MADE White Paper

Towards digital maintenance: needs, ambitions, and strategic approaches

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Innovationsfonden · Fremstillingsindustrien · Industriens Fond · IAD – Industriens Arbejdsgivere i Danmark · Dansk Industri · Danmarks Erhvervsfremmebestyrelse · Aktiviteter i Klyngen for Avanceret Produktion er medfinansieret af Uddannelses- og Forskningsministeriet

The relevance of maintenance

In the past years, maintenance has increasingly become a key topic for manufacturers and, consequently, for technology providers developing solutions for dealing with maintenance more efficiently and effectively.

The value of maintenance

25 years ago, the average maintenance-related costs accounted for somewhere between 15% and 40% of the overall production cost – reaching peaks of 60% in some industries (Al-Najjar, 1997 and Mobley et al., 2002) (*Figure 1*).

More interestingly, it has been found that, on average, 65% of these maintenance costs concern unnecessary or improper maintenance (Mobley et al., 2002). This means that a share of production cost that ranges between 10% and 26% - up to peaks of 40% - is caused by maintenance activities that we should not perform and by maintenance activities that we do not perform when we should, or that we perform in the wrong way (*Figure 1*).

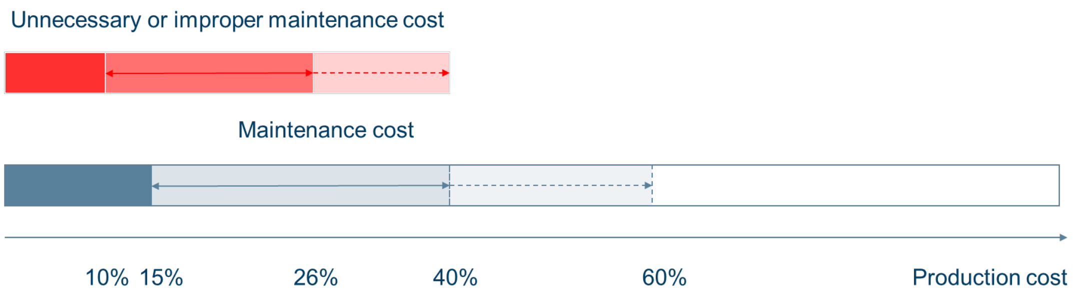

Figure 1 - Maintenance costs

What about today?

Despite the extensive adoption of digital platforms to manage maintenance operations (i.e. the CMMS – computerized maintenance management system) and the availability of organizational guidelines and technology solutions for improving maintenance performance and reducing costs, maintenance remains interesting.

The latest maintenance cost analyses highlight how, still, maintenance represents a significant cost driver for production companies: on average, maintenance costs represent 23.9% of manufacturing costs, 37.5% of the cost of ownership of a piece of equipment, and between 15% and 70% of the cost of the goods sold (Thomas & Weiss, 2021) *(Figure 2).*

Description	Maintenance Low	Maintenance High
Cost of Goods Sold[a,b]	15.0%	70.0%
Sales[c]	0.5%	25.0%
Cost of Ownership[d]	37.5%	
Replacement Value of Plant[e]	1.8%	5.0%
Cost of Manufacturing[f]	23.9%	
Percent of Planned Production Time that is Downtime[f]	13.3%	

Figure 2 - Maintenance costs (from Thomas & Weiss, 2021)

Not only cost

Nevertheless, maintenance does not only affect production costs. As a matter of fact, maintenance improvement helps:

- Satisfying shorter delivery times by avoiding unplanned stops and hence increasing the availability of the production equipment.
- Coping with higher quality standards by ensuring the production equipment operates within its correct functioning specifications.
- Becoming more sustainable by preventing (and avoiding) catastrophic breakdowns and hence prolonging the lifetime of the production equipment.
- Keeping the working environment safe by minimizing the unexpected behavior of production equipment.

The maintenance policies

There are different strategies for companies to deal with maintenance. These are called "*maintenance policies*".

A company should select the maintenance policy (or maintenance policies) to adopt according to the ratio between the costs of running that specific policy and the savings that that policy would bring.

There are two main families of maintenance policies: the "corrective" policies and the "preventive" policies (Figure 3). Corrective policies imply performing maintenance activities to solve failures after they happen, while preventive policies aim at avoiding failures, hence implying performing maintenance activities to prevent or solve situations that are leading towards failure. In the following, you will learn more about the policies belonging to each of these two families.

Corrective policies

Deferred maintenance – Maintenance activities are both decided and performed after a failure has happened.

Immediate maintenance - Maintenance activities are performed after a failure has happened, but there is a clear plan of what has to be done according to the experienced failure.

Preventive policies

Time-based maintenance – Maintenance activities are performed at well-defined time intervals, to inspect or replace components before the end of their life cycle and the consequent breakdown. The extent of such time intervals is provided by the equipment/components supplier, or it is based on direct experience.

Condition-based maintenance – Maintenance activities are performed when well-defined indicators are signalling the presence of critical behaviour, leading towards a failure. Such indicators are based on signals provided by sensors installed on the equipment/components to maintain.

Predictive maintenance – Maintenance activities are performed when an algorithm processing operating data from the equipment/components to maintain is suggesting an upcoming failure based on how such data is changing over time. Such data is collected through sensors installed on the equipment/components to maintain.

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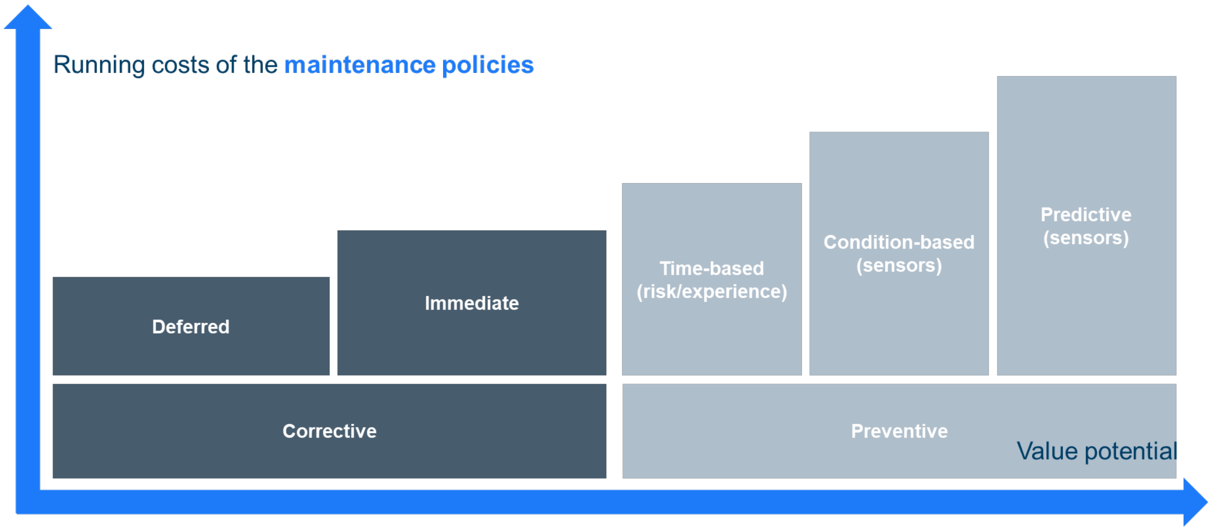


Figure 3 - Maintenance policies (figure from FORCE Technology)

No "one-size-fits-all" policy

Although predictive maintenance represents the general trend for companies working with maintenance innovation, it is important to remember that there is no "absolute best" maintenance policy. Generally, the policies that provide the highest value potential (e.g. by enabling the avoidance of un-planned stops and catastrophic breakdowns) also entail a higher running cost (e.g. due to the need for sensors and platforms to perform advanced analytics of the sensors' data on an ongoing basis) (Figure 3).

Different companies - and even different equipment - will require different policies according to their running costs and, especially, to the value potential that a policy can generate on a specific machine in a specific company.

Digitalization: a key enabler for innovating maintenance

Today, the data collection, transmission, and advanced analytics capabilities brought to the table by the Industry 4.0 agenda are providing significant support for a cost-effective evolution of maintenance policies toward condition-based and predictive maintenance. New digital solutions are, in fact, facilitating:

- The traceability of critical components
- The measurement of their operating conditions
- The recording of the failures
- The estimation of assets' remaining lifetime
- etc…

Industry 4.0-ready equipment VS legacy equipment: the importance of retrofitting

Although Industry 4.0-ready equipment is providing such data, small- and medium-sized companies (and often large companies as well) still rely on legacy equipment which often does not have such capabilities.

"How to take advantage of digitalization for supporting the innovation of our maintenance policies if our equipment does not even provide us with the right data?"

Fortunately, there are countless IoT solutions to "retrofit" legacy equipment and collect the necessary data from it. In fact, there are generally three possible scenarios to consider *(Figure 4)*:

1. Data is generated by sensors embedded in the equipment: the sensors that collect the necessary data are already integrated in the equipment, and by connecting to the equipment PLC it is possible to access the data.
2. Data is generated by sensors added to the equipment and connected to its PLC: the sensors that are necessary to collect the relevant data are added to the equipment and connected to its PLC. By connecting to it, it is then possible to access the data.
3. Data is generated by sensors added to the equipment and operating independently: the sensors that are necessary to collect the relevant data are added to the equipment and controlled separately, and they provide data through a separate gateway.

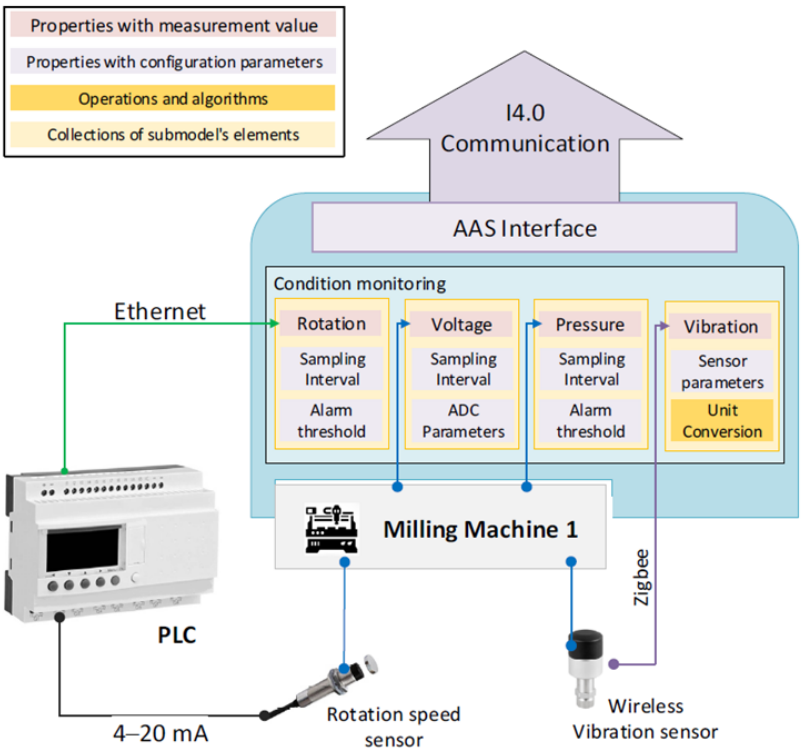


Figure 4 - Retrofitting equipment with digital solutions – Three different scenarios (figure from Cavalieri & Salafia, 2020)

The current status, needs, and ambitions in Danish industry

Corrective and time-based: the current policies

When it comes to maintenance, the vast majority of Danish companies rely on corrective policies – whether deferred or immediate - in combination with a time-based maintenance policy when it comes to critical equipment justifying a preventive approach.

Nevertheless, there is a significant interest among Danish manufacturers related to the improvement of how they deal with maintenance in order to reduce maintenance-related costs, and some recurrent questions that need to be answered (*Figure 5*).

In particular, current innovation projects in the maintenance area are generally focused on critical equipment and on the transition from a time-based to condition-based maintenance policy to optimize its maintenance reducing the related operational costs.

Figure 5 – Recurrent questions among Danish manufacturers interested in improving maintenance (figure from FORCE Technology)

Challenges: cost of capacity and quality losses

Currently, the most common cost drivers to be reduced when it comes to maintenance are often the cost of the lost capacity (and missed turnover) due to unplanned stops or slow-downs, and the cost of low quality (whether causing scrap or the need for re-works) due to equipment running outside the correct functioning specifications.

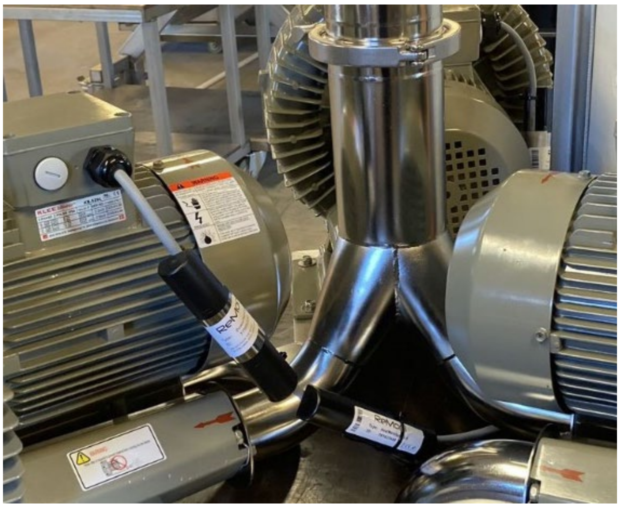
Kaj Olesen A/S – Case example

A good example is the MADE project with ReMoni– provider of IoT solutions for enabling condition-based and predictive maintenance, Kaj Olesen A/S – manufacturer of equipment for processing fish, and FORCE Technology.

Kaj Olesen A/S was interested in improving the performance of its machines *(Figure 6.1)* while reducing maintenance costs. An analysis, performed by FORCE Technology, of Kaj Olesen A/S' maintenance operations quantified the maintenance-related costs and high-lighted how the main cost-driver to be addressed was the fish waste generated when the equipment was increasing its vibrations due to wearing of its electric motors (up to 4% more than the ideal condition, i.e. 5% instead of ca. 1%). The related waste cost (up to 160,000 DKK/day per production line, when the vibration was present) was significantly higher than the cost of breakdowns and other unplanned stops, and particularly critical due to its un-detectability (i.e. the machines could keep running for days in this situation).

Based on these findings, the IoT solution was installed, monitoring and analyzing the power absorbed by the electric motors *(Figure 6.2)* to identify the upcoming failure and provide a warning accordingly.

The full case article can be read here (MADE, 2021) and here (FORCE Technology, 2021).

Figures 6.1 and 6.2 – Equipment from Kaj Olesen A/S (6.1, left) and ReMoni (6.2, right) (figures from MADE)

Strategically approaching "Digital Maintenance"

The question is: "*How can a company address its maintenance improvement activities in a structured way?*"

There are four key steps to go through (*Figure 7*):

- *Step 1 – Focus maintenance policy improvement*: FMECA - Failure Mode, Effect, and Criticality Analysis.
- *Step 2 – Identify efficiency improvement opportunities*: maintenance operations mapping.
- *Step 3 – Analyze maintenance costs*: maintenance cost analysis.
- *Step 4 – Activity plan formulation*: discussion and formulation of an activity plan.

Figure 7 – The steps to structure maintenance innovation (figure from FORCE Technology)

This systematic approach, developed by FORCE Technology, is part of the MADE "*Digital Maintenance Program*" involving a cluster of five production companies (Vestas, Vestfrost, BKI Foods, MAN Energy Solutions, AH Metal), five suppliers of IoT solutions to support maintenance improvement (Optipeople, Siana, Cedas, Ceramicspeed, ReMoni), and an additional production company showing the outcome of its collaboration with one of the IoT technology suppliers to improve its maintenance operations (Kvik).

Step 1: FMECA – Failure mode, effect, and criticality analysis

The FMECA (Failure Mode, Effect, and Criticality Analysis) is used to assess the criticality of experienced failures and identify where to focus maintenance innovation efforts (e.g. to change the adopted maintenance policy).

Failures are assessed (score 1-5; from "not significantly" to "very") in regard to their:

- Severity: how problematic/costly is the failure when it is experienced?

- Occurrence: how often is the failure experienced?
- Undetectability: how challenging is to detect that the failure has been experienced?

The product of severity*occurrence*undetectability scores gives the “Risk Priority Number” (RPN) characterizing the failure. High RPNs failures need to be addressed with better maintenance policies (*Figure 8*).

Failure type	Severity	Occurrence	Undetectability	RPN
Breakdown of electric motor	4	5	1	20
Fire in the cell	5	1	1	5
Unsharpening of cutting tool	4	2	4	32
…	…	…	…	…

Focus of maintenance policy improvement

Figure 8 – Example of FMECA (figure from FORCE Technology)

The FMECA inputs are collected by interviewing internal experts (e.g. maintenance responsible but also maintenance operators) that have in-depth knowledge concerning the different types of experienced failures, their criticality and implications on production performance, the way failures are detected and the way they are solved.

The output of the FMECA is used to define where to focus maintenance innovation efforts.

Step 2: Maintenance operations mapping

The maintenance operations mapping aims at identifying and quantifying inefficiencies across maintenance operations – those activities that are either non-value adding, or which could be improved by introducing new technology solutions. The overall goal is to identify how to run a maintenance policy more efficiently.

The mapping focuses both on planned and unplanned maintenance operations related to the critical equipment identified through the FMECA. All the activities performed in relation to maintenance, along with the related lead time, process steps, cycle time, and involved operators, are systematically mapped and analysed *(Figure 9).*

This leads to the identification and quantification of efficiency losses (in relation to equivalent manual labour cost, capacity loss or waste).

The output of the maintenance operations mapping is used to support the formulation and assessment of project proposals to improve the efficiency of the current maintenance policy.

Process	Lead time	Process steps	Cycle time	Number of operators
Support request	60 min	The support responsible receives a call from production requiring support	10 min	2
		The support responsible fills out a template in Excel introducing the problem information	10 min	1
		The support responsible calls the service technician and explains the problem	7 min	2
		The service technician reaches the problem location	5 min	1
…	…	…	…	…

Figure 9 – Example (extract) of maintenance operations mapping (figure from FORCE Technology)

Step 3: Maintenance cost analysis

The maintenance cost analysis aims at highlighting the most relevant cost drivers for maintenance and at quantifying the related values and cost distribution. The goal is, on one hand, to generate awareness in relation to the actual impact and ripple effects of maintenance on production. On the other hand, this provides the foundation to quantify the potential behind a maintenance innovation activity, as well as to assess the business case related to the introduction of a new technology solution and/or to the change of the adopted maintenance policy.

Generally, the maintenance-related costs are divided into four main categories *(Figure 10)*:

- Maintenance policy running costs: costs related to all those activities that are necessary to run the current maintenance policy (such as inspections, stock of spare parts, maintenance team salary, licenses, etc.)
- Downtime costs: costs related to stops and consequent capacity losses (missed profit) as well as to activities to deal with the stops (such as repairs and replanning)
- Quality costs: costs related to non-conformities (such as scrap or rework)
- Efficiency costs: costs related to the loss of productivity (such as yield loss or sales loss)

Maintenance policy running costs
- Inspections
- Spare parts (use and stock)
- Data processing
- Hardware
- Software licenses

Downtime costs
- Missed profit due to production stops
- Repairs (extra cost spent to deal with unplanned stops)
- Replanning (cost spent to adjust production plan after unplanned stops)

Quality costs
- Scrap due to equipment malfunctioning (wasted material and energy to produce scrap and cost of getting rid of waste)
- Rework (needed material, energy and manual labor)

Efficiency costs
- Yield loss (missed profit due to lower production output)
- Sales losses or penalties due to late deliveries

Figure 10 – Some of the key maintenance-related costs (figure from FORCE Technology)

The outcome of the maintenance cost analysis is used to:

- Identify what the maintenance improvement activities should be focused on reducing (i.e. the biggest cost drivers)
- Identify how much can be invested in the maintenance solution to have a good business case (i.e. positive delta cost) *(Figure 11)*
- Support decision-making on maintenance policy improvement (i.e. improve the maintenance policy if/where the business case is good)

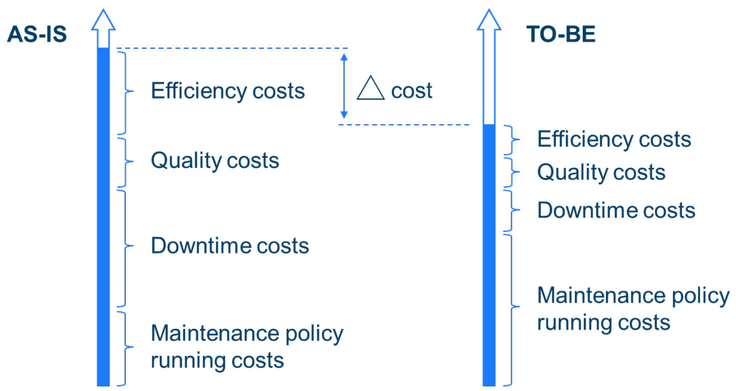


Figure 11 – Evaluating the business case of maintenance improvement activities (figure from FORCE Technology)

Step 4: Activity plan formulation

The activity plan formulation aims at translating all the findings into action, enabling the innovation of the current maintenance activities and the consequent improvement of the company's performance and profitability. The goal is to have an activity plan which is focused (and practical) enough, and whose value is backed by actual calculations on its potential impact, providing the necessary argumentation for its scaling.

The outcome of the activity plan formulation is a set of maintenance improvement activities (e.g. introduction of a solution for collecting vibration data from the bearings of a specific pump type, and of a platform to analyze the data and provide predictions regarding upcoming potential failures) with the related improvement potentials (e.g. the solutions would address current maintenance-related costs for 387,000 DKK/year), to be adopted to assess the business case behind the activities' investments.

Vestas - Case example

Vestas – a global manufacturer of wind turbines - has been one of the participants in the MADE Digital Maintenance Program.

The company was interested in understanding how to approach the improvement of maintenance in a complex environment and across different factories.

Based on the findings obtained through the Digital Maintenance Program from the application of FMECA, maintenance operations mapping, and maintenance cost analysis, Vestas re-designed its maintenance strategy with the aim of rolling it out first on a pilot factory, and later globally, as discussed at the 2022 MADE annual event *(Figure 12)*.

For Vestas, the valuable learnings obtained from the Digital Maintenance Program were related to the "*understanding of the cost drivers and the repartition of costs to be able to quantify the efficiency potential". "The interest from other companies has been very positive, and during the company visits there have been lively debates based on the topics*" (Kristoffer Hvisthule and Thomas Aalund Junker, respectively team leader of global maintenance and business domain architect at Vestas).

The full case article can be read [here (MADE, 2022).]

Figure 12 – Presenting the outcome of the Digital Maintenance Program at the 2022 MADE annual event: FORCE Technology and Vestas (image from MADE).

Conclusions and recommendations

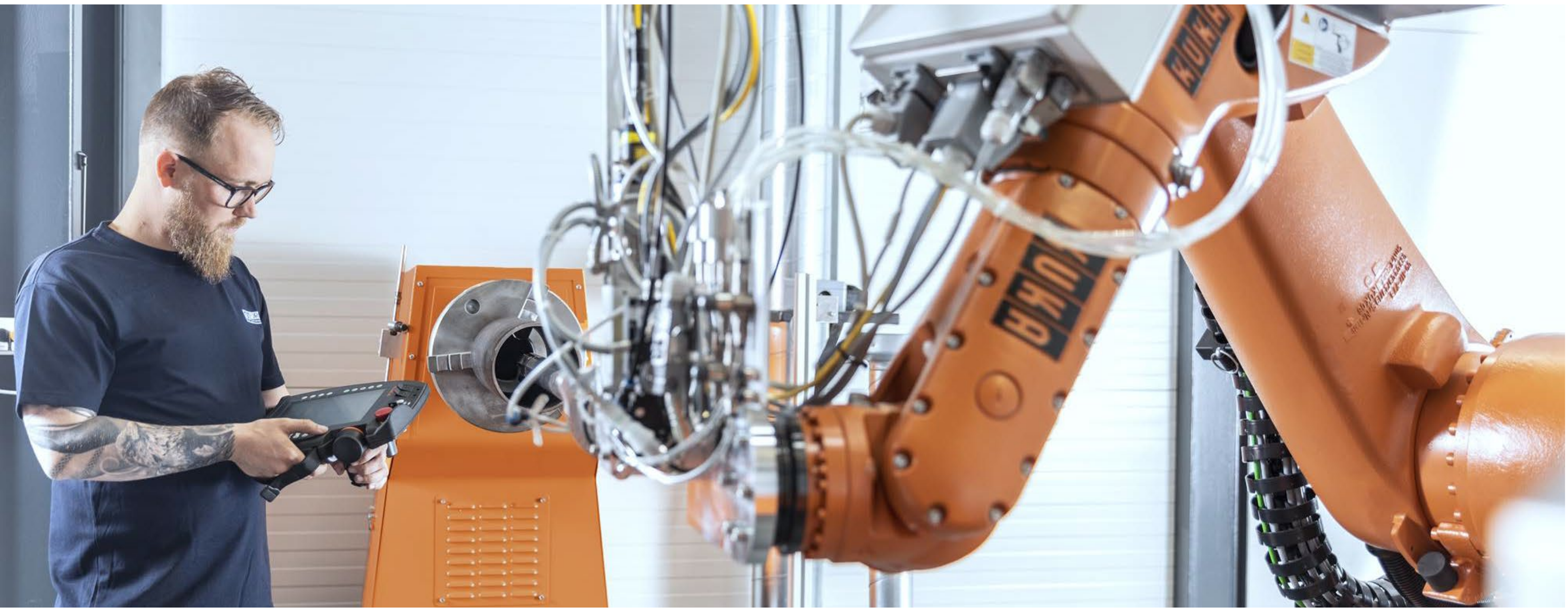
Maintenance is one of the key production areas that can be innovated through the integration of IoT and other digital solutions, which makes it possible to collect and analyse data from the production equipment, hence monitoring their performance, and identifying upcoming failures.

Although these solutions are increasingly cost-effective, it is fundamental to focus them where relevant, and where the value potential is higher than the cost for running a more complex maintenance policy, required to support such solutions.

To do so, there are four key steps to go through: a failure mode, effect, and criticality analysis (FMECA) to focus improvements on relevant assets and issues, a maintenance operations mapping to identify inefficiencies in how the maintenance policy is run, and a maintenance cost analysis to identify and quantify the costs that a maintenance policy improvement would address, and evaluate the potential transition towards condition-based or predictive maintenance.

> *We gained insight into a number of tools for mapping and selecting critical areas within digital maintenance, which we will continue to work on in relation to improving the data foundation so that we get closer to an automated maintenance system [...] We have established a collaboration with one of the technology providers involved in the collaboration project for the development of a sensor-based monitoring system.*
> Rune Christensen, AH Metal

> *We have changed from time-based maintenance to condition-based maintenance in some places [...] We had a lot of exchange between companies, and it was very rewarding. I think that we got a lot of gold nuggets.*
> Kurt B. Knudsen, Vestfrost



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