FIXING THE CHAIN: THE DATA ENRICHMENT CYCLE IN PROGNOSTIC HEALTH MONITORING

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Abstract

Only a very modest percentage of maintenance of capital goods is done condition-based, as opposed to plan-based or corrective. Doing much more would be very beneficial from a safety and operations perspective. Moreover, the basic methods have been known for some time. This paper addresses the question that, if condition-based maintenance (CBM) or Prognostic Health Management (PHM), as the terms commonly used to denote the same maintenance policy, is so logical and beneficial, why is it currently not more often applied in practice?

This paper suggests that the answer lies in a complex interplay of technical and organizational issues. This interplay is best conceptualized as a data enrichment chain, which starts and ends at the physical asset to be maintained and ends at the actual prognostic maintenance being executed and evaluated. This chain is described in more detail, and illustrated with examples from an open innovation project in the process industry in the Netherlands, the CAMPIONE fieldlab. From this description, it becomes evident that this chain is currently broken in many places. If CBM/PHM is to become more established as a business practice, these breaks will need to be fixed. The paper discusses several of the options of how to fix this data enrichment chain in practice.

1. Introduction

Of the three basic forms of maintenance, preventive, corrective and condition-based, clearly the latter is the optimal one. With preventive maintenance, one is in most cases too soon, leaving useful life unused. With corrective maintenance, one is too late, leading to production losses, rush orders et cetera. Only condition-maintenance is “just-in-time” maintenance. If that is so logical, then why isn’t condition-based maintenance (CBM) or Prognostic Health Management (PHM), as it the term commonly used in aerospace, more often applied in practice? In the process industry, one of the largest maintenance spenders in the Western economies, less than 10% of maintenance is done condition-based, leaving a potential of billions unused every year. Why isn’t that percentage higher?

In the past, the answer was simple: one didn’t have the data available to assess the current condition of the asset properly, and one didn’t have the theory, algorithms, models etc. available to translate these data into a sound assessment of the current status and the predicted trajectory of performance in the coming periods. Without such assessments, condition-based maintenance may be nice in theory but is far too risky or simply impossible in practice. In recent years, this simple answer is no longer sufficient. New theoretical insights on performance degradation in a wide variety of technical disciplines are becoming available, although much work remains to be done. More visible though is the rise of the Internet of Things (IoT) and Big Data. The Internet of Things, with countless cheap and effective sensors that signal statuses real time, which reverses a situation of data scarcity into data abundance. Big Data holds the promise of filling the gap between what we already know in theory and what we need to know now in practice.

So, if technology excuses no longer suffice, what is the real answer to the question why CBM/PHM is not used more often in practice? Clearly, this answer has to be sought, as often in situation of a major change in business practice, in organizational issues. To be more precise, it has to be sought in a complex interplay of technical and organizational issues. This interplay is best conceptualized as a data enrichment chain, which starts and ends at the physical asset to be maintained. Sensor data and human observation data start the cycle, which moves from the collection and preparation of data to data analytics and domain-specific model analysis to prediction trajectories, from there to the addition of business and financial considerations, from there to planning and scheduling, then to training and standardization issues, to workflow system availability, to standardized and IT-enabled maintenance execution, to automated job data capturing and from these to evaluation of effectiveness of maintenance work and possible adjustment of rules and guidelines, back to data capture again, ready for another cycle.

The paper describes this data enrichment chain in more detail and grounds it is an empirical setting of the CAMPIONE (Condition-Based Maintenance in the Process Industries) project. This is a so-called smart industry fieldlab in in The Netherlands, focusing on practical implementations of condition-based maintenance / prognostic health monitoring in the process industries, involving some two dozen public and private organizations over a four year time span in a multitude of open innovation activities. In this field lab, we employ insights from the aerospace sector into the process industry, but in our aerospace-related projects we just as easily borrow from insights from other sectors to boost maintenance innovation in aerospace.

The paper describes how in practice, the data enrichment chain may presently be broken, but also how it can be fixed and is being fixed in the CAMPIONE fieldlab. Once it is fixed, companies and society will start to reap the huge benefits from true prognostic health monitoring. The paper also presents a theoretical synthesis of the data enrichment or cycle based on a variety of theories on naturalistic decision making, systems engineering, feedback control systems, information management and organizational culture and change.

2. THE DATA ENRICHMENT CHAIN

There are some very visible technologies that lead from the technology side to more attention for CBM/PHM. Most notable among these are various sensor technologies and data analytics techniques. Invariably, these end at the top of the lists of most important technologies for advanced manufacturing or "smart industry" in general, and for CBM/PHM in particular. And indeed, sensor technology and data analysis techniques are becoming more advanced and much more affordable. However, they are by no means new technologies. Even absolute laymen may remember the scenes from the Apollo 13 movies, which depicts a dramatic aerospace event from the year 1970, where ground control in Houston was able to measure real-time several instruments and even key human health indicators from hundreds of thousands of miles away. And that was over 45 years ago…

So, if novelty is *not* the key reason why CBM/PHM is not used more widely, what is? Here we cannot suffice with a simple answer. The reality is, that there are a whole host of issues that need to be resolved before the entire industry can move away from a corrective and plan-based mode of operation. Figure 1 on the next page summarizes the main steps in the *data enrichment chain* in which raw sensor data is enriched into information, information into decisions, decisions are implemented and evaluated. Each of the 15 steps in this chain involves multiple challenges. In this paper we list some 20 of them, not with an attempt provide an exhaustive list but to illustrate in how many places the data enrichment chain can be broken, and what challenges need to be made to fix them chain in each of these places.

A. Measurement of current performance (sensors or human)

- *Challenge #1: extracting useful data from "old" assets*. Infrastructure in North-West Europe, and North America alike, is mostly old. Public infrastructure as well as factories are mostly towards the end of their lifecycle. Usually, they have very *few* sensors installed specific for maintenance / health management. However, that does *not* mean that such data cannot be found, on the contrary. Even old assets have data collected for operations, for energy usage, for safety, for sales, data collected by the OEMs who supplied the assets or the contractors maintaining the assets. If, for example, there is a pump with no sensors of the filters, but we have collected data on the energy needed to pump through these filters, these data may be used quite successfully to predict performance degradation of the filters. So, collecting these data can be done but it normally will require collaboration with other functions within the business, and with business partners. In the "old" antagonistic business settings, such collaboration may be problematic but not for technical reasons…

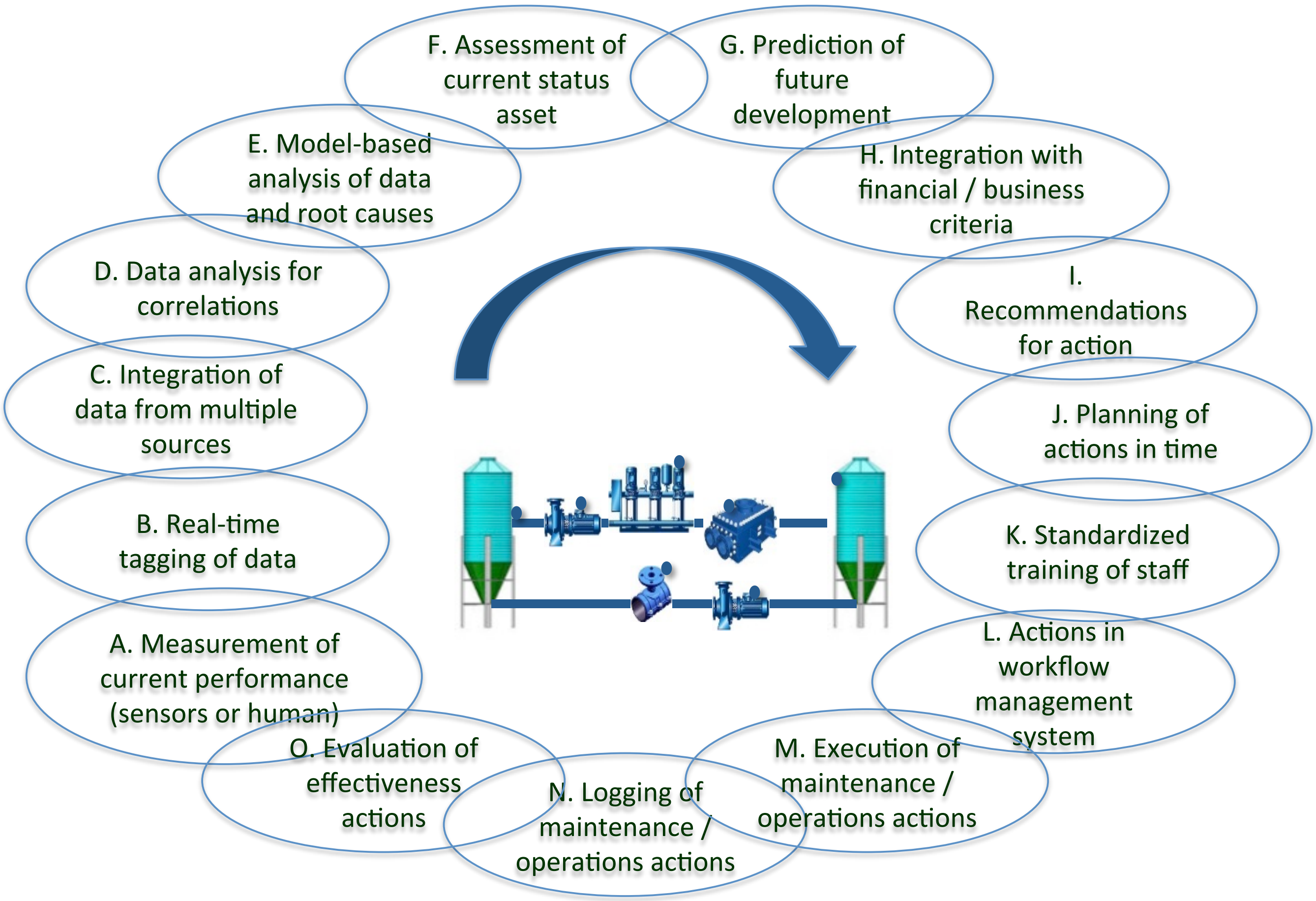

Figure 1. The data enrichment cycle in CBM/PHM

B. Real-time tagging of data.

- *Challenge #2*: *Navigating through a sea for data*. New assets often have the opposite problem: not the scarcity of data is the problem, but its abundance. A gas turbine may spit out a few hundred gigabyte of data in 24 hours: how to find the relevant Kb bits of information in that sea of data? One solution may be to collect *all* sensor data, tag it and spill it into a "data lake" for some future use, but probably it is wiser to select just a small percentage of all data for tagging, or to sample data not every millisecond but less frequently. What data will be relevant will become evident from the subsequent data enrichment steps, as we will see.

C. Integration of data from multiple sources.

In the bulk of cases, there is a multitude of sources for data to be used in CBM/PHM. The challenge to integrate these data is both organizational and technical.

- *Challenge #3: Aligning business objectives with multiple stakeholders*. There is internal data and external data (e.g., external temperature or wind velocity), there is data from the various OEMs that have manufactured the assets involved, and from their suppliers, there is data from Operations and from Maintenance, from Engineering and Design, from Procurement and from Sales, data from the Safety department and from product quality checks, from energy use and from utilities. There is data from customers and how they experience the quality of the products and services generated by the assets. A primary challenge of an organizational nature is how to align the business objectives from the parties that own the data most crucial for the CBM/PHM process.
- *Challenge #4: Synchronizing time stamps and data format from multiple sources*. The other side of the challenge is technical. All this data from all these different sources, with different data formats, different time steps, different granularity and level of detail, and still need to be integrated so that data analysis can be conducted on all the data, not just on several non-compatible subsets.

D. Data analysis for correlations.

This is a vast field in its own right. Two clear challenges from the CBM/PHM perspective here are:

- *Challenge #5: Fitting data analytics techniques with asset health challenge*. There are several different approaches to data analytics. There is the statistical approach, which comes up with strong correlations but with a need for high data completeness. There is the machine learning approach, with very complex behavioral patterns, but with a need for quite some data sets of equipment failures to "learn from". There is the data base SQL/Excel approach, with low complexity but again high requirements for data completeness. There is the control theory approach, often based on nonlinear dynamics analysis. When to use what type of technique, also in combination with the next step of model-based analysis, is at present certainly not a textbook / cookbook question.
- *Challenge #6: Fitting data analysis frequency with business use*. One can use data analytics one time, and off-line, to discover failure modes and root causes of issues, which then can be resolved. One can use it periodically, and one can use is continuously. When to make what type of use of these techniques is, again, at present not clear and we need to understand more before we can give clear fact-based recommendations

E. Model-based analysis of data and root causes.

- *Challenge #7: Integrating domain knowledge with data analytics findings*. Reliability engineers or structural integrity engineers, who work in most companies, have in-depth knowledge of the equipment to be maintained. The challenge is how to incorporate their knowledge with that of the data analytics experts, who often have a very different background (IT, cognitive science, statistics, databases, Artificial Intelligence). Often, these two groups do not talk to each other on a systematic basis. They also work very differently. The reliability engineering will have very deep knowledge of how the physics of 2, 3, 4 performance aspects interrelate over time. The data analytics experts typically start from gigabytes of data concerning hundreds if not thousands of variables, and gradually distill promising correlations between those. How to integrate these two very different approaches and people remains so far a major challenge.
- *Challenge #8: Incorporating expert knowledge from related domains*. Often, there is potentially very relevant and deep knowledge about the assets that are to be maintained in good health in other domains. For instance, in product development, where there can be decades of knowledge in how the product being manufactured is affected by the equipment used. Or in after-sales, where various aspects of product quality are systematically monitored and studied, aspects which may serve as early-warning indicators for performance deterioration of the equipment. However, these are very different functions, with people from a very different background working in different locations, with interests which are very different from the CBM/PHM staff, and management priorities which are also very different from them. How to bring this latent knowledge to the table for the CBM/PHM effort is even a more daunting challenge than the previous one, but a very promising one indeed.

F. Assessment of current status asset.

- *Challenge #9: Carving out a performance degradation path*. At this point, we have established that current performance is at X, whereas top performance is Y and unacceptable performance is at Z. However, what does that say about how long it will take for this asset's performance to deteriorate from X to Z? Or what factors will affect this deterioration? In other words, the information that current performance is at X is not so informative at all, perhaps only if X is very near or even below Z, so that it is certain that immediate action is required.

G. Prediction of future development.

- *Challenge #10: Predicting future behavior based on information about the past and present.* The more relevant question in most cases is not what current performance is, but what performance is likely to be in the near future. How does one carve out a likely degradation path? Again, this is a huge field in itself, with many cases where this is simply impossible because failure (performance drops below Z) is almost purely random. One can try to extrapolate from past behavior or one can correlate performance with one or more other factors, the future behavior of which is better known or better predictable. This is not an organizational challenge, purely a technical one, but a major challenge indeed.

H. Integration with financial / business criteria

- *Challenge #11: Finding a common language to combine financial with non-financial perspectives*. At this point in the data enrichment chain we leave the technical world and enter the world of business. For let's say that we have established in the preceding step that performance of a certain equipment will most likely drop to unacceptable levels in 4 weeks time. What do we do? We may accept run-to-failure, simply because the current output is just too profitable and time-sensitive. Or because the time available is simply to short to have adequate staff or spare parts available. We may also decide to reduce the load on the equipment, by a change in operations policy, because a shutdown of the whole plant is planned in 6 weeks time, which will reduce the costs of maintaining this particular part of the plant. And if we maintain, how do we maintain? If there are multiple options for maintenance, what are the life cycle cost implications of those options? And so, what option will be chosen? All these questions ask for multi-criteria analysis at the very least, and for a much better understanding of the financial implications of various specific technical alternatives in particular.

I. Recommendations for action.

- *Challenge #12: Achieving consensus across functions and across short and longer-term time horizons*. The main challenge may again be more organizational than technical. The data on which to base these decisions are owned by different stakeholders, these stakeholders have different interests, they even speak in a different specialist language. Getting them all at the same table is already a major challenge, having them converse constructively and arrive at an informed consensus for the best course of action is even a bigger one.

J. Planning of actions in time.

- *Challenge #13: Prioritizing and clustering work to address both job urgency and cost efficiency*. Once an organization has arrived at such an informed consensus on what needs to be done, it is still a plan made against infinite capacity. In the real world, there are very real limitations to capacity. Staff is occupied with other work, or not qualified or properly trained, or it may make more sense to group maintenance activities in one area first and then the other area next. For most ERP and scheduling systems, this complexity is too complex to handle. As a result, suboptimal work schedules are generated.
- *Challenge #14: Synchronizing planning of staff across multiple organizations and systems and time*. Together with the preceding technical challenge comes the organizational challenge that, typically, multiple companies and specialisms are involved in complex maintenance activities. How are the planning systems of these different organizations to be synchronized for specific maintenance activities? In shutdowns in the process industry, such planning is a multi-year activity, where availability is scheduled in great detail. Impressive in their detail, such plans are rarely impressive in their cost-effectiveness, as buffer upon buffer in capacity and time has to be incorporated to compensate for the lack of transparency of availability across multiple independent organizations. But how can one truly plan across multiple organizations at the same time?The field of supply chain management can lead to new insights here, as inter- and intra-organizational planning practices such as collaborative planning and forecasting (CPFR) and Sales and Operations Planning (S&OP) have become established business routines.

K. Standardized training of staff.

Most staff nowadays is *not* trained in CBM/PHM. If they are to be trained in this new way of working successfully, multiple challenges will have to be met.

- *Challenge #15: Safe multi-person training for hazardous activities*. For one, many maintenance activities are multi-person activities, but how can one train for these? Virtual reality systems that allow for multi-actor interactions may provide a solution. These will at the same time allow for training, as long as it takes, of hazardous and/or rarely occurring complex maintenance activities. Similar to pilots, who recurrently train to deal with low-likelihood high-impact events, CBM/PHM staff will need to be trained to work safely and effectively in these types of task settings.
- *Challenge # 16: Standardizing training based on the CBM/PHM mindset across independent companies*. The average chemical plant in The Netherlands sees a wide variety of contractors conducting various maintenance tasks. Each contractor is independent and has its own training methods and standards. They typically employ workers from different countries, vocation and experience. They are rarely trained in the CBM/PHM mindset. Nevertheless, if the chain is to operate intact, all these mindsets need to be standardized. How to achieve this is a serious challenge.

L. Actions in workflow management system.

- *Challenge #17: Achieving seamless integration of workflow management systems, tablets, augmented reality and… people*. What also helps to achieve a standardized way of working is to have IT systems that enforce, or facilitate, such a standardized ways of working. This goes beyond an up-to-date workflow management system, there needs to be integration with tablets, even with augmented reality tools.

M. Execution of maintenance / operations actions.

- *Challenge # 18: Ensuring compliance with standardized ways of working in CBM/PHM mode across companies*. What is true of training is also true of execution. Ensuring a standardized way of working, which is essential to make not just the degradation behavior of equipment predictable but also the performance after maintenance work, is essential but complex to achieve with a variety of workers coming to do the maintenance.

N. Logging of maintenance / operations actions.

- *Challenge # 19: Enabling automatic logging of findings and actions*. Often, maintenance logs leave much to be desired "Was broken – Fixed it" is not seldom the most informative statement in these records. Maintenance staff just don't have the time nor the incentives or the training to fully document what they have found and what they have done on the job. Therefore, to automate the logging of the actual work done on the equipment as much as possible is desirable. It is also a challenge from a technical perspective

- *Challenge # 20: Integrating log data with root cause analysis / FMECA analysis*. The data enrichment chain is not just a chain, it is really a cycle, one of the Plan-Do-Check-Act variety. So, after every action, the effect of that actual is evaluated and the lessons learned may affect future maintenance strategies. In the contect of CBM/PHM, we are talking about such tools as FMECA (Failure Mode, Effects and Criticality Analysis). This is often done in a standalone, ad hoc mode. Here the challenge is to integrate the log data with root cause analysis in a systematic matter.

O. Evaluation of effectiveness of actions

- *Challenge #21: Facilitating organizational learning over time from systematic comparisons between analyses, recommendations, actions and results*. Condition-based maintenance is a journey. In that sense it resembles production philosophies such as Lean Management or Total Productive Maintenance (TPM). How to transform CBM/PHM into a never-ending process of organization learning may be the most daunting challenge of all.

3. THE CAMPIONE FIELDLAB IN THE NETHERLANDS

How do we try to fix the data enrichment chain that was laid out in the preceding section, when in practice this chain is broken in so many places? In the CAMPIONE (Condition bAsed Maintenance in the Process Industry Open Network Environment) fieldlab project, fixing this chain is attempted in multiple places.

The fieldlab provides a project infrastructure that accelerates innovations that can fix the chain in an open network environment. Like all other World Class Maintenance (WCM) Fieldlabs, CAMPIONE picks up innovations at Technology Readiness Level (TRL) 3 (see Figure 2). Innovations are developed in a laboratory environment representative for the industrial end applications (e.g. a production plant) up till TRL 5. From TRL 3 to 5, the innovation is developed in a 'Fieldlab', typically a central project location. Within the central Fieldlab, innovators are able to develop and demonstrate the innovation in a generic, though relevant environment and raise interest at the side of industrial partners being the potential end users of the innovation. When a sufficiently high level of maturity has been proven, these end users, together with the innovator, can decide to take the innovation a step further towards one of WCM's 'Living Labs'. These labs are pilot environments within industry, providing all technical and organizational boundary conditions to further develop the innovation for a real and specific industrial application. A Living Lab could be a specific production line or specific production equipment that is operationally used.

In theory, the Living Lab activities will start at TRL 6 and finish at TRL 8, so that the final part of the innovation process (business development) can be taken up by the market. In reality, there may be some overlap between the Fieldlab and Living Lab activities.

The availability of the described innovation infrastructure (Fieldlab and Living Labs) has already proved to be crucial in bringing innovations into operations. With the CAMPIONE project, which is running for only 6 months now, already some twenty unique innovations that until then had remained stuck in the 'paper phase' ("promising, but thanks, not for us") are now running in this infrastructure and are quickly reaching the business development stage of TRL 9.

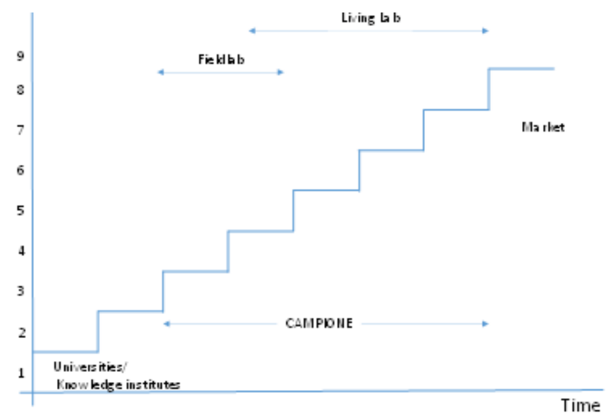

Figure 2: CAMPIONE innovation infrastructure versus Technology Readiness Levels (TRLs)

WCM Fieldlab projects are geared towards operational and commercial application of the innovations that are promoted by these projects. As described, the innovation infrastructure of the Fieldlab and Living Labs is designed precisely for that. However, also boundary conditions are met regarding the value chain supporting these innovations. Project teams are designed such that (i) all required knowledge is available, (ii) the maintenance value chain is covered and (iii) the data enrichment chain can be fixed. For CAMPIONE this implies that project partners represent a mix of large companies and SMEs, educational and research institutes. Various large companies can be categorized as asset owners, having an interest in optimizing operations and maintenance. CAMPIONE innovators are typically SMEs or (new) service departments of larger companies. The last category of companies are the OEMs proving the asset owners with technical systems that need to be maintained. As such the classical maintenance context is completely represented in the project.

However, this is not sufficient for working on the project goal to implement CBM in such a way that maintenance will get fully predictive. In order to follow a data driven approach to predict and optimize maintenance, new disciplines are required, typically provided by innovative data science companies and knowledge institutes. These CAMPIONE partners are crucial to make a difference in CBM and fix the data enrichment chain.

Finally, knowledge partners in the area of organization and human factor aspects are involved to ensure coverage of all issues that require attention when implementing innovations.

Obviously, each CAMPIONE project partner can work in the Fieldlab project on its own innovation contributing to CBM/PHM; i.e. a small part of the data enrichment chain. However, there is no better way to validate this innovation by testing it as part of a (possibly simulated) part of a complete value chain supporting data driven maintenance. Simultaneously, in such a setting the innovator can team up with relevant value chain partners to truly develop the innovation into a viable business solution for potential end users also present in the Fieldlab or Living Lab environment.

As explained before, intermediate results from the CAMPIONE Fieldlab can be picked up in Living Labs. But the flow can also be the other way; findings in the industrial Living Labs have resulted in new questions that are fed to innovators working in the central Fieldlab or even to researchers of universities in case of issues requiring fundamental research (e.g. regarding the effectiveness of applying virtual and augmented reality techniques for training maintenance personnel, attempting to make maintenance execution predictable).

So, in theory, the CAMPIONE infrastructure supports and accelerates innovations from TRL 3 up till TRL 8. This infrastructure proved to be successful considering the business results already achieved during the first six months of the project. By having the complete maintenance value chain and data enrichment value chain covered by the CAMPIONE participants in an open network environment stimulating and facilitating cooperation, it was assumed innovations would get connected resulting in more integrated solutions implying a fixed data enrichment chain or at least parts thereof. This can be best illustrated by a sample of cases from the CAMPIONE project.

- *Predictive maintenance of an industrial filter (challenges #5,7,7,9).* The strength of having the complete data enrichment cycle present in the innovation project is illustrated by the business results achieved by one of the asset owners in CAMPIONE. Condition monitoring and other IT systems generating lots of data on an industrial filter were in place for many years. Various attempts were made in the past by the very skilled reliability engineers to analyze this data and predict operational failures without success. As part of a pilot in one of the CAMPIONE Living Labs, this experience was enriched by expertise within the CAMPIONE team on statistics and big data modeling, leading to correlations that were not identified before. By combing this ‘data related’ expertise with the ‘technical’ expertise of the asset owner the project team was able in 10 working days to develop and connect a new data model to the internal maintenance planning software, resulting in the prediction of filter failures three weeks in advance, representing a business case of around EUR 100.000,-/yr.
- *Reduction of maintenance cost by CBM (challenges #7,7,10-13).* Business economy knowledge (second half of the data enrichment cycle) can support a sensible implementation of CBM innovations related to sensors and data analytics. CAMPIONE project partners demonstrated innovations regarding new sensors and data analytics software automatically generating alerts in case of anomalies. In case of a single asset a valuable and already sensible innovation business wise. But in case of multiple assets (e.g. 50), the number of alerts that need follow up quickly explodes resulting in many and difficult decisions for the maintenance manager. ‘Simply’ following the alerts quickly led to the conclusion that condition based maintenance is much more expensive than the traditional mix of corrective and preventive maintenance. Only after involving business consultants with expertise on optimizing maintenance and operations planning, the alerts could be fed to a management decision support tool, supporting the maintenance manager to not only optimize maintenance from a technical point of view, but from a business point of view.
- *Reduction of maintenance cost increasing uptime by CBM (challenges #16-21).* The same case illustrated this crucial connection between a technical, innovative solution on the data capturing side and aspects dealing with the maintenance planning and execution.

In the past, the asset owner invested in a state-of-the-art condition monitoring system providing a wealth of data on equipment with traditionally high maintenance costs and/or high impact on operational losses in case of downtime. Expectations were high since the system could generate lots of data and project members were confident that one would be able to reduce cost and improve uptime, leading to a return on investment within 12 months.

However, after 12 months the management review showed a very negative business case, dominated by the investment in CBM and without any improvements. Analysis showed that after 4 months one of the sensors of the CBM system failed and as a result the complete CBM system did not provide any data anymore. Unfortunately, nobody noticed this during the remaining months prior to the review. It was clear that the new CBM solution was not at all connected with the organization and daily processes.

Within CAMPIONE, when looking at the complete data enrichment chain, other project partners completed this chain with expertise, solutions and experience on how to tackle the organizational changes needed to establish the connection between the technical innovation and organization.

Rather quickly it became clear that the origination that would like to adopt the CBM solution needed a transition towards a 'data driven' organization. Obviously, this implied changes regarding processes and IT. However, a pilot project also illustrated that this transition would touch cultural aspects of the organization. Routines that were in place for decades had to change and part of the maintenance staff needed to acquire more IT skills in order to work in a data driven manner.

To achieve buy-in, the CBM implementation was changed such that maintenance staff would also benefit from the CBM data when performing maintenance in the field. The other way around, maintenance staff was appreciated as 'sensor in the field' and involved to capture valuable data to strengthen the data analytics.

The renewed implementation of the CBM innovation resulted in tangible business results and the complete solution is now further developed into a commercial proposition for third parties.

4. CONCLUSIONS

Assuring asset health and integrity on the basis of condition monitoring and prognostic maintenance looks so easy and logical in theory. Unfortunately, it turns out to be very complex and time-consuming in practice.

Nevertheless, CBM/PHM will prevail, simply because it makes so much better sense in many settings. As the technique and, more importantly, the mindset becomes more mainstream, and the percentage condition-based maintenance with double from 5 to 10%, double again from 10 to 20%, and perhaps double once or twice more (but no more than twice). Long before that, we as western society will have managed to fix the data enrichment chain, long overdue though as that may have been.

BIOGRAPHIES

Henk A. Akkermans (1964) is Director of the World Class Maintenance foundation in The Netherlands and Professor of Supply Chain Management at Tilburg University, School of Economics and Management. He holds a Ph.D. in Industrial Engineering from Eindhoven University of Technology (1995), next to a MSc in Information Management (Tilburg University, 1987) and a MA in Japanese Language and Culture (Leiden University, 1998). Henk Akkermans's research addresses the issue of how interorganizational supply chains and networks, where no single party exerts full control, can nevertheless effectively co-ordinate their behavior. His focus is on technical, innovation-driven sectors (such as electronics, aerospace, telecom, process industry and the maritime sector), but also on health care and public infrastructure.

He is fundamentally interested in the interactions between shop floor operations and customer demand, and in the roles that management information and cognitive limitations in decision-making play in this. His interest stretches all the way from new product/service development onto maintenance, repair & overhaul activities. In order to obtain deeper insight in these complex issues, he develops system dynamics simulation models of real-world settings.

Paul van Kempen is Operational Director of the World Class Maintenance foundation in The Netherlands and Director of the Dutch high-tech consulting firm KEC. He (Tilburg, 1968) holds a MSc in Aerospace Engineering (Delft University of Technology, 1992). His career started in aerospace. As project manager he was involved in many upstream projects like the development and manufacturing of the on-board computers for International Space Station (ESA project award in 1997 for 'value European contribution to Space Station') and downstream projects like management of primary rainforests based on satellite radar imagery.

Currently, he is working in various high-tech and innovative domains, with an interest for the full product lifecycle from design up till sustainment and disposal. He is managing various world class maintenance projects on condition based maintenance and big data for process industry, wind parks, aerospace and maritime sector. As project manager he is interested in cross-fertilization opportunities between the CAMPIONE fieldlab for the process industries and other sectors.