June 2017

Predictive Maintenance 4.0

Predict the unpredictable

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Contents

Foreword

PwC and Mainnovation have joined forces in the field of maintenance and asset management. We are both convinced that maintenance can be brought to a new level by combining the power of new digital technologies with a deep understanding of maintenance. We believe predictive maintenance with big data analytics can be a tremendous source of new value for asset owners and maintenance service providers.

To deepen our understanding and sharpen our insights, we have jointly carried out a market survey on predictive maintenance. This involved surveying 280 companies from Belgium, Germany and the Netherlands about their current use of, and future plans for, predictive maintenance, and conducting interviews with leading companies in the field.

This report presents the results of this research and our approach to successfully implementing predictive maintenance with big data. Our findings should be of interest to those responsible for the maintenance and asset management of fleets, factories and infrastructure, who are looking for new ways to increase the reliability of their assets.

We are proud to share these findings with you and look forward to fruitful discussions with you on this topic.

Michel Mulders
Partner at PwC Netherlands

Mark Haarman
Managing Partner at Mainnovation

Summary

Predictive maintenance is surely one of the most talked-about topics in maintenance and asset management. In order to find out where companies currently stand regarding predictive maintenance, and where they plan to be in the near future, we surveyed 280 companies in Belgium, Germany and the Netherlands.

In order to assess current practices, we have used a framework that identifies four levels of maturity in predictive maintenance. As companies move through these levels, there is an increase in how much data they use to predict failures. Visual inspections represent level 1 in this framework; instrument inspections and real-time condition monitoring are associated with levels 2 and 3. At level 4 big data analytics starts to drive decision-making. This is where the digital revolution meets maintenance. This level involves applying the power of machine learning techniques to identify meaningful patterns in vast amounts of data and generate new, actionable insights for improving asset availability. We call this Predictive Maintenance 4.0, or PdM 4.0. PdM 4.0 offers you the potential to predict failures that had been unpredictable up to now.

Key findings from the survey

We found that two thirds of survey respondents are still at maturity levels 1 or 2. Only 11% have already achieved level 4. The resources, capabilities and tools respondents use match their maturity levels: skilled technicians, standard software tools and maintenance logs play a dominant role in their current predictive maintenance processes. Only a few companies already employ the people and tools needed for PdM 4.0: reliability engineers and data scientists, statistical software packages and external data sources.

We also found that respondents are quite ambitious about improving their predictive maintenance maturity. Around half said they have plans to use PdM 4.0 at some point in the future. Taking into account respondents who are already working on PdM 4.0 and those who plan to do so within the next five years, around one in three companies will be using PdM 4.0 in some form within five years, provided they can successfully implement it. We conclude that PdM 4.0 is widely recognized as a potential improvement over current maintenance practices, but that the market is still in the very early stages of adopting this technology.

Uptime improvement is the main reason why respondents have plans for PdM 4.0. Other important reasons relate to other traditional value drivers in maintenance and asset management such as cost reductions, lifetime extension for aging assets and the reduction of safety, health, environment and quality risks. Respondents also identified a number of critical success factors for PdM 4.0 implementation. The availability of data was mentioned most often as a critical success factor, followed by technology, budget and culture. We conclude that, at this early stage in the PdM 4.0 lifecycle, companies still see considerable technical obstacles to its implementation. However, they recognize that PdM 4.0 implementation is not a purely technical challenge.

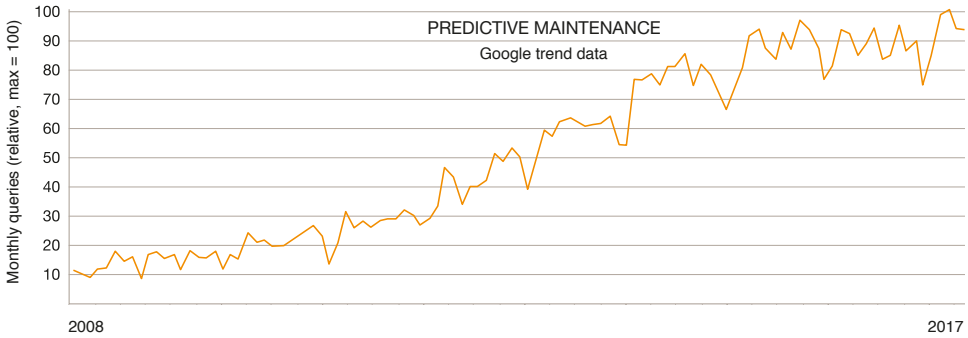
Our approach to successful PdM 4.0 implementation

The second half of this report highlights our approach for implementing PdM 4.0, which considers technical as well as organisational aspects. We have provided a framework for the step-by-step implementation of technical components in the PdM 4.0 model, in a manner that supports business strategy. Our approach also covers the technical infrastructure - data analytics platform, IoT infrastructure - needed to sustain PdM 4.0. Organisational aspects are also important if PdM 4.0 is to be successful. We have focused on two such aspects: building skills and capabilities needed for PdM 4.0, and building a digital culture. It is not enough to simply attract and develop talent in reliability engineering and data science. Companies must also create circumstances in which these people can flourish, and challenge and complement each other to generate valuable and actionable new insights for improving maintenance and asset management.

Digital culture is the final aspect to be addressed in our approach. In other words, a culture that embraces new, cross-functional ways of working, which allow companies to capitalize on the power of digital technologies. A culture where everyone from the boardroom to the shop floor understands the power of data analytics. Companies with a robust digital culture possess the confidence and ambition to become increasingly data-driven in their decision-making.

Chapter 1 Introduction
The next level in predictive maintenance

Predictive maintenance is a bit of hype these days. It is being proclaimed as the 'killer app' for the Internet of Things. Machine learning and predictive analytics - the main technologies that enable predictive maintenance - are nearing the 'Peak of Inflated Expectations' in Gartner's Hype Cycle. At the same time, Google Trend data reveals increased interest in the subject, as do articles that have started to appear in the mainstream and business press.



A historical framework

A historical perspective may help clear up some of the haze that surrounds predictive maintenance. Although it may be a bit of a hype, it is not an entirely new concept. Without really using the term, people have been doing predictive maintenance for many years. Over time, different levels of maturity have evolved.

When a technician performs a visual inspection and selects - based on his knowledge, experience and intuition - the best time to shut down a piece of equipment so repairs can be carried out, he is in fact performing predictive maintenance.

The next level of maturity involves augmenting the inspector's expertise with periodic instrument inspections that provide more specific and objective information about the condition of the asset in question. The next step in sophistication involves using real-time condition monitoring, where sensors continuously collect data about the state of an asset and send alerts based on pre-established rules or when critical levels are exceeded.

One thing that has changed over the years is the amount of data that goes into making these predictions. The enhanced use of data corresponds with increasing levels of maturity, and these are accompanied by improvements in maintenance performance. By collecting more and more data, maintenance staff are able to make better informed decisions that lead to increased reliability, higher up-time, fewer accidents and failures, and lower costs.

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The next step: big data analytics

The current buzz about predictive maintenance stems from new opportunities to capitalize on the digital revolution, and more specifically on advances in decision support tools powered by big data analytics.

In our increasingly digitized world, where virtually every activity creates a digital trace, there has been exponential growth in how much data can be used for predictive maintenance. Data sets can be obtained from both internal and external sources. Consider, for example, the vast pools of sensor data that can be collected from entire factories, transportation fleets or infrastructure networks and distributed via Internet of Things technology. In terms of external data, consider environmental data about temperature, humidity and wind speeds, or operator profiles or specifications of materials being processed at the time of failure. Data sets used for predictive maintenance may be structured, like spreadsheets or relational databases, but can also be unstructured, like maintenance logs or thermal images which can be 'unlocked' through text mining and pattern recognition software respectively.

One could easily drown in this sea of data. Fortunately, rapid advances in artificial intelligence techniques have enabled us to make sense of all this data. Machine learning algorithms are particularly crucial in this respect (see text box 'Machine beats human: the power of self-learning machines). These algorithms are not constructed as a predefined set of rules, as in traditional software programming. Instead, these algorithms are self-learning. They infer rules by performing a series of trials on a set of training data and thus construct their own model of the world. Every subsequent amount of data is then used to refine that model and improve its predictive powers.

Machine beats human: the power of self-learning machines

If you are somewhat sceptical about what artificial intelligence (AI) can achieve in your field of expertise, you are in good company. When we were writing this report, Google's AlphaGo had just defeated Ke Jie, the world's best player of the ancient Chinese board game Go. Ke Jie, who had boasted prior to the match he would never be beaten by a computer, lost 3-0 despite playing almost perfectly.

So why is this considered a groundbreaking achievement for AI? Essentially because the incomputably large number of options in a Go game make it impossible to 'calculate' your advantage a few moves ahead. Unlike chess grandmasters, top Go players do not 'calculate' their next move. Instead, they rely on experience, intuition and the ability to learn.

This difference matters when trying to teach computers how to play such games. In chess, you can use rule-based programming where human knowledge is coded into a set of instructions. This approach doesn't get you very far with Go. Professional Go players rely on so-called tacit knowledge: they know more then they can tell. The same is true for ordinary humans who drive a car through traffic, instantly recognize a face or who can tell if a picture contains a cat or not.

Recent breakthroughs in AI have occurred in tasks like these, where we can't exactly explain the steps followed to carry them out. This can be attributed to rapid advances made in a particular field of AI called machine learning. It works a bit like this: a machine learning algorithm is presented with a training set that has been classified (e.g. pictures labelled 'cat' or 'no cat') and is, after a large number of iterations, able to figure out what features to look for and how to weigh their importance in order to come up with the correct answer, either 'cat' or 'no cat'.

How is this relevant to predictive maintenance with big data? We can present self-learning algorithms with historical maintenance data and a failure history, and let the algorithm detect patterns and signals in the data that correlate with failure. If it detects such patterns in the future, the algorithm will predict an increased likelihood of failure and will give an early warning.

When self-driving trucks can deliver a cargo of beer, when computers outperform humans in speech recognition and when self-learning pattern-recognition algorithms can detect malignant cells that pathologists overlook, it is time to investigate whether this technology can also be applied to predict failures that had been unpredictable up to now.

Predictive Maintenance 4.0

The application of big data analytics in maintenance represents the fourth level of maturity in predictive maintenance, as shown in the PdM maturity growth model below. We call this fourth level Predictive Maintenance 4.0, which is abbreviated as PdM 4.0.

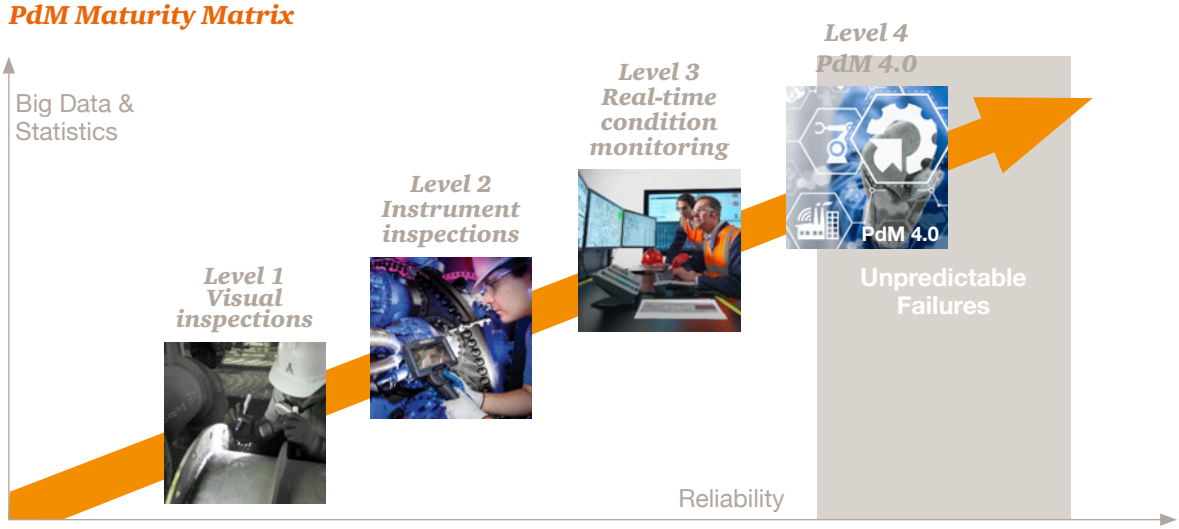
PdM 4.0 is about predicting future failures in assets and ultimately prescribing the most effective preventive measure by applying advanced analytic techniques on big data about technical condition, usage, environment, maintenance history, similar equipment elsewhere and in fact anything that may correlate with the performance of an asset.

Level 1 ***Visual inspections:*** periodic physical inspections; conclusions are based solely on inspector's expertise.
Level 2 ***Instrument inspections:*** periodic inspections; conclusions are based on a combination of inspector's expertise and instrument read-outs.
Level 3 ***Real-time condition monitoring:*** continuous real-time monitoring of assets, with alerts given based on pre-established rules or critical levels.
Level 4 ***PdM 4.0:*** continuous real-time monitoring of assets, with alerts sent based on predictive techniques, such as regression analysis.

Although predictive maintenance may be a bit of a hype, we are convinced that its potential is very real. Real-time condition monitoring will only get you to a certain level of reliability; a level where you will still be plagued by unforeseeable and inexplicable failures. But these failures could be tackled with big data analytics. PdM 4.0 involves harnessing the power of artificial intelligence to create insights and detect patterns and anomalies that escape detection by the cognitive powers of even the most gifted humans. PdM 4.0 gives you a chance of predicting what was previously unpredictable. PdM 4.0 lets you anticipate the failures and accidents that always catch you by surprise, squeeze out an extra few percentage points of uptime, and extend the lifetime of your assets even further.

The following chapter presents our survey findings about the current status of PdM 4.0 in companies in Belgium, Germany and the Netherlands, and their future plans regarding PdM 4.0. We will also present several leading companies in this field, who have decided to share their experiences with PdM 4.0.

PdM Maturity Matrix

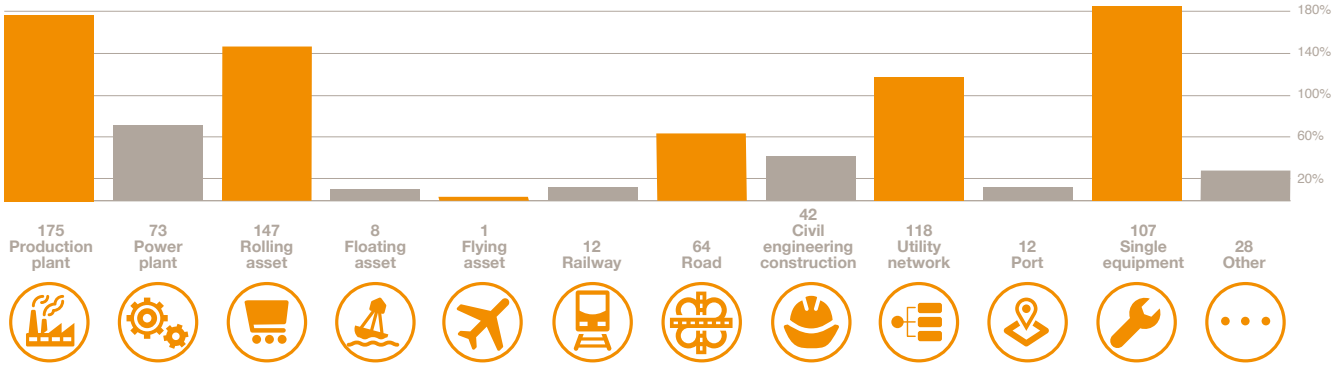


Chapter 2 *Key Findings*
Towards PdM 4.0: ambitions and capabilities

In their first survey about how the market views Predictive Maintenance with Big Data Analytics, PwC and Mainnovation surveyed 280 companies in Belgium, Germany and the Netherlands. We asked managers responsible for Maintenance & Asset Management about their organisation's current use of predictive maintenance and about their future plans in this domain.

What type of assets does your company do maintenance for?

Note: multiple answers allowed; refers to both internal assets and assets maintained for other companies.



A snapshot of our respondents

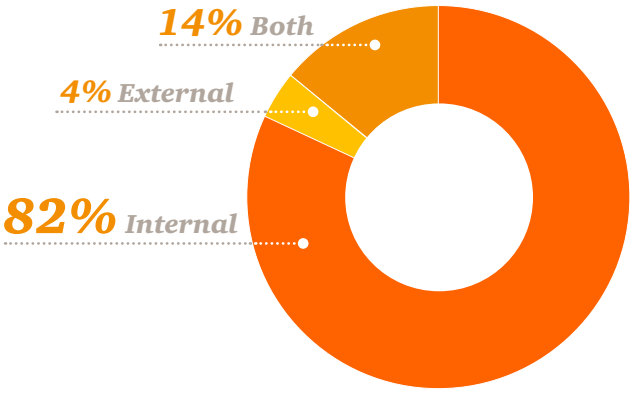
Respondents in this survey represent a wide range of sectors, asset types and company sizes (for more details, see the 'About the Survey' Appendix).

The vast majority of respondents (82%) only perform maintenance on their own assets, while 14% provide maintenance as a service to external companies. Only 4% of respondents are solely maintenance service providers. The findings presented in this chapter thus primarily pertain to asset-owners.

Current levels of maturity in predictive maintenance

A natural starting point is to identify how companies assess their current maturity levels in predictive maintenance, based on the framework we introduced in the previous chapter (included here again for convenience).

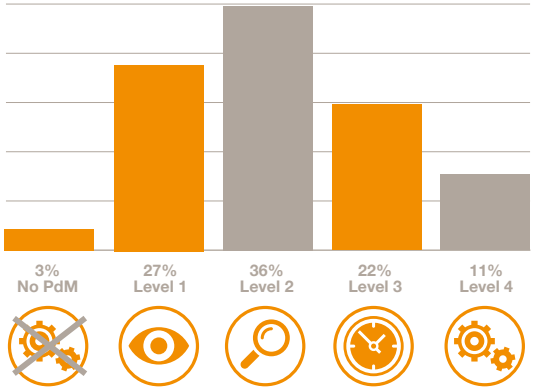
Which assets does your company do maintenance for?



Level 1 ***Visual inspections:*** periodic physical inspections; conclusions are based solely on inspector's expertise.
Level 2 ***Instrument inspections:*** periodic inspections; conclusions are based on a combination of inspector's expertise and instrument read-outs.
Level 3 ***Real-time condition monitoring:*** continuous real-time monitoring of assets, with alerts given based on pre-established rules or critical levels.
Level 4 ***Predictive maintenance with Big Data Analytics:*** continuous real-time monitoring of assets, with alerts sent based on predictive techniques, such as regression analysis.

Two thirds of respondents are still below maturity level 3 for predictive maintenance. Only around 11 percent have already reached level 4. These results indicate that, despite the buzz surrounding the use of big data analytics in the maintenance market, it really represents a new level of predictive maintenance, which only a few companies have already reached.

Current predictive maintenance maturity level



Discussion: Who are the front-runners in PdM?

We found that companies with ***similar assets*** *are further ahead in terms of predictive maintenance than companies with unique assets. This can be attributed to the fact that a base of similar assets provides a richer data set for advanced analytics. In addition, a base of similar assets makes it easier to build a positive business case.*

Looking across the sectors, we notice that the ***rail sector*** *seems to be a front-runner in applying PdM 4.0: 42% of respondents in the rail sector are at level 4, compared to 11% overall. This confirms our perception of the rail sector as being innovative and sophisticated in the field of maintenance (see also Infrabel case). The large bases of similar assets employed by rail companies lend themselves to PdM 4.0, and public and political pressures on asset performance provide a powerful incentive to use PdM 4.0.*

Comparing the three countries targeted in our survey, PdM 4.0 is more popular in ***Belgium*** *(23%) than in the* ***Netherlands*** *(6%) and* ***Germany*** *(2%). Belgium is also considered as a front-runner in real-time condition monitoring (PdM level 3).*

Case: Infrabel

Infrabel is the state-owned company responsible for Belgian rail infrastructure. Infrabel spends around a billion euros each year on the management, maintenance and development of rail infrastructure, which contains over 3,600 kilometres of railway lines, 86 signal boxes, 10,249 main signals and almost 12,000 civil infrastructure works like crossings, bridges and tunnels. Over 4,200 trains run on the Belgian railways each day, and the number of daily passengers has increased by 50 percent since 2000, to 800,000.

Growing pressure on Infrabel's maintenance

Pressure to improve the safety and reliability of rail infrastructure has also increased for a number of reasons:

- Safety is of paramount importance. To improve safety for its employees, for example, Infrabel wants to reduce the number of visual inspections by maintenance crews walking along the tracks.
- The railway network is becoming increasingly strained. Not only due to an increase in passengers and freight trains, but also because new high-performance trains exert greater stress on the tracks. A busier schedule also means smaller windows of opportunity for maintenance. Planned downtime must be communicated to railway operators a couple of years in advance.
- The general public and governments are demanding safety and accuracy. Every incident is negative publicity for Infrabel and further increases pressure to prevent future incidents.
- In the coming years, Infrabel will be confronted by a wave of retirements and will have to find ways to replace the knowledge and experience it will be losing.
- There is a trade-off between safety and reliability. The installed base of smart assets needed to monitor and improve safety is accompanied by additional susceptibility to failures compared to the old dumb assets, and hence necessitates additional maintenance.

Making dumb hardware smart

In response to these challenges, Infrabel has invested heavily in automating a number of maintenance processes. It has become exceptionally strong in developing innovative condition monitoring tools such as sophisticated measurement trains for inspecting tracks, railway ties and overhead lines; cameras mounted on overpasses to monitor the panthographs of passing trains; sensors for detecting overheating in shaft sleeves on passing trains; semi-automatic vehicles to check whether sign-post visibility meets the regulatory requirements; and meters to detect drifts in power consumption, which usually occur prior to mechanical failures in switches.

Building organisational foundations

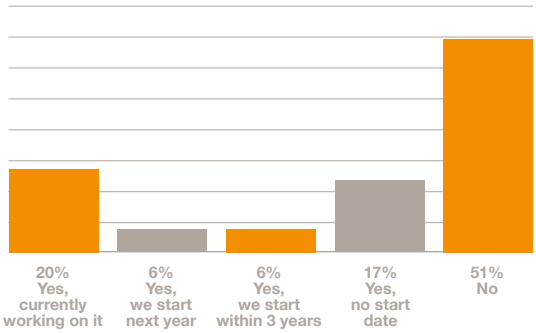
A number of organisational changes will be encountered when deploying smart condition monitoring tools. The once very fragmented maintenance organisation has been fused into larger units in order to reap synergy-related benefits. At Infrabel headquarters in Brussels, a central Data Cell has been created where increasing volumes of data generated by these tools are collected and analysed. A wide range of home-made IT applications for maintenance is being replaced by a single tool where data from various systems is integrated and standardized. A number of pilot projects to test predictive analytics in maintenance have been started, and Infrabel is currently recruiting data scientists to take its maintenance operations to the next level.

On the eve of a new era in maintenance

By making these preparations, Infrabel has put itself in an excellent position for the large scale application of data analytics in maintenance. Even though this implementation could face a few regulatory hurdles - stemming from strict safety requirements and current regulations that prescribe a minimum number of visual inspections per year, Infrabel is still expected to make progress in this area.

That would be a major step along the way of what Infrabel, describes as "a complete transformation of Infrabel into a digital enterprise in which 'basic' assets are replaced by smart assets that are integrated in an Internet of Things. This transformation enables Infrabel to become increasingly data-driven in its decision-making."

Future plans for PdM 4.0



Now that we know where the market currently stands on predictive maintenance, we want to know what companies' future plans are for PdM 4.0.

Almost half of the respondents (132 out of 280) have plans to eventually implement PdM 4.0, and one in five (54/280) have already started to implement it.

Only 58 out of 132 respondents currently working on, or with plans to work on, PdM 4.0 were able - and willing - to indicate a budget for their future investments in PdM 4.0. A similar number of respondents said they "have no idea", or that no specific budget would be set aside for implementing PdM 4.0.

Discussion: Ample ambition to advance to PdM 4.0

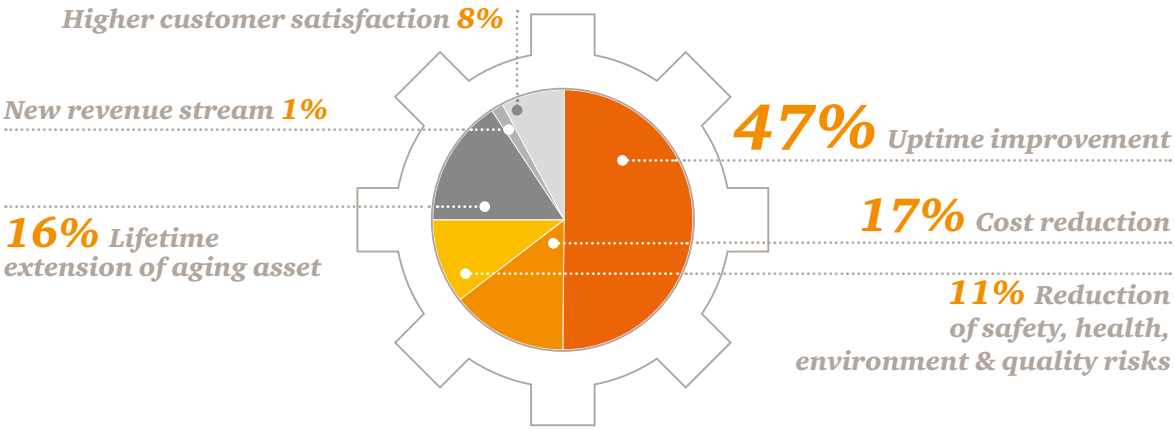
Assuming it takes two years to implement PdM 4.0, and that all such implementation projects will be successful, almost one in three companies will be using PdM 4.0 five years from now. This would represent a major increase from the 11% currently at maturity level 4, and also leave significant potential for further implementation.

Why do companies want to adopt PdM 4.0?

Knowing that almost one in three companies have ambitions to adopt PdM 4.0 in the coming years, it's worthwhile taking a closer look at what drives companies to implement PdM 4.0.

Respondents expect PdM 4.0 to contribute to further improvements in all 'traditional' value drivers in maintenance and asset management. Uptime improvement is clearly the most important in this regard, with almost half of the companies in our survey identifying it as their primary goal for implementing PdM 4.0.

Primary goal for adoption of PdM 4.0



Discussion: Secondary motives for implementing PdM 4.0

Low scores for primary goals like 'New revenue stream', 'Higher customer satisfaction' and 'Better product design' can be attributed to the relatively small share of respondents that provide maintenance services to external customers. If we zoom in on the survey results, we see that maintenance service providers think these goals are equally important as the traditional value drivers in maintenance.

'Dealing with employee turnover from an aging workforce' was never mentioned as the primary goal for implementing PdM 4.0. However, it is worth noting that both Infrabel and Sitech, companies that we portray as PdM 4.0 front-runners in this report, mention PdM 4.0 as a possible substitute for employees they expect to retire in the coming years.

How are companies placed to make the step towards PdM 4.0?

Successful implementation of PdM 4.0 requires capabilities in several key domains to be on par with the concerned level of maturity. (The next Chapter provides a more in-depth recommendation about how to approach such an implementation). The capability matrix below shows how mature a company's Processes, Content, Performance measurement, IT and Organisation need to be if it wants fully exploit the potential of PdM 4.0.

PdM Maturity Stage

Capability	1. Visual Inspections	2. Instument Inspections	3. Real Time Conditions Monitoring	4. PdM4.0
Processes	- periodic inspection (physical) - checklist - paper recording	- periodic inspection (physical) - instruments - digital recording	- continouos inspection (remote) - sensors - digital recording	- continuous inspection (remote) - sensors and other data - digital recording
Content	- paper based condition data - multiple inspection points	- digital condition data - single inspection points	- digital condition data - multiple inspection points	- digital condition data - multiple inspection points - digital environment data - digital maintenance history
Performance Measurement	- visual norm verification - paper based trend analyses - prediction by expert opinion	- automatic norm verification - digital trend analyses - prediction by expert opinion	- automatic norm verification - digital trend analyses - monitoring by CM software	- automatic norm verification - digital trend analyses - prediction by statistical software - advanced decision support
IT	- MS Excel/MS Access	- embedded instrument software	- condition monitoring software - condition database	- condition monitoring software - big data platform - wifi network - statistical software
Organisation	- experienced craftsmen	- trained inspectors	- reliability engineers	- reliability engineers - data scientists

Discussion: Five dimensions of PdM maturity

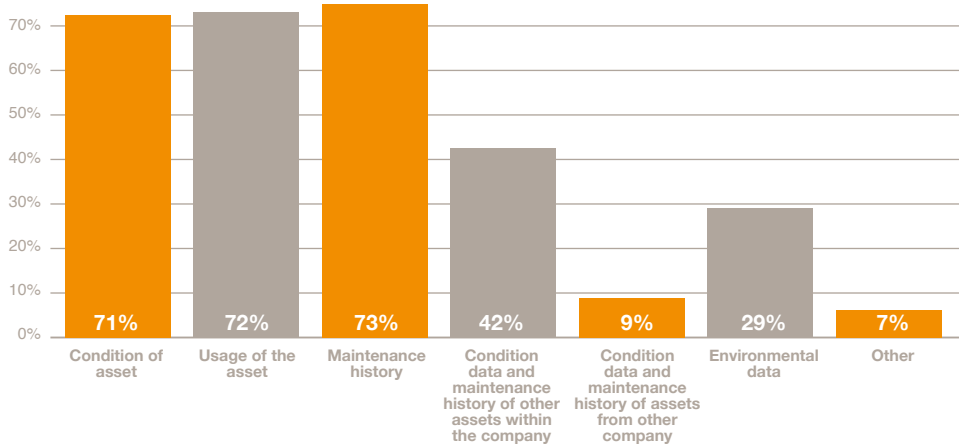
According to VDM^{XL} methodology[1], companies should develop capabilities in five domains in order to increase their PdM maturity:
Processes: *Design and implement work processes that will drive maintenance to the next maturity level.*
Content: *Make sure data required for these processes is available.*
IT: *Install the IT infrastructure needed to support these processes and data requirements.*
Performance Measurement: *Monitor asset performance and check if this meets business objectives.*
Organisation: *Make sure the organisational structure, skills, capabilities, incentives, etc. needed to support an improvement in PdM maturity are in place.*

[1] Taken from 'VDM^{XL}: Value Driven Maintenance & Asset Management', Mark Haarman and Guy Delahay, 2016.

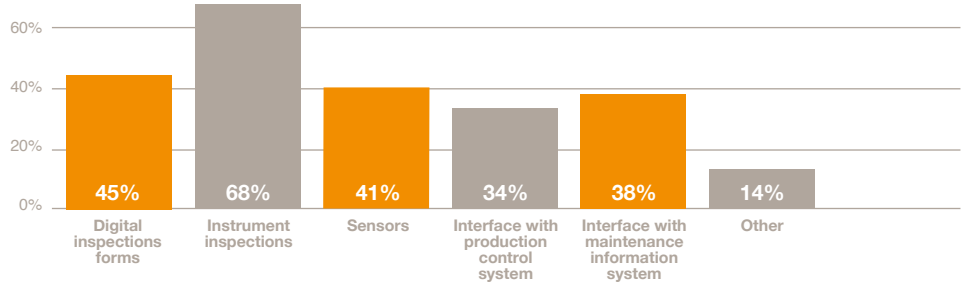
Our survey involved asking companies to provide information about their current capabilities concerning predictive maintenance. The labels used for these capabilities in the matrix above have been shown in brackets (note that 'Performance Measurement' is seen as an integral part of all PdM levels):

i) the types of data they use ('Content')
ii) how that data is collected ('Processes')
iii) which hardware and software tools are used ('IT')
iv) the functions involved in predictive maintenance ('Organisation')

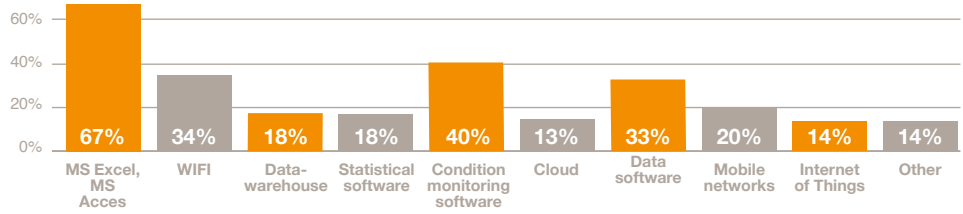
i) What types of data are used for predictive maintenance?



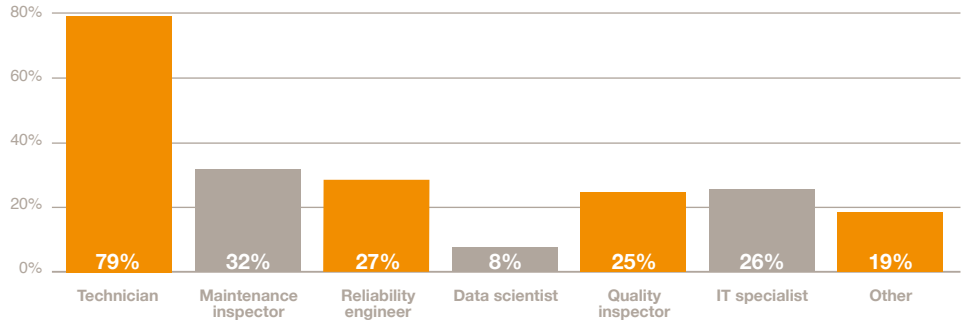
ii) How is data collected for predictive maintenance?



iii) Which hardware and software tools are used for PdM?



iv) What functions are involved with PdM?



Discussion: Capabilities and Ambitions

In general, responses to these questions - about companies' current capabilities - are in keeping with the distribution of current maturity levels we saw earlier in this chapter. The highest scores for these four question were given to 'Maintenance history', 'Instrument inspections', 'MS Excel / MS Access' and 'Technician'. These aspects are all associated with maturity levels 1 and 2, where most respondents currently find themselves. Furthermore, the low scores for 'Environmental data', 'Statistical software' and 'Data scientist' - all key ingredients for PdM 4.0 - seem to confirm that not many companies have already reached maturity level 4.

We found that around half the companies in our sample have plans to implement PdM 4.0; with one in three wanting to do so within the next five years.

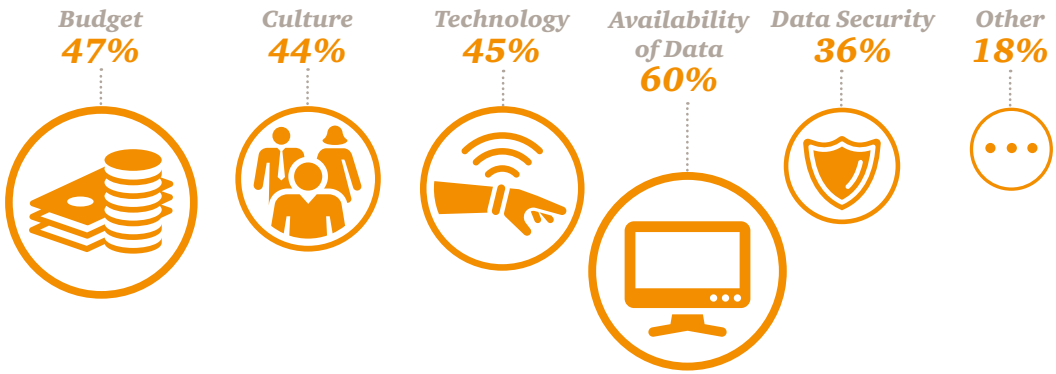
When these findings are combined, we can conclude that, even though ambitions regarding PdM 4.0 are high, many companies have not yet put in place the resources and capabilities (e.g. data scientists, reliability engineers, statistical software) needed to successfully implement PdM 4.0.

Naturally, it is normal to expect a gap between future ambitions and current capabilities when it comes to implementing a rapidly developing new technology. Nonetheless, we can conclude that it will require significant efforts and investments to build the required PdM capabilities. (The next Chapter recommends an implementation approach for PdM 4.0.)

What do companies think they need to succeed?

As our final question, we asked what respondents see as the critical success factors for successfully implementing PdM 4.0.

Critical success factors for implementing PdM 4.0.



Discussion: What is needed to successfully implement PdM 4.0?

'Availability of data' is seen as the most important critical success factor (CSF), while 'Technology' shares second place. This could be explained by the fact that it is still technologically challenging to collect sensor data from many assets continuously and in real-time. Large parts of an aging asset base may not yet be equipped with the required sensors; great demands are placed on data network capacity when collecting vast amounts of data from fleets of trucks and trains that move across large areas; and hazardous industrial environments demand an IoT infrastructure designed to meet specific safety requirements.

The fact that almost 50% of respondents mentioned 'Budget' as a CSF shows that many companies are finding it difficult to make a solid business case for PdM 4.0. This could be due to the fact that, at this early stage of the PdM 4.0 life cycle, it may be hard to find suitable reference cases and to quantify the expected returns.

The fact that 44% see 'Culture' as CSF can be seen as a case of 'glass half full or glass half empty'. On a positive note, culture is recognized by many as a key success factor, even for projects that may initially seem primarily technological in nature. The next Chapter argues that a robust digital culture is essential if the full potential of PdM 4.0 is to be exploited. Imagine what it takes for an organisation to become data-driven in its decision-making, possibly at the expense of human experience. Who dares to act on predictions made by a black box, which threaten to overthrow the traditional order of things?

Developing the maintenance function

"When Sitech was founded, we first focused on centralizing the maintenance function and standardizing maintenance processes across our customer base. This enabled us to cut maintenance costs by about 50 million euros. We then focused on improving the efficiency of our processes, which resulted in savings of a further 50 million euros. Today, the main drivers for our success are factory uptime and safety. Downtime costs can amount to half a million euros per day in missed revenue, so we have reached a point where reductions of maintenance costs by a few percentage points are of marginal significance compared to what we can gain from uptime improvements. Safety is our other main driver. We know we have aging assets, but will gradually lose the knowledge needed to maintain them. Therefore, we have to switch to predictive maintenance. This allows us to have fewer maintenance staff at the plants and provides much better insight into how a factory operates. Predictive maintenance thus contributes to the safety of both people and processes."

The initial approach to predictive maintenance

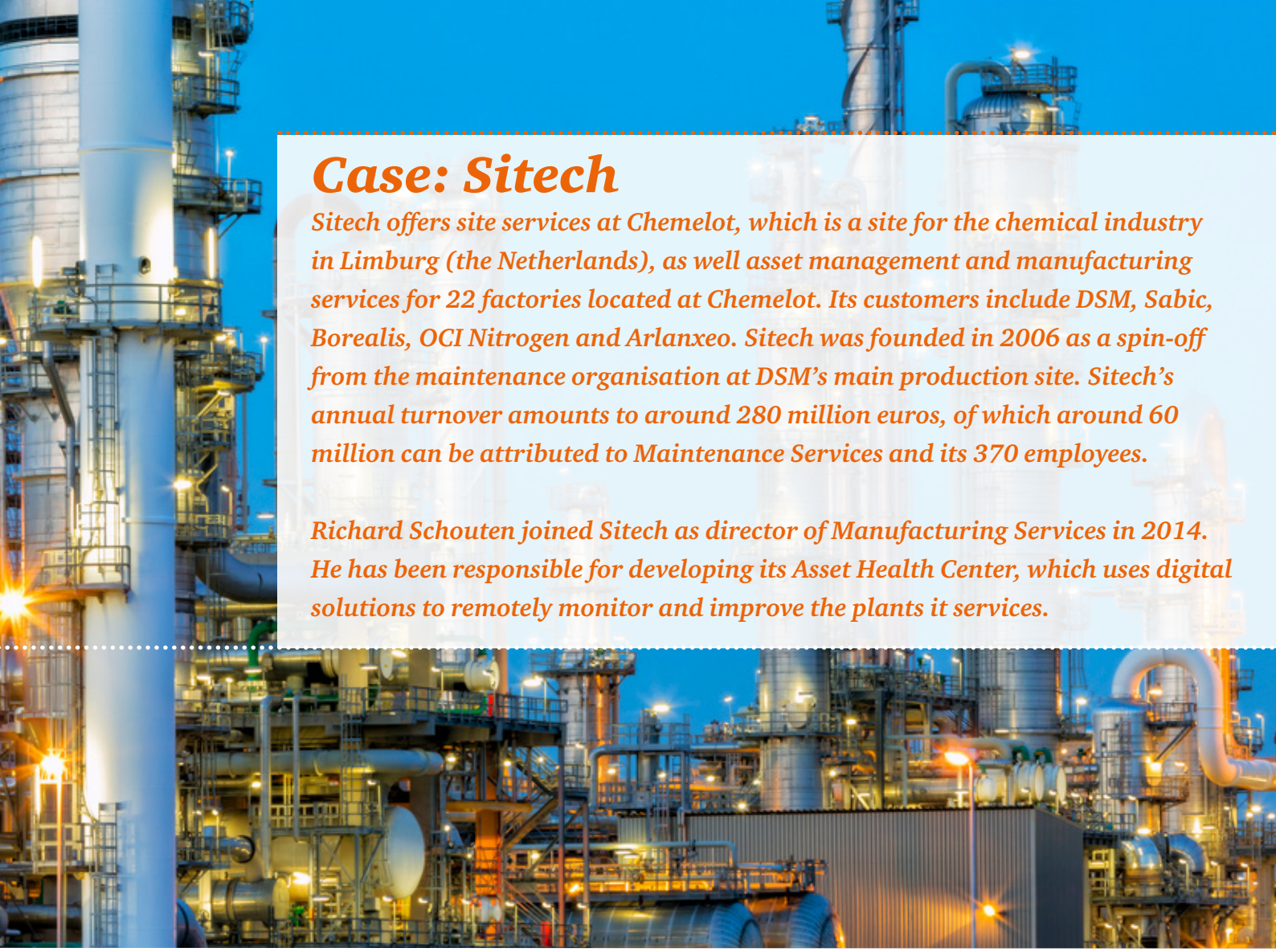
"We started off simple. We dedicated one reliability engineer to it, allowed him to become familiar with the subject and asked him to set up a pilot project. He identified a single, but critical, filter as the piece of equipment for our pilot. We installed sensors on this filter, started monitoring it and built a predictive model. This pilot turned out to be very successful because we can now predict when the filter will fail, include replacement activities in the regular maintenance schedule and thereby reduce downtime. We realise annual savings of around 60,000 euros for this filter alone, while the sensors and model development only cost a fraction of that."

The business case for predictive maintenance

"We were able to finance our initial pilot projects because I strongly believed in the concept and was able to convince plant managers about our approach. We have implemented seven models in the past two years, which helped to put together a very convincing case to show to our customers. I estimate that we spent around 200,000 euros on our pilot projects, and that these delivered us around half a million worth of uptime improvements and cost savings in return."

The roll-out of predictive maintenance

"We asked plant managers for funding to scale up and accelerate further implementation of predictive maintenance for all critical equipment. We originally planned to do this in five years, but were asked to do it in three. We develop models and perform roll-out for each type of equipment. For example, for all pumps of a certain type or for all heat exchangers at the site. Even though rotary pumps, for example, may have different manufacturers and different specifics, they all operate on the same physical principles. We can thus employ similar sensors and models for all rotary pumps.
We have now developed a predictive model for pumps and are currently rolling it out at the factories."



Case: Sitech

Sitech offers site services at Chemelot, which is a site for the chemical industry in Limburg (the Netherlands), as well asset management and manufacturing services for 22 factories located at Chemelot. Its customers include DSM, Sabic, Borealis, OCI Nitrogen and Arlanxeo. Sitech was founded in 2006 as a spin-off from the maintenance organisation at DSM's main production site. Sitech's annual turnover amounts to around 280 million euros, of which around 60 million can be attributed to Maintenance Services and its 370 employees.

Richard Schouten joined Sitech as director of Manufacturing Services in 2014. He has been responsible for developing its Asset Health Center, which uses digital solutions to remotely monitor and improve the plants it services.

The power of predictive maintenance

"When you know the main failures, you have a good idea about the data you need to collect and the sensors you need to install. FMEA's thus point you in the right direction. However, predictive maintenance is still feasible if you don't know what kind of data you need for your model in advance. To predict contamination for a drying column, we basically threw all the data we had into a black box and hired a data scientist to develop a machine learning model. It turned out that external air temperature is an essential piece of data for the predictive value of that model.

This came as a big surprise. Our engineers were confident it could not be important, given that the processes in the column run at over 250°C. What difference could a few degrees difference in external temperature make, they thought? But there was a major improvement in predictions when we added this temperature-related data, so we installed additional sensors and are currently training the model before we roll it out."

The biggest obstacle to overcome

"The first step is the most difficult one. Select a piece of equipment, choose an approach - I don't care what you do, but just do something and get started! That has been the biggest hurdle for us. Once the first success stories start emerging, people become enthusiastic and things start to roll."

The aging maintenance workforce

"Aging is a huge issue for us. In the next ten years, half of my staff of 160 engineers and technicians will retire. When it comes to replacement, I can only find two or three qualified people per year who are prepared to work here for the long term. I think further digitalization and predictive maintenance will allow me to cover half the short-fall."

The future

"We want to apply predictive maintenance and data analytics to all critical and semi-critical equipment. The next step is to develop predictive models for processing units, like a combination of several pumps and filters and a heat exchanger that operate together. For that to work, we must make sure the models for each equipment type can communicate with each other. If, for example, a heat exchanger gets contaminated, the system must learn it can be cleaned by pumping more volume through it and decide to do this by itself. We then want to apply the same concept to entire factories and eventually to the whole site. We want to move from an Asset Health Centre to a digital plant environment - that's our ultimate dream."

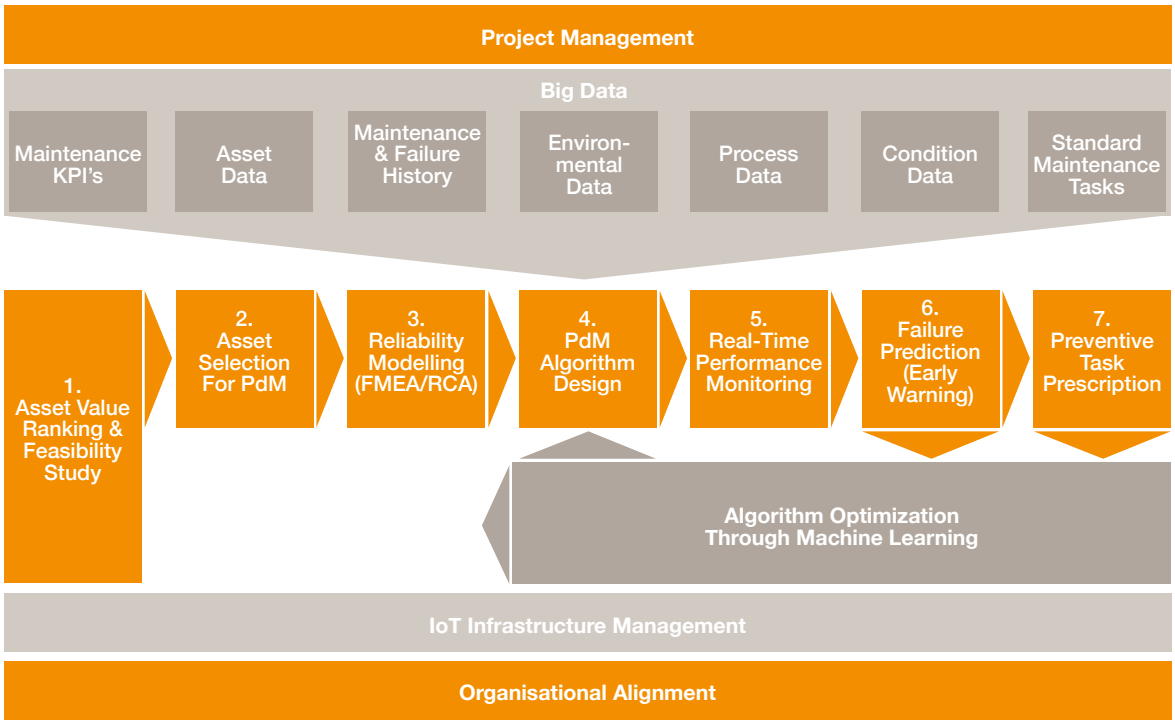
Chapter 3 *Recommendations*
Getting the most out of PdM 4.0

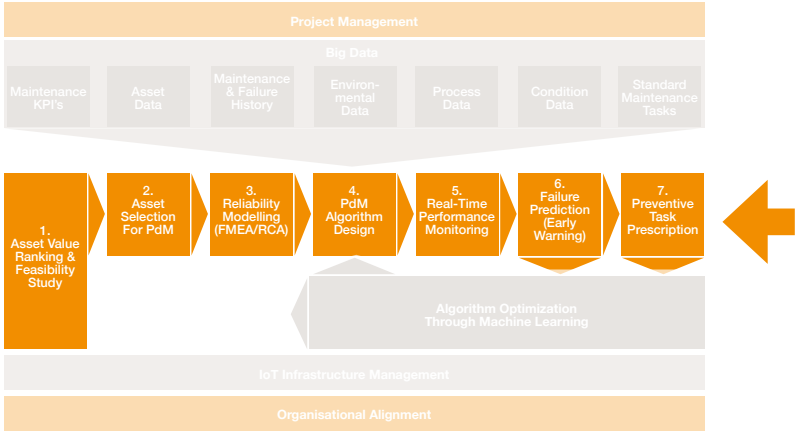
We have seen that many companies are ambitious when it comes to PdM 4.0; half of the companies we surveyed have plans to implement PdM 4.0; one in three wants to do so within the next five years. We have also seen that companies' current predictive maintenance capabilities are not yet at the level needed for PdM 4.0. We can conclude that significant efforts and resources will be needed to implement PdM 4.0.

While getting technology to work may be central to PdM 4.0, the scope of implementing it is far wider. Companies should also pay attention to organisational dimensions, and ensure the project management and change management skills needed for a successful PdM 4.0 implementation.

This chapter sets out an implementation approach for PdM 4.0, which includes the technological and organisational aspects that companies must address to make the most of PdM 4.0. The framework below addresses all of these aspects. We will start by discussing the technological part and in the next part focus on two organisational aspects: building data analytics and reliability engineering capabilities, and building a digital culture.

Implementation approach PdM 4.0





Putting the predictive model in place: the technical core of PdM 4.0 implementation

Our implementation approach is based on gradually building up the predictive maintenance model for selected assets. The seven steps involved in this build-up reflect what we have learned from working with our customers; you will, for example, encounter many of these steps in the Sitech case.

1. Asset value ranking & feasibility study: Identify assets for which it is worthwhile and feasible to apply PdM 4.0 in order to increase asset reliability. Only high-critical and possibly medium-critical assets will justify the required investments, and only assets for which the required data can be obtained are suitable candidates. This selection of assets will help to build an initial positive business case that should be part of the feasibility study.

2. Asset selection for PdM 4.0: Keep it manageable and don't try to cover your entire fleet or factory in one go. Select assets that can be tackled in pilot-projects, draw the necessary lessons from the pilots and apply these to the roll-out of PdM 4.0 per asset type.

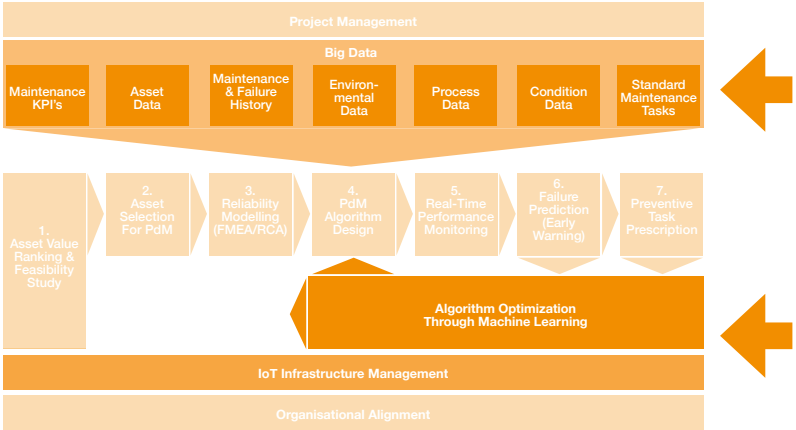
3. Reliability modelling: Use root cause analysis (RCA) and failure mode effects analysis (FMEA) per asset type to point you in the right direction. What data do you need to monitor root causes and failure modes? What sensory data and what external data sets do you need for this? How are the various root causes and failure modes interrelated?

4. PdM 4.0 algorithm design: This is really the art of data analytics. Choosing an algorithm is the single most important factor in determining the quality of your predictions. It may be relatively straightforward to design the best algorithm if you have already built a suitable model for asset reliability in the previous step. It may also require a number of data scientists to construct a self-learning algorithm capable of finding meaningful insights in pools of data.

5. Real-time performance monitoring: This is where your PdM 4.0 model goes live. The algorithm processes data from various sources - sensors embedded in the asset, the asset's maintenance and failure history, or third-party providers of environmental data - to monitor and visualize the performance of your assets in real-time.

6. Failure prediction (early warning): The algorithm will start to predict future failures. Acting on these predictions - by actually shutting down a machine or taking a perfectly operational train out of circulation - may initially require a big leap of faith, especially if management and maintenance staff have little experience with, or affinity for, data analytics. If this is the case, PdM 4.0 could run parallel to existing maintenance procedures without maintenance actions being taken based on its predictions. This may help to further build confidence in the predictions.

7. Preventive task prescription: At the top level of PdM 4.0, the algorithm not only *predicts* when a failure is likely to occur, but it also draws from a library of standard maintenance tasks to *prescribe* the best action to avoid such a failure. It may even execute such tasks, for example, by automatically issuing the corresponding work order.



Putting technology infrastructure in place: three additional building blocks

The technical core of this implementation approach features three additional building blocks.

- PdM 4.0 requires big data infrastructure that supports these consecutive steps. Companies will need to consider how they will collect data from both internal and external sources and what combination of in-house and cloud-based data storage solutions they want. Accessibility of data is also an important concern, and could have implications for the speed, reliability and bandwidth of your communications network.

- PdM 4.0 also requires an Internet of Things infrastructure, the backbone that wirelessly connects your assets to your maintenance data center and enables the collection and distribution of sensor data. Setting up the proper IoT infrastructure for your company involves choosing the right protocols for wireless connectivity, data encryption and security. Another key decision facing companies is the choice of data analytics platform, with the best option being a single integrated solution.

  Existing ERP systems do not yet have the capabilities required to handle the more sophisticated data trends, analytic methods and algorithms needed for PdM 4.0. A more sophisticated approach would be to invest in a data integration layer linked to the ERP systems, and use tailored analytics tools per case.

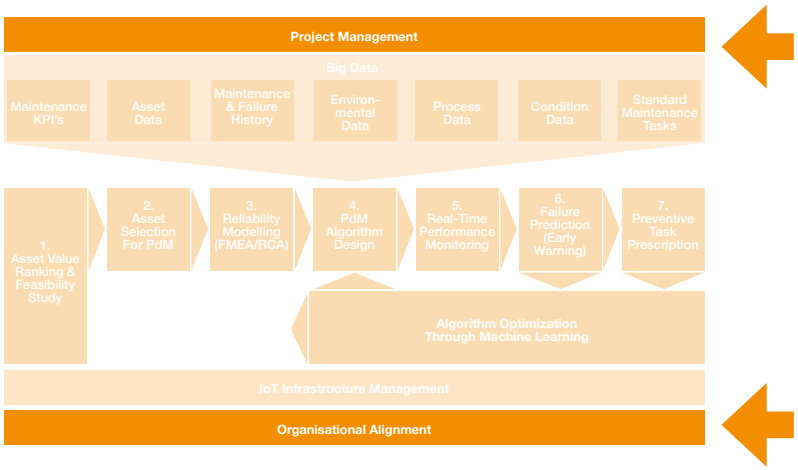
- Install feedback loops. Granted, this is not purely a technical issue. However, it is an essential step in ensuring that your PdM 4.0 model remains aligned with your business objectives. The algorithm at the core of PdM 4.0 can be self-learning, which means its predictive power will increase over time, when more data is used. However, as the model is optimized, lessons must also be learned about the overall approach to PdM 4.0. The algorithm may bring to light new failure modes or generate new insights into the asset's reliability model. Perhaps the PdM 4.0 business case for a particular asset type needs to be re-evaluated: it may be more expensive or yield worse returns than initially thought. Or the criticality of assets may change over time and warrant new feasibility studies.

Putting the organisational support structure in place: the softer side of PdM 4.0 implementation

Implementing PdM 4.0 should definitely not be viewed as a strictly technological challenge. Obviously, strong project management skills are needed to get PdM 4.0 'up and running' in the first place. However, in order to reap the rewards of PdM 4.0 in the longer term, companies will also have to create an organisational support structure. This is referred to as 'Organisational Alignment' in our implementation approach.

Successful implementation can only take place and be sustained within organisations that are capable of change, fostering a digital culture and developing and attracting the right capabilities. In PwC's Global Industry 4.0 Survey 2016[1], respondents said their biggest implementation challenge isn't the right technology, but a lack of digital culture and digital skills in their organisations. The right technologies are obviously important, but ultimately success or failure will not depend on specific sensors, algorithms or analytics programmes, but on a broader range of people-related factors. Getting such people-related, or 'softer', factors right may be the hardest part of PdM 4.0 implementation. The remainder of this chapter focuses on two key elements of organisational structures capable of sustaining PdM 4.0: data analytics capabilities and a digital culture.

[1] PwC 2016 Global Industry 4.0 Survey - *Industry 4.0: Building the digital enterprise* (www.pwc.nl/industry4-0)



Building data analytics capabilities

Success with PdM 4.0 will ultimately depend on skills and knowledge. In the 2016 Industry 4.0 report cited earlier, lack of skills or competencies in the company's workforce is the biggest challenge respondents see when it comes to using data analytics. We found that only 27% of our survey respondents currently employ reliability engineers in predictive maintenance, and even fewer (8%) employ data scientists. Companies' biggest obstacle thus may be their ability to recruit the people needed to put PdM 4.0 in place.

Companies generally understand that it's critical to have in-house data analytics capabilities in order to successfully drive Industry 4.0 applications. Building these capabilities takes far more than hiring new talent with PhD's in statistics, data science or AI. No matter how much talent companies bring on board, these talents will not be as effective as they could be without the right organisation and governance in place.

Perhaps the most important aim of designing a PdM 4.0 governance structure is to create an environment in which data scientists and reliability engineers can interact and complement each other. A reliability engineer's insights in how and why assets fail should be paired with, challenged by and harmonised with the insights a data scientist extracts from the data, and vice versa. This type of cross-functional interaction is key to successfully applying data analytics in maintenance and asset management.

A good first step for companies considering how to best arrange their data analytics could be cross-functional expert teams. Data analytics capabilities can later be fully embedded in the organisation as a standalone function. In addition, companies may need to introduce new roles like that of data scientist, update existing job profiles to take into account new digital skills, or establish a digital council that oversees the development and further deployment of analytics capabilities throughout the organisation.

However, the people needed for PdM 4.0 will not want to stay if the company culture does not suit their talents.

Building a digital culture

PdM 4.0 cannot be implemented in complete isolation within the maintenance organisation. It should be embedded into an overall digital manufacturing strategy that is owned and fully supported by top management. And not only because the implementation of PdM 4.0 requires significant resources and capital investments. Initially, there may be no 'hard data' for a positive business case for PdM 4.0. To get things rolling regardless, it takes vision and enterprise from company leaders who understand the power of new digital technologies.

Involvement from the boardroom is also needed because the implementation of PdM 4.0 can have wide-ranging effects within the organisation. PdM 4.0 implementation is likely to require cross-functional expert teams with reliability engineers, operators, process technologists, data scientists and IT specialists who together develop new ways of working and communicating. PdM 4.0 may shape new relationships with suppliers and customers with whom data - which becomes an increasingly valuable resource - could be exchanged. Far-reaching change is not always comfortable for the people who make it happen, so change management will also be critical.

All such aspects of a PdM 4.0 implementation require a robust a digital culture. This means a culture that stimulates experimentation with new technologies and new ways of working; a culture that stimulates cross-functional cooperation and a culture that is comfortable with data-driven decision-making, even if this goes against human experiences and how things have always been done. Such a digital-minded environment can only be cultivated with committed leadership from the top.

Chapter 4 *Call to action*

Follow the six steps in our blueprint for digital succes and become a front-runner in PdM 4.0

Blueprint for PdM 4.0 success

1. Plot your PdM 4.0 strategy

Evaluate your current PdM maturity level and set targets for the next five years that bring value to your business and that are consistent with your overall strategy. Make sure that company leadership is ready and willing to champion your approach.

2. Create inital pilot projects

Select asset types suitable for a PdM 4.0 pilot and use them to establish proof of concept and to demonstrate business value. Create cross-functional teams and provide them with sufficient resources and the freedom to pioneer new ways of working. With evidence from early successes, you can gain buy-in from the organisation and secure funding for a larger rollout.

3. Define the capabilities you need

Use the lessons learned from your pilot projects to map out in detail what capabilities you need to achieve your targets. Develop strategies for improving processes and for implementing new technologies. Your biggest constraint may well be your ability to recruit the people needed to put PdM 4.0 in place.

4. Become a virtuoso in data analytics

Your success with PdM 4.0 will depend on skills and knowledge. It is not enough to just recruit and develop talent; governance is also important. Create an environment where data scientists and reliability engineers can feed off each other's expertise.

5. Transform into a digital maintenance organisation

Deploy PdM 4.0 across your asset base and become truly data-driven in your decision-making. Continue to develop the support structure - master data management, data analytics platform, IoT infrastructure - in order to keep up with your progress in PdM 4.0.

6. Actively plan an ecosystem approach

As you become more mature in PdM 4.0, foster collaboration with suppliers, research centers and other external partners in order to keep up with the latest developments. Develop interfaces and benefit sharing models with partners in your ecosystem to generate even more value with PdM 4.0.

About the survey

The survey that was used to write this publication was conducted by Kantar TNS in three countries: Belgium, Germany and the Netherlands. The selected methodology was used to gather responses to 20 survey questions anonymously by telephone. A total of 280 respondents submitted their answers and were split between the countries as shown below.

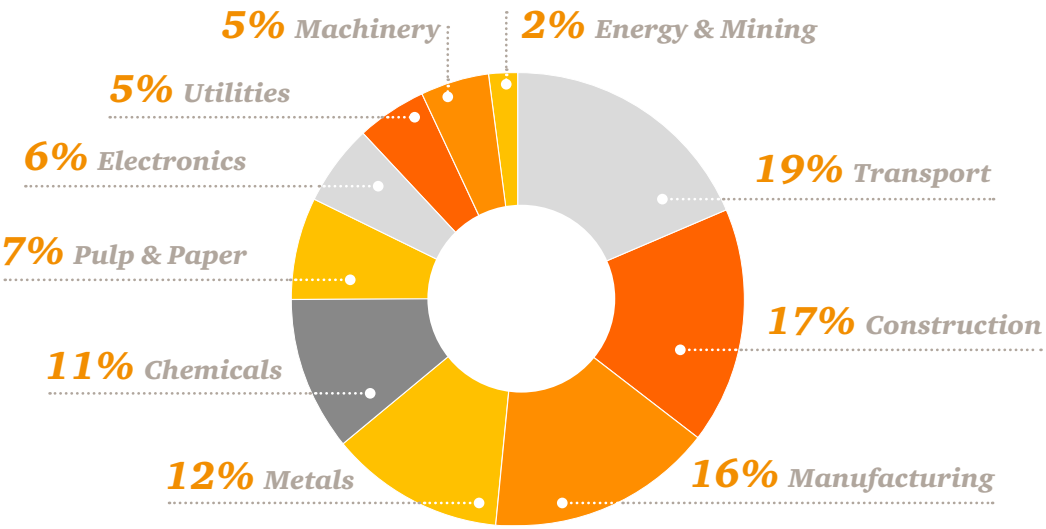
Respondents had one of the following position/responsibilities (or similar) within their organisations

Chief Operating Officer
Factory/Plant/Site Manager
Maintenance/Service Manager
Fleet/Asset Manager
Maintenance/Service Engineer

Country	*Respondents*
The Netherlands	100
Germany	102
Belgium	78

The survey was conducted between January and March 2017.

Industry split of surveyed companies



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