Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

# New Thinking Paradigm for Maintenance Innovation Design

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**Abstract:** Meanwhile the manufacturing paradigm changes towards predictive manufacturing, the role of maintenance function within manufacturing needs to be refined as a value creation function for achieving more sustainable operations. With the advent of internet of things (IoT), cloud computing, big data, PHM, and cyber-physical systems, e-maintenance necessitates new transformation. These changes are driving a new thinking paradigm for maintenance. This paper introduces new perspectives for maintenance innovation and proposes the value creation paths for maintenance transformation.

## 1. INTRODUCTION

The globalization of today's economy has drastically changed the business environment. The established manufacturing strategies have been challenged by the aggressive competition from emerging economies, with a severe strain on local manufacturing sectors in developed nations (Garetti and Taisch, 2012; Lee and Lapira, 2013). This fierce competitive context is requiring actions in order to sustain business capabilities and innovation is a well-known lever for long-term sustainability (Hart and Milstein, 2003). Concretely, technological innovations have been drivers of the evolution of manufacturing paradigms from mass production, through the concepts of lean, flexible, reconfigurable manufacturing, to the current stage of predictive manufacturing characterised by bringing transparency to manufacturing assets capabilities (Lee and Lapira, 2013).

The changes of manufacturing paradigms has further involved the business functions within manufacturing companies. As such, maintenance function has progressively experienced greater challenges in the way it is perceived from a "necessary evil" to an "enabling support function" (Parida and Kumar, 2006) and a "source of added-value", either just economic (Marais and Saleh, 2009) or extended to environmental and social aspects (Liyanage and Kumar, 2003). This evolution brings with itself a transformation of the thinking paradigm for the maintenance function, that should evolve from a problem-solving function to a means for problem avoidance through value creation. This would involve maintenance in the changing process, as a strategic business function that facilitates the introduction of a new predictive manufacturing system. The big deal is to overcome the traditional strategies that tend to assume operating conditions at a "stable" status – with a continuous asset availability and optimal performance – each time an asset is used. It is a weak assumption for real cases in factories, and to overcome its limited view, greater transparency to their assets is a relevant opportunity (Lee and Lapira, 2013).

The transition towards transparency should take advantage of advanced technologies including internet of things (IoT), cloud computing and cyber-physical systems, with the purpose to deal with the current big data environment (Lee et al., 2013). Indeed, collecting data is not a real problem today, with the advent of technological smart sensors, progressively smaller thanks to the progress in Micro Electro-Mechanical Systems (MEMS), and pervasive as they are embedded in the manufacturing system, e.g. RFID technologies. Furthermore, transparency is even enhancing thanks to the transformation of technological capabilities to process huge data volumes from field in a flexible way: e.g., performance analysis of processes or equipment variables, supported by the more "traditional" SCADA, could be enhanced by application of the SOA paradigm (Subramanian, 2008); cloud computing is clearly opening new perspectives as well (Lee et al., 2011), allowing to share the intelligent exchanges between different machines or assets, which is accelerating decisions in a real time environment effectively enabled to exploit the big data. At system or factory level, transparency can be achieved by the evolution of traditional solutions into web based platforms, e.g. e-CMMSs providing online information regarding availability of workers and spare parts, connecting with mobile technologies for retrieving data and loading maintenance action, and finally allowing fast and flexible scheduling (Holgado and Macchi, 2014).

The question still remains if these technological components provide the right information for the right purpose at the right time. Data has no meaning unless it is processed with the right content and meaning for people. Just connecting sensors to machine, or connecting machine to machine or, even more, machine to business, will not give the users more insights to make better decisions. In our concern, maintenance function is a relevant target user providing enhanced meaning to the big data sources within the factory: this is the real sense of maintenance contribution to the changes required in order to actuate predictive manufacturing.

Along the road-map towards predictive manufacturing, suppliers and equipment builders are relevant stakeholders, as they are a fundamental source of knowledge and information for manufacturing companies. Their role can be even extended, and then exploited, in the current manufacturing environment by the provision of maintenance related services as a result of a servitization strategy: technical services have been proofed to induce positive impacts on innovation in manufacturing (MacPherson, 1997) and, among technical services, maintenance services are key to improve after-sales services (Sheng et al., 2009) to support manufacturing assets.

The big challenge is to develop the new thinking paradigm for maintenance innovation. This paper presents a concept of the transformation process through the new thinking paradigm (section 3) and two industrial cases regarding innovations through the provision of maintenance services by suppliers or equipment builders and the exploitation of advanced technologies as enabling capabilities to accelerate the transformation (section 4). Around these core sections, the paper is organized to provide its background (section 2) and some conclusions (section 5).

## 2. BACKGROUND

### *2.1 New Role of Maintenance in Sustainable Manufacturing*

Industrial systems have evolved through competition and technological change, however, long term sustainability requires a different perspective that involves prediction and planning for a sustainable future and constructing more resilient systems (Evans et al., 2009). Indeed, long term sustainability in manufacturing is nowadays understood from economic, environmental and social perspectives. But, as a matter of fact, nearly all the current manufacturing models are based on the old paradigm of "*unlimited resources and unlimited world's capacity for regeneration*" (Garetti and Taisch, 2012), which clearly affect sustainability matters. More from an engineering perspective, sustainability can also be considered as "*a system property that allows the system to continuously meet the requirements of customers, possibly with design modifications over time*" (Lee et al. 2011). Thus, resilience is understood as a core issue of sustainability, related to capabilities to survive "large perturbations through adaptation and evolution" (Fiksel, 2003).

On one hand, the technology, on which manufacturing is largely based, has been considered an enabler to provide the tools and options for building new solutions to enable the "adaptation and evolution" required by a sustainable manufacturing concept (Garetti and Taisch, 2012). On the other hand, maintenance function would also play an important role in sustainable manufacturing, regarding to several aspects to which it can contribute, such as technological innovations and asset life cycle management (Garetti, 2011). This emphasis on the life cycle perspective of manufacturing assets has in fact caused a redefinition of the role of maintenance as "*a prime method for life cycle management whose objective is to provide society with the required functions while minimizing material and energy consumption*" (Takata et al., 2004), thus pointing out also the potential environmental value as maintenance target.

Predictive manufacturing paradigm, based on transparency, i.e. visibility of the actual condition and degradation state of manufacturing assets (Lee an Lapira, 2013), is the primary lever to combine asset life cycle management with the use of advanced manufacturing technologies. This would remove uncertainties regarding production capabilities, and enable more informed production decisions since the begin to the end of life of manufacturing assets (Levrat et al., 2008).

In particular, real time monitoring, performance assessment and advanced technologies are cornerstones to contribute to achieving transparency in manufacturing, as they are part of predictive maintenance systems, named traditionally as E-maintenance systems (Koç et al., 2005), now evolving under the vision of advanced computing and cyber-physical systems (Lee et al., 2013). New maintenance capabilities enabled by such evolved systems are creating further opportunities, and contributing to move the asset performance frontier, changing also the role of maintenance function within manufacturing.

### *2.2 Servitization and Service Innovation*

The term *servitization* was first used by Vandermerwe and Rada in 1988 and it can be defined as the process of creating value by adding services to products (Baines et al, 2009). In manufacturing industry, equipment builders are following a servitization strategy and moving into a transition path towards becoming service providers (Oliva and Kallenberg, 2003). This movement into service providers implies the adoption of a more customer centric approach, offering more tailored solutions to their needs instead of just products (Baines et al, 2009).

Technology is seen as the proper interface for the interaction between products and services (Geum et al., 2011). Then, technological innovations concern not only product innovation but also service innovation. The servitization strategy involves a change towards putting services in the centre of company's offerings (Oliva and Kallenberg, 2003): thus, service innovation gains higher importance as a means for identifying solutions and new offerings to meet customer needs. In this regard, it arose the concept of service dominant logic, for supporting the transition from product focus in manufacturing to a service-provider model (Vargo and Lusch, 2008). Innovations based on service dominant logic would bring opportunities to manufacturing companies that could not be achieved with the old mindset which gives priority to product-centric innovations.

### *2.3 E- Maintenance Transformation*

E-Maintenance and e-Manufacturing systems were first introduced by the NSF Center Intelligent Maintenance Systems (Lee, 2001). For the past decade, many new technologies have accelerated their development. Mobile technologies have assisted in overcoming barriers due to geographical and temporal constraints and have supported ubiquitous smart user interfaces to exchange information among different types of users, such as managers, operators, suppliers (Emmanouilidies et al., 2009).

Smart devices such as graphic tablets, PDA, smart tags … are hardware components equipped with wireless technologies in order to provide functionalities that support the operator in the field (Iung et al., 2009). Smart devices are becoming smaller with new capabilities of real-time data acquisition, data processing, data transmission and connection into applications in a networked environment made of transducers and actuators (Macchi et al., 2013).

The service-oriented architecture (SOA) has also contributed to the development of monitoring and control features, enabling interconnectivity between objects within an architecture. SOA is seen as the proper architecture for E-maintenance solutions (Karim, 2008). Recently, autonomic and cloud computing are also bringing new possibilities to implement capacities of self-management or decision making among a network of machines / devices (Lee et al., 2011).

The combination of multiple technologies applied to maintenance are the basis of E-maintenance platforms, which are seen as a tangible ICT support that enable services and management to enhance proactive decision process execution (Macchi et al., 2014). E-maintenance will further advance to a greater value with the development of Cyber-Physical Systems (CPS), which are defined as "*smart systems that encompass computational (i.e., hardware and software) and physical components, seamlessly integrated and closely interacting to sense the changing state of the real world*" (NIST, 2013). Their application in manufacturing would be related to smart production equipment, processes, automation, control, networks and new product design. Cyber physical systems could then provide higher transparency regarding data and information during the whole product life cycle (Lee at el., 2013).

## 3. NEW THINKING PARADIGM

This section introduces a new thinking paradigm for innovation in maintenance function within manufacturing industry. Inspired on the productivity transformation and opportunities spaces described in Lee et al. (2013), and considering the new role of maintenance (section 2.1), the new drivers of maintenance innovation are explained herein.

Fig. 1 illustrates the different thinking approaches towards maintenance and envisages several paths for identifying innovation opportunities. The figure is plotted as a two-axis graph where four quadrants are specified, thus setting up the thinking space for maintenance innovation: therein, the X-axis represents the visible and invisible evidence spaces; the Y-axis represents the problem solving and problem avoidance spaces. The quadrants represent four different situations and thinking approaches towards maintenance. The shift between quadrants expounds changes in the way of thinking and guides the identification of innovation opportunities.

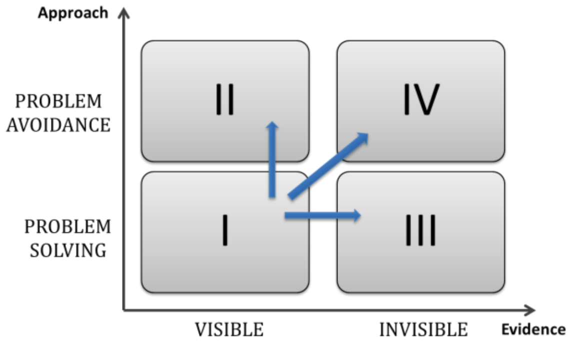


Fig.1. Thinking space for maintenance innovation

The lower left quadrant (I) represents a situation in which maintenance is seen under a traditional perspective and it still has connotation as "*a measure against troubles*" (Takata et al., 2004). Visible or physical evidence of equipment failure, or working out of its operating conditions, are faced in this thinking approach. The lower right quadrant (III) concerns an extension of the traditional approach which looks for solving latent or potentially oncoming problems, which do not have visible or physical evidence of their occurrence, such as machine unknown failures, degradation or component wear.

The two quadrants in the upper side of Fig. 1 relate to thinking approaches considering the avoidance of visible or invisible problems; thus, instead of thinking on how to solve problems they focus on looking for new ways of improving the operations performance by adding or creating value through maintenance activities to manufacturing operations. Holgado et al. (2013) propose some potential characteristic of the value provided by maintenance: technological update / upgrade; asset life cycle extension; product quality; production availability or flexibility; process design; brand or status; cost reduction; and risk reduction.

The upper left quadrant (II) represents a situation in which maintenance is considered as a source for operations improvements which are guided by visible or physical evidences of known problems. For example, an equipment redesign proposed by the OEM (Original Equipment Manufacturer) aimed at upgrading its reliability beyond the current performance, pertains to this quadrant. The upper right quadrant (IV)considers, under a broader view, how value can be created also regarding not evident issues. This quadrant denotes a step further respect performance improvements, i.e. aiming at creating value through maintenance innovations.

Shifts between thinking approaches would follow the arrows depicted in Fig. 1. The shifts may be supported by different means, either organizational, managerial or technological, and by both internal and external capabilities. Some examples are given herein of potential shift enablers. Techniques and methods which are based on physical evidence of already known problems, such as criticality analysis, would facilitate the shift from the lower left quadrant to the upper left quadrant, by focusing on how the knowledge obtained from these techniques and methods can add value to operations. The shifts towards the left side of Fig.1, i.e. towards facing unknown or invisible problems, would be mainly enabled by techniques or methods based on advanced technologies which can bring transparency to manufacturing assets and factory performance. The shift from the lower left quadrant to the lower right quadrant would be achieved by monitoring and condition based techniques that allow to keep track on not evident degradation processes and discover hidden problems affecting operations. The shift from the lower left quadrant to the upper right quadrant would be facilitated by techniques and methods such as prognosis and health management (PHM) supported by advanced technologies. Autonomic or cloud computing and cyber-physical systems are candidates to this end, together with other technological means useful to increase connectivity and accessibility to dispersed big data; Internet of things (IOT) is, for example, a relevant means to this last regard.

Further on, techniques and methods enabling the shifts could be performed either by internal personnel within the company, or by external personnel. Thus, external maintenance-related services offered by OEMs or MSPs (Maintenance Service Providers) could contribute to change the thinking paradigm for maintenance innovation.

## 4. INDUSTRIAL CASES

This section introduces two industrial cases regarding the application of the new thinking paradigm for maintenance innovation design. Each case presents a different level of analysis: the first one studies innovations at machine system level, thus considering the scenario of solutions that an OEM could provide for a single machine inside a factory; the second one concerns innovations at factory level provided by service offerings of a MSP.

### *4.1. Machine System level industrial case*

The case presented in this section regards the lubrication starvation of a ball screw system. The ball screw is one of the most stressed components on a machine tool and is key for positional accuracy. Recent studies have looked at techniques for monitoring the degradation of this component (Uhlmann et al., 2008). The test bed made for the case, consisted of a single motor driven ball screw, and the ball screw was rotated to push the table to do reciprocating motion, from the front bearing to rear bearing, and then come back to front bearing.

Figure 2 shows the evolution of maintenance thinking with respect to the ball screw system. First of all, the most important attribute of a ball screw system is accuracy. To achieve the required accuracy for the entire machine, ball screw systems need to be designed carefully. Thus, a design for accuracy can be allocated in Quadrant I. Secondly, a lack of lubrication would reduce the life time and performance of system. To avoid this issue the ball screw supplier will provide scheduled maintenance recommendation, like adding lubrication every 15 minutes. This solution belongs to Quadrant II, as providing a way to avoid a visible problem.

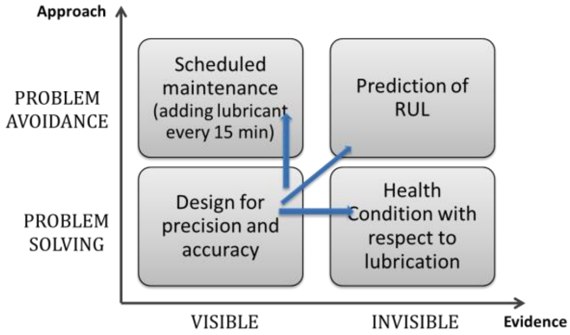


Fig. 2. Thinking space for maintenance innovation in the industrial case at machine system level

Thirdly, the relationship between lubrication and ball screw health condition is considered invisible. Although scheduled 15-minute lubrication provides a standardised solution to conduct maintenance, the real-time health condition information is missing. Considering the stress factors, load, speed, etc., ball screw should be lubricated on demand. In this case, 35 different features extracted from two different signals, using time, frequency and wavelet processing methods. The health condition is assumed to be, respectively, normal and failed at the beginning and the end of the test. Then, the Fisher criterion is applied and Mahalonobis Distance and Logistic Regression algorithms are used to calculate the health value. The calculation of this health value pertains to Quadrant III in the thinking space.

Lastly, not only current health condition can be revealed, considering a solution in Quadrant IV, remaining useful life (RUL) should also be predicted so that the customers can have a better idea on how to plan for their maintenance actions. The remaining useful life can be calculated by Autoregressive–moving-average model (ARMA) (Wang et al., 2008).

Health indicators like health value and confidence value can provide useful information and predict the machine's health condition. Thus, the predictive analytical algorithms provide significant improvements by adding these analyses to traditional maintenance schemes. Machine data is, then, effectively transformed by PHM algorithms into valuable information that can be used by factory managers to optimize production planning, save maintenance cost and minimize equipment downtime.

### *4.2. Factory level industrial case*

This case focuses on the innovations that a MSP with high engineering capabilities could bring through maintenance services offered to manufacturing companies at factory level. The service offerings provided for efficiency and reliability improvements, based on a sound methodology and supported by a web-based platform, is now analysed. The platform is compound by several modules that can be added to the offerings according to customers' requirements. The modularity makes this case very adequate for the application of the new thinking paradigm approach as it provides clear examples of modules that can be allocated in each quadrant. Fig. 3 shows the distribution of those modules in each quadrant, according to their characteristics.

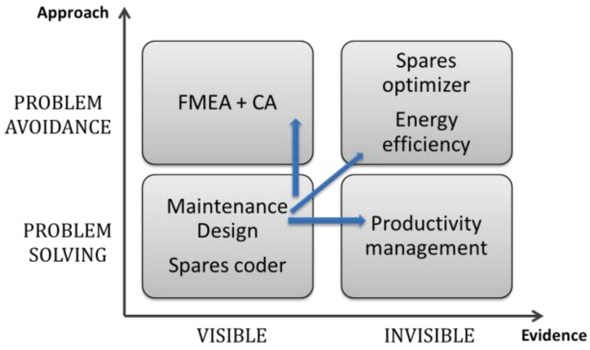


Fig. 3. Thinking space for maintenance innovation in the industrial case at factory level

Two modules within the web-based platform could be adopted in Quadrant I: a maintenance design module, providing support for the design of maintenance programs based on the equipment tree and the standard maintenance activities according to the equipment family; a spare parts coder module, supporting the standardization of materials within the factory warehouse and the codification of spare parts. Standardization – either related to equipment families or materials – should be considered an outcome of a traditional problem solving approach based on the physical evidences of known problems.

Service offerings may go beyond standards as in Quadrant II, implying, at factory level, the improvement of maintenance policies selection and production equipment reliability: the modules therein provide an online support for criticality analysis (CA) and failure modes effect analysis (FMEA), which can be meaningful aids to enhance operations (by avoiding problem occurrence) based on historical information of previous failures and their effects.

Further service offerings could involve, at factory level, the monitoring of the critical equipment performance, availability and degradation: modules in Quadrant III are those providing support for productivity management, such as a module for real time production monitoring based on field data and able to update its failure database according to the appearance of new unknown failures and a module for monitoring in real time the OEE of selected equipment within the factory. The problem recognition in the frame of a real time OEE monitoring is a promising mechanism for solving oncoming problems that otherwise would not be unveiled.

The problem avoidance approach, leading to improvements based on higher assets transparency brought by unveiling non-evident improvement opportunities, is the most advanced option for service offerings. In this regard, modules for energy efficiency implementation and spare parts optimization are services allocated in Quadrant IV, bringing new features to a factory by, respectively, (i) unveiling energy inefficiencies in an equipment or production line, thus preventing oncoming failures or working out of operating conditions; (ii) analysing the historical data and suggesting actively new stock levels for spare parts according to a given set of parameters, thus better adapting to the spare parts demand, avoiding materials inefficiency.

On the whole, this scalable web-based platform provide new opportunities for innovation in maintenance, according to the specific needs of each MSP's customer: it brings also a proper support for the new thinking paradigm based on the transparency brought to manufacturing factories. It is worth remarking that some services offered are still releasing traditional solutions (e.g. FMEA + CA), but revisiting them in a web-based platform leads to opportunities for operations improvement thanks to better use of historical data..

## 6. CONCLUSIONS

The role of maintenance function is evolving due to the predictive manufacturing paradigm, the challenges related to asset life cycle management, and the opportunities arisen by advances in manufacturing technologies. On the whole, they are bringing changes in the way of thinking maintenance. There is a new thinking paradigm of maintenance function, evolving from a reactive, traditional, problem solving approach towards a proactive, innovative, performance enhancement approach based on the potential of maintenance function to create value for manufacturing operations. This paper has introduced the characteristics of this new thinking paradigm. Moreover, it has envisaged how the shifts between approaches can be supported through maintenance services offered by third parties and the advancements based on a new technological wave of E-maintenance through advanced computing and cyber-physical systems; even the provision of traditional solutions through web-based platforms could help exploiting the new potentials to deliver services within the E-maintenance framework. New innovation opportunities must be explored in these two fields, in order to achieve greater performance enhancement in maintenance. In this regard, there is a need for a systematic method that supports the search for new ideas to add value to operations performance by investigating the innovation gaps and by exploring the potentials of maintenance-related services.

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