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Implementing a dynamic FMECA in the digital transformation era

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Abstract: The digital transformation of the manufacturing industry is currently unlocking new possibilities in terms of automation and improvement of existing business processes. Service is currently one of the key areas that are being affected by it and, while many use cases are proposed, their operational implementation often remains a challenge. This paper, focusing on the impact of information transparency on the formulation of an effective maintenance plan, is proposing a progressive implementation roadmap for a dynamic failure mode, effect and criticality analysis (FMECA), according to the digital maturity of the organization.

Keywords: FMECA, digital transformation, digital maturity, service, maintenance engineering

1. INTRODUCTION

The manufacturing industry is currently facing a major change labelled, due to its nature, as digital transformation. This has been identified as a new competitive lever (McKinsey & Company, 2015) based on the use of data and connectivity capabilities. Its operationalization consists in the integration of the multiple players along the supply chain in an interconnected system (Porter & Heppelmann, 2014), translating the conceptual structure of companies from a pyramidal structure to a network of nodes (Jeshcke et al., 2017). The promise is to unlock, through the exchange and use of data from across the supply chain, a new potential for improving the operational performance of multiple business areas. Hence, a key attribute of this transformation is the condition of transparency across this network (Schrauf & Berttram, 2016). This is translated in the availability of relevant information to the right instances for supporting the related decision-making processes (Winkler, 2000, Vaccaro & Madsen, 2006; DiPiazza & Eccles, 2002; Turilli et al., 2009).
Service is one of the key areas to be affected and improved by the digital transformation and maintenance costs are meant to be reduced using its enabled capabilities (McKinsey & Company, 2015). More specifically, advanced diagnostic and prognostic systems to support maintenance activities through self-reparation and autonomous learning are being introduced (Fasanotti et al., 2018). However, due to the limited set of contexts considered for their application, there is a need for explorative studies for building an understanding of how to capitalize on these new capabilities (Fasanotti et al., 2018). Furthermore, due to the currently increasing degree of automation in manufacturing environments, which is transforming more and more labor intensive processes into automated processes, the magnitude of the impact of maintenance activities on business is constantly increasing. In turn, this results also in the diffusion of a product-service system based business models (Ardolino et al., 2017).

As the digital transformation is considered to be a progressive transformation on multiple complexity levels (Schuh et al., 2017), the unlocked possibilities for the improvement of maintenance activities have to be investigated in relation to the available capabilities and, therefore, the level of digital maturity achieved by a company.
This research focuses on the failure mode, effect and criticality analysis (FMECA) currently used by manufacturing companies for the prioritization of maintenance activities. The concept of a *dynamic* FMECA, built around the capability to periodically update the analysis, has been proposed in extant literature and its positive impact on performance has been discussed, for example in regards to its influence on production processes (Mili et al., 2008a). However, an investigation regarding its implementation process is missing. The transparency and analytic capabilities, leading to decision making autonomy (Fasanotti et al., 2018), enabled by the deployment of novel digital technologies, such as the internet of things (IoT), are providing a new ground to be considered in regards to that. This paper investigates how these capabilities can support the implementation of a dynamic FMECA and how digital maturity progression can affect its deployment. According to that, the research presented in this paper addresses the following research question: *"How can the digital transformation support the implementation of a dynamic FMECA?"*
The research is performed following a design science approach in its abduction phase (Hevener, 2004) and aims at proposing a conceptual framework for guiding the implementation of a dynamic FMECA according to the digital maturity of the organization. The authors present, at first, a state of the art regarding the FMECA, the dynamic FMECA, and the digital maturity concepts. Secondly, the research methodology is illustrated. Then, the concept of a dynamic FMECA based on digital capabilities, and in relation to different digital maturity levels, is proposed. Eventually, its implication on maintenance performance and on the design of a customized service offer

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are discussed, and a conclusion that outlines the validation process of the proposed concept is provided.

2. STATE OF THE ART

2.1 The FMECA

The FMECA is recognised as one of the most renown tools, within the maintenance domain, to collect experts' knowledge and quantify the risks associated with the usage of the asset. Its outcome consists of an index, called Risk Priority Number (RPN) which prioritizes maintenance activities according to the risk related to a failure (Wang et al., 2014). The RPN is calculated, for each asset component, multiplying the following variables, usually provided by asset vendors and related to the production context:

- Severity (S), which estimates how severely the failure would affect the user;
- Occurrence (O), which estimates the probability of occurrence of a failure;
- Detectability (D), which estimates the effectiveness of control to prevent the failure (or the probability of detecting a problem before it happens).

The smaller the RPN, the better. Risks are then prioritized from the highest to the lowest according to their RPN, and the related maintenance activities are planned accordingly.

Due to the way it is conceived, the FMECA gives a clear picture of the initial state of the system. However, the variables involved in the estimation of the risks can evolve over time. For example, the diverse usage conditions of the asset, the technological evolution or new skills acquired by the maintenance resources could influence the variables used to compute the RPN, thus affecting the results of the analysis and, thus, the planning decisions. Such an update can be hindered by the current approaches commonly adopted in companies. Indeed, Mili et al. (2008a) affirm that a considerable lack can be found in the information collection and risk codification, which is mostly not standardized and dependent on human expertise. Moreover, as reported by Ben Said et al. (2016), FMECA updates are not frequent and are mostly based on human expertise. As of now, the FMECA is not always directly linked to the organizations' information system (Mili et al., 2008b). In fact, despite the possibility offered by current Enterprise Information Systems to extract production and process data, humans must interpret these before updating the values contained in FMECA. Moreover, the static nature of FMECA, heavily dependent on human intervention, puts boundaries around the possibility to update it dynamically. In this way, the possibility to be quick in the adaptation of maintenance policies according to new criticalities and, eventually, of the maintenance plan, fades.

2.2 Towards a dynamic FMECA

In response to the limitations listed in section 2.1, some authors proposed a novel approach to the FMECA, based on its more frequent update (Van Bossuyt et al., 2010; Mili et al., 2008b). What emerges from literature is that the FMECA can be used at an operational level if employed in a dynamic way, addressing, in addition to the maintenance plan, quality and process aspects based on the risk classification. Moreover, it could also be used as a performance measure for production processes (Mili et al., 2008a). Due to that, the risk prioritization through RPN computation remains one of its most important characteristics. Linked to this, as Ben Said et al. (2014) report, dynamic FMECA is fundamental for the provision of updated support to maintenance, especially by establishing a continuous bound between what happens in the shop floor, the risk analysis, and the maintenance activities (Bassetto et al., 2011). In support, (Ben Said et al., 2016) reports a case of mixed usage of FMECA and Bayesian Networks to use it in an operational way, enabling the possibility to identify causal relations between the information present in the system. In this case, the interactions between the Bayesian Network and the FMECA are aimed at supporting the renewal of experts' knowledge and improve the effectiveness of maintenance actions, providing feedback afterwards. As introduced earlier, the FMECA improvement not only has effects on the maintenance plans but, in turn, on the production process as well (Wang et al., 2014). In fact, on one hand, a reduced downtime, due to an improved maintenance plan definition, results in increased production time. On the other hand, the identification of risks and problems enabled by the FMECA allows also to make improvements to the production process, highlighting new potential process problems. One of the topics that must be addressed in order to pave the way towards a more dynamic update of the FMECA is the information collection, exchange and usage (Mili et al., 2009; Mili et al., 2008a). The literature analysis shows that the way information is managed, and the tools used to support it, affect the way FMECA can be dynamically updated. In regards to that, the importance of the adoption of a Computerized Maintenance Management Systems (CMMS) for asset management and, more specifically, for information management aimed at maintenance activities, has been highlighted (Lopes et al., 2016). Furthermore, Balouei et al. (2018) state that the role of CMMS in maintenance management will become even greater in the future, due to the growth of data and, thus, of the need for information management. In this sense, the possibility to automate information collection, processing and exchange through the use of a CMMS makes possible to provide support for the concept of dynamic FMECA and its possible declinations. These would depend on the autonomy of the information management processes. Literature reports different cases for this. While case studies about static FMECA are widely discussed, Wang et al. (Wang et al., 2014) describe a situation where FMECA is used in a dynamic way, but the process is carried out manually by human experts and in an intermittent manner. Instead, Mili et al. (2009) and Ben Said et al. (2016) describe two case studies where the software is able to compute failure data and to autonomously propose updates for the FMECA. However, the intervention of the human expert is still required for the validation of the updates and, in turn, for the update of the maintenance policies for the different components and, eventually, of the maintenance plan. However, no empirical evidence has been found supporting the implementation of this type of dynamic FMECA, considering the related increasing degree of autonomy.

2.3 The digital maturity progression

The digital transformation has been defined as a journey across multiple complexity levels (Schuh et al., 2017). Researchers and research institutions proposed multiple progression models – based on the maturity concept – through academic publications and industrial reports, for guiding the digital transformation (Colli et al., 2018). The concept of maturity as a development progression based on building incremental capabilities has been originated in relation to electronic data processing (Gibson & Nolan, 1974) and in quality management (Crosby, 1979). Looking at this concept under a digital transformation magnifying glass, in terms of capabilities, the development progression generally starts from being able to identify events and eventually reaches the ability of dealing with events autonomously, after building an understanding of the causes of the event and of the patterns that make possible to forecast future scenarios (Schuh et al., 2017). Colli et al. (2018), based on a review of existing digital maturity models, translate this progression in a sequence of steps consisting, technical wise, in the ability to generate digital data, the achievement of data availability where needed for supporting decision making processes, the introduction of analytic capabilities for analyzing it, augmenting the existing knowledge, and the establishing of an autonomous decision making process based first on company data and, eventually, on data from across the whole supply chain. Under a maintenance point of view, Fasanotti et al. (2018) see sensor-generated information as the catalyst for the transition towards a proactive maintenance planning, with less human involvement in the inspection and decision-making processes. Thus, the incremental progression of digital maturity related capabilities is used as a base line for the formulation of a currently missing implementation model of the existing dynamic FMECA concept.

3. METHODOLOGY

This research consists of model development, obtained following a design science approach (Hevener, 2004; Van Aken, 2004; Vaishnavi & Kuechler, 2008). This starts from the development of an artefact through an abductive process. The artefact, consisting of an implementation framework for the concept of dynamic FMECA, has its foundation based on literature regarding this concept. The model development process was complemented by a literature analysis as an outcome of research carried out on the SCOPUS database. The literature review focused on the concepts of FMECA and dynamic FMECA in the context of the technological revolution happening in the current decade. Specifically, authors were interested in studying the literature on the dynamic FMECA from the perspective of the organizations' digital maturity, investigating how the digital maturity of an organization could affect the FMECA capabilities and, in turn, its autonomy. Eventually, in order to propose an implementation framework based on the possibilities unlocked by the digital transformation, the needs in terms of digital capabilities related to the existing dynamic FMECA concept are identified and related to existing digital maturity concepts and to their maturity levels. As an outcome, a progression in terms of implementation stages based on the digital maturity level and on the related capabilities is proposed.

4. MODEL DEVELOPMENT

The implementation of a dynamic FMECA is based on the increase of integration from an Information System point of view, as its concept is strongly bounded with information availability and business process automation. This is meant to generate information transparency - and support its use - across assets to be maintained and who has to maintain them. This task is supported by new digital technologies, specifically IoT, which enable the achievement of information transparency (Brody & Pureswaran, 2015). As the digital transformation journey and, therefore, the achievement and use of information transparency and of analytic and autonomy capabilities are considered to be incremental, the authors propose a progression of dynamic FMECA solutions based on this progression. Hence, this outlined sequence of implementation stages sets its foundation on the available digital capabilities and, therefore, on the digital maturity of the organization which aims at implementing a dynamic FMECA. Three implementation stages for the adoption of a dynamic FMECA in the service department of a manufacturing company that has to take care of the maintenance of its own assets are proposed. They consist in three sequential typologies of dynamic FMECA – manual, assisted, and autonomous – meant to work on top of the existing CMMS and supported by increasing digital maturity (and of the related capabilities) and characterized by the increasing level of automation of the FMECA processes.

4.1 Manual dynamic FMECA

The service department of the manufacturing company, in order to perform the FMECA for defining a maintenance plan, is manually collecting the needed information by accessing the CMMS. Here, failure data from the monitored assets as well as reports of the performed maintenance activities are manually inserted by the operator. Data is then manually analyzed within the service department, where failure types and implications (e.g. related downtime, involved components) are identified and the FMECA performed, see Fig. 1. Eventually, failures are ranked by calculating the RPN.

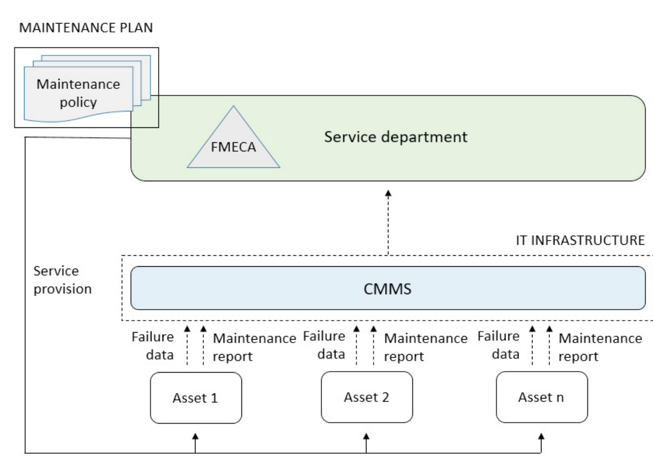

Fig. 1. Manual dynamic FMECA

According to that, the service department updates the maintenance policies defined for all the considered components and, thus, the maintenance plan. The service is provided accordingly. The digital capabilities needed in order to sustain the manual dynamic FMECA consist in an IT infrastructure that supports a CMMS accessible, on one side, by the operators for introducing failure and maintenance activities related data digitally and, on the other, by the service department for visualizing it.

4.2 Assisted dynamic FMECA

The service department of the manufacturing company, in order to perform the FMECA, is manually collecting the needed information by accessing the CMMS, where failure data are automatically uploaded by the assets and the performed maintenance activities are registered. Afterwards, as for the manual dynamic FMECA, see section 4.1, data is manually analyzed by the service department which, eventually, performs the FMECA and rank them by calculating the RPN. The service department updates, accordingly, the maintenance policies related to the different components and the maintenance plan that guides the service provision, see Fig. 2. The digital capabilities needed in order to sustain the assisted dynamic FMECA consist, in addition to the ones described for the manual version, see section 4.1, in having an IT infrastructure that includes the monitored assets, which have to be able to upload in the CMMS the needed failure data automatically.

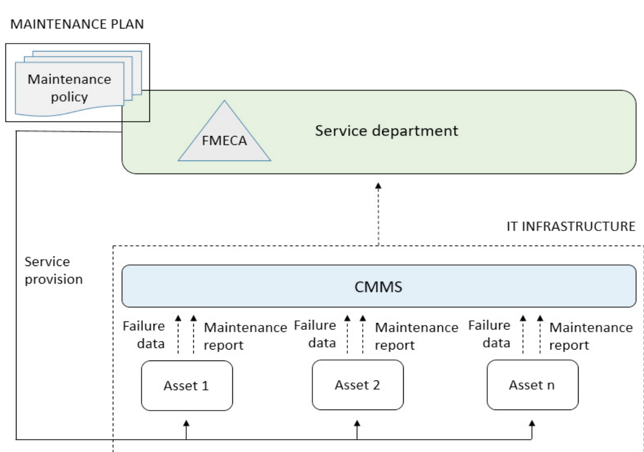

Fig. 2. Assisted dynamic FMECA

4.3 Autonomous dynamic FMECA

The service department of the manufacturing company, as well as the assets, are connected to an IoT platform which hosts the CMMS and an analytic engine. While the assets automatically upload failure data and maintenance activities to the CMMS, an analytic engine processes this data, automatically performing the FMECA. The service department receives, therefore, a constantly updated FMECA as well as RPN and, after validating the results, can constantly re-assign maintenance policies according to the FMECA results and optimize the effectiveness of the maintenance plan. The service department provides the service accordingly, see **Error! Reference source not found.**. The digital capabilities needed in order to sustain the autonomous dynamic FMECA consist, in addition to the ones described for the assisted version, see section 4.2, in introducing an IoT platform with analytic capabilities and which is hosting the CMMS. This platform has to be interconnected with the assets, data source, and the service department, data user.

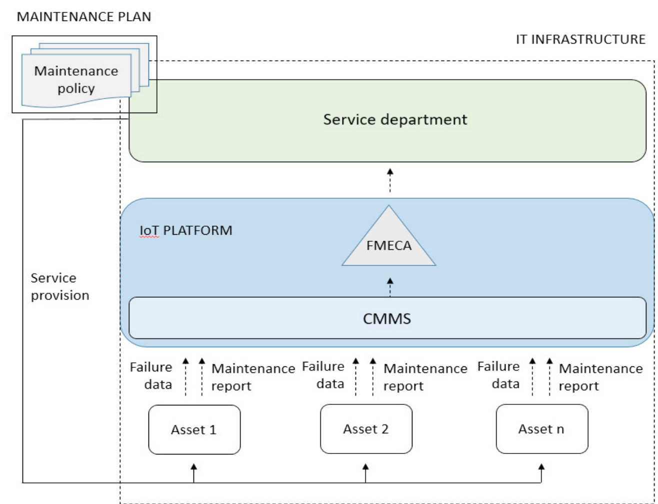

Fig. 3. Autonomous dynamic FMECA

5. DISCUSSION

The concept of dynamic FMECA is already existing and it has been discussed in the extant literature. However, implementation guidelines are missing. The digital transformation and the increase of digital maturity are expected to support its implementation and progressively unlock new capabilities – in particular, the increase of information transparency and the enabling of analytic capabilities first and autonomy next – that are considered to be key elements for the implementation of a dynamic FMECA, see Fig. 4. The organization's digital competencies play a central role in the determination of the way a dynamic FMECA can be implemented. The more companies are digitalized and able to manage the information across them, the higher is their digital maturity level. In fact, the human intervention required for different purposes, from data extraction to elaboration, ending in creating the logical connections between the FMECA update and the defined maintenance plans, is inversely proportional to the level of digital maturity. Increasing the digital maturity of an organization means that the Information System (IS) and, more specifically, the CMMS, is able, at different levels, to collect and elaborate data, and expose the results in a way that makes possible to update easily the maintenance plans. Possibly, at the maximum digital maturity level, the CMMS would be able to update autonomously the maintenance plans, reducing the necessity for a human-in-the-loop (HIL), which is the necessity for the system to interact with humans (Parasuraman et al., 1997; Pinto et al. 2013). However, in the proposed framework, it has been considered the need for a human validation of the updated FMECA results in order to translate it in the re-assignment of maintenance policies for the different components and, eventually, in the re-formulation of the maintenance plan. The

HIL still has a crucial role in translating raw data in operational decisions, mostly because of the current impossibility to collect and interpret data related to all the contextual elements that must be taken into account in the decision making process. The ability of the CMMS to update the FMECA strongly depends upon the data interpretability and their interpretation. The interpretability of data is a consequence of the way they are collected, structured and elaborated. Different components along the IS could require the same data structured in different ways: for this reason, it is fundamental to define a common language and methodology that guides the data collection, storage, and elaboration. Automating this aspect means enhancing and facilitating the communication among the components of the IS, allowing to automatize certain parts of the elaboration process and saving time for other operations. If there is no compliance between the IS components, the human intervention will be necessary to enable data collection and processing within the CMMS and the FMECA update. The concept of data interpretability is bond to the one of data interpretation. In fact, also in this case, giving the instruments to the IS components to understand the data under analysis and the meaning of the results means to shorten the time required to complete part of the process. Moreover, an IS able to interpret data correctly has a higher degree of autonomy, due to the diminished need for human expertise in some of the decision making processes. Something worth noting is that if data is not interpreted correctly, misleading information could be saved in the database, resulting in wrong risk estimation, maintenance policies and, thus, maintenance plans. Before updating one or more values in the FMECA it is important to verify that it is correct to do so. Updating a value in the FMECA after each maintenance intervention is not trustworthy and results in an unreliable instrument for the definition of the maintenance policies. Something that can be done in this sense is to implement a statistical test to understand if one or more values are significantly changed or not. To perform the test it is necessary to keep track of the maintenance interventions and analyze the related maintenance reports. The implementation of a dynamic FMECA allows to define maintenance policies tailored on single components on the base of the asset usage.

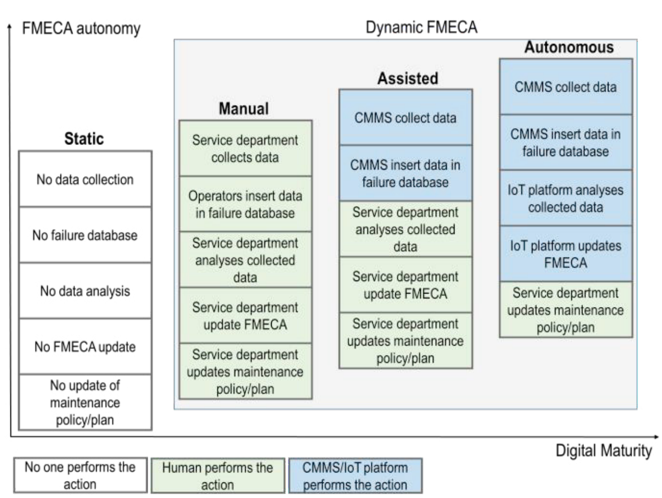

Fig. 4. Dynamic FMECA development progression related to digital maturity

Moreover, the update of the single maintenance policies allows to define and update the maintenance plans, which represent the ensemble of the maintenance policies for the single components. Being able to define improved maintenance plans make possible also to improve the scheduling of the operators based on their skills and the problems of the assets.

6. CONCLUSION

The fourth industrial revolution is changing the way organizations are exploiting their assets. The continuous generation, collection and analysis of data opens up for new possibilities for the improvement of the production processes, which can be enhanced in many ways and under different aspects. One of these areas is asset maintenance, as demonstrated by the considerable importance that this topic obtained in literature. One of the most diffused instruments to manage maintenance activities is the FMECA. This is used to identify the assets' most critical components and, thus, as an input for the definition of the maintenance policies and plans. Despite this, the usage of the FMECA in a static manner limits the effectiveness of a maintenance plan due to the lack of consideration of environmental changes (e.g. asset usage). Because of this, some authors proposed the concept of dynamic FMECA, based on the capability to periodically update components' criticality and, thus, guiding maintenance plans' update. This paper proposes a schematisation of the implementation stages for the dynamic FMECA, which are strongly bound to information transparency in the organization and, in turn, to the organization digital maturity level. Three stages are proposed, starting from manual data processing for supporting the FMECA and, after an assisted one, ending with an autonomous FMECA, where data processing is performed by an IoT platform. This paper presents a theoretical framework for implementing a dynamic FMECA. In order to provide implementation guidelines at a more operational level, additional research concerning its application in a real case is required. To do so, further information regarding the FMECA activities, the needed data and their use for defining maintenance policies and plans are required. In addition, for understating its implications on the organization's performance, historical data related to the assets' performance and to the maintenance activities are needed. This have to be compared with a simulation of the corresponding behaviour using a dynamic FMECA. Furthermore, the performance improvement corresponding to the digital maturity increase has to be validated studying the impact of the growing automation in the FMECA update process. To do so, differences concerning data reliability and needed resources in the three digital maturity stages have to be taken into account. These activities are planned for future publications.

REFERENCES

Ardolino, M., Rapaccini, M., Saccani, N., Gaiardelli, P., Crespi, G., & Ruggeri, C. (2017). The role of digital technologies for the service transformation of industrial companies, *International Journal of Production Research*, Taylor & Francis, pp. 1–17.

Balouei Jamkhaneh, H., Khazaei Pool, J., Khaksar, S. M. S., Arabzad, S. M., & Verij Kazemi, R. (2018). Impacts of computerized maintenance management system and relevant supportive organizational factors on total productive maintenance. *Benchmarking: An International Journal*, 25(7), 2230-2247.

Bassetto, S., Siadat, A., & Tollenaere, M. (2011). The management of process control deployment using interactions in risks analyses, *Journal of Loss Prevention in the Process Industries*. Elsevier Ltd, 24(4), pp. 458–465.

Ben Said, A., Shahzad, M. K., Zamaï, É., Hubac, S., & Tollenaere, M. (2014, July). A Bayesian network based approach to improve the effectiveness of maintenance actions in Semiconductor Industry. In *Second European Conference of the Prognostics and Health Management Society*.

Ben Said, A., Shahzad, M. K., Zamai, E., Hubac, S., & Tollenaere, M. (2016). Experts' knowledge renewal and maintenance actions effectiveness in high-mix low-volume industries, using Bayesian approach. *Cognition, Technology & Work*, *18*(1), 193-213.

Brody, P., & Pureswaran, V. (2015). The next digital gold rush: how the internet of things will create liquid, transparent markets, *Strategy & Leadership*, Vol. 43 No. 1, pp. 36-41.

Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., & Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. *Ifac-papersonline*, 51(11), 1347-1352.

Crosby, P. B. (1979). Quality is Free: The Art of Making Quality Certain. New York, McGraw-Hill

DiPiazza, S. A., & Eccles, R. G. (2002). Building public trust: The future of corporate reporting. New York: Wiley

Fasanotti, L., Cavalieri, S., Dovere, E., Gaiardelli, P., & Pereira, C. E. (2018). An artificial immune intelligent maintenance system for distributed industrial environments. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*.

Gibson, C. & Nolan, R. (1974). Managing the four stages of EDP growth. *Harvard Business Review*, Vol. 52, No. 1 (Jan/Feb 1974), pp. 76-88

Hevener, A. R., March, S. T., Park, J., & Ram, S. (2004) Design Science in Information Systems Research. *MIS Quarterly* 28:75–105.

Jeschke, S., Brecher, C., Song, H., & Rawat, D. B. (2017). Industrial internet of things, cybermanufacturing systems. Springer

Lopes, I., Senra, P., Vilarinho, S., Sá, V., Teixeira, C., Lopes, J., Alves, A., Oliveira, J. A., & Figueiredo, M. (2016). Requirements specification of a computerized maintenance management system–A case study. *Procedia CIRP*, 52, 268-273.

McKinsey & Company (2015). Industry 4.0: How to navigate digitalisation of the manufacturing sector, McKinsey and Company. URL: https://www.mckinsey.de/files/mck_industry_40_report.pdf

Mili, A., Siadat, A., Hubac, S., & Bassetto, S. (2008a). Dynamic management of detected factory events and estimated risks using FMECA. *In Management of Innovation and Technology*, 2008. ICMIT 2008. 4th IEEE International Conference on (pp. 1204-1209). IEEE.

Mili, A., Hubac, S., Bassetto, S., & Siadat, A. (2008b). Risks analyses update based on maintenance events. *IFAC Proceedings Volumes*, 41(2), 34-39.

Mili, A., Bassetto, S., Siadat, A., & Tollenaere, M. (2009). Dynamic risk management unveil productivity improvements. *Journal of Loss Prevention in the Process Industries*, 22(1), 25-34.

Parasuraman, R., Sheridan, T.B., & Wickens, C.D. (1997). A model for types and levels of human interaction with automation, *IEEE Transactions on Systems, Man, and Cybernetics,* 30 (3), pp. 286–297.

Pinto, R., Mettler, T., & Taisch, M. (2013). Managing supplier delivery reliability risk under limited information: Foundations for a human-in-the-loop DSS. *Decision Support Systems*, 54(2), pp. 1076–1084.

Porter, M. E. & Heppelmann, J. E. (2014). How smart, connected products are transforming competition. *Harvard Business Review*, 92(11): 64-88.

Schrauf, S. & Berttram, P. (2016). Industry 4.0: How Digitization Makes the Supply Chain More Efficient, Agile, and Customer-focused, Strategy, http://www.strategyand.pwc.com/reports/industry4.0

Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M., & Wahlster, W. (2017). Industrie 4.0 Maturity Index. *Managing the Digital Transformation of Companies (acatech STUDY) Herbert Utz Verlag, Munich*.

Turilli, M. & Floridi, L. (2009). The ethics of information transparency. *Ethics and Information Technology*, *11*(2), 105-112

Vaccaro, A. & Madsen, P. (2006). Firm information transparency: Ethical questions in the information age. In Social informatics: An information society for all? *In remembrance of Rob Kling* (pp. 145–156). New York: Springer.

Vaishnavi, V. & Kuechler, W. (2008). Design Science Research Methods and Patterns, Innovating Information and Communication Technology. *CRC Press, Taylor & Francis Group*. Pag. 31.

Van Aken, J. E. (2004). Management Research Based on the Paradigm of the Design Sciences: The Quest for Field-Tested and Grounded Technological Rules. *Journal of Management Studies* 41:219–246.

Van Bossuyt, D. L., Wall, S. D., & Tumer, I. Y. (2010) 'Towards risk as a tradeable variable in complex system design trades', *Proceedings of the ASME Design Engineering Technical Conference*, 3 (PARTS A AND B).

Wang, H., Ren, J., Wang, J., & Yang, J. (2014). Developing a Conceptual Framework to Evaluate the Effectiveness of Emergency Response System for an Oil Spill. *In CICTP 2014: Safe, Smart, and Sustainable Multimodal Transportation Systems* (pp. 3731-3742).

Winkler, B. (2000). Which kind of transparency? On the need for clarity in monetary policy-making. Frankfurt: European Central Bank.