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Risk driven engineering of Prognostics and Health Management systems in manufacturing

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Abstract: The paper aims at discussing a risk driven engineering approach to support the development of prognostics and health management systems in manufacturing. Through selected cases, the paper is shedding the light on the gaps existing between the current technological potentials available from prognostics and health management, and their engineering in real industrial contexts coping with the constraints and opportunities of existing ICT and machine infrastructure. The use of safety and reliability analysis techniques, within the proposed methodology, supports the development in accordance with the needs from production and maintenance processes operated in a factory.

Keywords: Risk based methodologies, Prognostics and Health Management, Systems engineering.

1. INTRODUCTION

Maintenance management has changed in the last decades thanks to the development of new ICT solutions. From a pure management perspective, Computerized Maintenance Management System (CMMS) has contributed to enhance the control of maintenance activities (Fumagalli et al., 2009). Further on, new ICT solutions have enabled the improvement of shop floor capabilities, enlarging the possibilities to implement Condition Based Maintenance (CBM) according to the well-known E-maintenance concept (Muller et al., 2008). Indeed, the availability of new sensors – thanks to the progress in Micro Electro-Mechanical Systems and the pervasive embedment of consolidated technological components in manufacturing, e.g. RFID (Garetti et al., 2007) –, the improvement of computational capability – spread through embedded devices, empowering the distributed control and monitoring of production plants and machineries (Fumagalli et al., 2011) –, and the larger flexibility of ICT systems – enhanced by the maturity of some technological paradigm, as Service Oriented Architecture (Lastra and Delamer, 2006) – have all contributed to create a favorable context where building solutions for condition monitoring is facilitated. During the next years, advanced technologies, including Internet of Things, Cloud Computing and Cyber-Physical Systems, will also play a role for the technology based-enhancement of maintenance activities, leading to a further exploitation of the big data (Lee et al., 2013). The E-maintenance concept is then undergoing a transformation, based on multiple technologies already in the market. A new era of CBM is then upcoming, thanks to the reduction of the implementation costs of technological applications, and the technology readiness reached by new components. Indeed, the shift towards a Predictive Manufacturing paradigm will be facilitated by full exploitation of techniques and methods, implementing Prognosis and Health Management (PHM) by means of advanced technologies (Lee et al., 2014). Overall, technology development is opening new opportunities for technology based-enhancement of maintenance activities. But this is not sufficient for developing advanced CBM and PHM systems in industrial context: while maintenance big data are potentially available on the shop floor, capability to properly analyze them for CBM/PHM programs is not yet available "on the shelf" (TeSeM, 2012).

In our experience, two problems still exist: the former relates to the adequate identification of PHM components, to create values for contributing to the competitiveness of a factory through technology-enhanced maintenance services; the latter is reflected by the needs to specify structure and functionality of PHM components, focusing on their operational features while hiding the technology dependent specification. The two problems are related, and they are both required to deploy advanced CBM and PHM systems in manufacturing.

Literature is still at its infancy on providing solutions for the two problems. Regarding value creation, the enhancement of maintenance methodologies through value orientation is nowadays observed: it is worth citing methodologies such as business-centred maintenance (Kelly, 1997), value-driven maintenance planning (Rosqvist et al., 2009) and value-driven engineering of E-maintenance platforms (Macchi et al., 2014). Regarding the specification of PHM systems, many papers are centering discussion on models and techniques for PHM with some concern also for manufacturing while a systematic approach is still missing: independently of specific models or techniques, this approach

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would help systems engineering, after target values for business are defined. In this regard, we consider risk as relevant concept: a risk driven engineering of PHM systems would help focusing the development efforts and enabling the capability to achieve the value creation as required at business level.

The paper presents the risk driven engineering approach (section 3) after a brief state of the art on PHM and on risk based methodologies (section 2); afterwards, two case studies illustrate this approach in selected manufacturing projects, within given business and ICT constraints (section 4). Remarks for future research conclude the paper (section 5).

2. STATE OF THE ART

2.1 PHM for advanced maintenance systems

PHM is going to have a primary role in advanced strategies for maintenance systems in the next years. Under the term of PHM the body of knowledge is nowadays considered a kind of engineering discipline (Petch, 2008; Cheng et al. 2010). It entails: i) methods and technologies to assess the reliability of an asset in its life-cycle conditions, and to mitigate system risks (Haddad et. al, 2012); ii) skills required along the entire process, from data collection to analysis and decision-making (Bird et al., 2014); iii) ICT development specifically applied in the maintenance function. A new technological wave based on advanced computing and Cyber-Physical Systems is then expected for the future, including PHM solutions as relevant component to provide technology-enhanced maintenance services (Lee et al., 2014). In their development, PHM solutions will require to blend skills and capacities relating to domain-specific knowledge (system physical modeling, life cycle analysis,...), technical expertise (data modeling, analytics, ...), ICT and organizational matters (software/hardware, human factors,…), business needs (cost/benefit analysis,…). Therefore, the development methodologies should evolve to approaches that will include domain-specific and systems engineering capabilities.

2.2 Risk based methodologies

Risk driven engineering approach requires a combination of qualitative and quantitative methodologies, for hazard identification and risk assessment. Most of them are well known because their first applications date back to the ‘60s, but they are unsurpassed for hazard identification, reliability assessment and risk prioritization in complex systems. Khan and Abbasi (1998) present a state-of-the-art review of the available techniques and methodologies for carrying out risk analysis in the process industry which is still valid today. For this paper, HAZOP, FMECA (Failure Modes Effects and Criticality Analysis) and FTA (Fault Tree Analysis) are mostly interesting.

Hazard and operability (HAZOP) methodology is a Process Hazard Analysis (PHA) technique used worldwide for studying the hazards of a system and its operability matters, by exploring cause and effects of any deviations from design conditions. Initially developed for a systematic hazard identification in chemical processes (Lawley, 1974), it is based on experts knowledge and a set of guidewords which pilot a structured brainstorming session (Kletz, 2001). Usually HAZOP studies generate only qualitative results, i.e. hazard identification, safeguards and team recommendations, but a quantitative risk assessment (QRA) based on team experience can transform this study in a semi-quantitative one (Rausand, 2013). The most accurate and recent literature review about HAZOP methodology and its evolution towards “automating HAZOP” is due to Dunjó and coauthors (2010), who show the effort made by many researchers to overcome the limitations (time-consuming, labor intensive) of HAZOP analysis. More recently some authors proposed a dynamic HAZOP-based approach to continuous risk assessment obtained by the integration of real time data, received from the distributed control system (DCS), about the state of operation of each component and process variables values (Compagno et al., 2012). Failure Modes Effects (and Criticality) Analysis (FMECA) is also an inductive semi-quantitative technique born in early ’50s when aerospace industry (MIL-STD-1629A) afforded reliability matters. Its application is quite similar to HAZOP but the brainstorming sessions are piloted by failure modes and the most relevant result is a Risk Priority Number, based on scales for occurrence, severity and detection. The most recent studies on FMEA regards the integration with quantitative techniques, such as Fault Tree Analysis, and artificial intelligence techniques, i.e. fuzzy systems, Bayesian method, Petri nets, etc. (Yeh & Chen, 2014; Sadeghi et al., 2014). This is opening new opportunities towards the integration with real data from the control system. Fault Tree Analysis (FTA) is the most used quantitative and deductive technique for the calculation of potential occurrence of the Top Event from elementary (basic) events which typically are the failure of a component, the deviation of a variable value from set point or a human error. In its first applications, only boolean static gate and rigid hypotheses about constant failure rates were considered but today dynamic fault trees, also using Weibull distributed failure (Chiacchio et al., 2013), solved both using analytical or simulative approach (Boudali et al., 2009; Chiacchio et al., 2011), represent the state-of-the-art. Fault Trees can also integrate real time information derived from the DCS (e.g. unavailable equipment, for failure or maintenance causes) to assess a more realistic probability of occurrence of the Top Event (Compagno et al., 2008). This ability to integrate real data from the control system makes these methodologies extremely relevant for the development of risk based prognostics and health management systems.

3. THE PROPOSED APPROACH

3.1 From business to technology system modeling

The application of PHM to manufacturing processes and equipment management is a lever to develop maintenance management from preventive maintenance to performance-based maintenance, and finally to proactive maintenance, with many benefits as product and process quality/reliability, and reduction of line stoppages, maintenance/spares costs.

The most effective way to achieve these benefits requires a deep understanding of maintenance process needs: this motivates a value-driven approach (Macchi et al., 2014) for better linking maintenance to business, with subsequent better ICT resource configuration and management. Value-driven engineering (VDE) is in general defined as "a proven management technique used to identify alternative approaches for satisfying the requirements of a project while lowering costs and ensuring technical competence in performance" (Acharya et al., 1995) and it could be seen as a systematic method for analysing and improving the value of product, design, system, service or process to increase customer satisfaction and investment value (Ojala, 2004). Applying these concepts to the PHM system engineering, a VDE can help identifying the ICT-based "services" mostly valuable to deploy PHM; thus, maintenance processes should drive development, leading to a recommended set of required "services" based on the expected values of the stakeholders in a given business case (see Macchi et al. (2014), for details on the concept of "services"). After the business case is known, services are not yet specified: this requires other steps. Thus, the overall approach, assumed by the authors, presents a multi-layer view of PHM system engineering, inspired by the model-driven service engineering (MDSE) proposed by Chen et al. (2012), and its further application in the maintenance context by Macchi et al. (2014) (briefly shown in table 1).

Layer	Scope
Business system modeling	This layer aims at gathering the needs from maintenance processes, with the purpose to drive recommendation of services to be developed, aligning with the target values of relevant stakeholders.
Technology Independent Modeling	This layer aims at identifying the most recommended services; it also provides the specifications of structure and functionality of the services, focusing on the operational details (hiding technological specifications).
Technology Specific Modeling	This layer aims at selecting the technological components (i.e. the ICT resources) required to develop the above specified services; structure and functionality of the technology specific development is also defined, before the implementation.

Table 1 – Multi-layer view of the overall approach (derived from Macchi et al. (2014))

3.2 The risk driven engineering approach

The paper focuses on the steps envisioned at second layer, starting from the set of services recommended based on target values. According to the multi-layered approach, in fact, VDE is introducing to the next steps of PHM system engineering; for these further steps, the proposition of the paper is that a Risk Driven Engineering (RDE) would help the system engineer to configure structure and functionality of the PHM system under development, assuming a more operational perspective; as it is a follow up of previous steps, it provides also detailed modeling views, leading to a full specification of the characteristics of the maintenance intelligence to be implemented through PHM capabilities. The description and the scope of each phase is synthesized in Table 2. Then, specific risk analysis methodologies can be used in compliancy with the scope of the different phases.

Phase	Description and Scope
Planning	Definition of the operational aim of the PHM system and knowledge improvement in regard to the monitored system. This step aims at identifying which processes / equipment could benefit the most from the PHM system; this is done by making a functioning / process analysis, and by defining the system / sub-systems / components and variables to be monitored, and the type of control (discrete, continuous, condition based, …).
Designing	Risk based specification of the PHM service requirements. This step aims at designing the PHM services to meet the needs identified at planning phase; this is achieved by executing a risk and process operability analysis of the PHM system, to identify critical system / sub-systems / components and prioritize them.
Building	Selection of the algorithms and techniques for the most efficient services. This step aims at identifying, within a library of algorithms and available techniques, the most efficient ones to treat with the selected variables, in order to generate the highest value-added service.

Table 2 – RDE for maintenance technology independent modeling

For Planning phase, a preliminary HAZOP study (for process plant) or a Project FMEA (for manufacturing plant), integrated by a preliminary Quantitative Risk Assessment based on experts knowledge and predefined scale, help improving the knowledge about equipment/process (i.e. the monitored system) and the related relevant variables. A preliminary list of anomalies/failures, causes and effects, and their association with a Risk Priority Number allows the "traditional" risk rating of system/sub-systems/components. The variables that can be measured for monitoring the system and the type of monitoring system (discrete, continuous, condition based, …) finally allows the definition of one or more recommendations for improving the detectability.

In the Design phase, the design choices for detectability are specified. A project of PHM system can be subjected to a risk and process functioning/operability analysis to identify critical system/sub-systems/components. In order to obtain information useful for the next phase of building, the integration of HAZOP or FMEA with a FTA, allows to select significant anomalies and failures which require attention (Top Events), and to quantify the risk through different methods (Top Event Occurrence and Rate of Failure, Importance measures of Basic Events, the assessment of the efficacy of a control system typology compared with another in reducing Top Event probability).

In the Building phase, a library of available algorithms and techniques would allow the selection of the most efficient one or ones to treat with the selected variables in order to finally generate the value-added service, i.e. data-driven prognostics (Regression, Neural Networks, Gaussian process regression, Bayesian updates, Relevance vector machines, …), model-driven prognostics (Population growth models as Arrhenius, Paris, Eyring, etc., Coffin-Manson Mechanical crack growth model, …) or hybrid systems prognostics. It is opportune to remark that such a library would constitute the PHM domain-specific knowledge base for assessing the asset life-cycle conditions of the monitored system; besides, the integration of the selected algorithms and techniques with the developed models will open new opportunities towards their dynamic use (Compagno et al., 2012) with real data from the control system (Compagno et al., 2008), further processed by the PHM system.

4. INDUSTRIAL CASES

4.1 Company Alfa

The Company Alfa is a manufacturer which treats fresh lemon peels to obtain thickeners for the food industry and for healthcare application (natural polymers). The production process cycle includes the use of both fresh and dried peels, which are firstly washed, then grinded with a hammer mill and washed again. An hydrolysis treatment in well-defined conditions of pH, temperature, agitation level, reaction time and presence of an inorganic acid is executed in a battery of six reactors. The solid/liquid separation obtained through decanters and centrifuges and the following filtration by a filter press has the ultimate aim to obtain a liquid that is totally free of suspended solids and which can be concentrated using evaporators. In fact, the process of precipitation, regardless of the specific application, must generate pure solids which have a purity in accordance with the standards of production and sale.

The risk based methodologies were used in this case in each phase of the PHM system engineering. A preliminary HAZOP study was executed, in order to identify processes and equipment which could benefit the most from the implementation of a PHM system (Planning phase). To this end, guidewords allowed the identification of the relevant variables (Flow, Pressure, Temperature) for each equipment in a “node” (according to HAZOP): this enabled to share the knowledge of the system through a systematic analysis. For example, starting from guideword “No Flow”, causes were identified related to the absence of water or other process fluids, or to pumps failure. Moreover, it emerged that “No Flow” is clearly a relevant deviation, as the production process takes place in a continuous cycle: the fluid transport equipment, particularly the pumps, have the highest relevance to guarantee the productivity and product quality.

In the Designing phase, the QRA of HAZOP study also allowed the risk prioritization in order to define Top Events for a detailed risk quantification. Indeed, the results of the FTA were the probability of Top Events but, more important, the Importance measure of Basic Events and Cut Sets, which allow to edit a list of components, variables and events which require to be monitored (see the example in Table 3).

A detailed analysis of the failure modes of the pumps showed a need to move to a predictive maintenance strategy through the use of advanced diagnostic systems: the pumps required the continuous monitoring of bearings and vibration, as these resulted the most critical issues.

In the Building phase two technological solutions based on standardized methods (Shock Pulse Method, for rotating rolling bearings, and ISO 10816, for vibration severity) were eventually proposed as the basis for an efficient condition monitoring of machines.

Block	Birbaum	Criticality	Fussel-Vessely
P405-2	0.004319	0.001413	0.001413
P404-3	0.004319	0.001413	0.001413
Filter press	1.000000	0.001262	0.001262
T404-4	1.000000	0.114326	0.114326
T501-1	1.000000	0.114326	0.114326
P401-1	1.000000	0.327174	0.327174
T501-2	1.000000	0.114326	0.114326
P401-2	1.000000	0.327174	0.327174

Table 3 - Fault Tree Importance Measures for the Filtration Section (Top Event: Absence of Limpid Essence)

4.2 Company Beta

The Company Beta is a manufacturer and supplier of tubular products used in the drilling, completion and production of oil and gas, in process and power plants, and in specialized industrial and automotive applications. The production process is based on the Electric Arc Furnace (EAF) as main relevant asset. The EAF is charged by selected scrap and varying percentages of pig iron. It is constituted by a lower sheet metal keel coated with refractory bricks, which serve to contain the liquid steel, and cooled by a cage with a structural function that supports panels cooled by a water circuit. The energy needed for melting the scrap is supplied from the electricity for about two thirds and for one thirds by chemical energy due to the lances and the burners located on board.

After motivating the value of PHM system in relationship to safety and capability to control the process, the focus of the case was directed on the analysis of an EAF subsystem: the burner – oxygen injection pipelines. These are relevant since the activity of the furnace depends by them. The information needed to specify the supporting tool at level of Technology Independent Modelling was then gathered, especially by the RDE Designing phase.

The Designing phase has been based on the HAZOP analysis. Each variable of the process has been singularly analysed to allow listing existing knowledge related to the phenomena of variation in such variables value. For example, for variation “High Pressure”, the possible causes were listed (the pipeline is obstructed by slag, injection nozzle is crushed, …) as well as effects (e.g. possible damage in flexible pipe, possible fire triggering with explosion,…). The analysis of variations was highly detailed to further support risk and process operability analysis. All in all, the HAZOP analysis was helpful to study: i) the process operability, with identification of key variations of relevant variables of the monitored system, i.e. pressure and flow; ii) the risks, with the identification of consequences of variations (deviations, according to HAZOP terminology). Finally, by means of this analysis, prioritization of the critical parts of the burner system was achieved.

The Building phase was then considering the company needs for an ease integration of the PHM system into the current IT infrastructure, and simplicity of algorithms and techniques was considered as a key requirement to this end. A control chart based on a physical model (derived by the Bernoulli law applied to the gas flow of the burners) was then selected as algorithm, preferred to other solutions based on artificial intelligence. The characteristics of the burner system, in fact, allowed to apply this algorithm with a good efficiency of the PHM solution, as specified in the process and risk operability analysis of the design phase. On the whole, the PHM system was capable to: i) monitor the process operability by a control of risks, as identified by the key variables resulting from the HAZOP analysis obtained at Designing phase; ii) provide more levels of alarm, according to a control chart, as defined by the algorithm elected at Building phase. Last but not least, as the tool displays to the operators the information about the occurring risks and identified consequences the HAZOP study will become an operational knowledge tool which is integrated with real data from the control system, further processed by the PHM system.

5. CONCLUSION

The paper presented a Risk Driven Engineering approach to support engineering of Prognostics and Health Management systems. The approach was used in two industrial projects in manufacturing, discussed as use cases. The importance of such a systematic approach was observed in both the cases, especially in regard to the support provided for integration of dispersed knowledge, required from different domains, in order to engineer the PHM system. In this regard, it is worth remarking that the experts from production and maintenance process were majorly involved in the Planning and Designing phase, as main roles; technical experts – i.e. supporting the knowledge on risk based analysis – were also contributing to the Planning and Designing phase; then, knowledge on PHM modeling techniques was used only at the Building phase. The use cases were useful for an initial experimental learning in regard to the methodology applied in given industrial organizations: this showed the needs to blend different skills and capacities, as expected when developing a PHM solution.

Based on these first experiences, it is worth remarking that a common characteristic of the approach is that the risk based methodologies (HAZOP, FMECA, FTA, …) represent an aid for driving the PHM implementation in manufacturing; even so, they should be used as part of a “toolbox”, avoiding a prescriptive approach, while adapting to a company context. In this regard, it is worth remarking the fact that Company Alfa needed also the Planning phase, hence the use of a risk based methodology for a preliminary study in order to share the knowledge of the system to be monitored: this could be motivated considering that this company was representing a non-mature case, historically and currently using corrective maintenance policy. Company Beta was instead characterized by an higher maturity, hence a Risk Driven Engineering was straightforward, thus skipping Planning phase and jumping at Designing phase.

The use cases presented in the paper aimed at illustrating the application of the methodology, while they are not enough for its validation. This requires further steps, considering the existent methodologies. The methodology herein presented is in fact based on the inspiring principles already used by other authors in the maintenance engineering domain (Weber et al., 2012, Medina Oliva et al., 2011): it is further developing a domain-specific technical analysis (i.e. a risk-based approach) integrated into a multi-layer view that ranges from business needs to ICT opportunities. Besides, the model based systems engineering, in accordance to INCOSE (Pyster and Olwell, 2013), is another relevant source on the background, providing modeling aids and principles; these will be especially required to transform the constraints and opportunities from the ICT integration in the company into the subsequent steps of Technology Specific Modeling of the PHM solution. In this regard, PHM system engineering will benefit from the evolution of technologies, for what concern the ICT and the PHM domain. Considering this expectation, it would be relevant to focus in the establishment of a library of algorithms and techniques for PHM, to systematize the deployment of efficient PHM services within an existing ICT and machine infrastructure. Model based systems engineering, in accordance to INCOSE, would enable to manage complexity, including that of software, further extending results of Value Driven and Risk Based Engineering.

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