Implementation of a Maintenance Management System for CNC machines

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Abstract: Computer Numerical Control (CNC) machines are relevant manufacturing equipment, and their reliability directly influences the quality of processed products. The maintenance of this type of equipment plays a strategical role in the functioning of an organization and could account for a large part of the product life cycle cost. A well-implemented Maintenance Management System (MMS) allows understanding maintenance in a global way through the integration of knowledge and information derived by different actors (e.g., operators, maintenance team, CNC machine manufacturer) and sources (e.g., automatic alarms, maintenance team reports, manuals). In this paper, this approach has been applied to support the decisions about maintenance planning and interventions in the workshop of a research centre, which only produces prototypes for internal activities and not meant to be sold, with the aim to preserve as much as possible the performance of the CNC machines. After a first analysis of the current maintenance approach and the available data, the new maintenance strategy has been selected as a form of a preventive maintenance plan based on a fixed schedule, and it has been implemented in a dedicated MMS. The main framework of the system is based on: (i) classification of maintenance activities; (ii) assignment of these activities to different service units, according to required knowledge and safety; (iii) scheduling of preventive interventions; (iv) definition of checklist options and customizable answers to consolidate the execution of maintenance activities; and (v) training of maintenance team. The main results are the traceability of maintenance interventions to ensure the execution of maintenance tasks according to CNC machine manufacturers, and the involvement of machine operators in maintaining their equipment to improve the production performance and asset reliability. In fact, this approach ensures a methodology for those companies that consider the improvement of maintenance planning for the first time, allowing the final user to have a first basic maintenance coverage of the equipment together with the guarantee of starting to accumulate maintenance data. It is fundamental to overcome the gap between maintenance research and maintenance practice.

Keywords: data management; preventive maintenance; intervention scheduling; Maintenance Management System.

1.Introduction

Computer Numerical Control (CNC) machines have ensured an increase in the performance of the manufacturing industry, in the quality of pieces, and in the precise repeatability of the processing, decreasing working time and unit costs of production (Lotti et al., 2019). To maximise these benefits, high availability of the production system is required, minimizing manufacturing delays and unplanned downtimes. For CNC machine optimization, a proper maintenance planning is necessary (Ashayeri, 2007). Ensuring a homogeneous flow of work into a company through good maintenance planning is the aim of consolidated tools/methods, such as Reliability-Centered Maintenance, Total Productive Maintenance, Total Quality Maintenance, Risk-based Inspection, and Value Driven Maintenance. However, according to Luo et al. (2020), some characteristics of CNC machines make the implementation of accurate and reliable maintenance more complex: (i) the integration of various parts (electro-mechanical and hydraulic components), affected by different faults and degradation models; (ii) the time-varying of the working conditions that differently influences the component performance; and (iii) the coupled structure and functions of the system that make it not possible to assume the residual life and reliability of the system simply equal to the residual life of the single components. These aspects result in a difficult collection of suitable data and information required in a great amount to prevent downtime, find faults and restore normal working conditions (Lotti et al., 2019). Making decisions for maintenance schedules based on available data and information brings advantages in terms of productivity and resource efficiency for maintenance operations. Different sources of data, from which extract knowledge, are useful for maintenance: maintenance history; asset usage; asset condition; data about condition and maintenance history of similar assets in the company or also in other enterprises; and environmental data (Bianchini et al., 2019; Sajid et al., 2021). However, building reliable, robust, and available data can become difficult (Rossi et al., 2020; Savolainen et al., 2020), making the complete implementation of previous cited tools/methods a challenge in the industry and determining a gap between maintenance research and maintenance practice (Lundgren et al., 2018). According to

Wolfartsberger et al. (2020), the lack of suitable data and corresponding maintenance protocols is one of the main barriers in implementing advanced maintenance strategies, such as predictive maintenance. In Woodall et al. (2015), seven dimensions of data/information quality and their issues in collecting them in the industrial sector are analysed, resulting still valid for the current context. (i) *Accessibility* (easily and quickly available and retrievable data). Some problems are: the dispersion of data among multiple sources, often retained in staff memory and poorly transferred; data are misplaced, not provided by third parties (such as external maintenance companies), and results irretrievable from old/obsolete systems. (ii) *Consistency* (data representation and meaning are the same in different uses). The problem is mainly related to the recording of the same data several times due to the lack of staff training, understanding, and involvement. (iii) *Interpretability* (linked to proper data languages, symbols, and units). Some issues are related to language translation and different interpretations of terms in manuals and for different assets. (iv) *Timeliness* (sufficiently up-to-date information). Problems in this dimension can often derive from the use of fragmented and not integrated tools to store and elaborate data and information in different company departments. (v) *Accuracy* (the stored value corresponds to the actual value). Mistakes in entering data and information, also due to misunderstanding and lack of training, generate issues in this dimension. (vi) *Relevance* (data are suitable for the objective). An excessive volume of data can make their analysis difficult and unnecessary data can guide inappropriate decisions. (vii) *Believability* (true and credible information). Subjective and qualitative visual inspection processes, above all in case of not expert staff, could generate false information.

An automatic Maintenance Management System (MMS) is recognized as a fundamental tool to access the equipment data and to transform them into information useful to control the system and organize maintenance schedule, above all when the complexity of the plants is high (Fumagalli et al., 2009). It consists of a more or less advanced ICT tool, traditionally standalone and integrable with other manufacturing execution systems (MESs), ensuring the users access maintenance data and information (Nourelfath and Châtelet, 2012; Rivera-Gómez et al., 2013). This type of solution enables different maintenance actors (experts, maintainers, production managers, operators), belonging to diverse company departments, to collect maintenance-related information and make collaborative decisions, through the systematization of the knowledge acquired from past experiences (Wan et al., 2017). The ITC tools available in the market for the industrial implementation of an MMS have grown in the last two decades, and numerous opportunities exist (Durán, 2011). However, their smooth and successful implementation and use in industry are not so widespread due to some barriers, identified in Jafarnejad et al. (2014), involving equipment availability, labor productivity, maintenance information, management support, inventory, and environment controls. In Ardekani et al. (2017) and Moballeghi et al. (2013), one of the main suggestions to overcome the critical issues in the adoption of an automatic MMS is related to preparing awareness and expertise of the involved staff at different level (managers, technicians, operators).

In this paper, the methodological steps to setup an automatic MMS are provided for a particular industrial case study, the workshop of CERN, the well-known European research centre. The use of CNC machines in this case study is particular since production is not the core goal, but it is an internal service for other departments, and the machines only perform prototypes (single pieces or small batches) that are not meant for the market. The lack of structured and systematized data about maintenance and past interventions make it difficult to optimize CNC machine use and ensure their high performance, above all in terms of production quality. The implementation of a dedicated computerized MMS allows the overcoming of these issues.

2.Methodology

A methodology consisting of four steps is proposed to support the definition of a proper maintenance planning. In comparison to other consolidated tools/methods to support the decision-making process about maintenance interventions (see the examples in Section 1), the proposed steps can be considered preliminary and hence necessary to activate other methods. In fact, the proposed methodology aims to be the starting point for companies that still do not have reliable data and competencies/experience to apply other methods. These preliminary steps are particularly necessary for CNC machines due to their complexity and differences in output data format, availability, and quality, acquisition methods, connection with external software, etc.

The four proposed steps are the following.

1. Analysis of the requirements and current maintenance approach: this first step is fundamental to understand the type, quality, and amount of available information and tools and how to use them. All the data and information regarding the maintenance of the selected equipment should be gathered and analysed, from the manufacturer's documentation to the failures and maintenance records.
2. Maintenance strategy selection: with the available data, it is necessary to choose the correct maintenance strategy (e.g., preventative, condition-based, predictive) for the specific application, based on feasibility, costs, and compliance with the organization goals.
3. Standardization of the approach: it means to standardize and categorize the maintenance activities on the involved CNC machines to generate an approach that can be implemented to different kinds of machines using the same structure. However, given the range of different machines, based on dimensions, applications, accessories, and manufacturers, this step is not easy.
4. Automatic implementation: thanks to the standardization of maintenance activities, the creation of a decision-making flowchart to assign maintenance activities, and the adoption of a dedicated MMS software, automatic maintenance requests can be released to the suitable user and recorder in a proper database.

The key feature of this method is the ability to unlock a new maintenance level without the necessity of a high degree of experience nor equipment maintenance history, while the use of the MMS from the very beginning will allow gathering data and expertise to switch to more advanced strategies when the need arises. In the following Paragraphs, the four proposed steps are described in more detail in relation to the specific case study.

2.1 Project requirements and boundaries

The first step of the methodology to successfully implement an MMS is to assess the specific needs and constraints of the host organization with the aim to fulfill the required goals and avoid project failure. In the specific case of the research centre, the main requirements were:

- All the maintenance interventions performed on the CNC machines must be registered and traceable;
- The recommendations of the CNC machine manufacturers must be followed as much as possible;
- The priority is to maintain equipment availability and performance and the quality of the prototypes.

According to these requirements, the best maintenance strategy has been selected to improve the organisation overall control over the maintenance activities and the traceability and execution of each maintenance activity. In this case, the requirements and specific context of the case study led to the selection of preventive maintenance with a fixed schedule based on the manufacturer's suggestions.
After an analysis of the breakdown maintenance interventions, it is possible to select also the typologies of CNC machines on which implement the new approach and the MMS. The types of the considered machines are milling and turning machines because they are the main types of machines in the workshop and therefore the ones that are working the most during the year and present first the need for a higher maintenance awareness, but the methodology should be scalable to other equipment types. The considered machines derive from many different manufacturers and have different characteristics and optional accessories, requiring maintenance as well.

2.2 Analysis of the current maintenance management

The second step is the analysis of the current situation about maintenance management to gather the instruments available and to better understand the environment in which the work should be developed. Therefore, it is necessary to perform a study of the current approach to the maintenance problems and how it can be improved to fit the project requirements. This first analysis is useful to understand the quantity and quality of data available for the implementation of the maintenance strategy and its optimization. In this specific context, for each prototype, the machine operator makes a new tooling set-up and corrects errors if needed. This behaviour, although it ensures precise prototyping, masks possible degenerations of machine performance and therefore signals/alarms for maintenance. Consequently, the internal maintenance team performs maintenance interventions only when a failure occurs (corrective maintenance), registering them when completed with open text descriptions used for weekly activity reports. After this analysis, a few considerations could be taken about the current maintenance management and its main limitations:

- The variety of the machines, brands, and optional accessories do not allow the implementation of a standard maintenance approach for all CNC machines;
- The type of production does not allow control on the products specifications and on the errors that can be used as a signal of a machine malfunction;
- The average young age of the equipment, together with the way breakdown maintenance activities are recorded, prevent to make more advanced studies regarding machines or components reliability;
- The information about past corrective interventions is not enough and structured to gain guidelines to shift to preventive maintenance for the selected CNC machines.

2.3 Maintenance activities definition and sorting

In the third step, the maintenance management must take three main decisions.
1) *Maintenance data sources* – Typically, the main sources for the selection of the preventive maintenance activities to perform are the maintenance manuals from the machine manufacturers, the experience of the maintenance technicians, and the machine operators.
2) *Staff involved in maintenance operations* – The maintenance activities can be performed by multiple teams: maintenance team, machine operators, manufacturer's service, or external specialised services. The activities must be assigned to the correct team according to their technical knowledge and safety considerations.
3) *Preventive intervention scheduling* - Another type of decision to be taken by maintenance management in preventive maintenance refers to the correct interval for the execution of each maintenance activity, which depends on manufacturers recommendations, existing knowledge about the machine failures, and preventive alarms generated by data available on the CNC machines.
Giving the organisation requirements and the lack of staff experience in preventive maintenance, in this case study, the maintenance data have been mainly taken from the manuals of the CNC machines (decision 1), and maintenance interventions have been scheduled according to the intervals suggested by the manufacturers (decision 3). To the activities suggested by the manufacturers, an overhaul of the CNC machine axis geometry has been added as maintenance data (decision 1) to keep track of its changes over time due to the importance of prototype quality. The maintenance activities derived from the manuals have been classified into the following categories:

- Controls: e.g., visual inspections of components, fluid level, wear;
- Direct actions: e.g., cleaning and lubricating;
- Measurements and readings: e.g., controls and registration of values on the machine, such as pressure, temperatures, or geometry dimensions;
- Replacements: e.g., planned replacement of parts and fluids.

To divide the maintenance activities between the teams, a decision-making flowchart shown in Figure 1 has been used (decision 2), considering two main concerns of maintenance tasks sorting and particularly the safety and technical skills of each team.

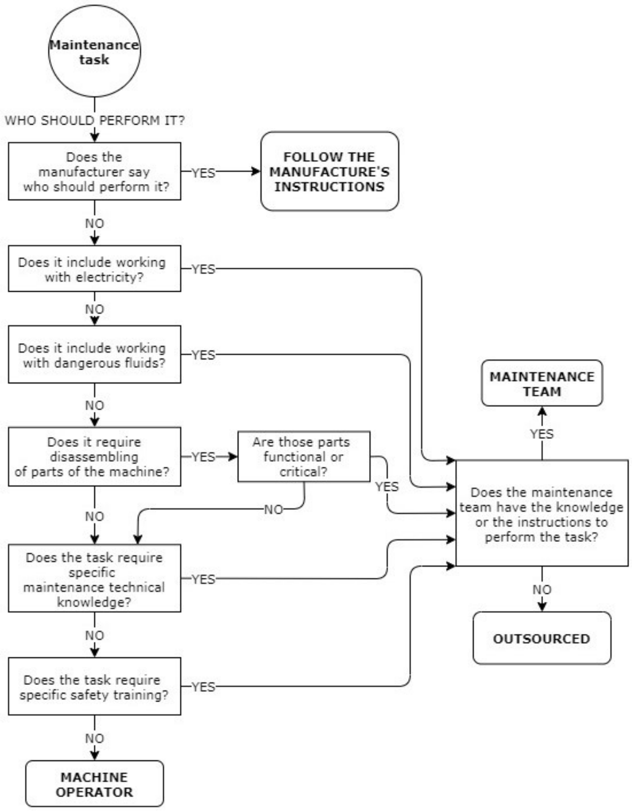

Figure 1: maintenance activities sorting flowchart.

Maintenance technicians are trained and more knowledgeable in terms of maintenance activities and their hazards both for the personnel and the machine, so the tasks involving specific safety training or technical knowledge were assigned to the maintenance team. On the other hand, the most frequent interventions, mostly composed of simple controls, cleaning, and lubricating, are assigned to machine operators. For exceptionally complex interventions for which no instructions are available, the research centre will request the support of the machine manufacturers' maintenance service.

2.4 Implementation of the maintenance management system

Once the maintenance activities have been assigned and scheduled, the maintenance plan can be implemented in the tool for the MMS. The research centre was already using MMS software for maintenance interventions for corrective maintenance activities on the CNC machines. The available software can manage many aspects of assets logistic and maintenance thanks to its multiple modules used to handle assets, spare parts, work, and the relation between those entities. Within the MMS software, the previously described decisions must be implemented with the aim of generating automatic maintenance activities, assigned to the most suitable person, according to the scheduling derived from CNC machine manufacturer's manuals. The work management module of the software has been used to organize work requests for specific assets, generating different "work orders" depending on the required activities. Each work order has been directly attached to the asset for which it has been requested, with the information regarding the activities to be performed, the requester, the spare parts (when used). The life-cycle of a work order is shown in Figure 2, and can be in open text or in code form.

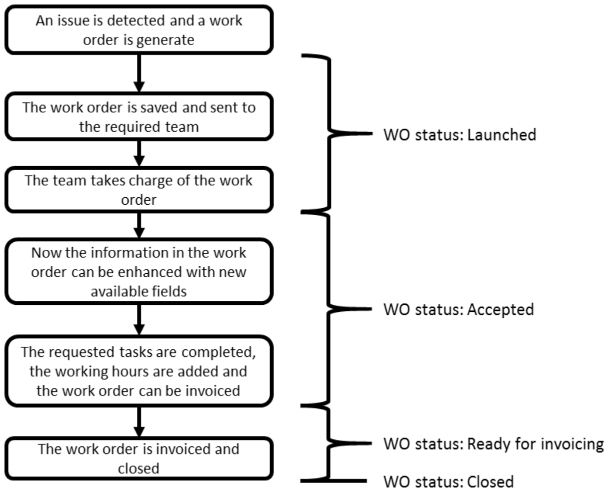

Figure 2: work order (WO) life cycle.

The work order can include multiple actions to be performed to conduct the maintenance intervention ("activities"), collected in a sheet containing task plans, which are sets of pre-defined tasks that describe more precisely the activities to be conducted. Work orders can be generated manually or automatically: the manual method is used in case of unexpected need of maintenance intervention on an asset, while the automatic method is used to release work orders for planned activities or in case of condition-based interventions.

After the completion of the maintenance intervention (work order), it is important to ensure that all the necessary activities have been correctly executed and registered. Consequently, useful data must be collected through reports. The MMS software provides the possibility to prepare some checklists associated with each task required for the maintenance interventions, providing different options of reply. Different checklists have been prepared according to the grouping of the maintenance activities into the four categories, pre-defined in Paragraph 2.3, which depend on the team assigned to the specific work order, which can be: maintenance team, machine operators, and external services. The MMS software allows the preparation of checklists in many different forms, but the most used types are:

- Qualitative: drop-down list of entries called findings that can be created by the user;
- Quantitative: empty field for numeric values, with the possibility to pre-fill the unit of measure;
- Meter Reading: similar to a quantitative checklist item, but the recorded value is registered as a meter for the specific asset. This last type has been used to measure, e.g., the CNC machine cutting hours and consequently triggering the work orders when planned.

According to the team in charge and the type of activity requested, the pre-defined replies to the checklist items has been set up as in Figure 3. In case of problems during the performing of the requested tasks, the user is asked to add a comment to the corresponding checklist item; then, he must generate the follow-up work order, which, in any case, will be sent to the maintenance team as a corrective maintenance work order.

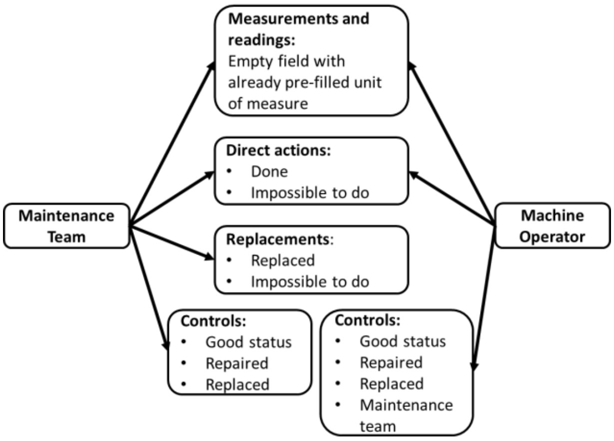

Figure 3: checklist replies according to activity types and teams in charge.

The comment needs contain the minimum information for the maintenance team to understand the general issue, while, in the follow-up work order, the comment will appear as the activity description. The gathered data from the checklists generates reports, useful to create the maintenance history of the CNC machines and recognize frequent problems or optimize the activities schedule.

Within the MMS software, the maintenance interventions have been scheduled following both the manufacturer specifications derived from manuals and the workshop requirements when maintenance tasks have been suggested by the maintenance team. The scheduling has been based on calendar days or operating hours: using these two parameters, the work orders can be planned to be released in advance through a specific MMS software tool ("PM schedule"). Each machine has multiple PM schedules, corresponding to a specific maintenance interval and generating a specific work order.

PM schedule, task plans, and checklists can be modified, deleted, and re-scheduled according to the needs of the users; therefore, this system allows the maintenance management to keep track of the interventions, study the results and take actions to make the preventive maintenance plan more efficient once they have enough data to make reasonable decisions.

When a work order is generated, the team assigned to the required maintenance activities has to be notified. To do so, it is necessary to filter both the activities and the teams in charge to selectively send the notifications. Some other MMS software feature has been unlocked to allow the maintenance management to assign each PM schedule to the suitable team and to assign each machine to a machine operator. A trade was assigned to each activity to better standardize in the system the necessary knowledge to perform the included tasks. Consequently, the work orders are generated automatically and sent to the single machine operator in charge of the machine or to the maintenance team or to both in case of work orders containing activities for both teams. Lastly, an alarm has been implemented to check the delay in the machine operators' work order execution.

3. Results and discussion

The demanded goals and requirements defined by the considered organisation to improve the maintenance management of its CNC machines have been reached through the practical and effective implementation of an MMS based on a preventive maintenance strategy. An available MMS software has been set up to ensure the data storing and traceability of the maintenance interventions, also generating detailed reports of each work order associated with each intervention. Therefore, the preliminary methodological steps implemented in this paper activated a more effective maintenance planning also for this critical type of machine. Being the preventive maintenance plan based on the CNC machine manufacturer's manuals, the factory needs for maintenance have been followed, including the instructions available for the execution of the maintenance tasks. It is also worth noting that compared to the factory maintenance manuals, the automated version presented in this work will allow for a higher information level, thanks to the multiple replies to checklists and the comments that can be easily accessed and used for future studies. The maintenance level of the machines included in the new preventive maintenance plan will improve compared to the previous corrective maintenance approach; thanks to the preventive approach and the automated system of notifications, the regular tasks like cleaning, lubricating, checking levels, filters, and wear will become a routine for the machine operators and will also enhance their awareness regarding the status of their machines.

The application of preventive maintenance was a constrain of the previously available maintenance information flow, characterized by few and unstructured data. Therefore, the work described in this paper can be only the first and quicker step in the adoption of tools and methods for maintenance planning. In particular, the systematized databases that will derive from the continuous use of the MMS will allow the potential activation of other pathways, based on the Industry 4.0 paradigm, such as the use of Digital Twin (DT) and the predictive maintenance. However, it is necessary to consider that the application of advanced maintenance strategies, such as DT, above all to CNC machines, still presents some issues, well described in O'Sullivan et al. (2020), for example, in terms of high time and costs to connect sensors, create the DT and due to the differences of CNC machines and their data quality, extraction, formats, and elaboration.

One of the main aspects ensured by the implementation of the MMS in the organisation is the possibility to enable different maintenance actors (and particularly maintainers and operators) to collect maintenance-related information and hence to make collaborative decisions through the systematization of the knowledge acquired from past experiences. As stated in Guariente et al. (2017), the key point for the implementation of successful maintenance management is to make the machine operators fully aware of their role in maintenance. In this study, it has been demonstrated that by doing that in association with the standardization and scheduling of some maintenance activities, such as the cleaning and checking operations on a regular basis, it is possible to improve the equipment performances and availability as well the product quality. On the other hand, the more complex tasks assigned to the maintenance team or to external services will be performed with a structured schedule and procedure. The maintenance plan is developed and managed using the native interface of the available MMS software, while the work orders are executed in a custom user interface created by the research centre specifically for field use. This second interface contains fewer features not needed for the work orders execution, but it is easier to understand and use, also on mobile devices, for example for the implementation of more advanced systems to manage maintenance actions, such as remote control (Mourtzis et al., 2016). Both interfaces can be customized to show to each unit only the fields necessary for its tasks. As it is mentioned in O'Hanlon (2005), the customization of the MMS software is a well-followed path to the pursuit of its successful implementation.

The role of the software must be stated as a support tool; it should not be considered a maintenance strategy on its own (Wienker et al., 2016) and also not a substitute for the technicians' knowledge. An issue in the implementation of an MMS software is often that it is perceived as a database that will store technicians' skills and experience and that will make their work less important for the organization (Costello et al., 2019). To avoid this problem, during the design of the checklist answers and the selection of the maintenance tasks, as well as in the testing period of the first few PM schedule work orders, both machine operators and maintenance technicians must be involved. Some training must be delivered to all the users, and the importance of their replies and suggestions for further improvement and optimization must be strongly underlined.

The maintenance strategy implemented in the research centre workshop is conservative; indeed, the implementation of all the activities in the manufacturers' documentation are oversized in this scenario, especially considering the moderate working conditions of the machines. As stated in Ahmad & Kamaruddin (2012), the real working conditions of the machines may be different from the ones considered by the machine manufacturers in the definition of the maintenance schedule. Therefore, this solution is the safest in terms of maintenance but also the most expensive, but the use of the MMS software ensures the registration of all the activities in the same work order, starting collecting more reliable data regarding failures and maintenance history. This will allow future studies and optimizations of the preventive maintenance plan to save resources in terms of workload and money and also to detach redundancy in the manufacturers' recommendations (Duarte et al., 2013). In Mostafa et al. (2015), redundant controls and inspections on components that rarely change their status or presents failures are presented as one of the seven main wastes in maintenance processes, and it is suggested to re-schedule the inspections with longer intervals to be decided according to the criticality of the component. Indeed, after the first period of implementation of the new maintenance plan, the need for scheduling optimization is already clear both to the management and the technicians. The manufacturers' documentation appeared redundant compared to the real needs of the workshop and did not include all the required instructions to perform the intervention. The excessive frequency of intervention together with the different needs of each machine makes challenging for the management to control the execution of each intervention while the lack of instructions makes technicians and operator reluctant to perform specific tasks that require higher knowledge. On the other hand, the machine operators' knowledge and awareness about the functioning, construction, and maintenance needs of their machines are already augmented, and everyone feels more responsible about their equipment status and is getting more interested in learning more. This approach, once optimized, will lead as an example for other CERN workshops, and some of them already showed interest in adopting this approach for their equipment.

4.Conclusions

This paper presented an approach to improve the maintenance planning for CERN main workshop, presenting challenges that asked for a practical solution. After a first study of the past corrective maintenance activities and the assessment of the operating environment, data available, and the project boundaries, a preventive maintenance plan on a fixed schedule was implemented. The maintenance schedule was based on the machine manufacturers' manuals, adding an annual geometry overhaul. Each activity was analysed and divided between different teams in charge, and the maintenance plan was set up on a dedicated MMS software already in use in the research centre. A notification and alarm system were then set up to ensure the execution and registration of the maintenance work orders.

This paper addresses some practical problems in: the selection and implementation of a preventive maintenance plan on a fixed schedule, the spreading of the use of the MMS software in the workshop, and the enhancing of the machine operators' awareness regarding their machine's status. Finally, the wide variety of software customization options and the way the maintenance plan was organized will allow the maintenance management to improve and optimize the current strategy.

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