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An iterative process to extract value from maintenance projects

Carolina Mejía Niño

Michele Albano*

Erkki Jantunen

Pankaj Sharma

Jaime Campos

David Baglee

*CISTER Research Centre

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Carolina Mejía Niño, Michele Albano*, Erkki Jantunen, Pankaj Sharma, Jaime Campos, David Baglee

*CISTER Research Centre

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: mialb@isep.ipp.pt, pankajtq@gmail.com, jaime.campos@lnu.se

http://www.cister.isep.ipp.pt

Abstract

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An iterative process to extract value from maintenance projects

Carolina Mejía Niño[1], Michele Albano[2], Erkki Jantunen[3], Pankaj Sharma[4], Jaime Campos[5] , David Baglee[6]

[1]Innovation and Technology Department, Mondragon Corporation, Spain

[2]CISTER, ISEP, Polytechnic Institute of Porto, Portugal

[3]VTT Technical Research Centre of Finland, Finland

[4]Dept. of Industrial Systems Engineering and Management, National University of Singapore, Singapore

[5]Department of Informatics, Linnaeus University, Sweden

[6]Faculty of Engineering and Advanced Manufacturing, University of Sunderland, UK

Email: cmejia@mondragoncorporation.com; mialb@isep.ipp.pt; erkki.jantunen@vtt.fi; pankajtq@gmail.com; jaime.campos@lnu.se; david.baglee@sunderland.ac.uk

Abstract Research and development projects are producing novel maintenance strategies and techniques. Anyway, it is not straightforward to transfer results from the lab to the real world, and thus many projects, both internal to a company and in cooperation between the members of a consortium, speculate how to perform this feat, called “exploitation” in the context of European projects. This paper discusses the necessity of novel techniques in modern maintenance, and then introduces a novel approach to the problem of transferring innovation from the lab to the market. The novel approach spawns from the “spiral software development” process and proceeds as a set of iterations that bring together different stakeholders to increase the number of products, techniques and results in general that can survive the end of a research and development project. The approach was applied to a large European project, which is described as use case, and the paper reports on the encouraging results that were attained.

Key words Exploitation, Research Projects, Machine Maintenance, Case Study; Advanced Maintenance.

1. Introduction

Maintenance came to prominence, in the last few year, as an important activity that can benefit companies, instead of a “necessary evil”. In fact, novel approaches such as maintenance-as-a-service (MaaS) and condition based maintenance (CBM) can provide new sources of income and save a great deal of time and money respectively.

Many research activities are currently active all over the world to advance current techniques for maintenance, and are advancing state-of-the-art by great lengths. On the other hand, there is an intrinsic gap between the lab and the real world, since the acceptance by the industry of new techniques depends on the existence of real-world applications of the techniques, which on its part requires the stakeholders to commit to creating applications and thus investing in them. Finally, to invest in a novel technique, the stakeholders must have accepted it, which creates a vicious circle. The problem appears in both research and development projects internal to a company, and to collaboration between multiple stakeholders.

To break this vicious circle, one solution is implemented by the Ecsel Agency of the Horizon 2020 program for European international research projects. Its approach is to finance collaboration between different international partners that end up being stakeholders to the project, with the financing depending on the creation of applications of the techniques in real environments. Anyway, in many cases the lifespan of a research project is not enough to ensure the creation of products, and there is no assurance that a company will provide continuity to the innovation created by a project. Therefore, most research and development project have, among their activities, the study of the potential exploitation of the project’s results.

Current processes to identify exploitable results are either ad-hoc, or based on a very rigid structure, and sub-optimal, since the number and extent of identified exploitable results end up being limited.

Inspired by modern software development processes, this paper proposes a novel approach to the problem of identifying exploitable results in a research and development project. The proposed approach is iterative, and considers to repeat a number of steps for multiple iterations, to grow and refine the list of potential exploitable results periodically, and measure their potential, until reaching convergence over further iterations. In each iteration, different stakeholders are brought together to analyze the exploitation list, with the goal of maximizing the number of products, techniques and results that can survive the end of a research and development project. The approach was applied to a large European project on maintenance called MANTIS (Albano, Papa, Jantunen, & Zurutuza, 2018), and the paper reports on the results from the exploitation point of view.

The rest of the paper provides background information in section 2 on the potential for advanced maintenance. Section 3 describes the MANTIS project, which aims at pushing forward the state-of-the-art of collaborative and proactive maintenance, and advanced maintenance in general. Section 4 describes and provides motivation for the proposed iterative process, and Section 5 describes how it was applied to the MANTIS project, and the results it provided. Finally, Section 6 discusses the results and provides a preliminary comparison to different approaches applied in similar projects, and concludes the paper.

2. Applying Maintenance advances in the Real World

This section discusses the importance of maintenance, and in particular starts from an analysis of current maintenance practices and their importance for the industry. Thus, it motivates the execution of research and development projects to push forward innovations in maintenance that can provide value.

Later on, the section delves into details regarding advanced maintenance practices. It turns out that many activities are pushing forward the state-of-the-art, and thus we can be on a turning point for maintenance.

Anyway, extracting exploitable results from research and development projects is not trivial. The last subsection considers software development life cycles, which are used as inspiration to study novel processes to bring novel products, strategies, and techniques for advanced maintenance from the lab to real-world pilots, to production environments such as the shop floor, up to the market.

2.1. The Value of Advanced Maintenance Practices

The Operation and Maintenance (O&M) phase in a machine's life cycle requires large expenses and more efforts than the installation (construction) phase, because in its long useful life, any accident of an asset can result in catastrophic damage to the entire company. Maintenance has gained lot of importance as the technical complexity of the machines has increased. Maintenance is defined as all technical and managerial actions taken during usage period to maintain or restore the required functionality of a product or an asset (Shin and Jun, 2015). Maintenance has been classified by various researchers and practitioners in the past. Most widely acknowledged classification defines maintenance as per the instant that it is executed, i.e., whether after the breakdown (corrective maintenance) or before the breakdown (predictive maintenance). Predictive maintenance concerns with the prediction of degradation process of the product, which is based on the assumption that most abnormalities do not occur suddenly, and usually there are some kinds of degradation process from normal states to abnormalities (Fu et al., 2004). This degradation process is characterized by certain responses that the machine provides to the sensors. These changes in the measured parameters can indicate that the machine is moving towards a possible failure in the future. The method can be used to reduce the uncertainty of maintenance activities and is carried out according to the requirements indicated by the equipment condition (Peng et al., 2010). A large number of advanced maintenance methods are being used today as the cost of failure is becoming increasingly prohibitive or simply catastrophic.

The need for implementing advanced maintenance strategies is no more a choice. Companies have no option but to implement them in order to remain competitive. These advanced maintenance strategies like CBM give prior warning of impending failure and increase the probability of accurately predicting the kind of failure. Some other machines, where the personnel safety is at stake, have CBM as the only viable option. Modern maintenance practices also enable the maintenance providers to better plan their resources. Resources like skilled manpower, spare parts, specialized tools, etc. can be placed at pre-planned locations to both optimize their usage as well as make them available in the shortest possible time to reduce administrative delays.

Implementation of modern maintenance methods was a costly exercise a few decades back. However, the reducing costs of sensors and computational resources, coupled with increase in computational power and decrease in the size of the sensors has made it a more technically and economically viable approach. It can lead to a decrease in the maintenance budget (Bengtsson, 2004). Modern advanced maintenance practices have the capability to optimize the production process and improve its productivity. It provides the ability for the system to continue operating as long as it is performing within predefined performance limits (Prajapati et al., 2012).

2.2. Advanced maintenance in real-world scenarios

Application of modern maintenance methods in real-world scenarios is not a very easy process. There are a number of technical issues that inhibit the free use of such advanced maintenance practices. First and foremost, the organizations must select the assets that require condition monitoring. CBM is supposed to be applied where appropriate, not as an overall policy as some techniques are expensive and it would not be cost effective to implement them everywhere (Starr, 1997). This selection should be based on technical and economic feasibility analysis. The machine should be critical enough to warrant large investments in a CBM system. Also, the selected asset must be such that it has parameters that matter for its functioning and that can be monitored with sensors. Most CBM implementations fail because the organizations start to measure 'what can be measured' rather than 'what should be measured'. The first challenge is to obtain effective features from many candidate features to reflect health degradation propagation in the whole life of machines (Yu, 2012). In machine-learning-based defect detection, the accuracy of prognostics and diagnostics models subsequently dependents on the sensitivity of the features used to estimate the condition and propagation of the defects. Therefore, it is critical to devise a systematic scheme that is capable of selecting the most representative features for current machine health states (Yu, 2012; Malhi et al., 2004). The complexity of selecting a suitable measure can be gauged from an example. Some research shows that the use of acoustic signal is better than vibration signal due to its sensitivity and accuracy (Al-Ghamd & Mba, 2006; Baydar & Ball, 2001; Tandon et al., 2007). However, in practice, the application of acoustic signal may not be appropriate due to the significant effects of noise (unwanted signals) from other equipment. In addition, alternative sources of information are important contributors to health monitoring. These sources include the OEM, ISO standards, experience of the workers, etc. The new challenge is to find ways to use these alternative sources of information in order to achieve better monitoring of assets and correct decision making (Ahmad and Kamaruddin, 2012).

Choice of a correct sensor with appropriate sensitivity is an important step. Selecting a costlier sensor when it is not required will make the CBM system unnecessarily expensive which will not be able to justify the cost-benefit argument. On the other hand, selecting a cheaper non-sensitive sensor when the data being measured has minute variations that require high quality sensor can also upset the cost-benefit balance as the diagnosis of the fault may not be correct. Other ICT challenges include sensor data quality related to gathering frequency, noise, and level of details of sensor data, data availability, wireless communication problem, frequency of diagnostics and prognostics, and so on (Shin and Jun, 2015). In addition, the technologies and technical methods for the CBM approach are still in their infancy. It means that there are some limitations in ensuring the accuracy of diagnostics and prognostics (Shin and Jun, 2015). Numerous different techniques and technologies exist but choosing the correct one, or even remembering to make the decision in due time can be a troublesome activity which can put an entire implementation effort at risk (Bengtsson, 2007).

The condition monitoring practice is based on the fact that a sensor is used to measure a parameter. When the value of the measured parameter crosses a pre-determined threshold, suitable maintenance actions are initiated. In practice however, deciding on the threshold is a complex process. The failure of each equipment may be defined and classified in different ways. Some organizations consider failure as the physical event such as a breakage that stops production. The machine stops to function as a result of such a failure. In some other cases, a functional failure may occur which results in the final product of the machine to have quality flaws but the machine may continue to work. It is necessary for the organizations to determine threshold based on their requirements. The definition and determination of failure limits should be considered from both the entire machining process perspective (system/sub-system) and the overall output of the system (e.g., product quality characteristics) (Ahmad and Kamaruddin, 2012).

Analysing waveform data is an intricate process because of noise effects, which are unwanted signals generated by other equipment. Noise must be minimised or eliminated from the data (Ahmad and Kamaruddin, 2012). Some noise also gets generated due to the transmission medium. It is necessary to identify which data transmission type (wire or wireless) is effective in terms of cost and reliability with least noise (Shin and Jun, 2015). Large data sets are required for effective data analysis and modelling. This collected data needs to be cleaned before any analysis. This is a complex task, especially for waveform-type data. Newly commissioned systems have no historical data. Even the OEM is not aware of the failure patters or failure rates. In such cases, it is not possible to identify the trends or failure thresholds. Such situations are no-data situations (Si et al., 2011). The quantity and completeness of data are insufficient to fit the full statistical models. Hence, it may be a better choice to develop physics-based models with the help of subjective expert knowledge from design and manufacturing (Si et al., 2011).

2.3. Software Development Life Cycles

In the Information and communication technology (ICTs) projects, there is a need to have an information technology approach for its project management phases, i.e. the use of a software development life cycle (SDLC). Brewer and Dittman, (2013) highlight different project variances between disciplines, such as requirement changes, sources of changes, requirements specification, etc., where requirements changes are slow and incremental for engineering while rapid and unplanned for information technology projects, for instance. The sources of changes are for engineering known and predictable while for ICTs projects many times unknown. Requirements are other factors that are different, namely for engineering it is an explicit plan while for ICTs projects normally ambiguous (Brewer & Dittman, 2013).

The SDLC approaches, such as the waterfall model, highlight the processes, namely the different phases of a system development process. Some reports highlight the death of the Waterfall Life-cycle Model, which are greatly exaggerated (Laplante and Neill, 2004), since it forms essential practices and might be seen as the pillars of the area of the methodologies in the area of system development. Hence, a methodology is defined as a system of methods used in a particular area of study or activity (Kuosa, 2016). The waterfall model is a sequential progressive process, whose development is a steadily downwards, i.e. resembling a waterfall through its stages. In the waterfall model, the requirements are evident before the next step of design is started. The testing of the code is done when the application is completely developed (Leau et al. 2012). This can be compared with the so-called V- model, which characterises a different SDLC process can be reflected as an extension of the waterfall model. The difference is that as an alternative of progressing linearly in its process paces, it is curved upwards after the programming phases and is, namely, the reason it is called the V – model, i.e. because it forms a V shape. Another well-known approach is the Agile methodology that emphases adaptive teams that are capable of reacting quickly to the changing requirements' specifications. In addition, it also accepts requirements update late in development phases.

Hence, the software is typically delivered frequently, i.e. within weeks instead of months. The key principle of the approach is customer satisfaction by providing rapid and constant delivery of its software applications.

However, to design and develop ICT applications for the domain of interest there is a need for a detailed and comprehensive understanding of the different algorithms suitable for analysing the different parts of the equipment. In other words, there is a need for an approach that considers the key aspects of the domain.

Still, organisations that are developing software applications are challenged with the difficulties of choosing the relevant SDLC or methodology and included methods (Balaji and Murugaiyan, 2012). The different aspects of the SDLC models among other are documented in Ruparelia (2010). New development life cycles have been suggested with the aim to increase the customer satisfaction (Kumar et al. 2013). In the suggested model such features as the understanding of requirements, costs, risk involvement, etc., are highlighted. The proposed SDLC plan attempts to achieve the objectives of an ICT project through the illustration of the requirements in a prototype to the clients to discover deviations from the planned order as well as to estimate the costs, schedule and work time invested more precisely, among other aspects. Another work that discusses improvements of the existent agile developments methods and traditional SDLC is (Leau et al., 2012). The different aspects of SDLC, such as the Waterfall model on large projects, are discussed in Petersen et al. (2009). A comparison between different SDLC methods in different scenarios are presented in Mishra and Dubey (2013). In brief, there is a need of a SDLC or project manamement methodology that contemplates the important aspects of the specific domain it inteds to be implemented in, i.e. that is flexible enough to fit into the required aspects of the particular domain.

It is, however, recommended that before deciding the model to be used it is essential to understand certain crucial aspects, namely how stable the requirements are, who are the end users of the system, the size of the project, and where the project teams are located, etc (Balaji and Murugaiyan, 2012). In the case that the requirements are volatile, i.e. that they frequently change, and it is about a smaller projects where there is a need to deliver the product in short time which includes skilled resources, then the Agile methods are of preference. In the case that the requirements are stable as well as precise, and it involves a larger project, then it is proper to choose approaches similar to the Waterfall model. In addition, in the case that the requirement specifications changes in a larger project where proper validation needs to be taken at each stage, as well as to have testers to be part of the project in early phases of the development process, then the approaches alike the V-model are proper.

In addition, aspects of the Rational unified process (RUP) and the Spiral methodology are discussed in (Mateen et al., 2016). The authors propose a new methodology for the development of software applications that overcomes the weakness of the waterfall, agile, spiral, RUP and RAD development life cycle. The life cycle models are complex because they involves rigorous processes and there is no “silver bullet" in software development methodologies (Zykov, 2016). In addition, the Agile methodologies entail distinct methods and a high level of discipline; else, they can end in a low-quality software application.

Consequently, the business analysis, as well as other aspects of the development life cycle, becomes crucial to evaluate in any ICT project. It results in a need of a project methodology or SDLC that consider among other aspects the essential aspects of the specific domain to understand and develop project management processes in order to be successful in the ICTs implementation of the industrial maintenance area.

3. The MANTIS project

The MANTIS Project (Albano, Papa, Jantunen, & Zurutuza, 2018) was a European initiative focused on innovation on advanced maintenance practices. The project was alive in the period 2015-2018, and studied many sides of maintenance, spanning from sensors and Cyber Physical Systems to collect data on the machines and the shop floor, to the communication middleware (Albano, Sharma, Campos, & Jantunen, 2018) to transport the data to the cloud in an efficient and secure manner, to the machine learning techniques that can be used to provide CBM to the machines using the collected data, to advanced data visualization systems to help the technicians make sense of the high volume of information that is collected in the machines and produced by the machine learning algorithms.

The MANTIS Project was driven by its real-life pilots. All studied techniques were applied to machines, and had to be validated as integrated in production environments. Many important industrial fields were tackled by the project, such as automotive, energy production and manufacturing. In this sense, the pilots are the testing ground for the innovative functionalities of the proactive maintenance service platform architecture and for its future exploitation in the industrial world.

Among the results of the project, there is the reference architecture for advanced maintenance techniques. This is the underlying architecture of the service platforms that were implemented in the different pilots, and is based on three tiers. The Edge Tier is on the production floors, and close to the machines in general, and its goals are to collect data from the environment and the machines; to preprocess the data; to transport the data to the cloud. The Enterprise Tier is close to the customer and/or to the personnel that operates and maintain the machines, and it allows for the visualization of the data, analyze it from a technical and economic points of view. It is also able to issue control commands to the other tiers. Finally, between these two tiers there is the Platform tier, which receives the streams of telemetry data from the Edge tier, and the control commands coming from the Enterprise tier. This tier consolidates the data flows by means of external data; analyzes the data by means of machine learning techniques; offers non-domain specific services such as data query and analytics.

The MANTIS Project was able to investigate a large number of matters related to maintenance. Anyway, the benefits in the real world depend on a process to extract the best results, corroborate them by integration in different scenarios, and package them for future usage. This process is called exploitation, and it was of the utmost importance to maximize the benefits of the MANTIS Project to the industry. Given the large size of the MANTIS Project, the exploitation process was target to innovation to be able to cope with the task at hand.

4. An Iterative process for defining exploitable results

Exploitation activities are characterized by identification, experimentation, characterization and investigation, which can result in new knowledge. This new knowledge or exploitable results, can be applied as an internal institution asset for new research projects, as such for the creation of new goods (products or services). The speed, cost efficiency and successfulness in the market of the exploitable results development depend on the extent to which the exploitation activities are completed in the project (Lantos, 2006).

The usual approach to exploitation is based on the creation of a list of potential results at some time in the project, and a refining at the end of the project. This traditional approach is similar to the waterfall SDLC, but it can be sub-optimal for large projects whose complexity does not allow for a clear vision of the whole project at once.

A novel approach can be based on an adaptive exploration/exploitation tradeoff that helps to identify and get the exploitable results to the market in an iterative and retrofitting approach.

The methodology follows a planned process of transferring the successful results of the project to useful exploitable results, based on diverse innovation processes and management tools such as Effectuation, Exploit, FoF-Impact, Value Chain, Innovation Radar, etc., giving a constant interaction and feedback all over the course of the project.

Figure 1 Iterative Exploitation Methodology

The methodology, represented in Figure 1, benefits from constant external interaction, getting assistance and feedback redefining the means and goals of the project. Corporations must identify continuously new opportunities, while devising strategies for their outcomes in diverse industries, helping on the definition or redefinition of the strategic vision, the needs of the market and the exploitable results configuration. The identification of the opportunity precedes to the necessity of acting on the opportunity through an iterative and heuristic process.

The methodology proposed (Figure 1) is a structured process formed by diverse phases and divided into three main blocks or processes:

1. Idea generation. Recognition of objectives, capacities, external threats and possible exploitable results.
2. Conversion contrasting a set of means and possible exploitable results within the project´s partners, identifying who would own the outcomes and how they would be further exploit.
3. Evaluation of the exploitable results, reconfiguring the means and goals of the project, examining the best ways to protect the outcomes, and designing guidelines to face the risk market hazards.

The proposed methodology considers to repeat a number and specific stages to strength and redefine the exploitable results as well as the way to protect and further exploit them. For each iteration a number of stakeholders are involved, bringing together diverse market and businesses perspectives, encouraging their interaction, and maximizing the project´s novel products and services. For example, Figure 2 represent the process when we consider two stages, where novel inputs from the industry forces to repeat the prioritization and evaluation, and leaves it open to further iterations.

Figure 2 Repetition of stages in defining exploitable results

5. Results of the iterative process in a case study

The approach presented in Section 4 was applied in an ECSEL predictive maintenance project called MANTIS (see Section 3), whose implementation is represented in Figure 3 and comprised the execution of six main workshops in a three-years period:

- 1st and 2nd workshop had the goal to advance in the search of servitization business models around predictive/proactive maintenance solutions. The ultimate goal was to establish a baseline for consortium members to start an early definition of their new business model and start identifying the possible exploitable results.
- 3rd and 4th workshop had the objective of characterizing the potential exploitable results, analyzing the possible ownership and exploitation claims.
- 5th workshop first exploitable results prioritization, identifying the most relevant outcomes for each institution.
- 6th workshop aim to identify, evaluate and respond to the critical market entry hazards of the exploitable results.

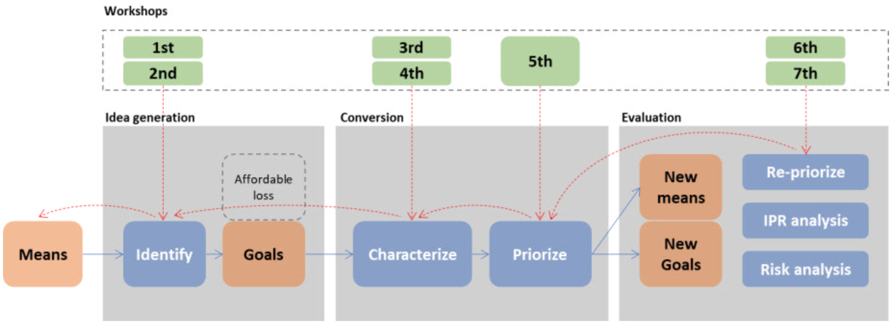

Figure 3 Iterative process for the exploitable results definition

- 7th workshop aim to recheck the exploitability, ownership, prioritization and intellectual property protection status of each of the reconfigured results.

The characterization of the iterative process for the exploitable results definition improved the consortium commitment in the exploitation process, providing constant interaction and feedback all over the project course. The workshop method revealed its effectiveness since it is easier to transmit a message with the goals and purpose of the survey, together with the data collection of the answers provided by the participating partners.

As part of the evolution and the iterative process, the MANTIS consortium identified 97 exploitable results at the middle of the project, readjusting to 76 in the last months. Some of the eliminated items couldn´t been tested due to the lack of base line data, they need to be verified in other uses in order that the entities are entirely sure to exploit them or they don´t fulfil the criteria for specific exploitation.

6. Discussion and conclusions

The outputs generated during a project can create an important impact during and after the project´s lifecycle. The further exploitation of the results, such as creating and marketing a product or process, or creating and providing a service, or even for internal usage activities, reveal the external impact of the project.

On preliminary industry 4. 0 projects, the exploitable results were identified at the beginning of the project, and weren´t exploit/used by the partners after the project´s lifecycle. The number of identified exploitable results differ from type of project and kind of products, MANTIS had a high number of exploitable results (estimated at 76) that can be transferred into 13 successful business cases taking into account the industrial and software partners. In previous projects of size comparable to MANTIS, a mean of 12 exploitable results were identified, and they had less impact in the entities´ business cases or could not be used afterwards.

In other projects, the exploitation process relied on a theoretical approach from the first months, and did not take into account the industrial process feedback to identify new exploitable results or to eliminate the ones that will not be exploited.

Future work will perform a final inventory of exploited results one year after the end of the MANTIS project, to provide a final evaluation. Anyway, the current number (76) is already the result of multiple iterations and refinement, and most exploitable results are already employed in production environment, thus there will probably be no surprises. Moreover, we plan to perform a thorough comparison between older projects that had no specific and explicit exploitation activities (work packages), traditional projects with a waterfall/ad-hoc exploitation process, and MANTIS and future project that adopt our proposed iterative process.

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Authors' Biography

	**Carolina Mejía Niño** **Carolina Mejía Niño** is an Innovation Technician in the Innovation and Technology Department of MONDRAGON Corporation, Spain. Her research focuses on the development of an accurate and complete exploitation methodology, helping to translate innovation results to market for Industry 4.0, Smart Cities, Raw Material and Big Data projects. The Innovation and Technology Department of MONDRAGON Corporation aim to facilitate and promote the innovation activity of the more than 100 cooperatives related to the group. Carolina received her degree from the Universidad de los Andes, Colombia, and her masters from Universitat Politécnica de Catalunya and Mondragon Unibersitatea. She has been a researcher at the UIA-CIMES Programme and participated in Proactive Maintenance and Smart Cities European projects.
	**Michele Albano** **Dr Michele Albano** is a Research Associate in the CISTER Research Unit of the Polytechnic of Porto, Portugal, and Adjunct Professor at Polytechnic Institute of Cavado e Ave, Portugal. His research focuses on Cyber Physical Systems and Communication Middleware, in particular for the application areas of industrial maintenance, smart grids, and vehicular networks. Michele received his degrees from the University of Pisa, Italy, and he was researcher at Universidad de Malaga, Spain, at University of New York at Stony Brook, and at Instituto de Telecomunicações in Aveiro, Portugal. He has been involved in more than 10 international research projects, and he is currently active in the context of European projects Productive 4.0 and MANTIS, and in the latter he is Work Package leader for WP3 "Smart sensing and data acquisition technologies" and for WP8 "Dissemination of knowledge and exploitation". His works have been published in more than 70 international conferences and journals, and he is the editor of the book *The MANTIS book: Cyber Physical System Based Proactive Maintenance*. Since 2015, Michele is the Editor in Chief for the *Journal of Green Engineering, River Publishers*.

	**Erkki Jantunen** **Dr Erkki Jantunen** is principal scientist at VTT Technical Research Centre of Finland. He has been a member of the editorial board and acted as a reviewer of a number of scientific journals. He has been project manager of many research projects. He is the author and co-author of several books and more than 150 research papers in the field of condition monitoring, diagnosis and prognosis and e-maintenance. He has a position as a visiting professor at the University of Sunderland.
	**Pankaj Sharma** **Pankaj Sharma** is a doctorte from Indian Institute of Technology Delhi, India. His PhD thesis is in the field of Spare Parts forecasting and Selective Maintenance Optimization. He is an MTech from the same Institute in Industrial Engineering. His research interests are in Maintenance Strategy Development, Supply Chain Management and Logistics. He had participated in project e-Mari at VTT Finland as an inter-university exchange student. He is currently working as a Research Fellow with the National University Singapore.
	**Jaime Campos** **Dr. Jaime Campos** is an associate professor at the Department of Informatics, Linnaeus University, Sweden. His main research interests include the Information and Communication Technologies in the industrial domain, mainly in asset management.
	**David Baglee** **Dr David Baglee** is a Reader in Advanced Maintenance at the University of Sunderland UK, a Visiting Professor of Operations and Maintenance at the University of Lulea Sweden and a Visiting Associate Research Professor at the University of Maryland USA. His research interests include the use of advanced maintenance techniques, Industry 4 and big data analyses to support maintenance strategy development within a range of industries.