Integrating Failure Mode, Effect and Criticality Analysis in the Overall Equipment Effectiveness framework to set a digital servitized machinery: an application case

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Abstract. Digital transformation and servitization have been merging in a coalescing paradigm called Digital Servitization, changing not only companies' business model but also their portfolio and thus their business. This hybrid paradigm is increasingly overwhelming manufacturing companies, compelling them to change their business model and provide more complex solutions to survive. Indeed, first a business model shift is needed (bringing to cope with organizational/managerial aspects), and then a suitable new technology stack has to be implemented. In the extant literature it is not clear how companies can define which are the improvements to implement on Smart Connected PSSs. These modifications on the physical products, if flanked by a concurrent definition and structuring of data requirement on the database on the cloud, would also lead to a better comprehension of the solution functioning, enabling to know which are the causes leading to breakdowns and performance and quality losses during the use phase. To address this, the paper proposes a method combining the Failure Mode and Effect Analysis with the Overall Equipment Effectiveness framework.

Keywords: digital servitization, machinery sector, Industry 4.0, FMECA, OEE

1 Introduction

Digital servitization is increasingly overwhelming manufacturing companies, forcing them to change their business model and provide more complex solutions [1,2]. Indeed, traditional physical products need to be enriched with digital technologies to enable the provision of the sol called Product-Service Systems (PSSs). Often shifting the possession of the product from the user to the provider, PSSs generate profit through the sale either of their use or of the result obtained with their use by the customer [3]. The benefits triggered by PSS are multiple and have been unveiled by the academics as valuable both for the provider and the customer (being able to enhance providers' competitiveness on the market, to better meet customer needs and to decrease environmental impact than traditional business models) [4,5].

In addition, digital technologies [6–8], recognized under the Industry 4.0 (I4.0) paradigm [9], can further increase and empower PSSs' functionalities. Their embedding on traditional physical products triggers the possibility of new knowledge-based services capable to address not only the monitoring functionality, but also to allow to control, optimize and even automatize the behaviour of the solution. By the way, the provision of Smart, Connected PSSs would require first of all a business model shift, bringing with itself organizational and managerial (human resources-related, and customer-related) challenges and in a second step also technical/technological [10]. Indeed, as suggested by [11], once the company manages to realize its need of business model shift and copes with the organizational/managerial aspects, a suitable new technology stack is needed to be implemented to actually develop and deliver the Smart, Connected PSS. Here, a new infrastructure made up of multiple levels is composed by product hardware, embedded software, a connectivity part, a product cloud remotely running on servers, a security tools suite, a gateway for managing external information sources and finally also an integration with enterprise business systems (e.g., ERP, CRM, PLM).

As a result, digital transformation and servitization have been merging in a unique coalescing paradigm called Digital Servitization [6–8], changing not only companies' business model but also their portfolio and thus their business [12].

The way products change into new integrated and more complex solutions is strongly driven and affected by the data that can be potentially generated, gathered and analysed along their entire lifecycle and somehow shared among customers and providers. Often also the relationship provider-customer becomes stronger (lightening the user from the commitment of managing the solution during its use phase).

To be able to deliver such data-driven solutions and address a sheltered digital servitization, manufacturers need to enact multiple modifications: cultural [13], customer-related [14,15], and also in the way the company approaches the PSS design [16,17]. However, most of the times, in the extant literature it is not clear how companies can define which are the improvements to implement on their product to enrich them with smart Connected functionalities and provide data-driven services.
The modifications on the physical products, if flanked by a concurrent definition and structuring of the data requirements to be stored on the database on the cloud, would also lead to a better comprehension of the functioning model of the solution, enabling to know which are the causes leading to availability, performance and quality losses during the use phase. For this reason, this paper has the aim of proposing a method combining the Failure Mode, Effect and Criticality Analysis (FMECA) [18] with the Overall Equipment Effectiveness (OEE) framework [19] and apply it in a pilot case. OEE is the standard metric for measuring internal performance of manufacturing productivity, effective for detecting losses, comparing progress, and enhancing the productivity of manufacturing equipment. It measures how well a manufacturing operation is utilized compared to its full potential, keeping in consideration the system quality (good pieces delivered), performance (speed) and availability (interruptions). Company A, developing and delivering machineries for plastic objects and containers decoration, has been chosen. In particular, from an analysis of the product portfolio, Machine 1 (Screen Printing) was selected as pilot machine to apply the method proposed. First of all, after analysing the bill of materials of the machine, detecting the main constructing groups and decomposing them at a detailed level, the FMECA

analysis is implemented to detect the main failure causes on the machine and to find the most critical components. Once prioritized through the FMECA method, each critical component is evaluated to understand which data are required to be monitored, which type of loss (availability, performance, or quality) the critical components cause, which sensors can be embedded on the product to improve its smart functionalities and to which part of the OEE (Availability, Performance and Quality) each loss of time due to the critical components' failures analysed is related.

The paper is structured as follows. Section 2 presents the research methodology and describes the Company A and the pilot machine chosen. Section 3 show the results, then discussed in Section 4. Finally, Section 5 concludes the paper and envisages future research.

2 Research Methodology

To achieve the research objectives, an application case was conducted.

2.1 The pilot case: Company A and Machine 1

From '60ies Company A delivers dry-offset and silk-screen printing machines for the decoration of plastic objects and containers. Along the time, the product portfolio was enriched with hot foil printers, multipurpose machines for flexible tubes and pails and heat transfer machines for digital printing. Today, Company A's portfolio includes over 40 basic models characterized by a good flexibility (due to a modular structure and a range of accessories) to face with the changing market's needs.
Company A is a convenient sample for this research, being involved in a funded project. Its choice for this research is justified by the fact that it represents a purposive case, since it is suitable to the particular problem or representative of a special population. In addition, this case is also an idiographic study, i.e. the intensive study of an individual case (20). Indeed, the method embedding the FMECA in the OEE framework, proposed and presented in this paper, has been applied in Company A in an mixed interpretative/interactive way [21] on the basis of a previous strategic analysis which brought to the need of improving the company's product portfolio with smart functionalities. Company A represents the traditional small manufacturing company, developing, producing and delivering industrial machineries according to the typical product-based business model. At the same time, Company A has also realized that it needs to go towards the digital servitization transformation to survive in the market. For this reason, a strategic analysis was performed in the company through a series of interviews with employees from all the functions involved in the order development process, detecting several hurdles throughout its digital servitization path. Indeed, among the others, Company A requires effort mainly in the Technical Department (with the introduction of smart components enabling to both define the machine operating models and provide data-driven services), in the R&D (to study innovative solutions) and IT (with the development of a database). In addition, the analysis previously performed led also to the choice of a pilot machine to be used in this research. Machine 1 (Screen printing) is one of the latest realizations

added to the Company A's portfolio. It is characterized by several electronic components on board and it has been already subject of incremental technical improvements (direct engine transmission and updating of the loading system). All the knowledge of its design and development, as for example the structure of the machine and its mechanisms, is completely known and easy retrievable. The main customers and thus users of this machines are European manufacturers of small tubes, bottles and mascara. Finally, Machine 1 has been chosen for this research by Company A since, despite its recent introduction on the market, it has already medium-high sales volumes (representing more than the 25% of the company's total sales).

2.2 The research process

Several workshops were performed in the company to conduct the research. First, the company involved in the research had been analysed from a strategic perspective (through a series of interviews with all the functions involved in the order development process), leading to the detection of its main issues related to the digital servitization (this preliminary phase is fully described in [22]). In parallel, also an analysis of the company's product portfolio was performed, providing as a result the choice of Machine 1 (Screen Printing) as pilot case for this research. In addition, to enhance its awareness about this paradigm, the company was also gradually introduced to all the concepts related to both servitization and digital transition. Indeed, to provide them further practical evidence, a demonstration of how a database could be implemented on their solutions was provided by a digital provider belonging to the Politecnico di Milano's ecosystem. Therefore, two theoretical workshops were organized to introduce the company first to the FMECA method and then to the performance measurement of production systems (with a special focus on OEE). Finally, two workshops to conduct the research were organized. In total, seven workshops were conducted, with a total duration of about 66 hours. In all the workshops after the strategic and product portfolio analysis, several employees of Company A Technical Department were involved in a pervasive way (involving the technical director, the Electronic Department Manager, one electronic department engineer and one mechanical department engineer). A wrap-up of the workshops conducted is also provided in Table 1.

Table 1. The research process

Workshop	Duration	Aim
1. Strategic and product portfolio analysis (interviews) [23]	14 hours	Gaps detection in the company from a digital servitization perspective and choice of Machine 1 as pilot case.
2. Servitization and digital transformation	20 hours	Introduction to the main concepts on PSS, Servitization transition, Digital transformation, Smart Connected Products and Technology Stack.
3. Digital provider demonstration	6 hours	Application of a technology provider solution for industrial machineries monitoring on Machine 1

		and dashboarding configuration.
4. Presentation of strategic analysis results and FMECA theoretical session	3 hours	Presentation of the gaps in the company in terms of digital servitization. Focus on the need for the Technical Department to define the machine operating models through the introduction of sensors and the analysis of the data generated.
5. FMECA practical session	6 hours	Decomposition of Machine 1 and detection of the failure modes, causes and effects. Risk Prioritization Number (RPN) definition.
6. OEE theoretical session	2 hours	Introduction to performance measurement of production systems with a focus on OEE
7. Combined FMECA- OEE practical session	5 hours	Possible activity to be done and sensors to be embedded, variables to be monitored, frequency of detection, unit of measure, standard interface, reference KPI, warning and fault rules.

3 Results

Through the research process described in the previous section, it was possible to apply the method embedding the FMECA results in the OEE framework. First, in sub-section 3.2, the results from the FMECA are presented: after analysing the bill of materials of the machine, Machine 1's main constructing groups have been detected and then decomposed at a more detailed levels, the main failure causes on the machine are also declined and components prioritized in terms of risk priority. Then, in sub-section 3.2, once prioritized through the FMECA, each critical component has been evaluated to understand which data are required to be monitored, which type of loss (availability, performance, or quality) the critical components cause and which sensors can be embedded on the product to improve its smart functionalities.

3.1 FMECA on Machine 1

First of all, Machine 1 was decomposed in twenty main constructing groups (i.e. Pneumatic system, Flame treatment air and gas system, Electrical system, control actuators and signalling devices, Central and peripheral structure of the machine, Plateau, spindles and rotating air distributor/intake, Drying group (LED/Mercury), Deionizer group, Flame treatment group, Quality control group, Paddle group, Screen printing head unit, Tailstock (printing and vision system), Discharge belt, Loading conveyor, Good parts unloading, Unloading of scrap pieces, Piece loading and handling unit (pick and place), Electronic rear positioning, Front electronic positioning, Automatic mechanical search). Then, the machine constructing groups were exploded in more detailed levels of components, leading to obtain 229 single parts. Therefore, the FMECA was performed to detect the most critical components to be monitored to better understand and define the machine operating model and provide more effective product-related data-driven services. Three categories of failure modes were considered in the analysis (clogging, opacification, breakdown/malfunction) led by 18 failure causes (e.g., damage during format change, accidental damage or breakage, transmission hardening, clogging, component mortality, reduction of reflection or emission, dirt, overheating of the motor, usury) and bringing to five failure effects, and thus status of the machine (1. Discontinuity in power circuits/Disturbances on the signal circuit; 2. Transmission hardening, games, movement inaccuracy; 3. Downtime for suction not adequate on the spindles; 4. Downtime; 5. No Downtime). Based on these failure modes, causes and effects, the two indexes Probability (P, in which time frame the failure occurs) and Severity (S, duration and effects of the fault) were set (defining their scales reported in Table 2) and used to calculate the Risk Prioritization Number (RPN), i.e. the numeric assessment of risk assigned to a failure.

Table 2. FMECA: Probability and Severity scale for RPN calculation

Probability		**Severity**	
Scale	**Description: in which time frame the failure occurs)**	**Scale**	**Description: duration and effects of the fault**
1	> 3 years	1	No downtime, no safety problems
2	1 year < x <= 3 years	2	Downtime <= 1h, no safety problems
3	6 months < x <= 1 year	3	1h < downtime <= 8h, no safety problems
4	3 months < x <= 6 months	4	8h < downtime <= 16h, no safety problems
5	1 month < x <= 3 months	5	16h < downtime <= 1 week, no safety problems
6	<= 1 month	6	1 week < downtime <= 1 month
-	-	7	Downtime> 1 month, no safety problems

The matrix of the critical components for Machine 1 was obtained (Table 3) neglecting 57 components considered not relevant by the Technical Department for the purpose of the analysis. As a result, the matrix assessed 172 components (Figure 1), evidencing that 1 component is classified as very important (red part in the bottom right of the matrix), 24 as moderately important (yellow part at the centre of the matrix), 147 as ordinary (green part at the top left of the matrix).
In particular, the aim of these tasks is to understand on which components it is better to act first to be able to improve the machine so that the data generated during its use phase could be better exploited. Indeed, the analysis started on the 16 most critical components, i.e., those in the yellow and red zones of the matrix in Table 3.

Table 3. Criticality Priority Matrix of Machine 1 based on RPN

P/S	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	9	12	42	54	0	15	8
2	1	13	1	5	2	4	0
3	0	0	3	0	0	1	0
4	0	0	1	0	0	1	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0

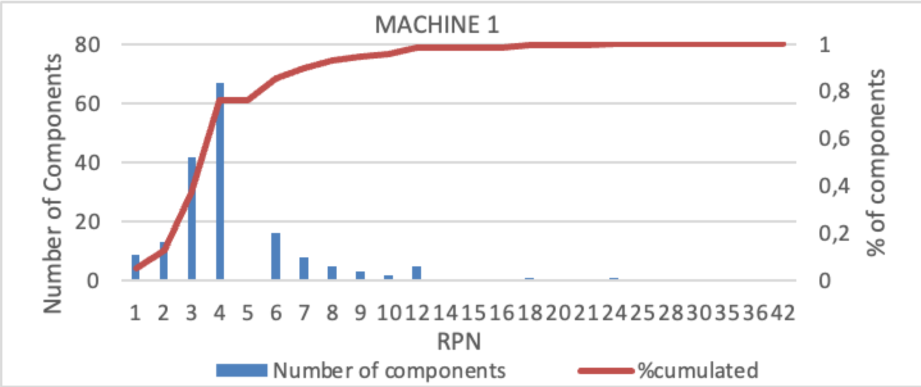

Figure 1 Classification of components through the FMECA

3.2 Embedding the FMECA in the OEE framework for Machine 1

Once prioritized the components, the concept of performance measurement of production systems was introduced to Company A, with a focus on the OEE framework. Therefore, the failures related to the Machine 1's critical components were declined by the Technical Department in terms of: which corrective actions are ongoing, which corrective actions could be introduced, which are the variables to be monitored (with which frequency of detection and with which unit of measure), which sensors can be embedded and which standard interface to use. Based on this analysis, each of these components was also declined in terms of OEE. That is to say that it was understood to which part of the OEE (Availability, Performance and Quality) each loss of time due to the critical components' failures analysed is related. Once defined the reference KPI, warning and fault rules have been envisioned to monitor the failures.

For example, the rotary table of the turret intermittent group is characterized by a dynamic mechanism that is controlled by the engine. The monitoring of this mechanism can provide important information to the machinery provider. Its breakdown/malfunctioning is due to the mechanical wear of internal components and causes the transmission hardening, with the creation of play and movement inaccuracy. The company is already measuring the motor winding temperature and the motor absorption to try to control this component but applying the method also realizes that other actions can be done, as e.g., the refinement of the measurement of the brushless motor torque and the monitoring of vibrations. In addition, also test cycles on all brushless motors of the machine should be implemented to gather enough knowledge on its behaviour and fully understand its functioning model in relation to the different output to be produced. Indeed, the dynamic behaviour of an axis managed by the brushless motor has to be controlled. To do this, a temperature and torque detection should be revealed every 2 ms. The Technical Department operators also added that dealing with this component it is necessary to contextualize the results of torque/current/lag error/vibration within one production cycle. In addition, they also planned to generate template cycles to be used as reference to detect the status of the components monitored. Thus, vibration warning and fault ranges should be defined based on the studies to be performed in the future on the machine so that, based on the amount of mm/ms^2 observed, a warning and fault status could be detected by the machine and communicated to both the machinery user and provider. In terms of sensors to be embedded on the system, the electric current/torque are already detected by the drives of the motion control system. Using a real time field bus, new sensors should detect vibrations or temperatures in different points of the windings of the brushless motors. The intervention on such component would affect both the Availability and Performance of the machine's OEE. Finally, also the other critical components were analysed following this level of detail but are not reported here due to the page limit.

4 Discussion

The method embedding the FMECA in the OEE framework revealed to be effective and brought to relevant results in Company A. Indeed, it supported the company in exploring new solutions to avoid failures, in understanding how each component contributes to the machine's OEE reduction (and to its single indexes, Availability, Performance and Quality) and in enabling the delivery of new services. However, it also raised the need to perform further analysis to better define functioning models of certain components (that can beat the same time be supported by the method). In addition, the last step of this method should consist in the evaluation of the feasibility and convenience of both the physical (hardware/component) improvements to be done on the product and the data analysis to be implemented. The Machine A (Screen Printing) needs to be used only as a pilot case to discover how to apply the method and to understand how to start to enrich a traditional machinery with smart connected functions, making it more compliant with the customers' needs and expectations. Therefore, the results obtained on this machine can also be extended to the entire company's portfolio. Nevertheless, to implement the corrective actions on the machine defined with the application of the method, a database and a cloud platform (hardware and software architecture) need to be built by Company A, enabling the collection of the data envisioned as those useful to understand the functioning model of the machine and to provide more effective data-driven services to the customer during its usage. Finally, after the improvement of the product portfolio with smart functionalities and the creation of a database, a service department (able to deliver the data-driven services added to the machines) should be created in the company.

5 Conclusions

This paper presents a method embedding the FMECA in the OEE framework to initialize the development of a smart servitized solution. In particular, its application in Company A (on Machine 1 (Screen Printing)) was triggered by a previous strategic assessment of the company's criticalities in the digital servitization domain. First, the machine selected has been decomposed in its constructive groups and single components based on its bill of material. Then, the FMECA has been implemented, first declining each component in terms of failure modes, failure causes and failure effect and then prioritizing the components based on the RPN calculated through the P and S indexes. Therefore, components were prioritized based on the RPN and the most critical ones were assessed. Using the OEE framework, each loss of time due to the component failure has been analysed to evaluate which sensors could be embedded to improve the monitoring and control functionalities of Machine 1. Per each of them, several factors have been explored: which corrective actions are ongoing, and which could be introduced, which are the variables to be monitored (with which frequency of detection and with which unit of measure), which sensors can be embedded and which standard interface to use. Based on this analysis, each of these components was also declined in terms of OEE. That is to say that it was understood to which part of the OEE (Availability, Performance and Quality) each loss of time, due to the critical components' failures analysed, is related. Then, warning and fault rules have been defined to monitor components' failures. It must be said that the adoption of this method requires the creation of the entire technology stack (with a database and a cloud, that so far are missing in Company A) and the development of a service function able to deliver data-driven services. Finally, this research is not free from limitations. The method, applied to one single case, can be integrated in a unique methodology with the strategic analysis previously conducted in the company to detect the digital servitization hurdles. Then, the integrated method should be applied in a systematized way in other companies willing to pursue the digital servitization path.

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