Value-driven engineering of E-maintenance platforms

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Abstract

Purpose – The purpose of this paper is to propose a methodology for the engineering of E-maintenance platforms that is based on a value-driven approach.

Design/methodology/approach – The methodology assumes that a value-driven engineering approach would help foster technological innovation for maintenance management. Indeed, value-driven engineering could be easily adopted at the business level, with subsequent positive effects on the industrial applications of new information and communication technologies solutions.

Findings – The methodology combines a value-driven approach with the engineering in the maintenance scope. The methodology is tested in a manufacturing case to prove its potential to support the engineering of E-maintenance solutions. In particular, the case study concerns the investment in E-maintenance solutions developed in the framework of a Supervisory Control and Data Acquisition system originally implemented for production purposes.

Originality/value – Based on literature research, the paper presents a methodology that is implemented considering three different approaches (business theories, value-driven engineering and maintenance management). The combination of these approaches is novel and overcomes the traditional view of maintenance as an issue evaluated from a cost-benefit perspective.

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1. Introduction

The present paper concerns the creation of value in maintenance processes through innovation enabled by information and communication technologies (ICT). As such, E-maintenance is considered an avant-garde strategy. The term E-maintenance emerged early in 2000 and is now commonly used in the maintenance-related literature. Tsang (2002) was one of the first author to suggest the role of E-maintenance in the ICT support of maintenance management and processes, because of its "unprecedented convenience and expedience for enhancing efficiency of maintenance activities". E-maintenance was also defined as "a maintenance management concept by which the assets are controlled and managed via Internet" (Devices World, 2013), leading to the expectation of "an unprecedented level of transparency into the entire industry" (see also Han and Yang, 2006; Crespo Márquez *et al.*, 2005; Levrat *et al.*, 2008). Regarding the integration and synchronization of maintenance and reliability applications to manage asset information, the Intelligent Maintenance Centre introduced two complementary definitions of E-maintenance, first as "the ability to monitor plant floor assets, link the production and maintenance operations systems, collect feedbacks from remote customer sites, and integrate it to upper level enterprise applications"; and second as the "transformation system that enables the manufacturing operations to achieve predictive near-zero-downtime performance as well as to synchronize with the business systems through the use of web-enabled and tether-free (i.e. wireless, web …) infotronics technologies" (Lee and Ni, 2004). Taking into consideration the European Standard (EN 13306:2010) of maintenance terminology, Muller *et al.* (2008) defined E-maintenance "maintenance support which includes the resources, services and management necessary to enable proactive decision process execution". These definitions indicate that E-maintenance has been discussed for more than a decade, which has engendered many different perceptions of this term. In this paper, E-maintenance is assumed as a relevant technological advancement providing key support to innovate maintenance management, which is the currently agreed definition in the scientific literature.

Nonetheless, E-maintenance cannot be understood as only technological support. It is also a relevant part of the maintenance management model, supporting different maintenance processes and human as well as technical resources (Muller *et al.*, 2008). Maintenance management models have become a relevant subject of research. They are considered a fundamental issue in achieving efficiency and effectiveness in order to meet business objectives (Prasad *et al.*, 2006): companies, in fact, recognize that maintenance can provide value to their business (Van Horenbeek *et al.*, 2011). Hence, a maintenance management model is now seen as a framework in which maintenance strategies and objectives can be aligned with business strategies and objectives (López Campos and Crespo Márquez, 2009). Furthermore, the maintenance management model is conceptual, thereby providing a mindful approach to the fulfillment of maintenance stakeholder needs while setting maintenance objectives (see Söderholm *et al.*, 2007; Al-Turki 2011). This is often discussed as a favourable approach in order to achieve efficient and effective maintenance management. Correspondingly, in this paper E-maintenance is interpreted as a key asset in developing the maintenance management model. Furthermore, its valuable benefits are considered for the competitive advantages they may bring, both leading to the transformation of the maintenance management model itself, and providing positive benefits for not only maintenance users but also relevant stakeholders outside the maintenance function, which was another theoretical concern driving the research presented in this paper.

Another important matter, which has received scant attention in the literature, is the industrial adoption of E-maintenance platforms. However, some interesting cases prove the capabilities of E-maintenance platforms through industrial demonstrations (see Mascolo *et al.*, 2010). A few research works present E-maintenance platforms that are actually run in real industrial contexts, with the purpose of discussing their benefits and merits for industrial users. Specifically, some recent studies showed how maintenance processes benefited after technologies provided by an E-maintenance platform in an industrial context were introduced. An example is the case of the support of mobile maintenance through the use of personal digital assistants (PDA) integrated within an E-maintenance platform through a standardized database (Fumagalli *et al.*, 2010). In another case, the support of an integration system attained the synergic adoption of a computerized maintenance management system (CMMS) and tools for reliability-centred maintenance (RCM) and condition-based maintenance (CBM) (López Campos *et al.*, 2013). This industrial perspective was further investigated in a recent work (Macchi *et al.*, 2012) where value assessment was addressed as important in answering questions, such as "how much money would a company save, or gain, by adopting these technologies? How much is the investment rewarding for the invested capital?" In that research, the support provided by an E-maintenance platform was studied for the valuable benefits achieved by using E-technologies and their services, which were supported in the targeted maintenance processes of a given company. This in fact led to the development of a tailored approach to cost-benefit analysis (CBA) with the purpose of fostering the use of E-maintenance and its positive effects on company profitability.

The present study extends these previous perspectives. Instead of examining the pros and cons of E-maintenance technologies for value assessment in the frame of a CBA, the study focuses on the value of an E-maintenance platform and on the subsequent identification of solutions to obtain this value for the company. Also considered is the development of a perspective with which to view formalized approaches of value engineering modelling (e.g. Acharya *et al.*, 1995), with the purpose of building a structured methodology aimed at developing E-maintenance solutions driven by business needs. Finally, the methodology developed in this study is flexible, considering both the perspective of stakeholders directly involved in the use of the E-maintenance platform, such as the maintenance operator or the maintenance manager, as well as other relevant stakeholders identified within other business functions or among external actors with influential stakes in the maintenance processes and their results.

Considering this focus, we begin with a brief background of the most promising E-technologies, which foster innovation in maintenance management (Section 2). Keeping in mind a process-oriented view and the supporting technologies, the concept of maintenance-technology independent service (M-TIS) is introduced in Section 3. Based on the M-TIS concept, the E-technologies assume their proper role as the means of supporting maintenance processes. The methodological approach proposed to engineer E-maintenance platforms is presented, followed by the methodology for value-driven engineering (Section 4). The paper then discusses a case study in which the methodology is tested, providing empirical evidence in the case of a Supervisory Control And Data Acquisition (SCADA) system as a component of the E-maintenance platform in a company in the textile industry (Section 5).

2. Literature review

2.1 Background

Since the 1970s, companies have understood that they need to integrate the maintenance area within the organization and facilitate its interaction with the management of other functional areas (Pintelon and Gelders, 1992). Maintenance management refers to the activities of management that determine maintenance objectives, priorities, strategies and responsibilities, and implement them by maintenance planning, maintenance control and supervision, as well as several improvement methods including the technical and economic aspects of the organization. Therefore, maintenance management is clearly a multi-disciplinary area consisting of a wide set of different interrelated approaches (Söderholm *et al.*, 2007). Interesting integrated maintenance management models have been reported in the literature as reviewed by López Campos and Crespo Márquez (2009) and Barberá *et al.* (2012). Each proposal usually identifies a list of processes, activities, actions or steps, which are part of an integrated and comprehensive management system. For instance, Crespo Márquez (2007) suggested eight sequential managerial steps to ensure efficiency, effectiveness and continuous improvement of the maintenance management system:

(1) definition of the objectives, strategies and maintenance responsibilities;

(2) ranking of the equipment;

(3) analysis of weak points in high-impact equipment;

(4) design of maintenance and resources plans;

(5) maintenance scheduling and resource assignment;

(6) control, evaluation and data analysis;

(7) life cycle analysis; and

(8) continuous improvement.

In their discussion of the pillars of maintenance management, Crespo Marquez and Gupta (2006) highlighted how maintenance management models for complex systems need to be supported by ICTs. At the same time, a proper understanding of the needs of a maintenance management model may facilitate the resource design and management of ICTs. This is usually achieved by a specific taxonomy of processes, actions and activities to be carried out and a set of related tasks (and subtasks) to be supported. This model also motivates a value-driven approach, with the primary purpose of better linking maintenance to business and finding the most effective way to exploit the benefits of adopting E-maintenance solutions.

According to Muller *et al.* (2008), E-maintenance can be seen from different perspectives, each one highlighting a specific characteristic of the concept. E-maintenance can be seen as a maintenance strategy (i.e. a way to perform maintenance with digital technologies), as in Tsang (2002). This interpretation is useful in the development of supporting frameworks to structure maintenance processes according to a strategic vision. Nevertheless, it is incomplete in its technological scope. From the perspective of application, E-maintenance is sometimes conceived as a maintenance plan (i.e. a way to plan maintenance using a collaborative approach), as in Ucar and Qiu (2005) and Muller *et al.* (2008). It is also intended as maintenance policy (i.e. a shift in the maintenance policy towards more predictive/proactive types), as in Han and Yang (2006). This last view underlines the link between E-maintenance and a CBM policy, focusing on CBM-related technologies. This however neglects other technologies that can be useful for other maintenance activities; thus, it represents only a partial view of what E-maintenance comprises.

In the present study, E-maintenance is seen as maintenance support, that is, a set of technologies supporting existing maintenance processes and/or enabling new ones, as in Crespo Marquez and Gupta (2006), Muller *et al.* (2008) and Ucar and Qiu (2005).

2.2 E-maintenance platforms

The term E-maintenance platform emerged in the literature, along with the concept of E-maintenance (see Muller *et al.*, 2008; Crespo Marquez and Iung, 2008). An E-maintenance platform is formed when conventional tools are replaced by an intelligent structure (Ucar and Qiu, 2005). In other words, production equipment is provided with "intelligence" by ICT. E-maintenance platforms are thus tangible ICT support that enables services and management to enhance the proactive execution of decision processes. To this end, E-maintenance platforms are not products on the shelf. Some examples in the literature of tools that can be considered E-maintenance platforms are Watchdog Agent (Djurdjanovic *et al.*, 2003), Telma Platform (Iung, 2003; Levrat and Iung, 2007) and Proteus (Szymanski *et al.*, 2003; Bangemann *et al.*, 2006). These examples encompass the implementation of multiple technologies applied to maintenance. They were developed for research purposes in order to demonstrate the applicability of specific new technologies as enablers of services to enhance proactive maintenance activities. Indeed, their different technologies, namely technological components, were combined and orchestrated to provide the capability of the platform to support different services. Finally, they demonstrated, or at least helped to discuss, their positive effects in an industrial context.

In the present study, the most promising technological components of E-maintenance platforms are discussed, beginning with what proposed by Macchi *et al.* (2012). Each component (hardware, firmware or software) is discussed by focusing on the main functional features that affect the functionality of the E-maintenance platform.

Ramamurthy *et al.* (2007) and Zhang *et al.* (2004) discussed the features and possible use of smart sensors, which are transducers that provide functions to generate the digital representation of a sensed/controlled quantity (temperature, pressure, vibration, strain, flow, etc.). Smart sensors have become progressively smaller, thanks to the progress in micro electro-mechanical systems technology. From the point of view of communication, the use of a web-service communication paradigm allows these smart sensors to be easily integrated into a complex architecture. To this end, the service-oriented architecture (SOA) paradigm strongly contributes to the development of monitoring and control architecture, enabling interconnectivity at an object level, and consequently impacting E-maintenance platforms. Indeed, SOA is claimed to be the proper architecture in the development of E-maintenance solutions (Karim, 2008). In summary, a smart sensor supports the following functional features: real-time data acquisition from a physical environment; data processing based on predefined algorithms; digital data transmission; and connection to applications in a networked environment of transducers and actuators. Smart sensors guarantee a distributed approach, physically addressing the link with the shop floor. This link can also be further improved by the use of radio frequency identification (RFID) systems, as postulated by Chien-Ho (2009) and Emmanouilidis *et al.* (2009). RFID allows better tracking and tracing of (maintenance) objects on the shop floor and the storage information in the field. Indeed, the RFID technology can be used to identify an entity, such as a maintenance operator, physical asset, tool or spare part, and store information. The RFID tag is attached to the entity and enables the exchange of data locally with a RFID reader. This leads to the following functional features of the RFID system: capability of identifying the tagged entity; capability of storing, reading and writing the entity's data; the connection to a back-office system for further data processing (e.g. a CMMS for storing more data about the entity).

Communication with the shop floor for maintenance monitoring purposes can be also guaranteed by the use of a SCADA system (Bangemann *et al.*, 2006). This is possible because of its different functional features: real time data acquisition from a physical environment through remote devices (e.g. programmable logic controllers (PLC) or remote terminal units (RTU)); synchronized communication between remote devices in the system; closed-loop process control of the equipment (using PLCs and RTUs); capability of processing huge volumes of data from the field; support for performing (online and offline) analyses of different processes or equipment variables; and report generation. SCADA could also be enhanced by the application of the SOA paradigm (Subramanian, 2008). Information from the machines could then be analysed within E-maintenance platforms through diagnostic and prognostic toolboxes (Jardine *et al.*, 2006; Lee *et al.*, 2006), thus enabling the improvement of machine behaviour assessment and prediction. To this end, from the point of view of computational capabilities, Cloud Computing has opened new perspectives (Lee *et al.*, 2011), allowing the sharing of calculation efforts on different machines (i.e. equipped with embedded devices) and thus accelerating the decision-making process.

Technology is evolving not only to support communication with machines but also for better management of the information exchanged among maintenance personnel. Hence, PDAs, smart-phones, and mobile devices play an important role, as confirmed by Campos *et al.* (2009) and Emmanouilidis *et al.* (2009). Indeed, these devices provide many functional features that are useful for supporting the activities performed by mobile personnel: in-field support of office activities (e.g. take notes, keep records, use spreadsheets while near the equipment); support in reading bar codes or RFID tags; wireless connection to internet or other local area networks; download and upload data from/to remote computers, equipment and databases; provision of multi-media tools for photos, videos and audios; geo-localization when the device is equipped with GPS, for instance. Mobile devices enhance the information that can be computed into the CMMS (O'Hanlon, 2005). In particular, the CMMS is seen as the main information system to which an E-maintenance platform could be linked. It is endowed with a number of functional features to support maintenance planning/scheduling, work order management, performance monitoring, budgeting/cost controlling and spare parts management. Finally, the information retrieved by using such devices and information systems can then be properly analysed by reliability and maintenance engineering software in order to improve maintenance plans (Tucci and Bettini, 2006; Stegmaier *et al.*, 2011). Software tools for reliability and maintenance engineering are generally endowed with a number of functional features in order to provide support for reliability analysis/prediction at the component level, failure mode, effects and criticality analysis (CA), reliability and availability analysis at the system level (e.g. through a reliability block diagram).

2.3 Concluding remarks

E-maintenance platforms have been analysed for more than a decade from mainly a technological perspective. The majority of E-maintenance platforms were developed beginning with the previously mentioned technological components primarily for technical experts, such as maintenance and diagnostics experts.

It is worth observing that the main research works on the topic date back to the beginning of the twenty-first century, the period when new technologies were emerging, and the scientific community was discussing their possible use. E-maintenance platforms were then conceived as emerging from the technologies that were available at the time, and they addressed mainly technical expertise. This approach is evident in the scientific literature. Nowadays, after a decade has passed, the scenario has changed greatly: advanced ICT solutions are currently being adopted in manufacturing processes, and they are progressively entering the maintenance management process of manufacturing companies.

According to the Gartner's hype curve (Linden and Fenn, 2003) technologies go through different development and adoption phases during their lifecycle. Such phases correspond to the increasing maturity of the technology – from "Technology Trigger" to "Slope of Enlightenment" and "Plateau of Productivity". The last two represent more mature industrialization phases. It can be then considered that some of the technologies previously mentioned are reaching or have already reached these ultimate phases. For instance, according to Gartner's reports on the web site (www.gartner.com), SOA was already in the "Slope of Enlightenment" phase in 2008. According to the 2009 evaluation, RFID is achieving the "Plateau of Productivity". Cloud computing is not yet established but is approaching the "Slope of Enlightenment". Thus, the solutions are technically mature or nearly so. Research should also consider approaches to foster industrial applicability, not only the development of technology. Hence, it is important to identify how technologies can satisfy different business needs, namely how an E-maintenance platform can be tailored to obtain the expected benefits for the target stakeholders in a concrete business context.

A value-driven approach, inspired by a business perspective, seems advisable for the better linking of maintenance to business, with the subsequent benefits of better ICT resource management and related innovations. The authors of this paper strongly believe that good maintenance management can create value for a company by making operations more effective and/or efficient. The E-maintenance concept may also be used to speed up and contribute to transforming maintenance processes, as a means of creating added value. Regarding the latter concern, it is worth remembering that technology alone cannot improve maintenance results. Required is a combination of technologies that are arranged to provide appropriate services that create value for a business.

The current challenge is the identification of the functional features of technological components to be selected and exploited for the preparation of ICT solutions that meet the needs of stakeholders. Thus, the technological components should be combined according to an articulated analysis of the target value. Hence, technologies return to their proper role of the means of supporting maintenance processes. Accordingly, Section 3 discusses the relation between processes and technologies in the context of the concept of technology-independent services.

3. From processes and technologies to technology-independent services

The term "service" is now better detailed and discussed regarding its role in the comprehensive value-driven approach. The term "service" has largely been adopted although several definitions exist in different domains (e.g. industrial, economic, etc.), and sometimes more than one definition appears in the same domain (Grida Ben Yahia *et al.*, 2006). The present study does not consider the meaning of service as a concept in the software domain (the reader may find more information on this concept in Huang and Mason, 2006). In this study, "the services can be interpreted as 'operational processes' having different granularities with respect to the 'enterprise processes' they support" (Macchi *et al.*, 2012).

According to Zhao *et al.* (2009), service creation is based on service composition, which allows the creation of enhanced services from the combination and improvement of already existing services, by applying new technologies to existing processes (i.e. we intend this to mean existing "enterprise processes"). The value-driven engineering approach is based on the concept that value must drive the selection of a service that can improve the company business (i.e. in this study, a maintenance process). Thereafter, the service can be tailored and detailed by selecting the proper technology with which to apply the service.

Figure 1 summarizes the main concept of the present research in three layers.

The paper postulates that "maintenance processes" drive the development of "services". According to the "model of the maintenance business functions and processes" proposed by Levrat *et al.* (2008), maintenance processes can be linked to strategic, tactical and operational levels. The present research focuses on the operational level and thus on processes which "assess performance and future condition of the equipment" and "carry out and support a safe maintenance action" (according to Levrat *et al.*, 2008 terminology). To provide further details of the analysis, the concept of M-TIS is adopted in order to identify the services that bring value to the maintenance processes. These services are then decoupled from the technology that is used to implement the service. Indeed, the enabling technology can be selected from among the components used in E-maintenance platforms, such as those mentioned in Section 2.

The concept of M-TIS is a revision of the concept of "applied services", as presented in Macchi *et al.* (2012), through combination with the model-driven service engineering (MDSE) approach that was proposed by Chen *et al.* (2012). In the MDSE approach, modelling levels are defined in order to analyse services. These include business system modelling (BSM), technology independent modelling (TIM), and technology-specific modelling (TSM). These concepts have been adapted to our focus on maintenance and contribute to the definition shown in Figure 1. At the BSM level,

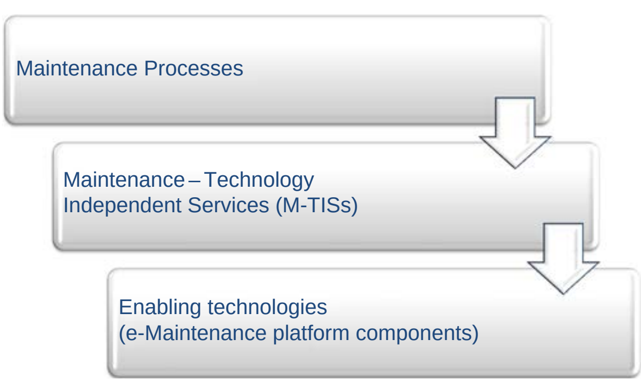

Figure 1.
A multi-layer view of a value-driven approach to consider technologies for maintenance services

maintenance processes are considered; at the TIM level, the above-mentioned M-TISs are considered.

At the TIM level, in fact, specifications of the structure and functionality of the service are given without technological details. Indeed, the TIM level focuses on the operational details, hiding technological specifications in order to comply with the different technologies (Chen *et al.*, 2012). The TIM level of abstraction thus allows the examination of the use of the functional features of technological components to support maintenance processes.

TSM is not specifically addressed by this study. The aim of the value-driven methodology proposed in this paper is to consider how to identify M-TIS specifications, and then to decide which components of the E-maintenance platform to introduce in service deployment. At present, the approach does not consider how to model and thus design the E-maintenance platform component as a technological solution to deploying the M-TIS.

The practical use of the presented multi-layer view (Figure 1) considers that each maintenance process may thus require one or more M-TISs as support, which are re-engineered from an AS-IS state to a TO-BE state. Similarly, a service may need one or more functional features to be sourced or developed, beginning with the features available from the technological components of an E-maintenance platform. In other words, a set of E-technologies and technological components (bottom layer) is applied to develop services (mid layer) that are originally considered independent from the technology. Such services then support a set of enterprise processes as part of a maintenance management system (top layer).

The present research considers that value is the leading concept. The layers of service and process are additional matters of concern. Therefore, the approach proposed in the paper aims at the top-down derivation of technical specifications of the components of the E-maintenance platform, beginning with the value that the supported services can bring to processes.

4. Methodology for the value-driven engineering of E-maintenance platforms

4.1 Value-driven engineering

The concept of value is widely used in the literature, and it is widely applied in many fields. For example, Den Ouden (2012) proposed the value framework that encompasses four different perspectives of value from the viewpoint of four social sciences (economics, psychology, sociology and ecology), pointing out that value does not hold the same meaning for everyone in every context. Thus, several definitions of value apply to different authors and contexts. The Oxford Dictionary of English defines value as “the regard that something is held to deserve; the importance, worth, or usefulness of something”. According to Mason and Spring (2011), value can be also defined as the benefits derived by a customer from an exchange. In addition, it is noteworthy that the scope of value includes a wide range of stakeholders, which involves not only economic transactions but also relationships, exchanges and interactions (Allee, 2011). Furthermore, many of these valuable issues lead to intangible benefits for the stakeholders, which are hard to measure.

Although it is also discussed in other disciplines, the concept of value receives particular attention in the business literature. For example, Porter’s value chain framework can be used to understand or analyse the logic of firm-level value creation regarding the economic performance of a company (Porter, 1985; Stabell and Fjeldstad, 1998); Richardson (2008) used value as a central concept in the analysis of business logic adopted in implementing a strategy. This concept has been thoroughly studied in business theory, which has led to the emergence of several related concepts, such as value creation, value chain, value network and value proposition. Used mainly in discussing business models, the concept of value proposition has been defined in many ways: it is variously seen as an aggregation, or bundle, of products and/or services that a firm offers to customers (Osterwalder and Pigneur, 2010) and represents the value of competitiveness with respect to other companies in the market (Richardson, 2008).

The concrete application of the concept of value to engineering domains has led to related concepts, such as value-driven decision making (e.g. Lazarus (1997) proposed it for air combat simulation) and value engineering. Value engineering is 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). It is seen as a function-oriented systematic method for analysing and improving the value of product, design, system, service or process in order to increase customer satisfaction and investment value (Ojala, 2004). Furthermore, value engineering is also considered a synonym for value management and value analysis concepts (Ojala, 2004).

The literature shows evidence regarding the application of the value concept to maintenance. Since the value analysis of maintenance operations carried out by Weiss (1979), few other authors have studied the value of maintenance activities. Most have focused on economic value. In this regard, Marais and Saleh (2009) asserted that maintenance has intrinsic value, although it has been frequently dismissed or neglected because its benefits are difficult to quantify. Liyanage and Kumar (2003) extended the meaning of value regarding maintenance, emphasizing not only its economic benefits but also its social and environmental value in the cases of social equity and environmental concerns, respectively. Moreover, business theory has been used to enhance maintenance methodologies through value orientation. It is worth citing, for example, methodologies such as business-centred maintenance (Kelly, 1997) and value-driven maintenance (Rosqvist *et al.*, 2009).

The methodology presented here follows this theoretical background. It aims to exploit the concept of value in order to explicate the logic behind the identification of alternative E-maintenance solutions to satisfy the needs of target stakeholders. Therefore, it is expected to enhance the value orientation of planning methods regarding new technologies and services related to maintenance.

4.2 Methodology

According to Marais and Saleh (2009), "the value of an engineering system is determined by the market assessment of the flow of services the system provides over its lifetime". Thus, in this work, the value of an E-maintenance platform can be determined by the benefit analysis of the maintenance services (i.e. M-TIS), which are provided throughout its lifetime. This section introduces a methodology that considers this approach in order to drive the planning decisions regarding new technological advances in E-maintenance platforms. In this methodology, the focus of value engineering is on increasing the satisfaction of stakeholders and the value of the solutions. To this end, the logic, which drives the methodology presented here, is the concept of value for the stakeholders in the E-maintenance platform. The value for the stakeholder is considered through the capabilities that M-TIS can provide, namely the beneficial effect on business objectives.

In particular, the following assumptions are considered as the background of the methodology: value proposition can be better understood and estimated when the planner considers how the process is innovated – from the AS-IS to the TO-BE state – thanks to the new practices; technological development leads to new operational practices at the process level; and value is created when the process is innovated, which enables the achievement of business objectives.

By re-interpreting the definitions in the business literature, we can then assert: "the value proposition is the bundle of competitive advantages for maintenance processes that an E-maintenance platform offers through the deployment of some related services". Accordingly, competitive advantages are gained through new operational practices enabled by the implemented M-TISs in one or more concrete maintenance processes; this process innovation eventually allows the creation of value.

The methodology involves the concept of value, in particular the creation of value envisaged through services enabled by maintenance technologies. It has a process-oriented view regarding the innovations on operations and maintenance. It is organized in five steps that lead the process from the identification of stakeholders' requirements to the final assessment of the value achieved by the deployment of M-TISs (see Figure 2). The methodology proposes a path for actions to be taken, but not the use of any particular tool. However, some potentially useful tools or methods for each step and for decision support in the methodology are mentioned later as suggested means for realizing the methodology in complex cases.

The first step, "target value identification", is based on the premises that stakeholders' requirements and needs are the focus of value-driven engineering, and it aims to determine the target value that the company requires from the potential innovation guided by maintenance services. In order to identify clearly the requirements regarding what stakeholders value in the potential implementation of an E-maintenance platform, the use of a very simple tool is proposed – a value tree – which will help to identify the value target, that is, the benefit/s targeted by the implementation. An example of a value tree is given in Figure 3. This example is not intended to be comprehensive but to aid stakeholders in the definition of the targeted value. Although the definition of value can be extremely complex, as discussed in the previous section, the value tree presented here considers only the simple categorization of two branches: tangible value and intangible value, discussed within maintenance scope in Macchi *et al.* (2012) and within a different scope in Miragliotta *et al.* (2009) and Balocco *et al.* (2011). The tangible value branch includes efficiency, effectiveness and quality as possible benefits that can be obtained, whereas intangible value branch concerns safety, brand reputation, customer satisfaction and loyalty, skills and

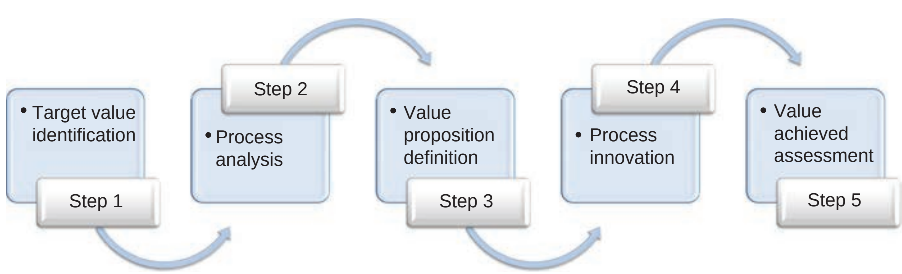

Figure 2.
The methodology for value-driven engineering of E-maintenance platforms

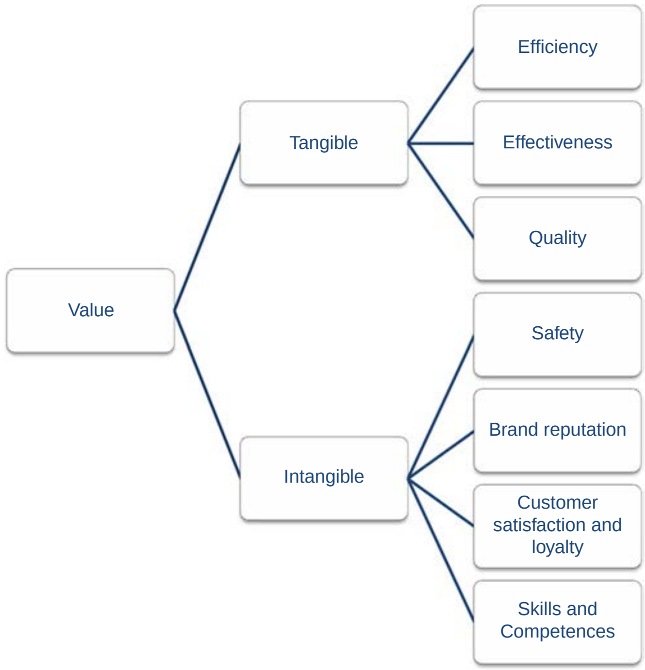

Figure 3.
Generic value tree

competences as improvements that could be provided by the implementation of an E-maintenance platform. It is possible that the requirements cover more than one type of value within the value tree, in which case it would be essential to establish a scale that could be applied in subsequent steps for the selection of the M-TIS to be implemented.

The second step, "process analysis", refers to a comprehensive study of the company's specific case. This consists of the in-depth analysis of the processes that could be potentially involved in the implementation of the E-maintenance platform, its related equipment and its required functions. Specifically, this step aims at identifying which processes and equipment could benefit the most from the implementation of E-maintenance technologies. In this step, the main assumption is that the study is driven by the failure analysis of the equipment. Hence, any technique or tool that allows the detailed study of the functions of equipment and its failure modes could be used in this step to determine the practices and processes that are more likely to be the highest value-added from the services enabled by E-maintenance technologies. Some examples of these techniques are mentioned by Crespo Márquez (2007) in the definition of asset priorities and maintenance action planning. These include quantitative or qualitative CA, failure root-cause analysis, and failure mode, effects, and criticality analysis (FMECA). In this regard, RCM should be mentioned because it is a well-known, traditional approach to carrying out CA to plan decisions based on FMECA (Rausand, 1998).

The third step, "value proposition definition", encompasses the integration of the results from previous steps in order to define the value proposition, that is, a proposal of the recommended M-TIS that caters to the stakeholders' requirements in relation to the target value. One or more value propositions could be identified and proposed at this step in order to match the stakeholders' targeted value with the maintenance processes that were identified as adequate for obtaining the required benefits. Because several value propositions could be suggested, it is necessary to identify clearly the value offered by each in order to facilitate the selection of the most adequate. However, the company may not be able to implement all proposed solutions because of financial constraints. This decision-making process should be performed by prioritizing all value propositions proposed, to facilitate the company's decision to invest in the M-TIS/s that could add the most value regarding their targeted goals.

In the fourth step, "process innovation", the process innovation is realized by the implementation of one or more M-TISs, depending on the value proposition/s selected in the previous step. As previously explained, the services will be deployed through E-maintenance technologies that encompass an E-maintenance platform.

The fifth and last step, "value achieved assessment", aims at calculating whether the value targeted at the beginning of the methodology before the practical deployment of the M-TIS/s has been achieved or not. The estimation of value achieved can be done using information sources, such as benchmarks, experts' opinions and mathematical models, as well as periodic monitoring practices, depending on the specific nature of the targeted value. In a proposal, specifically for tangible value, a set of key performance indicators (KPIs) could be the best assessment approach because they could be fixed at the third step of the methodology in addition to the prioritization of the targeted value. In this way, the relation between the KPIs and targeted benefits is established, which could help to verify the level of achievement of the value propositions when the E-maintenance solutions have been implemented.

4.3 Methods for supporting the methodology

Some steps within the methodology may require additional support if the case under study is complex in terms of the number of stakeholders' requirements or if the M-TISs potentially affect many maintenance processes. In this case (e.g. in the case of the study reported in Section 5), the use of a method for multiple criteria decision making (MCDM) is advisable.

As mentioned in the first step of the methodology, the stakeholders' requirements may include more than one type of value within the value tree. Therefore, ranking the different types of value would be useful for initial decisions and those in subsequent steps. Similarly, the analysis of processes and equipment failure in the second step may also require the ranking of the possible improvements according to the types of value expected by the stakeholders. An integration of both ranking classifications, which is done in the first step for the types of value and in the second step for the potential process improvements, is needed in order to prioritize all value propositions proposed. This final prioritization of value propositions assists in recommending the M-TIS/s that would better address the stakeholder's requirements and then enhance the added value by selecting the processes that could provide the highest potential for improvement related to the value expected by the stakeholder.

The confluence of several types of value and processes, which could be potentially improved by the implementation of an M-TIS, necessitates the ranking process during the use of the methodology. Thus, a method for MCDM would be useful during the first three steps. The selection of a method for MCDM in the first step by assigning priorities or weights to stakeholder's requirements would imply the use of that method in the next two steps. Methods such as the analytic hierarchy process (AHP), the compromise ranking method (VIKOR, which is the acronym of the original name in Serbian) or the technique for order preference by similarity to an ideal solution (TOPSIS) could be used depending on the complexity or particularities of each case. AHP implies the reduction of complex decisions to a series of pairwise comparisons and rankings in which both qualitative and quantitative criteria are taken into consideration (Saaty, 1980). VIKOR, which was developed for the multi-criteria optimization of complex systems in the presence of conflicting criteria, and TOPSIS, which was developed by Hwang and Yoon (1981) with an unique approach considering both an ideal and a negative-ideal solution, are both based on functions representing closeness to the ideal solution, using different normalization processes (Opricovic and Tzeng, 2004). This list of methods is not comprehensive, so either those mentioned here or other supporting methods for MCDM could serve for the same purpose of supporting the use of the methodology.

5. The case study

5.1 Context and purpose of the case study

The case study concerns a multinational group that produces high quality textiles for the fashion sector. The strategic goal of high quality requires the accurate selection of raw materials, the use of control technologies in different production phases, the adoption of advanced machining systems within the plants of the company. The seven plants owned by the company are distributed through Europe and the Mediterranean area. The total number of employees is about 1,400, an average of 200 employees in each plant.

In this context, the company invested in a SCADA system as the enabling technology to innovate process and plant operations. Indeed, the primary objective of the investment was the achievement of high quality in production processes because of the high level of automation for controlling the plant's utilities and production lines. In addition to the function of production control, the SCADA system was used as the IT architecture for the development of services supporting the tasks of maintenance personnel. After the initial investment, a follow up should allow the proper exploitation of SCADA in maintenance, which is in accordance with the company's philosophy of achieving the potential high synergies between production and maintenance functions.

The case study was developed in the context of a main plant of the company, which is located in Northern Italy. Another plant, where similar technology was implemented, is also taken into account as further evidence. In both sites, the technology was introduced to upgrade existing facilities. The purpose of the case study was to test the methodology proposed by the present work, considering the development of services run by the SCADA system, which is the main component of the E-maintenance platform. The test focused on the support of the execution of maintenance interventions in the plant's utilities for the distribution of electric energy, water and steam, processing and draining water outflows, processing the chemicals used in the production process and the critical equipment used in the production lines. In this section, only the case study in the main plant located in northern Italy is considered.

5.2 Methodology for the case study analysis

The test consisted of formalizing the decisions for the development of M-TIS deployed through the SCADA. These decisions were already taken in the last five years, during which focused improvements were progressively implemented through specific services deployed to the plant operations. Therefore, the analysis of the case study required beginning before the decisions were taken in order to simulate the use of the methodology to identify the relevant improvements:

- The first phase of the case study aimed at collecting the major information regarding the company in terms of maintenance processes, as well as the technological and architectural features of the IT and the plant automation system, with specific focus on the SCADA and its links to the lower levels of the plant automation (i.e. PLC and other devices). The purpose was to obtain a descriptive model of the current situation of maintenance services and their advantages for improving maintenance and operational performances. This phase consisted of interviewing selected personnel in the company and the collection of documentation in order to obtain a concrete picture of the current practice. In order to understand the operation of the SCADA system used for maintenance, the researcher took a reactive position.
- The second phase of the case study consisted of moving back in order to simulate the use of the methodology for identifying the M-TIS to be deployed through the SCADA. In this phase, the researcher played a proactive role, leading the analysis and coaching the company's personnel when they applied the methodology, in order to decide on the focused improvements in the SCADA. Subsequently, the technical manager of plant automation for the group, who was also the maintenance manager of the plant under analysis (referred to here as the technical-maintenance manager), was primarily involved in a number of meetings in order to share the methodology and decisions achieved so far. Because of the double role, his considerations could represent two views: the potentials available from the technologies and the service needs arising from the maintenance processes. This eventually resulted in a plan of E-maintenance service deployments prioritized for progressive implementation (i.e. from the highest to the lowest priority). This encompasses the first three steps of the proposed value-driven engineering methodology presented in Section 4.2.

Figures 4 and 5 present samples of the results of the first phase of the case study. They show the existing architecture and some screenshots of the current maintenance practice using the SCADA. Referring to the first three steps of the methodology described in Section 4.2, the second phase of analysis is presented in Sections 5.3, 5.4 and 5.5.

5.3 Target value identification

Target value identification is aimed at determining the target values that the company requires from the potential innovations resulting from SCADA. The generic value tree shown in Figure 2 was presented to the technical-maintenance manager who expressed that only tangible values for driving E-maintenance service deployments were required, assuming that intangible values would be achieved as a consequence. Later, MCDM logic, proposed to support the methodology, was deemed essential to discriminate the importance of each tangible value. During the case study, AHP was proposed as a MCDM tool, to which the manager agreed because its systematic procedure appeared flexible and affordable enough for introduction to the experts involved in the company.

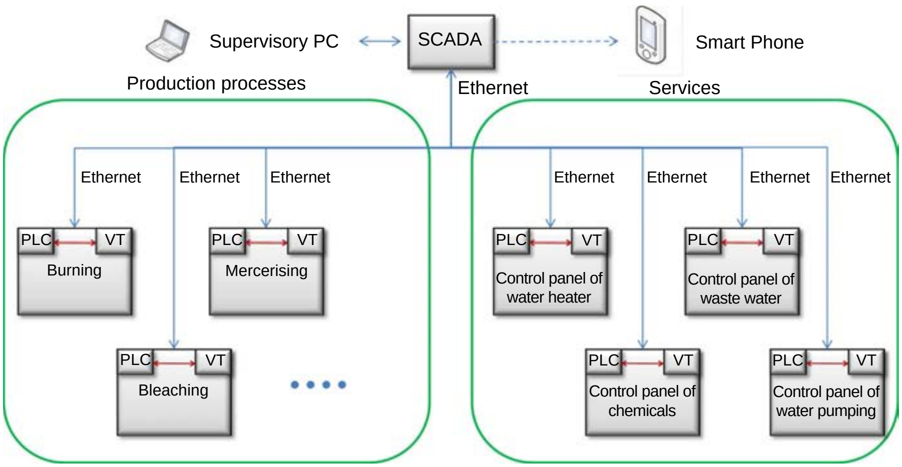

Figure 4.
Hardware architecture of plant automation

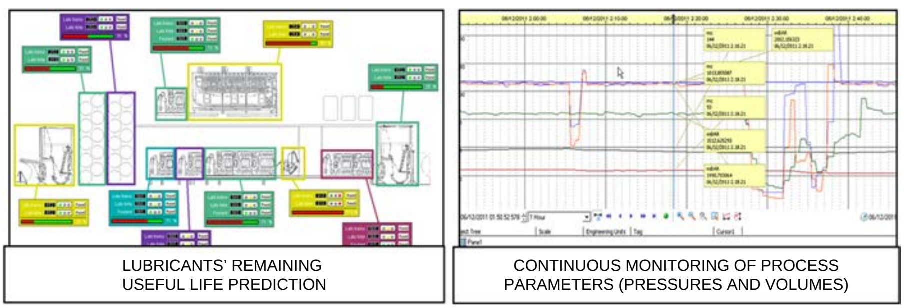

Figure 5.
Screen shots available as graphic user interface of the services of the SCADA system operated as the E-maintenance platform

Briefly, AHP consists of a procedure that supports complex, unstructured and multiple-attribute decision making. It is a powerful tool for determining the relative priorities or weights (reflecting the given importance) assigned to the criteria that characterize a decision (Saaty, 1980). A typical AHP analysis starts with a hierarchical structure of the decision problem. The structure is built from the top level, which represents the goal of the analysis; the intermediate levels then define the relevant criteria and sub-criteria adopted for the analysis; the bottom level introduces the possible alternatives under study according to the criteria and the sub-criteria. Once the hierarchy is built, a series of pairwise judgments by the experts allows the assignment of the relative importance of criteria, sub-criteria and alternatives. This enables the reduction of complex decisions to simple rankings of criteria, sub-criteria and alternatives, which helps the expert identify the best decision accordingly to his/her own interests, while perceiving a clear rationale for the decisions taken.

In our context, we use a different approach to AHP analysis, the so called ratings mode, in which, instead of choosing the best of several alternatives, gives different weights to more than two criteria when looking for the prioritization among them. We do this by adding a level that is above the alternatives, consisting of ratings that are refinements of the criteria or sub-criteria governing the alternatives (e.g. high, medium, low ratings) (Saaty *et al*, 1991; Partovi and Burton, 1993).

AHP has been used for MCDM in the maintenance domain, especially in supporting the selection of maintenance strategy (Bevilacqua and Braglia, 2000; Wang *et al.*, 2007), spare parts classification (the first applications are Partovi and Burton, 1993; Gajpal and Ganesh, 1994), and CMMS selection (Braglia *et al.*, 2006). The case study revealed the interest in adopting AHP for driving the deployment of E-maintenance service based on multiple criteria. AHP was then carried on in the step of target value identification, thus obtaining the AHP hierarchy of tangible values and expressing the relative importance between criteria: quality, efficiency and effectiveness selected from the value tree. The ratings for each criterion – high, medium and low – were defined to represent different degrees of effects to obtain an overall criticality score of the various types of maintenance activities regarding each criterion.

Figure 6 presents the AHP hierarchy, which is simply a value tree reduction, extended by the rating options and developed for the calculation of a criticality score, as the goal of the analysis. Table I shows the results of the AHP analysis obtained by asking the technical-maintenance manager, operations manager and quality manager, who were selected as the main stakeholders in the investment, to ascertain the relative importance of criteria and rating options. The results shown in Table I are the average of the total answers as well as the single answers of each stakeholder. They represent the AHP scores that as a normalized value, determine the relative priorities or weights (reflecting the given importance) of each criterion and of the rating options within each criterion. Each criterion and rating option was compared pairwise to the rest by using a judgment ratio scale as derived by Saaty (1980).

The analysis of the importance assigned by each stakeholder showed that the target values were homogeneous and well aligned within the company. In particular, in all responses quality was the most important criterion and aligned to the strategic goal of the company; effectiveness was the least important, in relation to the decrease in market demand in the challenging context of competitive forces of new economies and

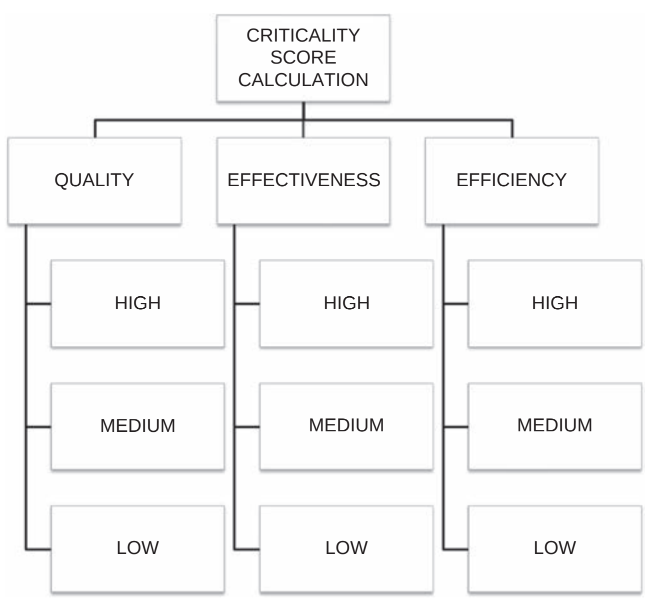

Figure 6.
AHP hierarchy derived from the value tree

	Tech.–maint. manager	Operations manager	Quality manager	Average
AHP score expressing the relative importance between criteria (AHP_score_j)				
Quality	0.55	0.60	0.80	0.65
Effectiveness	0.10	0.10	0.20	0.13
Efficiency	0.35	0.30	–	0.22
AHP score expressing the relative importance between rating options ($AHP\_score_{k,j}$)				
High quality	0.6	0.7	0.8	0.7
Medium quality	0.2	0.2	0.2	0.2
Low quality	0.2	0.1	0	0.1
High effectiveness	0.5	0.6	0.4	0.5
Medium effectiveness	0.3	0.2	0.4	0.3
Low effectiveness	0.2	0.2	0.2	0.2
High efficiency	0.6	0.5	0.4	0.5
Medium efficiency	0.2	0.3	0.4	0.3
Low efficiency	0.2	0.2	0.2	0.2

Table I.
Results of AHP analysis from different perspectives (single stakeholder, average of stakeholders)

low-cost countries[1]. Nonetheless, some bias in relative importance was indicated because the interests of single enterprise function may still be recognized. Indeed, the fact that the technical-maintenance manager showed more preference for the criterion of efficiency could be explained by the constraint of the low number of maintenance operators available at the plant and the subsequent need for their efficient operation.

5.4 Process analysis

This step consisted of a comprehensive, in-depth study of the company's specific maintenance processes, in which the innovations resulting from the use of SCADA could be potentially realized. Considering the type of technological support available in this system, the study promptly focused on a sub-domain of maintenance processes, which concerned the operational level and the execution of corrective and preventive maintenance interventions. Indeed, the technical-maintenance manager agreed with this as the focus of application of SCADA in the company. This was later aligned with the expectations of the methodology, in accordance with the above-cited "model of the maintenance business functions and processes" (Levrat *et al.*, 2008). Instead, other sub-domains at the tactical and strategic levels of maintenance management were excluded as targets of the application of services potentially implemented in the SCADA. Hence, at this moment, the first phase of process analysis step was agreed by all stakeholders involved in the project, primarily the technical-maintenance manager, regarding the scope of maintenance processes addressed by the E-maintenance platform under development.

A second activity carried out in this step aimed at further investigating the process criticalities that SCADA, operated as E-maintenance platform, would help to limit or avoid. To this end, A RCM-like approach was performed. This resulted in the identification of the hotspots present in the plant's utilities and production line equipment, for which the SCADA system was introduced (i.e. utilities for distributing electric energy, waters and steams, processing and draining water outflows, and processing chemicals used by the production process, which were the main functions of the equipment on the production lines). The RCM-like approach was selected in this step of the process analysis because of the culture already present in the company, as well as the good technical expertise and adequate set of data for its actual enactment. Based on known approaches to carrying out RCM (Rausand, 1998), the study initially aimed at assessing the actual criticalities within the plant's utilities and line equipment, by means of a traditional functional failure analysis using simple table formats. The peculiarity of this RCM study was that, with feedback from the technical-maintenance manager, the AHP analysis was adopted as previously developed in the target value identification step (Table I) to establish the criticalities of the functional failures in the plant's utilities and line equipment. Later, the activities included in the maintenance plan were also assessed for their criticalities, using the AHP analysis already developed. This decision was made to support the general assessment of both corrective and preventive maintenance interventions performed at the plant, as background useful to focus on where to introduce E-maintenance solutions. An extract of the results of the RCM study is shown in Table II.

The functional failure modes (thus, the correspondent corrective maintenance interventions) and the methods of machinery controls included in the maintenance plan (thus, the correspondent preventive maintenance interventions) were evaluated for their impacts on the target values (see Table II). The evaluation exploited the AHP scores calculated in the target value identification for criteria and rating options (see Table I). Moreover, the involvement of experts was required to characterize the effects. The involvement was achieved in a brainstorming meeting with two maintenance technicians (one mechanical and one electric), which was coordinated by the technical-maintenance manager.

Equation (1) was adopted to formulate the AHP-based criticality analysis:

$$AHP\_score_w = \sum_{j=1}^{J} \sum_{k=1}^{K} AHP\_score_j \times AHP\_score_{k,j} \times B_{w,k,j} \quad (1)$$

where AHP_score_j is the AHP score assigned to the jth criterion (see Table I); $AHP\_score_{k,j}$ the AHP score assigned to the kth rating option within jth criterion (see Table I); $B_{w,k,j}$ the effect of wth maintenance intervention (either in the functional failure or the method of machinery control) with respect to kth rating option within criterion j (a Boolean variable equal to 1 if the effect exists, 0 if not, defined during the brainstorming meeting with maintenance technicians); AHP_score_w the AHP score assigned to the wth maintenance intervention (either for the functional failure or the method of machinery control) (reported in Table II).

For example, the functional failure mode "drifts of oils in the production lines" caused by "over-lubrication" was considered to have a great effect on quality and a medium effect on effectiveness and efficiency. This was formulated as the Boolean variable $B_{w,k,j}$ equal to 1 for the rating option "high" of criterion "quality", "mid" of the criterion of "effectiveness", and "efficiency", which eventually results in the AHP score for the functional failure, as shown in Table II.

5.5 Value proposition definition

The value proposition aims at reducing maintenance process criticalities through the better control of the functional failure modes and/or maintenance plan improvement. This hypothesis was discussed with and agreed by the technical-maintenance

Table II. Extract of the results of the criticality analysis in the RCM study

Failure analysis				Maintenance plan			Maintenance policies
Functional failure mode	Cause of failure	Effects of failure	Criticality analysis (AHP score functional failure mode)	Methods of machinery controls prevention	Methods of machinery controls detection	Criticality analysis (AHP score methods of machinery control)	Type of maintenance
Drifts of oils in the production line	Faulty lubrication-overlubrication	Potential spoilage of product quality	0.56	Lubricants' re-integration	Periodic control of lubricants' levels through walk around inspections	0.20	Preventive maintenance
Stoppage of roller conveyor in the production line	Faulty lubrication-underlubrication	Production losses with unexpected downtimes	0.20				
Pump use not properly driven by the inverter	Faulty measures from pressure sensors	Production losses with unexpected downtimes	0.24	None	None	None	Corrective maintenance
Valve does not open/does not close	Mechanical wear	Production losses with unexpected downtimes	0.31	None	None	None	Corrective maintenance
Electric motor stoppage	Low insulation resistance	Production losses with unexpected downtimes	0.17	None	None	None	Corrective maintenance

manager. Accordingly, a set of recommended M-TISs to be deployed through SCADA operating as E-maintenance platform was defined. In fact, the criticalities defined in the previous step of the process analysis were the main driver for selecting the services to be developed in order to cater the company's requirements.

Once the recommended service was identified, its competitive advantages were thoroughly defined with assistance of the technical-maintenance manager. This considered the analysis of both the functional failures and the maintenance plan (Table II) and envisioned how the service would reduce the respective criticalities (see the competitive advantages identified for each service in Table III). Subsequently, the AHP score of the service was the sum of all the AHP scores of the functional failure modes and methods of machine controls prevention/detection that the service expected to reduce:

$$AHP\_score_s = \sum_{w=1}^{W} AHP\_score_w \times B_{s,}w \quad (2)$$

where $B_{s,w}$ is the effect of sth recommended service for the wth maintenance intervention (either for the functional failure or the method of machinery control) (a Boolean variable equal to 1 if the effect exists, 0 if not, as defined in a meeting with the technical-maintenance manager); AHP_score_s the AHP score assigned to the sth recommended service.

A classification method was then agreed with the technical-maintenance manager in order to enable a pragmatic approach to the definition of the value proposition. This allowed the prioritization of the E-maintenance services to be deployed. Indeed, the classification was based on the well-known Pareto method, which was adopted to organize the AHP scores of recommended services according to three different classes of importance – A, B and C – from the most to the least important class (i.e. from services of the highest priority to services of the lowest priority). Each class corresponds to a range of AHP scores of the recommended services: class A refers to services of the highest importance (i.e. highest scores); class B represents services of intermediate importance (i.e. intermediate scores); class C includes services of the lowest importance (i.e. lowest scores).

Finally, the target completion date for the implementation of the recommended services was also determined, which resulted from a discussion with the technical-maintenance manager. The completion date was driven by both the priorities of E-maintenance service deployment, and the limits of the yearly budget. The main hypothesis was to build an E-maintenance plan, during the five years considered for the simulation of the methodology. The purpose was to deploy focused improvements in the SCADA system, subject to the budget constraints normally expected in each year.

The following example is noteworthy:

- A service for "the prediction of the remaining useful life of lubricants" was considered in order to prevent faulty lubrication, which caused risks of drifts of oils or roller conveyor stoppage as functional failures in the production line. This predictive service would reduce criticalities in concern about the value of "quality" (i.e. reduced product quality because of drifts of oils) and "effectiveness" (i.e. roller conveyor stoppage with unexpected downtimes). Furthermore, this service would improve the maintenance plan. By working with the visual aid of SCADA, the maintenance personnel in the control

Failure analysis	Maintenance plan		E-maintenance plan				Maintenance policies
Functional failure mode	Methods of machinery controls prevention	Methods of machinery controls detection	Recommended service(s)	Competitive advantage(s)	Priority (class and AHP score recommended service)	Target completion date	Type of maintenance
Drifts of oils in the production line Stoppage of roller conveyor in the production line	Lubricants' re-integration	Continuous monitoring of lubricants' levels and operating time and plant conditions	Lubricants' remaining useful life prediction	Prevention from over-lubrication and risk of drifts of oils; and under-lubrication and risk of roller conveyor stoppage; avoidance of walk around inspections for control of lubricants	Class A, 0.96	Year 1	Preventive maintenance
Valve does not open/does not close	None	Continuous monitoring of valve processing time (time to open/close the valve)	On line analysis of monitored performance	Anticipated detection of failures and reduction of unscheduled equipment stoppage	Class B, 0.31	Year 1	Preventive maintenance
Pump use not properly driven by the inverter	None	Voting procedure on measures collected from pressure sensors operated in redundancy	Surveillance and alarm handling (after fault detection based on the voting procedure)	Plant surveillance 24 hours and quick intervention	Class B, 0.24	Year 2	Corrective maintenance
Electric motor stoppage	None	Continuous monitoring of electric motors' power absorption	On line analysis of monitored performance	Anticipated detection of failures and reduction of unscheduled equipment stoppage	Class C, 0.17	Year 3	Preventive maintenance

Table III.
Extract of the results of the RCM study: maintenance and E-maintenance plan to reduce process criticalities

room would be able to monitor the lubricants' features continuously, instead of frequently making inspections throughout the plant's utilities. This would reduce the criticality of the value of "efficiency" in the maintenance plan. The service clearly fostered a number of competitive advantages aimed at the reduction of process criticalities.

- Accordingly, the AHP score Equation (2) resulted from the AHP score of functional failures (i.e. drifts of oils and roller conveyor stoppage because of over/under-lubrication) and one method used to detect machinery control (i.e. periodic walk-around inspections). All related interventions were influenced by the recommended service, which affected all the target values – quality, effectiveness and efficiency – of the company. The service then resulted in class A because of its highest importance (i.e. highest AHP score) in all such values.
- The service was planned in Year 1 because of its high priority as a service of class A as well as its expense within budget constraints.

Table III shows an extract of the results obtained for the value proposition definition, showing the priorities and target dates for a sample of services recommended to reduce process criticalities.

Methodologically, similar to Tables II and III can be considered the result of a RCM-like approach. Indeed, known RCM tools inspired the table format. Nonetheless, new concepts were also included. These were incorporated from value theory in the background of the methodology. In particular, the value proposition definition, expressed in the E-maintenance plan section of Table III, is formalized in "recommended services" and the subsequent bundle of "competitive advantages".

5.6 Concluding remarks about the case study

Figure 7 illustrates workflow, synthesizing the concept of the methodology developed for the value-driven engineering of E-maintenance platforms, showing how it was understood and applied in the case study.

It is worth underlining that the step involving the definition of value proposition followed the identification of criticalities measured through the AHP scores of functional failure modes and methods of machinery control prevention and detection included in the maintenance plan. Furthermore, related to the target values elicited by the value tree, the AHP analysis was the means of effectively enabling the value-driven engineering. With regard to the budget constraints, although they were essential in planning the deployment of the E-maintenance service throughout the project, they were related to cost assessment. Hence, the technical-maintenance manager agreed that they were not part of the value-driven engineering concept. On the other hand, the budget constraints were essential in the post-processing step in order to assess and make the plan for the development of E-maintenance solutions.

With regard to the results of the study in terms of decisions, it is noteworthy that from the sample shown in the extracts, the new maintenance plan (Table III) improved the original plan (Table II) by implementing methods of machinery control detection, based on the continuous monitoring supported by the SCADA system. It was then evident that the type of maintenance changed. The increased preventive maintenance replaced corrective maintenance (compare Tables II and III). This change aligns with

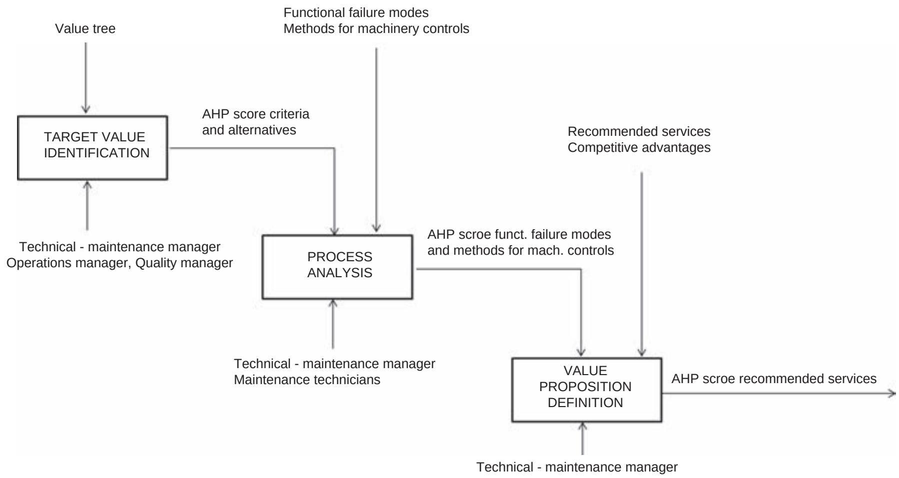

Figure 7.
Work flow in the case study highlighting the three steps of the proposed value-driven engineering methodology: AHP-based criticality analysis as a driver of value proposition definition

the results actually achieved at the end of Year 5 concerning the share of personnel time, the dramatic increase of condition-based predictive maintenance, and the corresponding reduction of corrective maintenance and other frequent activities of assistance in plant control and regulation. Specifically, performance changed after the actual deployment of E-maintenance services in SCADA. Three KPIs relevant to the target values driving the decisions were assessed to measure the changes occurring over the five years in the simulation of the methodology:

- It was decided to control the non-conformity rate as a measure of the target value of "quality". This standard indicator of the company was adopted to assess the number of products to be reworked with respect to total products released to the plant. This was decreased at the end of Year 5 to about 60 per cent compared to its initial value taken as reference base. This technical value was agreed with the company expert and allowed the reduction of more than 15 per cent, which was an effect of the improvements made by the deployment of the E-maintenance service through SCADA.
- Related to the target value of "efficiency", the share of personnel time for condition-based predictive maintenance almost doubled, growing from an initial value of about 15 per cent to a final value exceeding 30 per cent. Thus, more value-added activities were carried out by maintenance personnel now involved as supervisors in the control room. An additional advantage was relevant savings in the assistance to production in plant control and regulation, which previously was an inefficient activity because of the time taken to walk around the plant's utilities. Assistance is now limited to about 3-4 per cent of personnel time. Previously, it amounted to 25 per cent of personnel time before the improvements guaranteed by the services deployed through SCADA.
- Availability was used to measure the target value of "effectiveness". In this measure, the growth was about 5 per cent in five years because of the reduction of corrective maintenance. This result was clearly related to the new maintenance plan and E-maintenance support.

With regard to the effects on managerial capability resulting from the application of the methodology, the technical-maintenance manager made some interesting observations:

- The methodology may help to formulate properly the priorities of recommended services to be deployed. Nonetheless, without using the methodology, these nearly aligned with the actual service deployments realized during the five years of the case study. In particular, some differences were identified, although a minor percentage accounted for less than 10 per cent of the total recommended services. Typically, they consisted of the different timing of service deployments during the five years. Moreover, a few additional recommended services – not yet implemented – were identified. Based on this empirical evidence, the technical-maintenance manager confirmed the initial beliefs, finding the methodology helpful to reveal the decision-making rationale. On the other hand, he remarked that the decisions might not change much if they were made by an expert that was both sensible and capable of evaluating the business potential of E-maintenance technologies. Hence, the decisions would align with the target values relevant to the business strategy of the company. In this case, the methodology did not seem relevant to enhancing the managerial capability of the company.
- Conversely, the technical-maintenance manager found that the methodology would have greater justification when applied to larger companies where people with diverse roles, duties and expertise make decisions. In this context, decisions may be characterized by the hidden risks that are biased by different understanding of and motivation by the needs of the business, which may lead to potential misalignment with company objectives. The value-driven engineering methodology used to revealing the decision-making rationale would be highly beneficial in this case. Indeed, the priorities of E-maintenance service deployment could be tracked, and hence verified in audits with the purpose of confirming that decisions are aligned with business needs. To this end, another property of the methodology was particularly remarked by the manager. The multiple value-based analysis enabled by AHP procedure would be helpful in controlling and detecting any misalignment, because of the concurrent concern of different decision-making criteria.

Finally, it is worth observing that the value-driven engineering applied to this case study led to the selection of E-maintenance solutions driven especially by quality and efficiency as the most important target values. Indeed, Table I shows that on average the AHP score of "quality" is approximately three times higher than the AHP score of "effectiveness", whereas the AHP score for "efficiency" is approximately 1.5 times as high. The prioritization subsequently adopted for the maintenance and E-maintenance plans clearly led to tangible results that were aligned with the business needs, as proven by the dramatic improvements in the KPIs of non-conformity rates and the share of personnel time in value adding and efficient activities, although limited improvements in effectiveness occurred.

6. Conclusions

This research is a starting point for the further development of a value theory of E-maintenance. The proposed approach considers value a key element in the definition of an E-maintenance platform applied to a service, independently of the technology used to deploy it. This approach allows a focus on the development of services that provide results in the values pursued by companies. In the case study considered here, detailed examples of the implementation of the proposed methodology were presented. The possibility of linking the developed methodology to other supporting tools was shown, thus highlighting the flexibility of the proposed methodology. Furthermore the methodology could be customized according to the competence and tools normally adopted. This flexibility was clearly demonstrated by the case study.

Future works will consider three directions of development.

The first direction in the development of the present research will look at the possibility of standardizing the tools adopted in each step of the methodology. The tools should not be compulsory, which would constrain the methodology. Instead, the tools should be presented as a list of possible applications. From a practical perspective, further empirical tests oriented to the application of the methodology to different cases would help to identify the tools that maintenance managers select for analysis in different situations.

In the second direction of development more attention will be paid to deployment activities, namely, research that is more technology oriented should be employed to apply the methodology. The increased implementation of technology would provide supporting tools and procedures to deploy the defined M-TIS, which would bring a better focus on the last steps of the proposed methodology.

The third direction should consider to better analyse which is the effect of the proposed services at higher levels of business. This may involve the practical application of the concept of the business model. This will be applied to understand the logic of maintenance management in technology innovation in order to achieve the advantages for the company's business. This further development would also extend the scope of maintenance processes. The present study focused on a sub-domain of maintenance processes at the operational level, whereas other sub-domains at the tactical and strategic levels of maintenance management should be included as targets in the services potentially implemented, which provide different types of technological support in E-maintenance platforms.

Note

1. It is worth reminding that the methodology is applied in the case study by rolling back to five years ago: this means when crisis did not happen. In other words, the stakeholder expressed his/her past preference considering the market in the textile industry before the crisis happened.

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