FRAMEWORK FOR THE IMPLEMENTATION OF SMART MAINTENANCE

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Recent developments in sensor technology and systems for connecting digital and physical systems, often associated with the terms Industry 4.0 and cyber-physical systems, are expected to bring substantial changes to how maintenance and asset management will be conducted in the coming years. Most of the research related to Industry 4.0 and maintenance have focused on technical aspects, and less attention has been given to how to organize and manage maintenance in order to take advantage of the new possibilities offered by the fourth industrial revolution. While many claims have been made about the potential improvements related to maintenance that can be achieved from implementing Industry 4.0, empirical studies suggest that industry practitioners are struggling to realize these improvements. There are also signs that there exists overall a poor understanding of how to implement Industry 4.0. The contribution of this paper is to address these socio-technical challenges with a multidisciplinary framework for the implementation of Smart Maintenance. The framework is divided into three levels: strategic, tactical, and operational, and is influenced by lean production, systems engineering and maintenance management.

Keywords: Industry 4.0, Predictive Maintenance (PdM), Plan-Do-Study-Act (PDSA), systems engineering, SPADE, Smart Maintenance, cyber-physical systems (CPS), Prognostics and Health Management (PHM), maintenance management, Lean Production (LP), Hoshin Kanri (HK).

1. Introduction

The notion of a fourth industrial revolution instigated by the introduction of internet technology into the manufacturing industry has been popularized under the term Industry 4.0 (I4.0) (Schneider 2018). The introduction of I4.0 is believed to have the potential for large improvements across industry sectors and business functions, including maintenance and asset management (Zio 2016).

Several manufacturing companies have started or are planning to implement I4.0 (Staufen 2019), but according to Oztemel and Gursev (2020, 166) "there is still a high uncertainty and fuzzy understanding among the manufacturers with respect to the way to implement Industry 4.0 philosophy". They further claim that "it is now main responsibility of the research community to develop technological infrastructure with physical systems, management models, business models as well as some well-defined Industry 4.0 scenarios in order to make the life for the practitioners easy" (Oztemel and Gursev 2020, 127).

The increase in complexity and interconnectivity associated with the introduction of I4.0, has elevated the importance of maintenance and Smart Maintenance has been defined as "the enabler of Industry 4.0" (DIN/DKE 2018, 59). Predictive maintenance (PdM) based on online condition monitoring is often the first specific application of I4.0 mentioned (Bokrantz et al. 2020; Staufen 2019). But empirical studies suggest that industry are struggling with the implementation of data-driven PdM (Golightly, Kefalidou, and Sharples 2018; Veldman, Klingenberg, and Wortmann 2011; Van De Kerkhof, Akkermans, and Noorderhaven 2015).

This paper will address these socio-technical challenges by offering a framework for the implementation of concepts related to I4.0 in maintenance in the manufacturing industry. Because integration and interconnectedness of IT-systems, processes and people are central aspects of I4.0 (Schuh et al. 2017), approaches to utilize the potential of this concept will require an interdisciplinary and holistic approach. Systems engineering methods have proven useful in managing this type of complexity (Kossiakoff et al. 2011). Based on recent empirical studies that suggest that there are complementary effects between Lean Production (LP) and I4.0, the suggested framework also uses principles from LP.

The next section presents a brief literature review of I4.0 and Smart Maintenance. A framework for the implementation of Smart Maintenance in an I4.0 context is proposed in Section 3. The paper ends with a discussion in Section 4 and conclusions in Section 5.

2. Literature Review

2.1. *Industry 4.0 - overview*

The term Industry 4.0 or "Industrie 4.0" was first coined by a working group sponsored by the German government with the aim of strengthening the competitive position of the German manufacturing industry. According to Kagermann et al. (2013) a fourth industrial revolution is inevitable as a result of the introduction of Internet of Things and Internet of Services into the manufacturing sector.

As noted by Drath and Horch (2014), I4.0 is the first industrial revolution to be announced before it happens. The research on I4.0 has so far mostly been conceptual (Buer 2020) and there is still no commonly accepted definition of I4.0 (Oztemel and Gursev 2020).

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Previous concepts for the digitalization of manufacturing, like Computer Integrated Manufacturing (CIM) had a vision of complete automation without human intervention (Schneider 2018; Schmidt et al. 2020). In Kagermann et al. (2013) there are several references to the need for considering the socio-technological aspect in order to take full advantage of I4.0, but this appears to have been overlooked in much of the following literature (Davies, Coole, and Smith 2017).

The understanding of I4.0 that will be used in the remainder of this text is based on a report by the German research organization Acatech. Acatech defines I4.0 as "real-time, high data volume, multilateral communication and interconnectedness between cyber-physical systems and people" (Schuh et al. 2017, 11). This definition clearly places I4.0 in the category of socio-technical challenges.

2.2. *Industry 4.0 and lean production*

Lean production (LP) has for several decades been the most prominent concept for performance improvement in the manufacturing industry (MacKelprang and Nair 2010). There are however several examples of LP implementation projects that have failed to improve performance (Bortolotti, Boscari, and Danese 2015), and Schuh et al. (2017) suggest that experience from LP implementation holds valuable lesson for how to succeed with the implementation of I4.0. According to lean literature these failures are often caused by insufficient attention to organizational culture and too much focus on hard lean practices (tools and techniques) (Liker 2004; Rother 2010). In a survey on organizational culture and lean implementation Bortolotti, Boscari, and Danese (2015) found that plants that succeed are characterized by an organizational culture that focus on high institutional collectivism, future orientation, and humane orientation alongside the lean soft practices: problem solving, employee training, supplier partnership, customer involvement and continuous improvement.

There are still disagreements among academics and practitioners of what comprises LP (MacKelprang and Nair 2010). In this paper LP is understood in line with Shah and Ward (2007, 791) as an "integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability."

The notion that LP and I4.0 complement each other is popular among industry practitioners (Staufen 2015) and academics (Buer, Strandhagen, and Chan 2018), and the connection between these two concepts is a topic that has received increasing attention in operations research literature in the last 5 years (Ciano et al. 2021).

Surveys of European (Rossini et al. 2019) and Brazilian manufacturers (Tortorella and Fettermann 2018) has shown that there is a significant association between implementation of I4.0 technologies and LP practices among high performing companies.

In a survey of Indian manufacturing companies Kamble, Gunasekaran, and Dhone (2020) found a significant positive effect from implementation of I4.0 on performance, but when controlling for implementation of LP the effect became negative and insignificant. In contrast to this Buer et al. (2020), in a survey of Norwegian companies, found that companies that have implemented both I4.0 and LP performed better than can be explained by their individual effects.

Common to all these studies is that the relationship between I4.0 and LP has been studied on a high level. There is a need for further research on the relationships between the specific elements of I4.0 and LP to increase the understanding of how to succeed with implementation of both I4.0 and LP (Rossini et al. 2019; Ciano et al. 2021).

Empirical studies that investigate the effect of I4.0 and lean principles on maintenance have not been found in the literature, but in a conceptual paper by Sanders et al. (2017) Total Productive Maintenance (TPM) is postulated to be the LP tool that will benefit the most from I4.0 technology, while LP principles such as standardization, quick changeover and value-stream mapping are presented as LP tools that can support the implementation of I4.0.

2.3. *Industry 4.0 and maintenance*

There is an abundance of reports and white papers from consultancy and software companies related to the potential benefits to maintenance by implementing I4.0. One example is a report from McKinsey where it is estimated that a 10 – 40 % reduction in maintenance cost can be achieved from fitting products with sensors that monitor both condition and usage (Manyika et al. 2011). In another report from the same company it is claimed that "typically, predictive maintenance decreases the total machine downtime by 30 to 50 percent and increases machine life by 20 to 40 percent" (Baarup et al. 2015, 24). Similar statements of the potential improvements have been presented in reports by the consultancy firms Accenture (Spelman et al. 2017) and PwC together with Mainnovation (Haarman et al. 2018). However, all these reports offer few details on how the potential benefits are achieved.

Other sources paint a more moderate picture. One example of this is the software company Arundo that claims that "true predictive maintenance is not immediately applicable for most equipment, due to the paucity of relevant data" (Dobson and Misra 2019, 8). Another example is the consultancy firm Staufen that based on a survey of 450 German companies states that the "added value of predictive maintenance is likely to be far lower than is often claimed" (Staufen 2018, 35).

The potential for improvement by implementing data-driven PdM and related maintenance concepts are also presented in the academic literature, with claims of the potential to reduce maintenance costs, improve availability, reduce risk and provide valuable information to the design process of new equipment (Zonta et al. 2020; Porter and Heppelmann 2014; Lee et al. 2014; Sun et al. 2012). But the focus in the academic literature on maintenance optimization is mainly on developing new models with few examples of the use of data-driven PdM available in the literature (de Jonge and Scarf 2020). There are empirical studies that suggest that it is hard to succeed with the implementation of data-driven PdM in practice. In a multiple case study of Dutch process industry Veldman, Wortmann, and Klingenberg (2011, 49) found that “all the firms claimed to be struggling with prognostic condition-based maintenance tasks.” In a later case study of Dutch process industry Van De Kerkhof, Akkermans, and Noorderhaven (2015, 236) found that “many firms in the process industry struggle with systematically employing CBM activities in general and prognostic CBM approaches in particular.” Based on a series of interviews of maintenance experts from UK industry, Golightly, Kefalidou, and Sharples (2018, 640) found that implementing “full, predictive maintenance solutions were extremely challenging.”

2.4. *Smart Maintenance*

Several terms are being used in the academic literature for describing maintenance concepts that can exploit the possibilities offered by the fourth industrial revolution (Bokrantz et al. 2020). Examples are Maintenance 4.0 (Jasiulewicz-Kaczmarek and Gola 2019), Prognostic and Health Management (PHM) (Sun et al. 2012), E-maintenance (Márquez and Pham 2007), Predictive Maintenance (PdM) (Golightly, Kefalidou, and Sharples 2018), and Smart Maintenance (Akkermans et al. 2016).

In this paper we use the term Smart Maintenance because we believe that this term best describes the distinct characteristics of maintenance in an I4.0 context. Smart Maintenance is defined by Bokrantz et al. (2020, 11) as “an organizational design for managing maintenance of manufacturing plants in environments with pervasive digital technologies.” Based on interviews with 110 industry experts Bokrantz et al. (2020) analyzed the elements that constitute Smart Maintenance. These have been grouped into the four categories: data-driven decision-making, human capital resource, internal integration, and external integration (Bokrantz et al. 2020).

According to Golightly, Kefalidou, and Sharples (2018), one important contribution to the complexity of data-driven maintenance is that knowledge and competence are needed on a wide range of topics: the equipment that is monitored; the sensor technology to collect the data; the ICT-system to log and transmit the data; methods to analyze the data and make predictions; understanding of the operational context; visualizations to present the information to the decision makers, and a thorough understanding of the actions the maintenance department can take based on this information. This diversity of elements makes collaboration within and across different organizations necessary.

Roda, Macchi, and Fumagalli (2018) conducted interviews with 20 maintenance experts from Italian companies and concluded that the most important barriers are lack of a culture for data-based decisions making, lack of cooperation internally and between organizations, and lack of skills in digital technology accentuated by the difficulty of calculating the payback of the digital transformation of maintenance.

3. The Proposed Framework

This section proposes a framework for the introduction of Smart Maintenance, based on the challenges identified in the literature review. The proposed framework is built using contributions from LP, systems engineering, and maintenance management, as illustrated in Figure 1.

In accordance with Tsang, Jardine, and Kolodny (1999) the framework has been split into three different levels: strategic, tactical, and operational. Strategic decisions are understood as long-term decisions, for instance the selection of the maintenance management system. The tactical level is related to the use of available resources to realize the strategy in an effective and efficient way. The operational level is concerned with the execution of the daily maintenance activities. The different stages of the framework are explained in the rest of this section.

3.1. *The overall layout*

The overall layout of the framework is inspired by a LP concept called *hoshin kanri* (HK) which is a tool for linking strategy with the operational level (Jolayemi 2008). HK is more participative than traditional western approaches for strategy deployment, which makes management more process minded and is considered more effective to manage change (Witcher and Butterworth 2001).

The use of HK in connection with I4.0 has previously been explored by Villalba-Diez et al. (2018) and Schmidt et al. (2020) but these studies are rather conceptual and do not mention maintenance. Empirical studies on use of HK in connection with I4.0 and maintenance has not been found in the literature, but there are compelling arguments that the HK process is well suited for implementation of Smart Maintenance.

The first of these arguments is the focus in HK of having a thorough process for establishing the values, mission, and vison of the organization in order to establish the direction for the organization (Jolayemi 2008). Golightly, Kefalidou, and Sharples (2018) have found that because of the large number of stakeholders and lengthy time frames involved, a clear strategy is vital to succeed in a project with the aim of implementing data-driven PdM.

The next aspect is the process of vertical and horizontal integration when deploying this strategy (Jolayemi 2008). The approach for achieving this integration in HK often is referred to as catchball, which refers to a game of throwing a ball back and forth between players. In a corporate environment it can be defined as a facts-based dialog, up, down, and horizontally in the organization to align objectives and iterate towards the vision (Jolayemi 2008). This fits well with the need for internal and external integration that are central aspects of Smart Maintenance (Bokrantz et al. 2020). The use of PDSA is important to structure the catchball process (Jolayemi 2008).

The influence of HK is illustration in Fig. 1 by having a strategy and operational process that are connected by a PDSA-loop at the tactical level. Between all three levels are arrows to illustrate the constant dialogue and feedback between the different levels (the catchball process). The processes at all levels are circular to illustrate the iterative nature of continuous improvement.

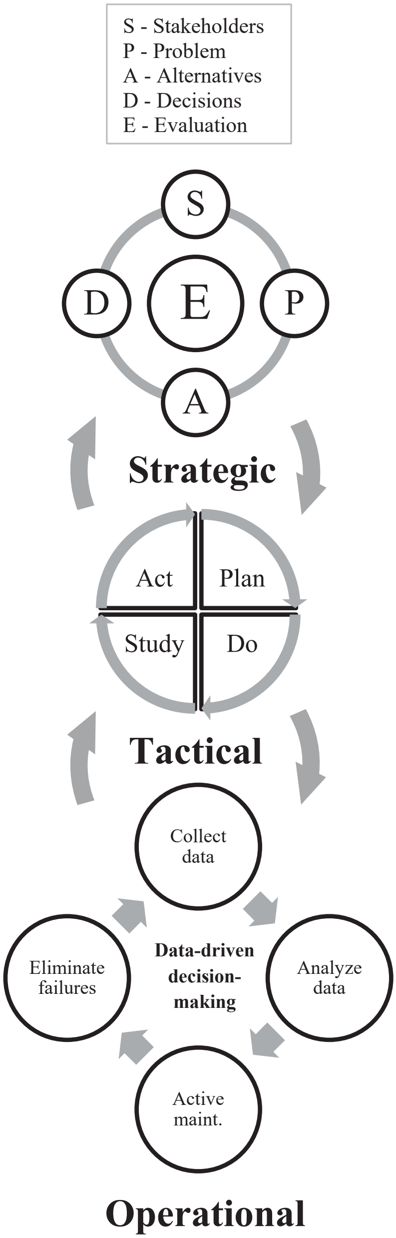

Fig 1. The proposed framework. The strategic level is based on the SPADE-model by Haskins (2008). The four phases at the operational level are inspired by Van De Kerkhof, Akkermans, and Noorderhaven (2015).

3.2. *The Strategic level*

The basic idea of I4.0 is to improve performance by combining many elements onto one system by vertical, horizontal, and end-to-end integration (Kagermann et al. 2013). Systems engineering is a discipline that offers principles and practices for how to handle such complex systems (Kossiakoff et al. 2011). At the same time, the introduction of I4.0 will affect large parts of the organization, and the framework must be easy to communicate to people who are not familiar with I4.0 or systems engineering. The SPADE-framework developed by Haskins (2008) was created to support this kind of situation and embodies the essential aspects of systems engineering in a simple and jargon-free way.

3.2.1. *Stakeholders*

Because of the importance of internal and external integration in Smart Maintenance (Bokrantz et al. 2020) it is essential to identify all the stakeholders involved. This is normally the starting point in the SPADE-model and involves finding all the relevant stakeholders, understanding their roles, and resolving conflicting interests among them (Haskins 2008).

3.2.2. *Problem formulation*

The important factors in this part of the SPADE framework are (Haskins 2008):

- to understand the current situation and the problem that needs to be solved,
- to imagine possible alternative futures,
- to establish measures of effectiveness that solutions developed at later stages can be measured against.

For a maintenance strategy to be effective it must be consistent with the manufacturing and business strategy (Pintelon, Pinjala, and Vereecke 2006). It is also important to assess the maturity of the maintenance organization (Suzuki 1994) and the digital maturity of the organization as a whole (Schumacher, Schumacher, and Sihn 2020) to be able to later set realistic targets for its implementation. Finally, in the problem formulation one must develop measures of effectiveness (Sproles 2000). See Lundgren, Skoogh, and Bokrantz (2018) for a review of models for quantifying the effect of maintenance.

3.2.3. *Alternatives*

There are several different alternative strategies available when implementing Smart Maintenance (Pedersen and Schjølberg 2020). The viewpoints collected during the problem formulation will be natural starting points for development of solutions to solve the problems (Haskins 2008).

3.2.4. *Decision-making*

When making decisions about the strategy for implementing a new technology one needs to consider not only technological aspects but also commercial aspects and organizational culture (Phaal, Farrukh, and Probert 2004). Among the choices the organization must make is what capabilities to develop internally and what to outsource (Porter and Heppelmann 2014).

A specific example related to Smart Maintenance is the recent development in remote sensing technology which has opened new possibilities for servitization of physical assets (Grubic 2018). One potential benefit of servitization is better alignment of operators and manufacturers when both have an incentive to maximize availability (Grubic and Jennions 2018). But relying heavily on an external service provider will reduce the possibility to develop the maintenance capability as a source of competitive advantage (Pintelon, Pinjala, and Vereecke 2006).

3.2.5. *Evaluation*

This is an activity that must be done continuously in order to secure that all relevant stakeholders are included; that the problem formulation is still relevant; and that feedback is used to make improvements (Haskins 2008).

3.3. *The Tactical level*

This level is related to the process of implementing the strategy. In other words, putting the strategy to work. According to a study by Kane et al. (2016) one of the main characteristics of the organizations that are successful in their digital transformation is a culture that emphasizes risk-taking and rapid experimentation. Based on this the Plan-Do-Study-Act cycle (PDSA), which is a tool for iterative improvement by testing ideas in practice (Hayes 2010), is chosen to illustrate the process at the tactical level.

3.3.1. *Plan*

In order to implement new maintenance concepts in a controlled way they must be segmented into manageable parts. Waeyenbergh and Pintelon (2002) have developed a framework for developing and implementing maintenance concepts that are suited to the needs of the organization. Several authors have proposed to use financial measures, such as return on investments, when prioritizing and planning for the implementation of Smart Maintenance and related maintenance concepts (Zio 2016). Calculating the return from the implementation of Smart Maintenance can however be hard in practice (Roda, Macchi, and Fumagalli 2018). According to the experience of Waeyenbergh and Pintelon (2004), in a manufacturing environment normally it is sufficient to elicit the most important system from the operators and begin there to implement any new plan.

3.3.2. *Do*

This is the point where the ideas and concepts from the strategic level meets the real world. Running pilots can be an effective way of testing out the new digital solutions and learn how to use them (Hayes 2010, 254). But it is important to keep in mind that a major part of the potential of I4.0 is the integration of data, processes and organizational infrastructure, and that certain benefits only can be achieved when implementation has reached a certain scale (Schuh et al. 2017; Schneider 2018).

3.3.3. *Study*

Because activities normally do not go as planned it is important to study and compare the actual results against the expected results (Hayes 2010). This stage is often referred to as the check-stage, but Deming, who is one of the most important contributors to the development of the PDSA-cycle, has argued that study is a better word because it better indicates the importance of learning (Moen and Norman 2006) from the real-world feedback.

3.3.4. *Act*

Based on the results and lessons learned, together with feedback from the strategic levels, actions are taken and adjustments are made. A new plan informed by the accumulated learning is developed, and the PDSA-cycle is restarted (Moen and Norman 2006).

3.4. *Operational level*

This is the level where the digital solutions are used to achieve improved maintenance performance. Maintenance decision have traditionally been dominated by experience and intuition (Van De Kerkhof, Akkermans, and Noorderhaven 2015). The aim of Smart Maintenance is to improve performance by data-driven decision-making. The process that is needed to achieve this is illustrated with a variant of the PDSA-cycle that is inspired by the steps for a successful CBM program defined by Van De Kerkhof, Akkermans, and Noorderhaven (2015).

3.4.1. *Collect data*

Maintenance optimization models have been a popular topic for research for several decades (de Jonge and Scarf 2020), but lack of data has traditionally been a barrier for using these models in practice (Dekker and Scarf 1998; Bokrantz et al. 2020; Sikorska, Hodkiewicz, and Ma 2011). The increase in availability of data from recent technological developments offers the possibility to lower this barrier (Zio 2016).

3.4.2. *Analyze data*

This step is about making assessments of equipment health and estimating remaining useful life based on the collected data. A large number of review papers for prognostics models for maintenance are available in the literature. See for instance Lee et al. (2014), Sikorska, Hodkiewicz, and Ma (2011), Si et al. (2011), Carvalho et al. (2019) or Zhang, Yang, and Wang (2019).

3.4.3. *Active maintenance*

Data collection and analysis have value only to the extent that it contributes to better decisions (Bokrantz et al. 2020). These decisions have been split into two groups: decisions related to when and how to perform active maintenance and decisions related to improvements that eliminates the causes of failures.

3.4.4. *Eliminate failures*

PdM will fail in an environment with too much variability (Suzuki 1994). It is important to continuously improve procedures and equipment design to reach sufficient level of stability (Van De Kerkhof, Akkermans, and Noorderhaven 2015).

4. Discussion

It is a widely held belief among both academics and industry practitioners that I4.0 and CPS have the potential to bring large changes to manufacturing environments and maintenance is one of the business functions that will be affected. But there is no consensus definition of what I4.0 entails or how to implement this concept. The large number of overlapping and sometimes poorly defined concepts for describing maintenance in a I4.0 context has contributed to the confusion.

The technological development and falling cost of sensors and systems for collecting and analyzing data have led to an increasing interest in CBM, and several claims have been made on the potential for improving maintenance by using condition monitoring data to estimate remaining useful life of assets. But empirical studies indicate that the manufacturing industry struggles with the implementation of data-driven PdM in practice.

The connection between LP and I4.0 has received much attention from the operations research community in the last 5 years. Several authors have proposed that LP forms an important foundation for succeeding with I4.0 and empirical evidence that support this has started to emerge. These studies have been done at a high level and the links between specific principles from LP and I4.0 and their effect on maintenance are still unclear. There are however compelling arguments that the introduction of lean principles such as standardization, focused improvement and empowerment can form a basis for successful implementation of I4.0.

We propose in this paper a framework for the implementation of Smart Maintenance to help alleviate the challenges related to the introduction of I4.0 and data-driven PdM identified in the literature study. The implementation of Smart Maintenance is a complicated set of activities and no model or framework can cover all aspects. Because of this there will be a need for different models and frameworks with different levels of abstraction to support this process (Rauzy and Haskins 2019). The framework in this paper has been developed with the aim of making a simple model that is well suited for facilitating communication among all the stakeholders and that provides a holistic overview for implementing Smart Maintenance. Because of this, the illustration in Fig. 1 has a high level of abstraction and the labels are purposely generic so it can fit a wide range of organizations with different levels of maturity when it comes I4.0 and maintenance management. There will be a need for several other models, frameworks, and tools for succeeding with the implementation of Smart Maintenance and some of these have been mentioned in Section 3.

5. Conclusion

As reported in this paper there are indications that industry is struggling with the implementation of I4.0 and data-driven predictive maintenance, and that there is a need for models and frameworks for alleviating this situation. The framework proposed in this paper, which combines the underlying principles of I4.0 with existing models and frameworks from systems engineering, maintenance management and lean production is intended to inspire other researchers and offer pragmatic assistance to industry practitioners.

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