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Current Practices for Preventive Maintenance and Expectations for Predictive Maintenance in East-Canadian Mines

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Abstract: Preventive maintenance practices have been proven to reduce maintenance costs in many industries. In the mining industry, preventive maintenance is the main form of maintenance, especially for mobile equipment. With the increase of sensor data and the installation of wireless infrastructure within underground mines, predictive maintenance practices are beginning to be applied to the mining equipment maintenance process. However, for the transition from preventive to predictive maintenance to succeed, researchers must first understand the maintenance process implemented in mines. In this paper, we conducted interviews with 15 maintenance experts from 7 mining sites (6 gold, 1 diamond) across East-Canada to investigate the maintenance planning process currently implemented in Canadian mines. We documented experts' feedback on the process, their expectations regarding the introduction of predictive maintenance in mining, and the usability of existing computerized maintenance management software (CMMS). From our results, we compiled a summary of actual maintenance practices and showed how they differ from theoretical practices. Finally, we list the Key Performance Indicators (KPIs) relevant for maintenance planning and user requirements to improve the usability of CMMS.

Keywords: maintenance; preventive maintenance; predictive maintenance; CMMS; underground mining; usability

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1. Introduction

Equipment maintenance costs are estimated to constitute from 30% to 50% of a mining operation's annual budget [1,2]. As a result, maintenance is a popular research topic in the mining sector, with cost optimization being a primary focus of attention. Lhorente et al. [3] have shown that preventively maintaining haul truck armature, as opposed to executing maintenance after failure, can reduce maintenance cost by a factor ranging between 1.31 and 4 [3]. They concretized how a carefully devised maintenance management plan may save mining companies hundreds of thousands of dollars in both maintenance expenses and production opportunity costs. Cost reduction can also be achieved by leveraging newer maintenance technologies that allow for intelligent equipment monitoring. For example, genetic algorithms for equipment reliability assessment were proposed in 2004 by Yuriy and Vayenas [4]. They were proven to be a valuable tool to evaluate the effect of component failures on a mine's development cycle [4] and as means to optimize cost reduction via opportunistic maintenance [5]. Additionally, a recent study showed how mines can make use of these technologies to conduct dynamic simulations that offer insightful decision-support [6]. Alas, as most research focuses on mathematical models, simulations, and data-driven approaches [7], we found no papers that defined the constraints and expectations associated with the maintenance process. More specifically, papers did not document maintenance practices and procedures followed in the studied mines, nor was any data collected from industry practitioners and maintenance experts regarding this topic. With the advent of mining equipment automation and the evolution of maintenance tasks, it is more crucial than ever for researchers and industry stakeholders to analyze and comprehend the maintenance process of mines in the 21st century [8]. This study's main objective is to investigate and map the maintenance planning process currently implemented in Canadian mines—specifically, East-Canadian mines. At the same time, we wish to document and analyze the tools used to plan maintenance and obtain expert feedback and avenues for improving the process. To achieve this, we conducted interviews with maintenance personnel of 7 mining sites across East-Canada. Other subgoals were:

- Record expectations and concerns on predictive maintenance Analytics (optimization, artificial intelligence (AI), and simulation techniques),
- Compile user requirements for computerized maintenance management software (CMMS) to improve their usability.

The rest of this article is structured as follows. Section 2 reviews related work on maintenance best practices, active work on predictive maintenance and usability studies on CMMS. Section 3 presents the methodology used to conduct interviews. Section 4.1 presents the maintenance process in Canadian mines along with Key Performance Indicators (KPIs) and expert feedback and comments. Section 4.2 documents expectations and concerns for predictive maintenance, and Section 4.3 presents user interface (UI) guidelines for mining CMMS. Section 5 puts into perspective our findings with the current state of the art and Section 6 concludes the work.

2. Related Work

2.1. Maintenance Background

According to *Introduction to Maintenance Engineering* [9], "maintenance is the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it may perform its required function" [9]. Maintenance can be executed on an equipment following a failure (reactive maintenance) or on a preliminary basis to prevent failure (proactive maintenance). Many types of maintenance exist but those of concern to this study are the following [10]:

- *Corrective maintenance.* Often called repairs, this type of reactive maintenance involves the work done to correct a fault or recondition a broken equipment. The work is executed before the failure's impact on operations becomes critical.
- *Preventive maintenance.* As another form of proactive maintenance, this type of maintenance consists of jobs scheduled and executed at specific intervals. During maintenance, components are replaced or restored, regardless of their apparent condition, according to a predetermined maintenance plan.
- *Predictive maintenance*. Additionally, called "condition-based maintenance", this type of proactive maintenance monitors equipment status so that corrective maintenance may be executed on an equipment before a failure occurs. Sensors on equipment and frequent inspections are used to estimate equipment reliability with the help of AI algorithms.

Maintenance literature identifies multiple steps for effective maintenance implementation which are often tailored to the targeted industry. Despite different naming conventions and specific additions, four steps are always present: identification of issues, maintenance planning, maintenance scheduling and maintenance execution [10–13]. Whereas some authors only comment on these four steps, a common theme is to include a continuous improvement step in which the maintenance team analyses the quality of the maintenance planning for the week. The goal of this last step is to improve maintenance for subsequent weeks by reflecting on what could have been done differently. An example of the steps mentioned in [10] is presented in Figure 1. Notice how, despite there being 6 steps, the 4 core steps are present.

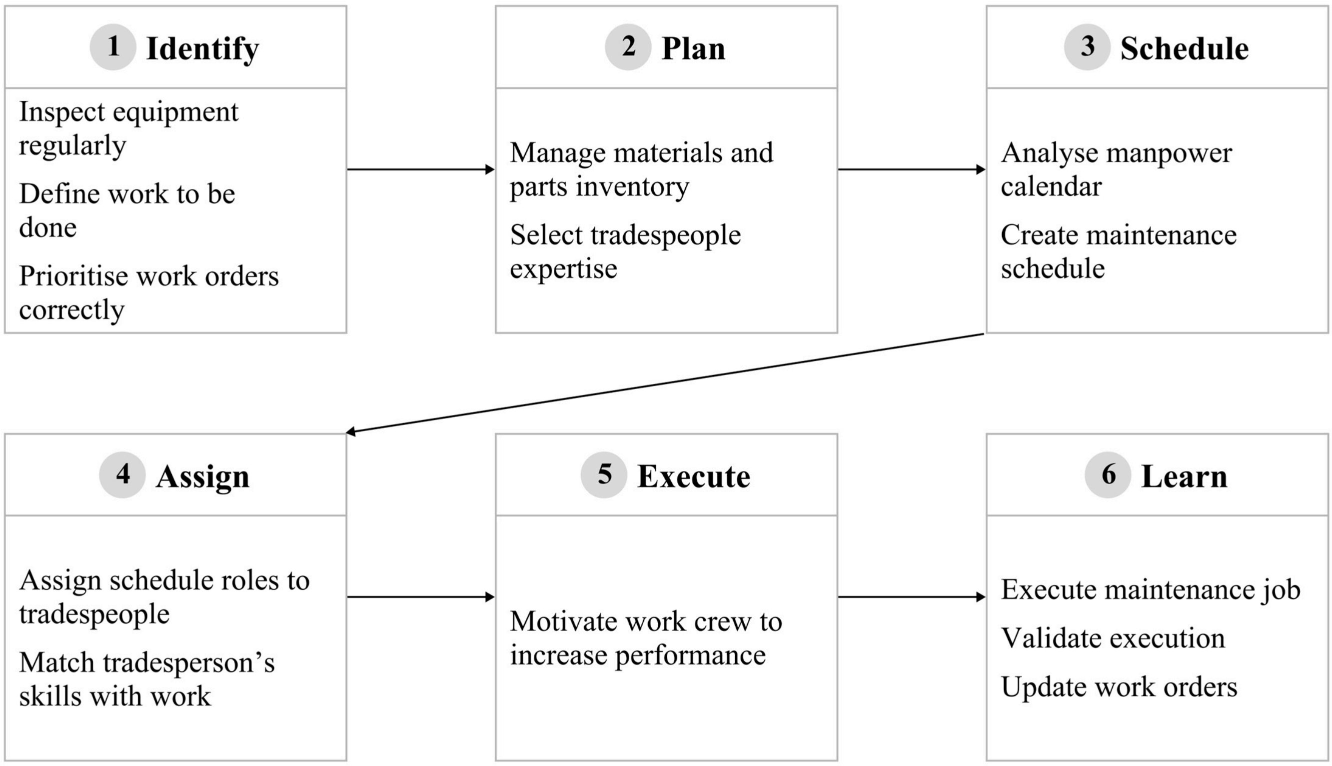

Figure 1. Six key steps in effective maintenance management according to [10].

Throughout the maintenance process, the main transaction document is the work order. A work order represents a maintenance job and contains a detailed description of what to do, the estimated completion time and other relevant information and comments. Work orders are used to monitor maintenance progress and constitute an insightful statistic for process optimization.

Nowadays, work orders are saved electronically in a CMMS, which is a system to aid management and planning of maintenance. It offers a database to store asset-related data such as owned equipment and equipment parts, work orders, workforce, etc. For most of these systems, however, usability is an issue due to obscure features being hard to access and time-consuming to implement [14–16].

Maintenance evaluation would not be possible without the use of KPIs. These are ratios formed from data that are analyzed to form trends. These trends are then used to evaluate the quality of the maintenance process or elements related to it. A study targeting a mine in Ontario, Canada marked KPIs importance by making them the primary source of decision-making in their proposed maintenance methodology [17]. This methodology was then found to improve maintenance planning and scheduling while reducing costs [17]. Later work from Lafontaine in 2006 queried 12 underground mines in Québec, Canada and highlighted the most used KPIs at the time [18]. Figure 2 summarizes her results.

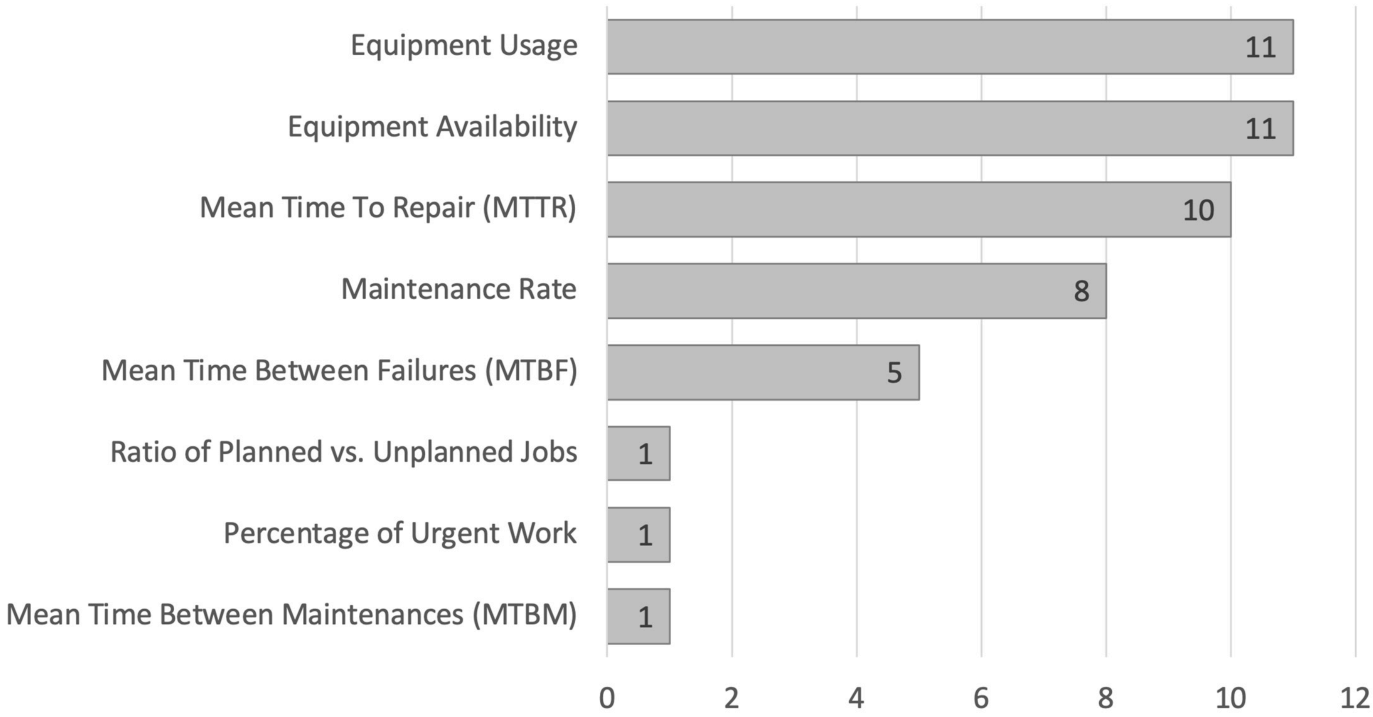

Figure 2. Mining KPIs by number of mines (out of 12) found by Lafontaine [18].

Figure 2 emphasizes the importance of equipment availability and usage which were the KPIs the most used among all 12 mines. Yet, several maintenance KPIs identified by Lafontaine in her literature review were not used at the time by the mines interviewed. Those relating to equipment and maintenance evaluation are:

- Percentage of downtime
- Mean time to maintenance (MTTM)
- Percentage of planned maintenance
- Respect of schedule
- Manpower efficiency

2.2. *Preventive Maintenance*

Preventive maintenance (PM) is a subject greatly discussed in industries such as manufacturing [19,20], maritime [21] and mining [22]. In fact, when it comes to mechanical systems, PM is the predominantly employed form of maintenance [21]. Concerning research, however, most PM planning studies focus on mathematical algorithms and simulations instead of targeting concrete problems in the industry [19]. Where most research offers solutions using matrices, mathematical notation, or AI (techniques that are rarely understandable by maintenance experts), industry practitioners still rely on methods based on time, cost and equipment failure to plan their PM activities [19]. The authors defined the need for a framework grouping related systems in a way that is comprehensible by maintenance personnel. We believe that the first step to achieve such a framework is to understand the real industry practices concerning PM planning.

In the mining industry, La Roche-Carrier conducted interviews with maintenance personnel at the LaRonde mining site in Québec, Canada and mapped their maintenance process in detail [23]. His findings concerning the steps executed in the PM process at the LaRonde Complex respect the general steps identified in Section 2.1 and added implementation details specific to LaRonde. While a statement was given regarding similar practices being implemented at other mining sites, the author did not elaborate any further on the subject. No other experimental research studying the maintenance planning process in Eastern Canadian mines was found in the literature review.

2.3. Predictive Maintenance

Predictive maintenance, oftentimes called condition-based maintenance, refers to the "intelligent monitoring of equipment to avoid future failures" [24]. While in the past this monitoring was executed through visual and auditory inspections of the equipment by human operators, nowadays it uses equipment sensor data and analytical algorithms [24]. Predictive maintenance practices have been linked to cost reduction and increase of equipment reliability [25,26] as well as a reduction of equipment environmental impacts [27]. Research in predictive maintenance is active in the manufacturing and process industry where fixed equipment is predominant. Paolanti et al. [24] proposed a predictive maintenance architecture for the process industry that offers a cloud-based solution obtaining a 95% accuracy in machine state prediction [24]. Similarly, Alves et al. [28] deployed a predictive maintenance system in a manufacturing plant which achieved a prediction accuracy of 99% despite a time range limitation of 5 min [28]. A study on integral type fault prediction using a novel machine learning parallel classification technique has obtained an average accuracy nearing 100% in the benchmark semiconductor manufacturing maintenance problem [29]. When it comes to mining equipment, however, predictive maintenance research is less precise. No actual implementation of a predictive maintenance algorithm for mobile mining equipment was identified from the research carried out. In fact, predictive maintenance has been an active research topic for many years and is a concept recently adopted by world-leading solution providers like Dingo [30], Baker Hughes [31] and ABB [32]. Yet, industrial articles who present its integration in different mines do not actually document the implementation process [33–35]. Concerning research, most studies focus on theoretical literature reviews of predictive maintenance technologies (i.e., [36]), and potential issues and challenges linked to its adoption (i.e., [37]). At the same time, other studies propose architectural solutions that remain unimplemented as of the writing of this article (i.e., [38,39]). On the other hand, a 2016 study aimed at predicting off-highway trucks' availability in open-pit mines developed an algorithm. They obtained a prediction accuracy of 85% based on 52-week historical data but no follow-up on-site implementation was ever provided [40]. On actual implementation, technical guidelines have been proposed as early as 2002 [41], but no study focused on user-related guidelines concerning predictive maintenance practices. Overall, an important research void is present in this field both from a technical and a user-oriented point of view.

2.4. CMMS Usability

CMMS have existed for a long time and have, since the beginning of user-centered studies, been linked to usability issues [15]. One study highlighted the need for a user-oriented design in a world where automation gains increasingly more traction [42]. When visiting specific issues with CMMS design, Tretten and Ramin [43] offered an insight on actual personnel needs and suggestions for improvement [43]. Their results were obtained from interviews with expert personnel in the paper and pulp, mining and airplane manufacturing industries and are summarized in Figure 3.

Figure 3. Industry CMMS needs and recommendations based on [43].

Figure 3 offers an insight on common issues that maintenance operators need to deal with daily. The authors concluded their work by stating that a CMMS covering all aspects of the maintenance process presented with a user-friendly interface would be the most desirable solution but offered no concrete implementation. Despite being properly trained on how to use the CMMS, its poor usability hinders task performance to maintenance personnel [15]. Unfortunately, none of the studies' recommendations have been tested in the field. All in all, CMMS usability, specifically in the mining industry, is a research field requiring a more pragmatic approach targeting maintenance experts.

2.5. Problem Statement

Our literature review establishes a baseline concerning what is known in terms of maintenance practices as a general procedure or specific to industries such as manufacturing and energy. However, the only study exploring the real-life maintenance processes in East-Canadian mines was the one conducted by La Roche-Carrier, and it was limited to one mine only. Hence, the main objective of our study is to investigate the maintenance processes and tools used in the Canadian mining industry. Furthermore, studies researching CMMS usability have concluded that most CMMS have poor usability. Hence, the second objective of our study is to validate these conclusions by analyzing different CMMS actively used in East-Canadian mines. Finally, with the ever so increasing possibility to integrate predictive maintenance practices in mobile mining equipment maintenance processes, our third goal is to investigate expectations, concerns and opportunities on predictive maintenance from a maintenance expert's perspective.

3. Materials and Methods

The main objective of this study was to investigate the maintenance planning processes and tools used in the mining industry. To achieve this goal, we conducted semi-directed interviews – online and in-person – with maintenance personnel from five underground mining sites located in the Province of Quebec: LaRonde Complex (Gold, 11.9 tons/year [44]), Lamaque (Gold, 4.9 tons/year [45]), Éléonore (Gold, 7.7 tons/year [46]), Westwood (Gold, 3.1 tons/year [47]) and Renard (Diamond, 1.6 million carats/year, [48]), one mining site in the Nunavut territory: Méliadine (Gold, 11.9 tons/year [49]), and one open-pit site in Ontario: Côté Gold (Gold, site in construction [50]).

3.1. Participants

Fifteen participants (13 male, 2 female) took part in this study. Participants' ages were 38 on average, with 31 being the youngest and 58 the oldest. Most participants had more than 10 years of experience in the mining sector and their expertise was distributed as follows: General Supervisor (or any supervisor role associated with maintenance) (60%), Maintenance Planner (13%) and Reliability Engineer or equivalent (27%). The study received the approval of the Polytechnique Montréal Ethics Research Board (CER-2122-04-D), and all participants signed an informed consent form.

3.2. Materials

Online interviews were conducted via Zoom or MS Teams, depending on participants' preferences. Notes were taken throughout the interview with pen and paper and interviews were not recorded. In-person interviews were conducted on-site without additional material. We used an interview guide that covered the main themes of maintenance planning as it is currently done in the mine (i.e., as-is) and future requirements for predictive maintenance. The interview guide contained three sections: (1) participant's demographic, (2) tools and processes used for maintenance planning, and (3) software and interface preferences. The first section contained questions related to the age of the participant, the number of years they occupied their current job and the number of years they spent working in the mining industry. The second section queried the participant on their functions and responsibilities within the occupied job, the tools used to plan mobile equipment maintenance and the participant's preferences or comments regarding those tools. We also asked questions concerning the current maintenance process and the participant's opinions. The third section focused on the software used for maintenance planning. We used the critical incident approach and asked participants to give specific examples of situations where the software helped them considerably to achieve their goals or was unable to help them. Finally, participants were asked to identify features they considered to be missing from the software and whether they had suggestions on how to improve it.

3.3. Procedure

Depending on mining sites' availability, either individual or group interviews were conducted, though individual interviews were predominant. Most interviews were completed online except for two instances where an on-site visit was planned by the mining site. Necessary precautions were taken on-site to ensure the safety of all participants and researchers. Questions of Section 1 of the interview were always asked first but, due to the nature of the interview, questions in Sections 2 and 3 were not asked in a particular order. In fact, participants were allowed to reasonably diverge from the specific topic of the question and would often answer precedent or subsequent questions simply by following their trail of thought. Quality and quantity of responses were therefore increased, albeit causing some interviews to last longer than the predetermined 60 min. This divergence also allowed us to adapt the questionnaire for future interviews by selecting the most pertinent topics and expanding on them. After each interview, we reviewed our draft maintenance process and adapted it based on the last participant's responses. During the next interview, we presented the draft maintenance process to the new participant and obtained feedback and suggestions on how to improve it further. We reached data saturation when participants were unable to suggest additional modification. As a last note, participants often mentioned tools or files they used daily. Whenever such mentions were made, we would ask the participant if they could share the documents or, alternatively, take screen captures of the most relevant sections. In most cases, due to the lack of confidential information in the documents, the participants agreed to share the documents by email.

3.4. Data Analysis

We used an inductive and a deductive approach to organize the data into categories. Categories created using the inductive approach stemmed directly from participants' responses whereas those identified via the deductive approach were primarily based on the themes specified in the interview guide. The inductive approach's main focus were the problems with currently used maintenance tools and the requirements for a new tool. To facilitate data manipulation, we transcribed elements of each response onto individual cards and grouped the cards by similarity. We then labelled the clusters of cards to name the formed category. The deductive approach focused on participants' tasks and work organization.

We were able to validate intermediate results via presentations with domain experts and the non-profit organization MISA Group. Additionally, during select interviews, we asked participants to validate our comprehension of the maintenance process and the decision-making involved. Two participants accepted the role of mentor and allowed us to further elaborate on the collected data.

4. Results

We structured the main findings from our interviews into 6 categories (see Table 1) that will be described in detail in the following subsections.

Table 1. Categories extrapolated from the interviews.

Category	Definition
1. Maintenance Process (Section 4.1)	The maintenance management process and its challenges along with participants' opinions and comments.
2. Maintenance Planner (Section 4.1.3)	List of tasks and responsibilities of a maintenance planner.
3. KPIs (Section 4.1.6)	An exhaustive list of KPIs used to plan maintenance.
4. Tools (Section 4.1.7)	Overview of the suite of tools used to plan maintenance along with participants' feedback.
5. Predictive maintenance Analytics (Section 4.2)	Requirements and issues to be considered for predictive maintenance Analytics according to participants.
6. Decision Support System (Section 4.3)	List of guidelines for a decision support system aimed at maintenance personnel.

The following subsections describe the 6 categories in detail. Section 4.1 gives an in-depth summary of the maintenance process currently implemented in East-Canadian mines and recorded best practices. Section 4.1 also includes findings on KPIs (Section 4.1.6), the role of the maintenance planner (Section 4.1.3) and the suite of tools used to manage maintenance (Section 4.1.7). We made this decision due to their close relationship to the maintenance process. Section 4.2 presents participants' thoughts and fears concerning predictive maintenance Analytics and Section 4.3 defines a series of guidelines for a decision support system used to assist experts in maintenance planning.

4.1. The Maintenance Process and Best Practices

In this section, we present a detailed description of the maintenance process of mobile equipment based on participants' responses. It relies on a rigorous series of steps that have been established through years of mine development (Figure 4). Every subsection contains the description of its respective step in the process accompanied by participants' opinions, suggestions and comments where relevant. At the end, we include a summary of participants' general comments on the process.

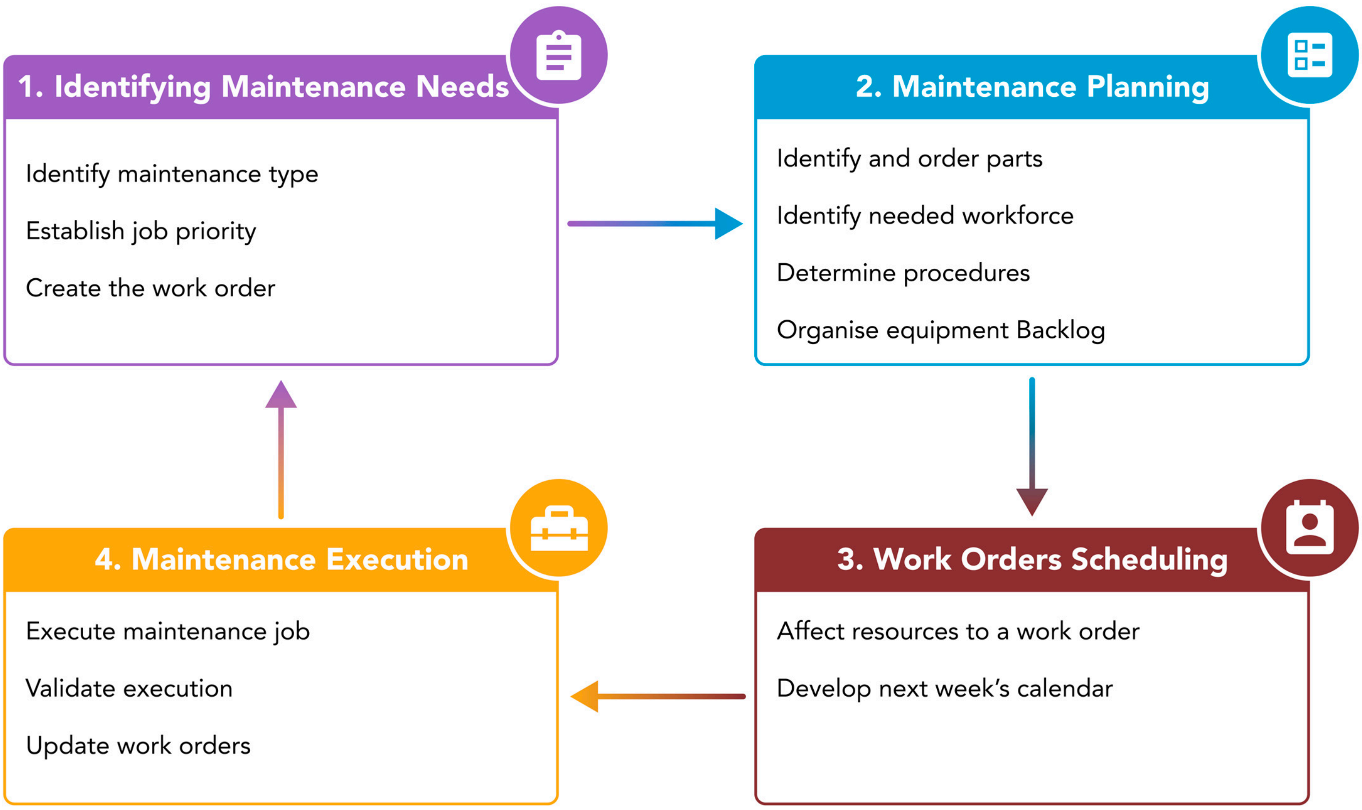

Figure 4. The maintenance process.

4.1.1. Workforce

The maintenance process concerns many members of the workforce often requiring expertise tailored to each step. From our interviews, we found that four professions were crucial to the mobile equipment maintenance planning process. Other professions exist but were not explored in detail by the participants.

- **General Maintenance Supervisor**. Additionally, known as "General Maintenance Foreman", the supervisor's role is to oversee and coordinate equipment maintenance according to the maintenance schedule. The supervisor decides in which garage section to distribute manpower depending on available groups' expertise. Additionally, the supervisor ensures adherence to government norms and collaboration between maintenance departments. Supervisors take part in scheduling meetings alongside the maintenance planner.

- **Maintenance Planner**. Responsible for planning maintenance activity in the mine, the planner's main concern is to adhere to the PM plan. Additionally, developing and managing equipment KPIs and programming the maintenance schedule constitute a large portion of the planner's tasks. Finally, the planner establishes maintenance procedures and determines the timetables of the workforce. More information on the planner's tasks and responsibilities is presented in Section 4.1.3.
- **Reliability Engineer**. The reliability engineer works closely with equipment-related data. With tasks ranging from engine oil analysis to availability monitoring, the reliability engineer uses advanced tools and techniques to ensure correct functioning of the equipment fleet. Results provided by the reliability engineer assist the planner in the decision-making process.
- **Maintenance Superintendent**. The superintendent's main roles are those of managing the global maintenance process and establishing the PM plan. Along with setting and revising the financial budget, the superintendent is responsible for approving or rejecting employee's requests, monitoring KPI trends along with reliability engineers and ensuring that industry best practices are followed by the workforce. Overall, the superintendent has a long-term overview of the maintenance activities to be able to recognize opportunities and bottlenecks to improve and optimize the maintenance process.

4.1.2. Identifying Maintenance Needs

The maintenance process begins with the work order. The addition of a new work order to the CMMS varies between mining sites and depends on a company's workflow. At one mining site we interviewed, almost all maintenance personnel could create a work order and add it to the system. For all the other interviewed sites, work order requests filled out by an employee were verified and approved by a select member of the team before they could be added to the CMMS. The work order creation process is circumstantial. Some work orders can be automated therefore delegating work order creation to the system. This creation process depends on fixed triggers set by the general superintendent that are based on the established maintenance plan. The triggers often check an equipment's total engine-hours and append a PM work order to the system if a certain threshold is surpassed. That said, many KPIs can be used as triggers. Automatic work order creation is favorable for recurrent maintenance jobs such as those concerning PM. Alternatively, work orders can be created manually. Manual work order creation happens most often after a PM inspection by the mechanic or following equipment usage by the operator. Of course, the active work order creation procedure at the mine needs to be respected. Regardless of the method used to create work orders, the creation step is essential to ensure the minimization of equipment downtime. It is therefore strictly regulated. Work order documentation and explanation must respect specific standards to optimize maintenance planning and scheduling. The most important of such standards is the prioritization of a work order.

Work order priority determines the urgency of the job. Subsequent steps in the process depend primarily on this value. Table 2 summarizes the priorities mentioned by participants and their definition. Naturally, priority codes and exact meanings may differ between mining companies, some companies having as many as 5 priority levels. However, priorities P1, P2 and P3 were mentioned by all participants of the study.

Table 2. Work order priorities and description.

Code	**P1**	**P2**	**P3**
Description	The job is critical. An immediate action is required to amend the situation.	Schedule break. The job needs to be executed in the current week (unplanned).	The job is planned.
Criteria and conditions	Major integrity and health risks of personnel. Immediate negative impact on the environment. Malfunction slowing down production.	The job will become a priority 1 if not executed before the end of the week. Critical equipment can be stopped in a way that will minimize negative impact on production.	The job can be included in the scheduling calendar for upcoming weeks and is of corrective or "equipment improvement" nature stashed in the Backlog.
Notes	The maintenance planner is not concerned by this priority. Usually, a mechanic will open this type of work order.	The maintenance planner is not concerned by this priority. Usually, the maintenance supervisor opens this type of work order. Great attention to detail must be dedicated to evaluating the risk factor of P2 work orders. These work orders tend to be forgotten.	Work orders generated by the CMMS are of this type. The maintenance planner opens this type of work order.

In addition to the priority, a work order's life cycle is clearly defined in the maintenance process and updated as the work order is handled. Work order update is generally executed by the maintenance planner. Table 3 summarizes the main life cycle states of a work order according to participants. The order in which the states are presented in the table matters. For example, a work order needs to be marked as "Ready for Scheduling" before it can be marked as "Scheduled". In parallel with the priority, the values and meanings of the life cycle states can vary from mine to mine.

Table 3. Work order life cycle states and description.

State	**Description**
Registered	The work order has been added to the CMMS's database. It needs to be reviewed by the maintenance planner and general maintenance supervisor before it can be flagged for planning.
Ready for Planning	The work order was revised and approved. The required material and manpower have been established.
Waiting for Parts	Material to execute the work order was ordered but is not available yet.
Ready for Scheduling	The work order has been validated by personnel in charge and materials needed are available. The work order can be added to the calendar.
Scheduled	The work order is set to be executed on a specific date.
Completed	The work order was executed by a tradesman.
Closed	The finished work order was validated by the maintenance planner and can be safely considered as done.

4.1.3. Maintenance Planning

The second step in the maintenance process is the planning of the maintenance. Of the mentioned work order priorities, P1 and P2 constitute generally unplanned or urgent work for which the planning and scheduling process is often skipped. Urgent jobs are executed as soon as possible. The maintenance planner's concerns do not include maintenances that do not allow for planning such as urgent or emergency maintenances.

The responsibilities and tasks of a maintenance planner may vary between mines. In fact, one participant stated that their job as a planner did not include scheduling but was limited to maintenance planning. For simplicity's sake, and due to the fact that this distinction is made mainly in more advanced mines and is therefore not a standard practice, the tasks of a maintenance planner will include those of a "scheduler". Following, is a list of tasks executed by the maintenance planner:

- Validate work to be executed
- Understand and implement the maintenance plan
- Study and observe the fleet and its status
- Plan next week's maintenance
- Reevaluate priorities on calendar changes
- Account for maintenance impact on operations and production goals
- Minimize unplanned maintenances
- Print the developed schedule
- Manage a data volume management report
- Ensure material procurement in reasonable time
- Clean up equipment Backlog

All these tasks are generally executed every week with the exception of the Backlog clean-up which may be executed less frequently (on a three-month basis). An important note mentioned by all planners interviewed is that "*maintenance planners do not handle emergencies*". Emergencies have a different lifecycle in the maintenance process which is outside the scope of this study. One participant expressed the difficulty of balancing what needs to be done versus what the team could realistically handle. This aspect constitutes a major challenge for maintenance planners. Another participant stated that a vicious cycle can ensue when planning for future works. This cycle concerns equipment availability needed to respect operational objectives and the PM plan requiring certain equipment to be scheduled. In an attempt to meet the weekly production objectives, the maintenance planner may postpone maintenance on an equipment with the risk of the equipment breaking sooner, thus reducing availability later on. On the opposite side, the decision could be taken to maintain the equipment prematurely which will guarantee high availability in the future at the expense of parts being replaced too soon. It is a maintenance planner's main responsibility to handle risk-related choices such as these ones.

A crucial step in the process is the prioritization of maintenance jobs, while ideally, all work orders should be executed, realistically the planner needs to compromise on the tasks that need to be done. Many mining sites have therefore established a priority to the tasks to execute depending on the type of job they entail. The following list is an example given by a participant highlighting the order of work order priority:

1. PM on production equipment
2. Production equipment with "DOWN" status (either broken or unused)
3. Weekly priority (P2)
4. PM on auxiliary equipment
5. Corrective maintenance on production equipment
6. Corrective maintenance on auxiliary equipment
7. Old corrective work orders in the Backlog.

Note how the third planning priority concerns P2 work orders—or even P1 work orders—that can be planned for the upcoming week. This happens when such work orders cannot be executed in the current week and need to be scheduled as soon as possible for the next week hence removing the "unplanned" status. Examples of such a situation is a critical production equipment breakdown whose repair time is too long or a breakdown requiring parts and materials not available in the mine during the week.

Once the work orders are ready for further planning, the maintenance planner is responsible for ordering the necessary materials and parts. Seven participants have pointed out that, for automatic work orders, parts can be ordered automatically once the work order is pushed to the database by coordinating efforts with parts providers and manufacturers. Additionally, in some instances, mechanics and maintenance supervisors can directly order some parts required for the work order at the moment of submission. Ordering and tracking of the parts and materials is done through the CMMS.

The final step in the planning process is known as the "Kitting" stage. Once all parts and materials for a work order have been received, they are thoroughly organized into Kits, labelled, and placed in an easily accessible location to save time before executing the maintenance job. The label is also added to the work order's entry in the CMMS. All participants have mentioned having a system allowing such Kits to be made and kept track of, but only one participant expressed the presence of an official "Kitting Standard" in their mine. Only once the required materials have been received for a work order can it be marked as "Ready for scheduling".

Throughout the planning step, the maintenance planner needs to consider many aspects of the operation. Two participants occupying this role mentioned that the ageing of the fleet is a crucial factor impacting their decision-making: the older the equipment, the higher the maintenance frequency. Another participant indicated that the team needs to respect manufacturers' recommendations for maintenance intervals and execution. More information regarding this point was not given but it was made clear by the participant that warranty is rarely considered while planning. Two participants stated that workforce absences and vacations made the development of the calendar quite a difficult task along with variable operational needs depending on the season of the year. Four participants occupying supervisory roles and two maintenance planners stressed the impact that equipment usage has on maintenance planning. Specifically, operators and the way they operate their equipment can have nefarious consequences on the lifetime of said equipment. One of these participants expressed how operators, who are paid by bonus, have a tendency of overstressing the equipment to surpass the production goal. This factor contributes greatly to equipment wear and is a major cause of unplanned maintenances.

4.1.4. Work Orders Scheduling

Once work orders have been properly filtered and prioritized, they can be scheduled. Scheduling implies the addition of work orders to next week's calendar for maintenance execution. Participants have pointed out that, as of now, mobile equipment maintenance scheduling rarely exceeds one week in advance. This is due to uncertainty caused by many factors in the maintenance process. These factors range from manpower availability and material supply chain reliability to risk-related decision-making due to emergencies and the consideration and handling of unexpected events. More mature maintenance teams, albeit being able to start scheduling 2 to 3 weeks in advance, often find themselves having to rethink the schedule because of the aforementioned factors.

One participant highlighted some of the scheduling methods that exist in the mining industry (frequency-based, by engine-hours, by date, etc.). However, he stated that mobile equipment is most often scheduled using the "engine-hours" approach due to PM being the most used maintenance type for this kind of equipment. The engine-hours counter on an equipment is verified after every usage and its value is logged in the system. At specific thresholds established in the maintenance plan, the equipment is expected to be scheduled for PM. Most common thresholds are 250, 500, 1000 and 2000 engine-hours.

Scheduling tasks can be fixed or cascading. When a maintenance job is postponed, dates for fixed tasks will not be affected and the schedule will be organized around those tasks. On the contrary, postponing cascading tasks will cause all subsequent tasks to also be postponed. Mobile equipment scheduling tasks are rarely fixed due to the constant evolution of equipment engine-hours throughout the week. Cascading scheduling tasks are therefore preferred.

All participants working at underground mining sites mentioned a difficulty issued by the limited space in underground garages. For a clearer understanding, Figure 5 presents the diagram of an underground garage belonging to one of the interviewed mines.

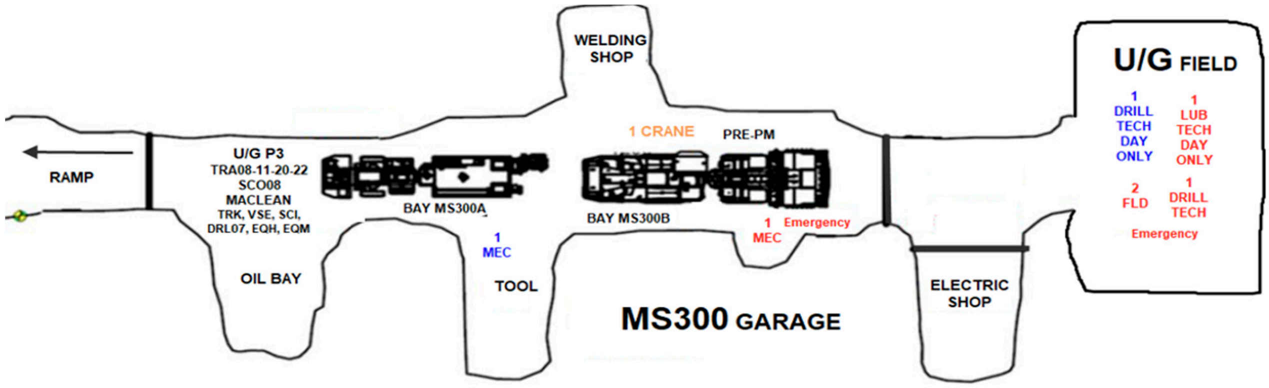

Figure 5. Underground garage diagram.

As can be seen by Figure 5, a typical garage in the mining industry is subdivided into sections known as bays. Bays tend to offer a suite of tools specific to a certain job or equipment, for example the presence of a crane for engine-related jobs or a toolkit for tire replacement. This is a concept that the maintenance planner needs to keep in mind during the creation of the schedule. Additionally, underground garages have a limited number of entries and exits, making the logistics of equipment turnover crucial to the scheduling process. One participant illustrated how placing a maintenance job of long duration in a certain bay may end up obstructing an equipment whose maintenance is over. Albeit this being a rare occurrence, the impact of this event may be detrimental to operations.

The creation and handling of the scheduling calendar depends on the mine. This calendar is the result of the scheduling task done by the maintenance planner. It specifies which equipment shall be at which location on what date. Due to communication and logistic constraints, once the calendar for a week has been approved, it may no longer be modified by the maintenance team. All changes to the scheduling timeline will only affect successive weeks. During the creation of the calendar, established best practices mandate a certain flexibility to account for unplanned maintenance during the scheduled week. Unplanned maintenance jobs include corrections following an inspection of the mobile equipment or, for example, other emergencies during the week. The calendar's flexibility is based on the amount of time scheduled for maintenance versus the amount of time left unoccupied for unforeseen events. Most participants (8/15) stated that, in their mine, the schedule cannot surpass 80% of available manpower. Concretely, if 336 h of manpower are available during the week (12 h shifts $\times$ day & night shifts $\times$ 2 workers per shift $\times$ 7 days a week) the planner will not schedule more than 270 h of maintenance work. Three participants stated that their calendar's flexibility target was 60% or lower (60% planned, 40% unplanned) due to, among other factors, the ageing of the fleet. As a last note on the creation of the calendar, some priority constraints need to be respected while scheduling work orders. In fact, work orders necessary to complete maintenance jobs of the previous week have the highest priority. Following, are work orders declared urgent or high priority during the scheduling meeting and, finally, those concerning critical equipment. These scheduling priorities are different from work order priorities defined previously, i.e., an unfinished P3 work order scheduled in the previous week will be prioritized in this week's schedule.

Great emphasis is accorded to in-person meetings during the scheduling phase. A unanimous opinion was voiced among participants concerning meetings. Daily and weekly meetings are conducted and serve different specific purposes depending on the maintenance team and its needs. One of such purposes is the estimation of time needed to execute work orders, which is necessary for the planner to start scheduling. The general purpose of daily meetings is keeping the team up to date and aid the planner in decision making. In fact, during those meetings, the planner will present the current schedule and obtain feedback from participants. Along with the planner, participants include the maintenance superintendent, the general maintenance supervisor and, oftentimes, reliability engineers. In order to prepare for the meetings, the planner needs to identify which work orders may not be completed by the end of the week and propose an adapted schedule respecting the established priorities. Further flexibility is required for this preparation to allow for modifications to be requested by the people participating in the meeting all the while respecting the manpower occupation goal set in the mine.

4.1.5. Maintenance Execution

This step encompasses the results of all previous phases and constitutes the culmination of the maintenance process. Although a detailed specification of this step is outside the scope of the study, some aspects need to be expanded upon.

Firstly, the general maintenance supervisor uses the scheduling calendar to assign workers to the respective work orders. Worker assignment depends on factors such as equipment criticality, manpower availability, worker specialization, current mining operations state and others. That said, the schedule remains the decision-making pivot on which the supervisor needs to base all decisions. One participant stated that the reason as to why the general maintenance supervisor oversees worker assignment is that the supervisor knows workers' strengths and weaknesses. This knowledge allows for a more optimal placement of the workforce. In contrast, another participant described how the assignment process is done by the supervisor in conjunction with the maintenance planner and superintendent, to maximize coordination between the maintenance teams.

Once the work orders have been executed, they need to be validated and closed by the general supervisors. The work orders closing process differs between mining sites. Five participants explained that, in their mine, the updating of the work order status to "Closed" in the CMMS can directly be done by the general supervisor. A participant from a different mine contradicted this fact by stating that only the maintenance planner may officially close a work order. Other members of the workforce can only indicate that the maintenance job was validated. Regardless of its implementation, the work order closing procedure marks the end of the maintenance process. Next week, maintenance jobs will be based on the scheduling calendar developed during the current week and maintenance planning will organize maintenance for the week after. Such is the mobile equipment maintenance cycle.

4.1.6. KPIs

Members of the maintenance team base their decisions on an array of KPIs which allow them to maximize maintenance efficiency. Table 4 presents a list of KPIs mentioned by participants organized by the participant's role in the team. Other KPIs exist in the maintenance planning process but were not explicitly mentioned by participants. Of course, these KPIs, albeit being more important to the associated occupation, are not exclusively limited to it. Indicators such as equipment availability and usage, maintenance cost, and others are relevant to all team members.

Finally, an equipment's Backlog constitutes a crucial KPI for the maintenance planner and supervisors to evaluate the state of maintenance procedures throughout the mine. All participants stressed the importance of correctly managing Backlog workload. Managing the Backlog implies minimizing the amount of cumulative work to be executed on an equipment. Backlog workload is generally measured in weeks. One participant shared the thresholds used in their mine to manage risk via the Backlog. The participant stated that these thresholds are conservative, but respect guidelines established at other mining sites. The thresholds and respective interpretations are shown in Figure 6.

Table 4. KPIs by participant's role.

Maintenance Planner
• **Fleet Availability**: Determines the amount of equipment in a fleet which is available for operation.
• **Equipment Usage**: Measured in engine-hours, it is the defining KPI to plan PM on an equipment.
• **Equipment Downtime**: Measured in hours, it is the amount of time that an equipment is not used for production. Equipment undergoing maintenance is also categorized as "Down".
• **Equipment Parts Lifetime**: Measured in engine-hours, it defined the amount of useful life of an equipment part.
• **Maintenance Frequency**: Number of engine-hours between different maintenance jobs for the same equipment.
• **Work Order Criticality**: Count of the amount of work orders grouped by priority.
• **Backlog**: List of work orders to be executed for a given equipment.
Maintenance Superintendent
• **Mean Time Between Failures (MTBF)**: The average time between equipment or components failures.
• **Mean Time to Repair (MTTR)**: The average time needed to repair an equipment.
• **Planning Estimate Precision**: Percentage of hours needed to complete maintenance jobs versus the number of hours initially estimated.
• **Schedule Completion**: Often associated with planning estimate precision, this KPI represents the percentage of scheduled work that was completed over the amount of work that was originally scheduled.
• **Maintenance Costs**: From cumulative cost of parts and material to the cost associated with necessary manpower, this KPI covers the maintenance-related budget.
Reliability Engineer
• **Oil Analysis**: Analysis generally verifying oil temperature and presence of particles.

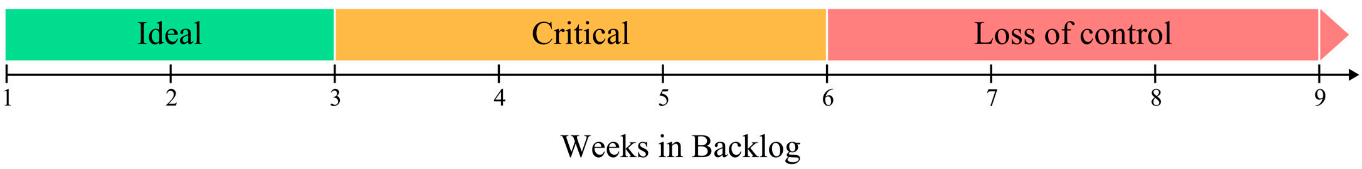

Figure 6. Mine operational status by Backlog value.

Figure 6 shows how the ideal Backlog workload does not surpass 3 weeks. After 3 weeks, the mine's operational status becomes critical due to a cumulative workload of more than a month. Finally, surpassing 6 weeks of Backlog workload indicates a loss of control of the maintenance work. This last threshold should never be reached by the maintenance operations and ought to be of critical concern to maintenance managers.

4.1.7. Maintenance Management Tools

The tools used in the maintenance process can be both computerized and paper based. Computerized tools are associated mostly with asset management, maintenance scheduling and stakeholder communication whereas paper tools are used mainly to connect different steps of the process where a more suitable software solution is not yet available.

Concerning asset management, all participants use a CMMS. Figure 7 displays the most used CMMS ordered by the number of participants actively using it. Note that total usage adds up to more than 15 participants since some mining sites use several CMMS during their operations ex. GuideTi and Oracle.

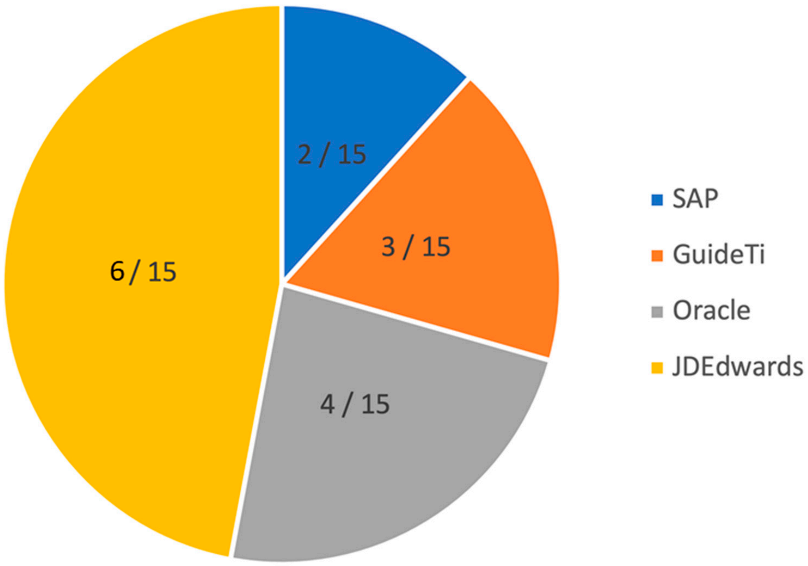

Figure 7. CMMS by number of mentions.

Screenshots of a work order as defined in JDEdwards and GuideTi are presented in Figures A1 and A2, respectively. Following, Table 5 records participants' most frequent feedback on the used CMMS.

Table 5. Participants' feedback on CMMS.

Positive	Negative
JDEdwards	
Programmable email notifications Automatic work order creation Work order table sorting and filtering Easily accessible data Multiple personalization options and great customizability	Scheduling maintenance is very complicated CMMS is not user friendly Difficulty in programming automatic work order creation Standardization complicates addition of custom features Requires advanced programming knowledge to customize workflow
GuideTi	
Programmable email notifications Great interface customization Automatic work order creation Easily accessible data	Scheduling maintenance is very complicated Unorganized database due to poor access restrictions
SAP	
Automatic work order creation Offers many options	Scheduling maintenance is very complicated Constant importing/exporting of data
Oracle	
Automatic work order creation	Scheduling maintenance is very complicated Equipment addition to the CMMS is convoluted Standardization complicates addition of custom features Maintenance plan is hard to program

As can be seen, one of the most appreciated features of every CMMS is the automatic work order creation. Additionally, interface customization was a feature frequently praised by participants having access to it. On the other hand, poor usability and integration in the maintenance workflow were the most often mentioned disadvantages.

Almost all participants used Excel for maintenance scheduling (12/15) except one participant who used an addon for SAP called Prometheus and two others who stated that the Oracle addon Vz Scheduling was used by the maintenance team. The SAP addon enabled the team to create the maintenance schedule directly from the CMMS; however, the participant also mentioned that the addon's usability is quite poor. Concerning the Oracle addon, the two participants stated that it was a great addition to the CMMS but made no further comments. An example of the Excel scheduling document is presented in Appendix B, Figure A1.

Participants using Excel explained that their worksheet was connected to the CMMS via Macros, custom Excel programs written in Visual Basic. All participants stated that this connection was crucial to their workflow but that it required an extensive knowledge in programming to implement. Additional specialized workforce was therefore required to develop Macros rendering this feature inaccessible to most personnel. That said, 8 out of the 11 participants using Excel expressed their approval of the platform stating that it was a "very good software" and that its high adaptability together with a customizable color palette made it a useful tool in maintenance scheduling. Excel's main weakness stemmed directly from its high customizability. Participants mentioned that, due to a lack of standardization, data organization in Excel was arbitrary and depended on the person handling the file. This made data monitoring and querying extremely tedious. Additionally, issued from the lack of standardization, the presence of "too many Excel files" was problematic according to most participants.

Sharing of the maintenance schedule or communication between stakeholders was done either via email or through in-person meetings, as stated in Section 4.1.4. For email communication, Outlook was the software mentioned by most participants.

Finally, the paper-based tool used most often by participants was the printed version of the maintenance schedule. Participants stated that a paper copy facilitated sharing and encouraged discussion during in-person meetings. Two participants stated that they had to enter work orders in the system from a paper sheet filled by the operator of an equipment. Several other aspects of the maintenance process relied on paper, but they were not executed directly by the participants of this study. Two participants with supervisory roles affirmed that steps were being taken to limit the amount of paper tools used in the mine.

4.1.8. Comments and Feedback on the Maintenance Process

The maintenance process is appreciated by participants. A recurring opinion among all participants is that the process is clear. A clear and standardized process facilitates the application of suggested guidelines. One participant stated that it also facilitates the evaluation of established practices by offering an exact list of objectives. Additionally, another participant noted that a standardized process avoids discussions. Hence, deliberation time during meetings is reduced.

On the other hand, all participants stated that the process is decisively time-consuming. The step of identifying maintenance needs requires the organization of work orders submitted to the CMMS. Many work orders have a chance of being duplicated and the job of removing duplicates from the system is a major cause of what is considered by participants to be wasted time. Concerning maintenance planning, one participant expressed that the "Kitting" procedure in their mine could be improved greatly. Two participants stated that they are not able to know the exact reason for an equipment failure and that keeping track of equipment availability is quite complex. Another participant stated that handling unexpected events such as unavailable workforce is very complicated. On the topic of unexpected events, two participants expressed how, during emergencies or critical moments in the mine, deviations from the theoretical process are possible. On maintenance execution, three participants stated that the PM checklist, which contains the list of verifications that were completed during a PM, is not stored in the CMMS. Hence, it is useless for future planning analysis and evaluation. Furthermore, all superintendents noted that unnecessary replacement of functional parts (due to recommendations of the maintenance plan) leads to a rise in maintenance costs. Shifting to a predictive maintenance paradigm was therefore an appreciated solution by most participants.

4.2. Predictive Maintenance: Expectations and Concerns

Predictive maintenance uses equipment-sensor data to predict maintenance intervals based on historical data, as opposed to fixed usage duration thresholds. Interval prediction is achieved generally via the use of AI. Predictive maintenance represents a major change of work method compared to established PM approaches. When asked to comment on the introduction of predictive maintenance on their sites, participants expressed wariness mixed with anticipation. In this section, we cover participants' feedback on predictive maintenance on three topics: opportunities to improve the entire maintenance process; suggested Analytics features; fears and concerns. A summary of our results is presented in Figure 8.

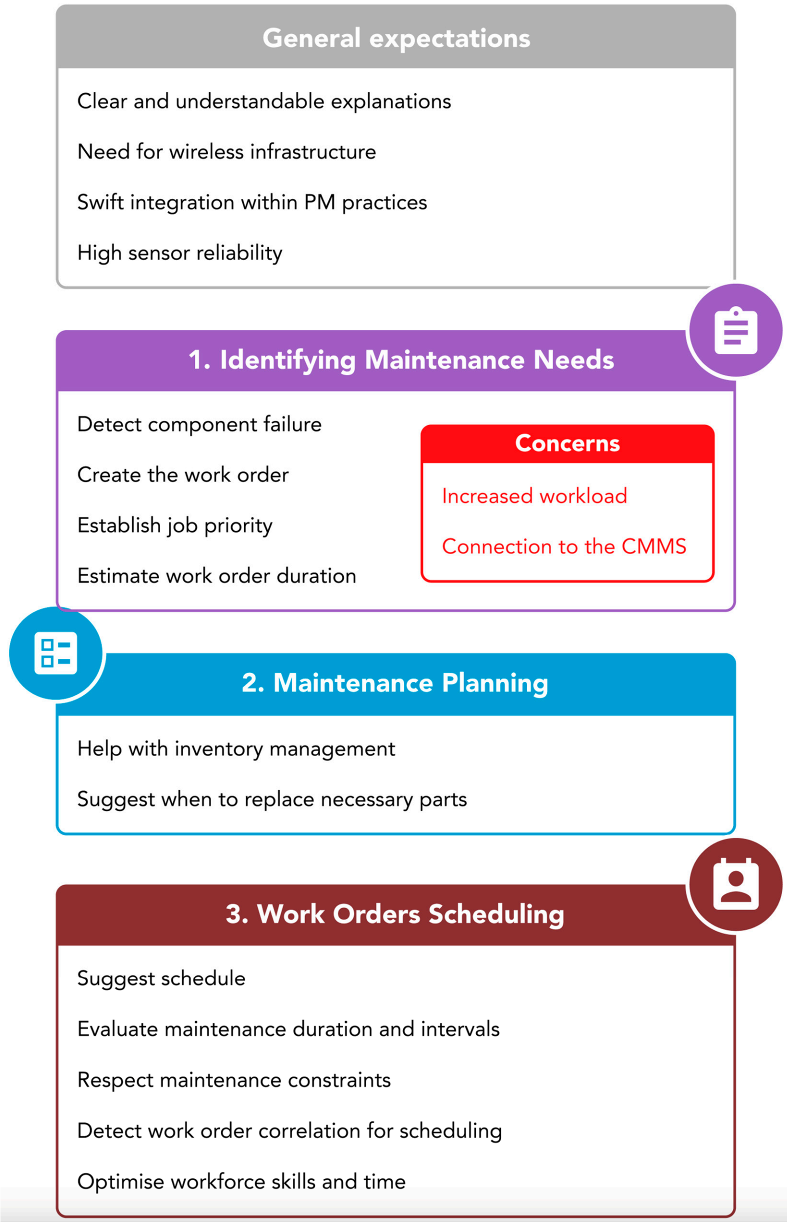

Figure 8. Predictive maintenance opportunities and concerns.

When asked to voice their opinions on predictive maintenance, participants expressed their opinions targeting the process as a whole. A unanimous need among all participants is for the Analyticssolutions to be connected to the CMMS. This connection, as stated by one participant, could help minimize the risk of increasing personnel workload. Additionally, all participants noted how a predictive maintenance AI should express and justify its results through a clear diagnostic understandable by non-expert personnel. Participants occupying supervisory roles stated that Analytics can help minimize human intervention but pointed out that, to properly integrate AI in the process, its addition needs to be diligent and successful in the short term. Fears concerning AI's reliability and trustworthiness along with maintenance teams' maturity were also shared among these participants. Taking a step back, a participant noted that their mine does not even possess the required infrastructure to manage wireless equipment sensor data required to implement predictive maintenance analytics. It was also mentioned that, in some instances, manufacturers already record data for their equipment but limit its access to their own employees. Two superintendents stated that Analyticssolutions should account for different requirements in mines operating both underground and on the surface. Participants occupying the role of maintenance planners shared similar opinions. One participant indicated that the addition of an AI to the maintenance process would need to force a complete transition from preventive maintenance to predictive maintenance. This participant stated that, when presented with a choice, adhering to the PM plan would be the desirable action even if an AI suggested otherwise. This is because, in the participant's opinion, preventive and predictive maintenance cannot coexist in the planning process. Two participants concentrated on the development of AI as they raised concerns about difficulties issued by fleet diversity, fleet ageing and variable equipment criticality.

Regarding the identification of maintenance needs, two participants stated that a helpful AI would be able to identify component failures and create a work order containing a detailed description of the issue. This work order would then be automatically added to the CMMS. Taking it one step further, one of the participants noted that an AI could aid the prioritization of the work order either by prioritizing the work order directly or offering suggestions to the maintenance planner based on the contents of the work order. Participants expressed some concern regarding the addition of Analytics in this step of the process. Firstly, they feared that workload would increase due to having to filter additional work orders. Secondly, they mentioned the possibility of sensors malfunctioning or getting detached from the equipment which would lead to incomplete or erroneous AI suggestions. One participant stated that much caution should be taken whilst mounting sensors on an equipment. Harsh conditions in underground mines, such as temperature, humidity and frequent wall collisions would reduce the integrity and lifetime of the sensors.

The integration of Analytics was globally more appreciated by participants, specifically maintenance planners, when targeting the maintenance planning phase. Two participants stated that this addition could be an opportunity to improve the process of managing equipment parts. Albeit recognizing the difficulties in modifying the supply system, these participants mentioned that Analytics tools could allow them to order new parts before the need of them became critical. Hence, an equipment would rarely need to await parts before commencing maintenance. This implies, as stated by participants, that Analytics solutions be aware of an equipment and its components' residual lifetime and that it be able to suggest when to replace the necessary parts.

The greatest impact Analytics can have on the process, as agreed upon by participants, targets the scheduling phase. In fact, requirements for this step are more numerous and creative than the previous steps. The following list presents some of the mentioned optimization and AI requirements:

- Suggest a schedule based on available manpower and workforce specializations.
- Evaluate maintenance duration and intervals to optimizemechanics' time.
- Account for maintenance and work order constraints (such as equipment needing to be in production at a specific date).
- Detect work order correlation (a work order that can or should be executed at the same time, or before or after, another work order).

Some mines delegate maintenance to external garages. Two participants stated that Analytics solutions should consider these garages while developing the schedule. Additionally, one participant mentioned how garage topology could be used by an AI to suggest equipment entry and exit strategies to optimize bay occupation. The predominant opinion among participants concerning the addition of Analytics to the scheduling phase is that equipment downtime could be diminished greatly.

4.3. Decision Support System: Requirements and UI Guidelines

Participants were enthusiastic to share opinions and suggestions on a decision support system that would aid them with their daily routine. The system aims to facilitate the current maintenance process and augment it by using Analytics to aid personnel in their decision-making. This section explores requirements and UI guidelines voiced by participants as well as comments and fears regarding the integration of the system in the mining process. Table 6 shows the UI requirements and guidelines.

Table 6. Requirements and guidelines for a decision support system.

General

- Displayed information:
    - All mobile equipment in the fleet
    - Detailed information of an equipment
    - Reason and duration of active stoppages
    - Operational objectives (amount of equipment needed to reach production goal)
    - Work orders for each equipment
    - Maintenance KPIs and their trends
    - Available workforce
- Allow ordering of parts and materials for maintenance
- Allow managing of workforce calendar
- Allow managing of the maintenance schedule

Equipment Information

- Displayed information:
    - Number of equipment in the fleet
    - Equipment ID, name, and description
    - Equipment status (available, in maintenance, inactive or down)
    - Number of engine-hours since last maintenance
    - Work orders executed in the last maintenance
    - Equipment Backlog
    - Equipment parts available and ordered
    - Real-time sensor data
- If down, display the reason of the stoppage (mentioned by three participants)
- Allow to mark equipment for maintenance.

Work Order Information

- Displayed information:
    - Workforce types needed to complete work order (mechanics, electricians, welders, etc.)
    - Total amount of hours needed to complete the work order, organized by workforce type
    - Work order ID, description, criticality, creation date and estimated execution date
- Allow to set a custom criticality to the work order to facilitate scheduling meetings
- Prevent the modification of a work order's duration once it's established

KPIs

- Fleet availability
- Equipment usage
- Work order criticality
- Planned vs. Unplanned maintenance jobs underway

Scheduling

- Overview of the current schedule
- Creation and modification of future schedules
- Assignment of manpower to individual work orders

On requirements, all participants mentioned that the system needs to show a list of maintenance KPIs. From the list in Section 4.1.6, the most quoted KPIs were fleet availability, equipment usage and work order criticality. Along with KPIs and their trends, fleet and equipment information is mandatory. All participants stated that the system should display the equipment's engine-hours and Backlog. For the Backlog, individual work orders' ID and description are crucial to help with decision-making. Additionally, three participants stated that information about equipment parts and suggestions on parts management would be of great help. A section to manage and order equipment parts was therefore suggested by these participants. According to one participant, the system should help the user to answer the question: "Are we late on the PM plan?". A maintenance planner specified another question: "If an equipment is down, is it due for maintenance?". To be able to investigate such prompts, the system needs to display equipment status and operational objectives along with the established maintenance plan. Specifically targeting Analytics, one participant suggested that the system should be able to propose a series of schedules respecting constraints established by the user. The user can then select the most suitable schedule and modify it to fit the team's needs. The same participant indicated that the system should show equipment entry and exit times from the garage in a clear manner. This introduces another requirement, unanimous among participants, which is to allow for creation and modification of the maintenance schedule. Some participants (6/15) also pointed out that managing the workforce calendar would be of great help while developing the schedule. Two of these participants suggested allowing direct assignment of human resources to a work order in the schedule.

Concentrating on less functional requirements, participants also shared their opinions on purely aesthetic and constraints related to user experience (UX). Four participants indicated that the system should offer field modification via tables, similar to data handling in Microsoft Excel. However, they also expressed the need for quality-of-life improvements with features such as the dragging and dropping of items during scheduling. One participant stressed the importance of having a clear and structured color convention. Another participant suggested using a Web Interface, like the one used by all CMMS mentioned, but pointed out that internet connection could cause latency issues. This claim was endorsed by two other participants who already faced issues with internet connectivity at their mining site. Finally, one participant suggested the addition of a dark theme feature, indicating that it was the preferred method of display by all members of their team.

5. Discussion

The main purpose of this study was to document current maintenance practices for mobile mining equipment. Simultaneously, our sub-objectives concerning users' expectations and concerns for predictive maintenance and user-oriented CMMS design were respected. All objectives of this study were therefore achieved. After interviewing maintenance experts from 7 mining sites in East-Canada, we were able to map the currently implemented maintenance management process which can be divided into 4 main steps:

1. The identification of maintenance needs
2. Maintenance planning
3. Maintenance scheduling
4. Maintenance execution

Additionally, thanks to participants' answers, we were able to obtain information pertaining to useful KPIs and feedback on the maintenance process. Furthermore, expectations and concerns regarding a predictive maintenance AI allowed us to conclude that connection to the CMMS is crucial. A high level of reliability is also required along with a clear and precise explanation of AI suggestions. Finally, by asking questions concerning the CMMS, we were able to compile a series of functional and nonfunctional requirements to better adhere to user preferences.

The main contribution of our study is the mapping of the maintenance process utilized in East-Canadian mines. Our findings showed that current PM practices in the targeted mines respected the 4 maintenance steps described in the literature. However, while most work offers a broad overview of the maintenance process, our study dives deep into the actual implementation of maintenance practices in mining. Our results offered a real-life endorsement of Basri's findings [19] applied to the mining industry, where we confirmed that PMs are planned based on time, cost and failures. Building on the experimental results obtained by La Roche-Carrier [23], we were able to generalize his findings to 6 mining sites other than LaRonde, which was the mine targeted by his study. The process is indeed similar between different mining sites for theoretical and experimental reasons. The predominant reason being that of effectiveness. Many resources, such as [10], exist to guide maintenance directors in the creation of a maintenance management process which has been proven successful at other sites or plants. As to the experimental reasons, 6 out of the 15 participants were working at LaRonde Complex at the time of the interview. Additionally, due to a limited job candidates pool, many participants have worked at different mining sites hence utilizing the experience acquired at other sites to create the maintenance plan. This particular finding is consistent with Richard & al.'s [13] study where it was stipulated that the transfer of best practices can hinder creativity [13]. Finally, open collaboration between mining companies allows for a standardized process which is approved and adopted by all East-Canadian mines. Collaboration is facilitated by meetings and conventions set up by entities such as the non-profit organizations "The MISA Group" where maintenance best practices are shared and discussed. Project managers at MISA have highlighted the importance of having a standardized maintenance process, especially with respect to predictive maintenance research and its implementation in the future.

In maintenance management, the analysis of KPIs constitutes an essential step in the improvement and tracking of maintenance quality. KPIs help in establishing baselines to allow for data comparison [10,23] and are used to quantify goals and objectives at every step of the process [18,51]. Most of the maintenance KPIs collected in this study overlapped with best practices in the mining [18,23] and industrial sectors [10,51]. However, our results showed that the Backlog was, by far, the most crucial KPI for maintenance evaluation. Its correct management is a necessary skill to ensure the long-term success of the maintenance plan and its mismanagement may lead to a rapid decline in maintenance operations. Yet, despite its importance, the backlog has received little attention in previous work. During our evaluation, many tools were used to manage the fleet's Backlog. The CMMS, for instance, plays an important role in identifying the actual work orders that constitute the Backlog; however, statistical analysis was most often conducted using external tools. The most common tool used to analyze the Backlog was Excel which was used to construct visual aids on each fleet's cumulative work hours and their evolution throughout time. Other mines used CMMS extensions (like VzAnalytics) and external tools such as PowerBI to conduct Backlog evaluation along with other KPI studies. Regardless of the software, Backlog minimization is an essential process integrated in a planner's toolkit and its trend can be used to determine the advancement of maintenance jobs in the mine.

On garage occupation, maintenance literature does not cover the importance of equipment distribution to optimize entry and exit from an underground mine's garage. For these mines, our findings emphasized the important role that equipment placement plays in a successful maintenance schedule. Experts stated that an optimized distribution will ensure that an equipment is able to resume production upon maintenance completion and that it should be unhindered by other ongoing maintenance jobs. Hence, it is our recommendation that research focusing on automatic scheduling algorithms consider garage topology as a serious constraint in the production of a schedule.

At every step of the maintenance process, we studied the tools used and observed their impact on maintenance practices. Our findings indicated that standardization and improvement of the tools was a welcomed and greatly needed change, and that Excel was not a technology suited for scheduling, despite its frequent use in the mining sites interviewed.

Our results regarding users' expectations and concerns on predictive maintenance and Analytics highlighted features overlooked by active research in predictive maintenance. In fact, while most studies concentrate on data-oriented approaches (*see* [52]), we found a pressing need to address human-factors aspects related to the introduction of predictive maintenance and how it will impact the planner's work. So far, research in the mining industry is aimed at creating predictive maintenance algorithms ([33,34]) that are hardly usable by maintenance personnel. Predictive maintenance AI usability is hindered by the lack of explanation [53]. Our results endorsed the need to develop human-understandable AI algorithms, specifically when targeting expert personnel whose decision-making process depends on the ability to explain and defend maintenance opinions [54]. We also found that the need for predictive maintenance Analytics to be connected to the CMMS was pivotal to ensure its adoption and usability. This requirement is rarely considered by existing predictive maintenance algorithms who offer architecture solutions that are added on top of the existing software tools, i.e., macros or extensions, as opposed to being fully integrated into the CMMS already used.

Our results on guidelines for decision support toolsand interfacesoffer a potential direction for improving existing CMMS. The general sentiment voiced by users was that of chaos. In fact, as shown by our results, the large quantity of tools available make it difficult for users to organize and connect data. A maintenance expert needs to switch between different software and files to obtain the information needed. This increases cognitive workload and decreases motivation. These results are in accordance with Tretten and Ramin's evaluation of maintenance data management systems [43]. A tool specialized in maintenance planning should integrate all the necessary systems to conduct proper maintenance. It should also offer functions to monitor the maintenance plan and KPIs while presenting a clear and concise interface displaying only the information required by the maintenance team. Our study, in accordance with existing literature, showed that CMMS usability is of great concern [15,16]. Time-consuming activities such as developing Excel Macros require a programming expertise that the average maintenance team member does not possess. Additionally, information architecture in the studied CMMS requires a mindset adaptation on the user's end. This is a vivid illustration of the issue mentioned by Tretten and Karim [43] where system designers develop a system based on their conception on how maintenance is conducted as opposed to what expert personnel truly needs [43].

There are two limitations to this study. First, the diversity between participants was restricted by geographical boundaries and by the small pool of maintenance experts available at the time of the interview. Future work should cap the number of participants per mining company and interview participants from more companies from all around the country. Second, when asked to describe the maintenance process, participants had a tendency of explaining it on a theoretical basis rather than concentrating on their actual decision-making process. To limit this impact, we reformulated the interview questions to use the more direct "you" form and obtained significantly more subjective answers.

Further research in predictive maintenance should concentrate on a more user-oriented approach. It should consider AI explanation as a core requirement of the predictive maintenance architecture as opposed to a mere addition or an afterthought. The field of explainable AI (XAI) is a promising avenue to achieve this goal and to have a clearer understanding on the type of explanations best suited to the maintenance team. In aviation, a study aimed at combining maintenance practices with XAI practices for component failure detection highlighted the benefits of XAI [55]. In manufacturing, XAI applications are numerous and are linked to an increase in trust [56]. Finally, more usability research should be conducted concerning CMMS design for mining facilities. The current state of management applications is unacceptable. The unreasonable amount of maintenance files and the multitude of non-standardized tools whose interconnection needs to be developed manually have a harmful impact on the maintenance planning process.

6. Conclusions

In this study, we interviewed 15 participants from 7 mining sites in East-Canada to obtain information on the currently implemented maintenance management process. Sub-objectives included recording expectations and concerns for a predictive maintenance AI and compiling user-defined CMMS guidelines. Our main contribution is the mapping of the maintenance process for mobile mining equipment in East-Canadian mines.

Additionally, our results indicate a need for a highly reliable predictive maintenance AI whose explanations are understandable by maintenance personnel. Finally, maintenance management tools' usability is an issue and lack of integration between different tools increases cognitive workload by forcing the maintenance expert to navigate between many platforms and files. Future research can focus on many aspects of our study. For instance, our findings on the maintenance process' best practices and users' comments and fears regarding AI can direct AI-related research. Existing algorithms for predictive maintenance of mobile mining equipment can be adapted to maximize employee acceptance and facilitate integration in the maintenance process. Further research is needed to identify the specific needs of a predictive maintenance AI for this kind of equipment. Additionally, participants' comments and wishes pertaining to the UI for a decision support system can be used to develop a new type of CMMS befitting users' needs. All in all, future research should focus on the integration of predictive maintenance practices in the currently used PM workflow.

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Appendix A

Figures A1 and A2 display work orders as they are presented in JDEdwards and GuideTi respectively. Please note that some information was redacted to guarantee anonymity.

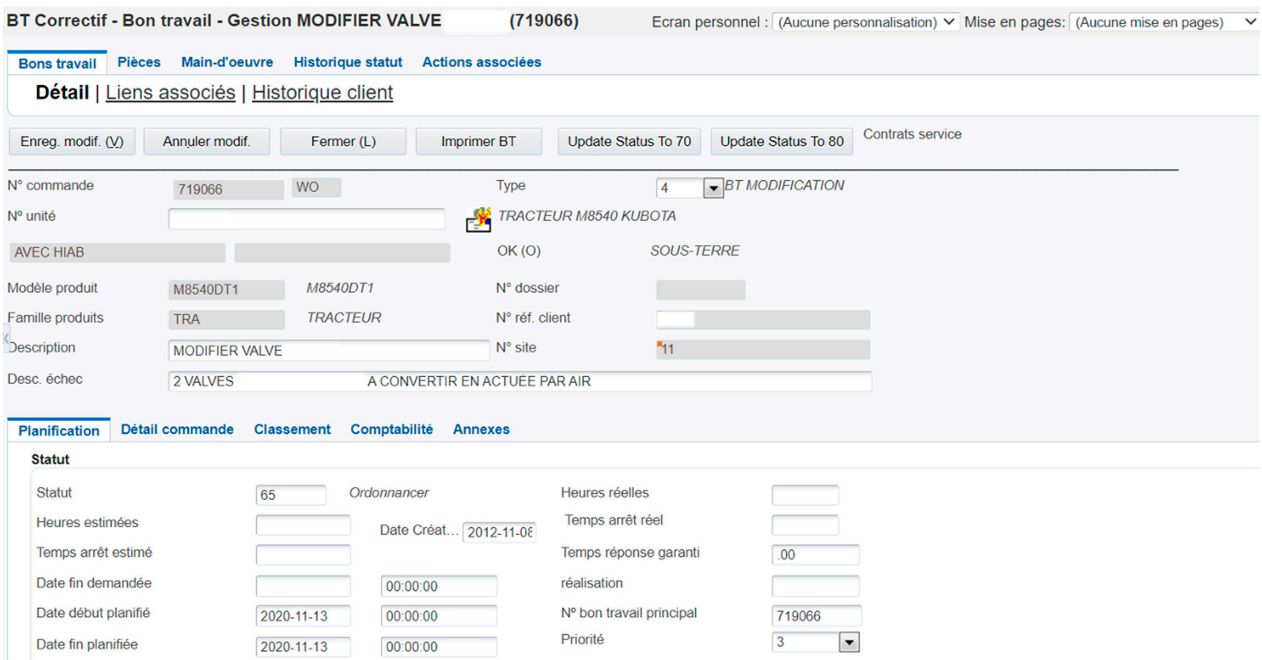

Figure A1. JDEdwards example work order.

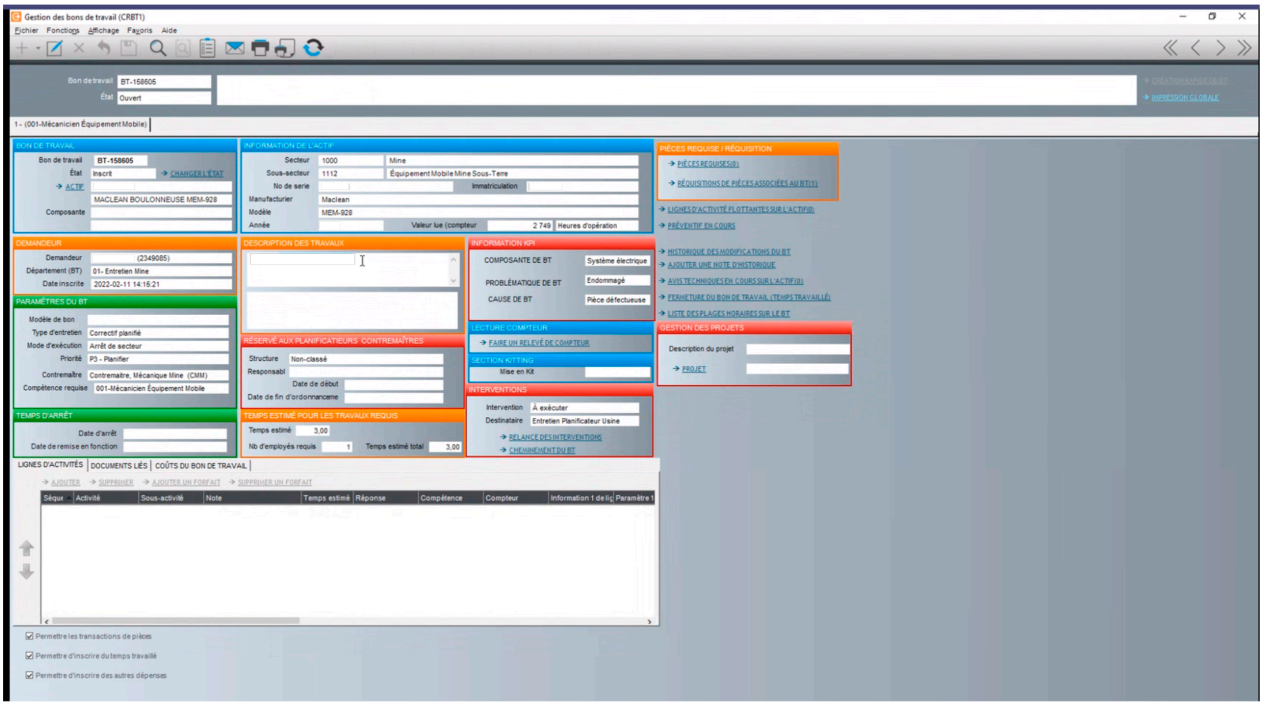

Figure A2. GuideTi example work order.

Appendix B

Figure A1 presents the Excel schedule for a participating mine. The rows represent the mine's bays, and the columns constitute the timeline. Cells are grouped to organize equipment information such as its ID and engine-hours trends, real values, and predictions. The schedule is color coded to indicate the status of the maintenance job.

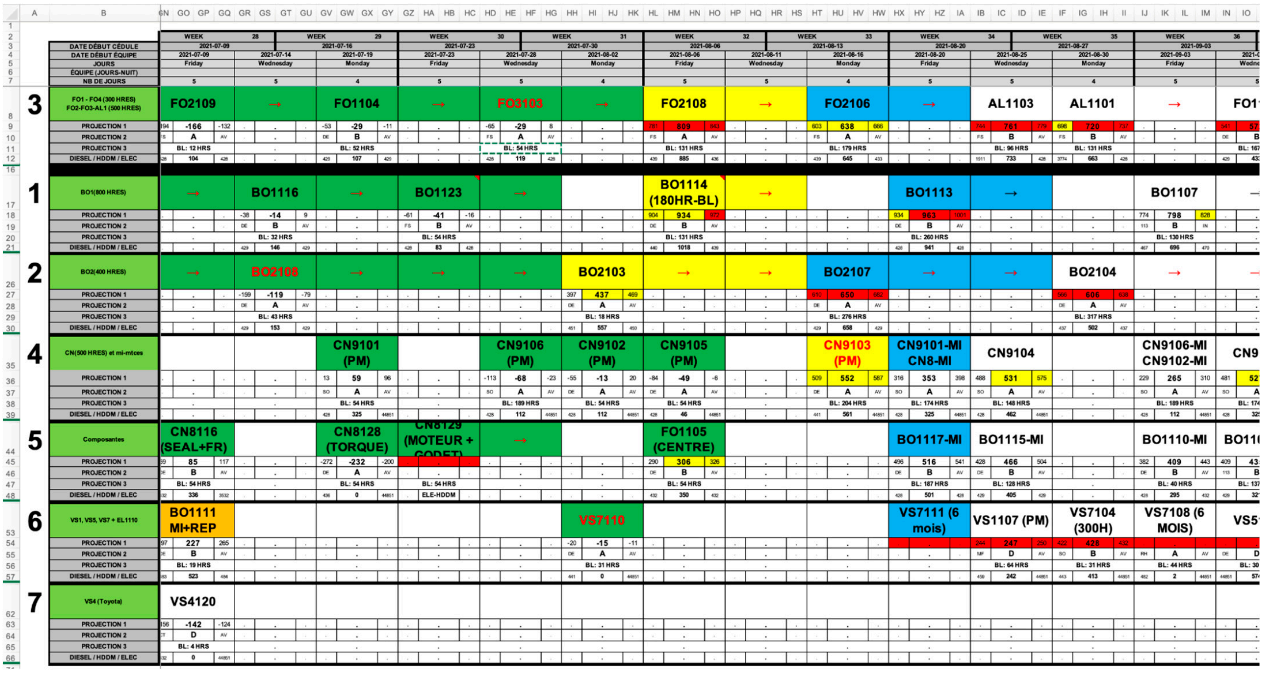

Figure A1. Excel schedule.

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