monitor symptoms of deterioration. This information can be used for the purpose of just on time warnings and as data for condition assessment for guiding maintenance and replacement activities, hence supporting AM decisions, especially, on operation level.

The interpretation of data coming from condition monitoring systems, the reliability miss-match of diagnostic systems with the equipment being monitored and the volume of data (big data challenge) damped the application of condition monitoring systems. Another important issue is the timeliness with which the acquired condition data can be provided and the relationship with the time to failure of this specific asset [7]. Nowadays, most of these challenges remain and form an obstacle for large scale applications of condition monitoring, especially in combination with the costs for setting up a condition monitoring programme. Due this, it is often unclear to asset managers what the added value of condition monitoring systems are, especially in terms of potential benefit to risk-based management.

However, the above mentioned obstacles can be avoided in the risk-based AM regime. In the next section the role of condition monitoring within the scope of technically triggered risk stimuli on an operational level, represented in figure 2 in the left triangle, is explained.

3.2 Role of condition monitoring within risk-based management

In figure 2 we explain that the focus in this contribution is on the left triangle (risks with a technical trigger) and especially on the O1 (operational) area where the assessment of asset condition forms an important part. In order to fulfil the tasks for the assessment of asset condition, it is required to have insight (information) of the following aspects [7]:

- Technical knowledge of the component
- Functional description of the component
- Stresses which are imposed by loads or environments
- How these stresses deteriorate the components

In quantitative risk studies, measurable data is required to determine the equipment condition, probability of failure and associated risk(s). In order to calculate the probability of failure requires statistical failure analysis. However, to meet the requirements stated above in order to fulfil the tasks for the assessment of asset condition requires the application of at least some form of diagnostics or condition monitoring.

In table 2, we list the aspects in which condition monitoring contributes to the assessment of risks with technical stimuli, hence contributing to the operational level of the left triangle shown in figure 2.

Table 2: Detailed listing of the role of condition monitoring to technically triggered risks

Contribution of condition monitoring to the assessment of risks with technical stimuli
• Asset specific: o Contribute to a specific asset service condition and remaining life assessment o Contribute to sub-systems (families of population) of assets long time condition behaviour assessment o Contribute to gain knowledge of measured condition in the whole lifecycle of assets (e.g. assessing the changing risk of failure of critical components based on whole lifecycle condition data) • Just in time reaction: o Contribute as warning as an input for alarms for timely made decisions for preventing failures o Contribute to environmental hazards prevention such as warnings for harmful substance release (this can additionally be used in the non-technical risk stimuli) • Predictive performance contribution: o Contribute to obtain predictive information about the degradation of assets operating in the network. This can be useful for identifying critical service condition for equipment. o Contribute to study the impact of environmental influences on the condition of assets

In general, this list can be regarded as input for the probability of stimulus (root cause) and as influencing input for the consequence of failure (impact of a failure). The consequences can be reduced because component deterioration can be remedied before, for example, safety is affected, service is interrupted or significant damage occurs. This is explained as follows:

- Regarding the probability of stimulus (failure mode)
    - Reducing equipment major failure probability
    - Preventing extensive life cycle loading and/or temporary overloading of an equipment

- Disclosing already deteriorated equipment conditions before they develop into a major failure and cause unplanned outage

- Regarding the consequences of failures
  - Preventing high cost of major and fatal failures equipment repair (incl. replacement)
  - Preventing consequential damage of neighbouring equipment
  - Controlling outages (planned outages)
  - Lowering insurance fee at insurance companies

4 Summary & Discusions

An internationally observed trend within asset management is to adopt risk-based approach as a state-of-the-art and cost effective maintenance regime to control risk profiles. This is widely accepted and applied by utility networks nowadays. This paper aims to find out how condition diagnostic and monitoring technology can contribute to risk-based management in two steps.

The first step is to reveal how specific RBM activities benefit from condition diagnostic and monitoring technology. In order to locate such activities within the RBM framework, we firstly divided the RBM framework in two dimensions: (1) the three different AM levels – *strategic*, *tactical* and *operational*, and (2) the two different categories of risks – *technically triggered* and *non-technically triggered*. After introducing these levels and categories, we have identified that condition diagnostic and monitoring systems will mainly contribute to the operational AM level when technically triggered risks are managed. By applying this, the technical hazards can be quantitatively assessed and maintenance activities, as the countermeasures, can be further optimized.

The second step was to propose how condition diagnostic and monitoring systems can facilitate quantitative risk assessment through proper management on information acquired from them. We provide a list of aspects that contribute to risk evaluations with technical triggers. The listed aspects are: (1) *asset specific condition data*, (2) *timely condition data* and (3) *predictive condition data*. These can be regarded as input for the probability of failure and as influencing input for the consequence of failure, hence benefiting quantitative risk studies and AM activities, such as condition assessment/ maintenance or replacement.

As a consequence, when above mentioned two steps are taken into account, asset managers can evaluate the benefits afterwards in a risk-based AM planning stage. Moreover, such evaluations can help to reconsider decisions on necessary technical improvements of condition diagnostic and monitoring systems and to justify future investments into these systems.

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