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affiliée à l'Université de Montréal

**Conception et évaluation d'un outil d'aide à la décision pour la maintenance
préventive et prédictive d'équipements miniers mobiles souterrains**

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Conception et évaluation d'un outil d'aide à la décision pour la maintenance préventive et prédictive d'équipements miniers mobiles souterrains

présenté par **Simon ROBATTO SIMARD**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DÉDICACE

*“Remember that there is nothing noble in being superior to some other man.
The true nobility is in being superior to your previous self.”*

- W. L. Sheldon

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RÉSUMÉ

L'extraction minière a occupé une place primordiale dans l'histoire de l'humanité et a grandement évolué au fil des années. Les avancées technologiques ont permis la conception d'équipements de plus en plus complexes devant opérer dans des conditions exceptionnellement ardues. Ces conditions engendrent un taux de bris particulièrement élevé par rapport aux autres industries et accentuent ainsi l'importance de la maintenance d'équipements miniers. Dans l'industrie, la maintenance préventive (PM), soit une maintenance systémique où l'équipement est entretenu à des intervalles réguliers, est le type de maintenance le plus communément implémenté. L'arrivée de technologies sans-fil dans les mines souterraines a motivé les chercheurs et les industriels à entamer la transition vers la maintenance prédictive (PdM), soit une maintenance conditionnelle qui dépend de l'état de l'équipement. Cependant, les outils de gestion de la maintenance (GMAOs) disponibles à ce jour n'offrent pas de support pour la PdM et sont souvent compliqués et frustrants à utiliser.

Dans ce mémoire par articles, j'ai conçu, développé et évalué un GMAO axé sur la prise de décision pour la PM et PdM d'équipements miniers mobiles. Pour ce faire, j'ai suivi la méthodologie de conception centrée sur l'utilisateur. Ces travaux ont fait l'objet de deux articles publiés ou soumis pour publication dans des journaux revus par les pairs.

Le but du premier article était d'établir le contexte d'utilisation et les besoins des utilisateurs. Des entrevues avec 15 experts en maintenance provenant de 7 mines canadiennes ont permis de cartographier le processus réel de maintenance actuellement implémenté dans les mines souterraines. Cette cartographie applique les divers concepts déjà connus en littérature au domaine minier et indique aussi des aspects rarement mentionnés tels que la sous-catégorisation des bons de travail et le rôle exact du planificateur de maintenance. De plus, les résultats concernant les indicateurs de performance utilisés en planification de maintenance respectent les travaux existants et montrent un changement minimal par rapport aux études effectuées il y a 20 ans. Finalement, l'identification des irritants face à l'utilisabilité des GMAOs jumelés à la compilation d'une liste de requis pour ce type de systèmes constituent la base des travaux qui suivent.

Le deuxième article avait comme objectif de concevoir le GMAO, nommé VulcanH, sous forme de prototype fonctionnel et d'évaluer son utilisabilité auprès des experts en maintenance. Les résultats de tests utilisateur auprès de 9 responsables de maintenance travaillant parmi 5 mines canadiennes ont validé l'utilisabilité de VulcanH pour la planification de la PM ($UEQ^+ = 2,00 \pm$

0,43) et de la PdM ($UEQ+ = 2.28 \pm 0,61$). La confiance des experts en l'automatisation engendrée par la PdM était élevée ($RIS = 4,83 \pm 1,07$ sur 7) mais le besoin d'explications détaillées permettant l'évaluation des suggestions avec justesse était manifesté souvent par les participants.

En somme, ces travaux suggèrent qu'une intégration harmonieuse des pratiques de PdM dans le processus actuel de PM est possible et que l'ouverture des experts face aux changements amenés par des telles pratiques est considérable. Quant à l'utilisabilité des GMAOs, les résultats démontrent l'efficacité de la conception centrée sur l'utilisateur. Cette méthode permet d'optimiser l'expérience utilisateur et de faciliter la prise de décision en maintenance. De plus, notre étude est la première instance où RIS a été utilisée pour évaluer la confiance d'experts en maintenance d'équipements miniers et témoigne de l'efficacité de cette méthode dans le contexte donné. Finalement, nos résultats montrent que l'ajout de l'intelligence artificielle aux outils de PdM doit inclure des algorithmes pouvant fournir des explications pertinentes et utilisables par l'expert.

Dans le futur, VulcanH devrait intégrer plusieurs outils d'analyse de données pour l'optimisation des PMs et des PdMs dans le but de fournir un outil centralisé d'aide à la décision.

ABSTRACT

The mining industry has played a significant role in the history of mankind and underwent multiple evolutions throughout the years. Technological advancements allowed for the construction of equipment of ever-growing complexity capable of operating in strenuous conditions that result in failure rates much higher in other industries. Thus, equipment maintenance is a crucial aspect of a mining venture. In the mining industry, most equipment undergoes maintenance on a systematic basis depending on predetermined maintenance interval. This approach is known as preventive maintenance (PM) and is the most implemented type of maintenance in the field. Recent wireless technologies have facilitated the active monitoring of equipment and encouraged researchers and practitioners to transition towards a more novel approach, that of predictive maintenance (PdM). Contrary to PM, PdM maintenance intervals are dependent on equipment status which, in theory, allows for a more accurate maintenance execution window. Despite the introduction of new maintenance technologies, available maintenance management systems (CMMSs) are not equipped to handle PdM practices and provide a complex and frustrating user experience.

In this article-based thesis, I designed, developed, and tested a CMMS capable of providing decision support for PM and PdM of mobile mining equipment. To achieve this goal, I implemented the human-centred design methodology. My research efforts culminated in the creation of two articles published in (or submitted to) peer-reviewed journals.

The first article's main objective was to understand and establish the context of use and to gather user requirements. Interviews with 15 maintenance experts from 5 mining sites allowed me to document the maintenance process that is currently implemented in Canadian underground mines. This documentation is based on existing concepts in maintenance literature and applies them to underground mining sites. Furthermore, it expands knowledge on the subject by presenting activities that are rarely mentioned in literature, such as work order sub-prioritization and the effective role of a maintenance planner. Also, results on key performance indicators (KPIs) and their usage respect observations from past studies and prove that the KPIs used in maintenance planning have generally remained the same for over 20 years. Finally, common CMMSs' usability pitfalls were established and were used to compile a list of user requirements for CMMSs. These requirements constitute the basis of the research that follows.

The focus of the second article was to design and develop a functional prototype of a CMMS, named VulcanH, and to evaluate its usability among maintenance experts. Results from user tests

conducted among 9 participants from 5 mining sites validated the prototype's usability for both PM ($UEQ+ = 2.00 \pm 0.43$) and PdM ($UEQ+ = 2.28 \pm 0.61$) planning and scheduling. Moreover, experts' trust in the PdM-enabled automation was elevated ($RIS = 4.83 \pm 1.07$, out of 7) but most participants voiced their need for detailed explanations. In fact, these were necessary for experts to successfully evaluate the system's suggestions.

Overall, this thesis suggests that a harmonious integration of PdM practices into the current PM workflow is possible and that maintenance experts are ready for this introduction into the maintenance workflow. Additionally, results on CMMS usability prove that a human-centred design methodology improves user experience and decision making for maintenance experts. Concerning trust, our study is the first to have applied RIS to maintenance experts and CMMSs. Our work validates the scale's usefulness and efficiency in the given context. Lastly, our results show that the addition of artificial intelligence to PdM should consider algorithms capable of providing useful and actionable explanations that may aid in the expert's decision making.

Future research should integrate novel decision analysis tools for PM and PdM optimization into VulcanH to implement a centralised decision-making system.

TABLE DES MATIÈRES

DÉDICACE.....	III
REMERCIEMENTS	IV
RÉSUMÉ.....	V
ABSTRACT.....	VII
LISTE DES TABLEAUX.....	XII
LISTE DES FIGURES.....	XIII
LISTE DES SIGLES ET ABRÉVIATIONS	XV
LISTE DES ANNEXES.....	XVI
CHAPITRE 1 INTRODUCTION.....	1
CHAPITRE 2 REVUE DE LITTÉRATURE	3
2.1 Types de maintenance	3
2.1.1 Maintenance proactive	3
2.1.2 Maintenance préventive (PM) systématique	5
2.1.3 Maintenance prédictive (PdM).....	6
2.1.4 Maintenance réactive.....	7
2.1.5 Maintenance corrective	7
2.2 Systèmes de gestion de la maintenance assistée par ordinateur (GMAO).....	8
2.3 Expérience utilisateur (UX) et utilisabilité.....	9
2.3.1 Conception centrée sur l'utilisateur (CCU).....	9
2.3.2 Techniques d'évaluation UX.....	10
2.3.3 UX et intelligence artificielle (IA)	13
2.4 Confiance en l'automatisation (TiA).....	14
2.4.1 Théorie de la confiance	14
2.4.2 Évaluation de la TiA	15

CHAPITRE 3	OBJECTIFS DE RECHERCHE	19
3.1	Problématiques	19
3.2	Objectifs	20
CHAPITRE 4	ARTICLE 1: CURRENT PRACTICES FOR PREVENTIVE MAINTENANCE AND EXPECTATIONS FOR PREDICTIVE MAINTENANCE IN EAST-CANADIAN MINES	21
4.1	Introduction	22
4.2	Related Work.....	23
4.2.1	Maintenance Background.....	23
4.2.2	Preventive Maintenance	25
4.2.3	Predictive Maintenance	26
4.2.4	CMMS Usability	27
4.2.5	Problem Statement	29
4.2.6	Participants	29
4.2.7	Materials.....	30
4.2.8	Procedure.....	30
4.2.9	Data Analysis	31
4.3	Results	31
4.3.1	The Maintenance Process and Best Practices	32
4.3.2	Predictive Maintenance: Expectations and Concerns	47
4.3.3	Decision Support System: Requirements and UI Guidelines.....	50
4.4	Discussion	53
4.5	Conclusions	57
CHAPITRE 5	ARTICLE 2: DEVELOPMENT AND USABILITY EVALUATION OF VULCANH, A CMMS PROTOTYPE FOR PREVENTIVE AND PREDICTIVE MAINTENANCE OF MOBILE MINING EQUIPMENT	58

5.1	Introduction	59
5.2	Background and Related Work	60
5.2.1	Maintenance	60
5.2.2	Usability Evaluation	63
5.2.3	Trust in Automation	65
5.2.4	Synthesis and Research Objectives	66
5.3	Method	67
5.3.1	VulcanH	67
5.3.2	Usability Evaluation	75
5.4	Results	78
5.4.1	UEQ+	79
5.4.2	RIS	81
5.4.3	AI Explanation Ranking	81
5.4.4	Debriefing Questionnaire	83
5.5	Discussion	85
5.6	Conclusions and future research	89
CHAPITRE 6	DISCUSSION GÉNÉRALE	90
CHAPITRE 7	CONCLUSION ET RECOMMANDATIONS	91
7.1	Synthèse des travaux	91
7.2	Limitations de la recherche	92
7.3	Implications et recommandations	93
RÉFÉRENCES		94
ANNEXES		107

LISTE DES TABLEAUX

Tableau 2.1 Dimensions de l'UEQ+ selon [39].....	12
Tableau 2.2 Méthodes d'évaluation de la TiA [53].	17
Table 4.1 Categories extrapolated from the interviews.....	31
Table 4.2 Work order priorities and description.	35
Table 4.3 Work order life cycle states and description.	36
Table 4.4 KPIs by participant's role.	43
Table 4.5 Participants' feedback on CMMS.....	45
Table 4.6 Requirements and guidelines for a decision support system.	51
Table 5.1 Common work order priorities, adapted from [101].	61
Table 5.2 VulcanH changes due to the addition of PdM.	74
Table 5.3 Equipment count by equipment family.	76
Table 5.4 Alpha-Coefficient per UEQ+ Scale.	79
Table 5.5 Item-Correlation of the scale “Trustworthiness of Content” for the PM scenario.....	79
Table 5.6 Participants’ suggestions and comments on prototype improvement.	84
Table C.1 User requirements for VulcanH.....	110
Table D.1 RIS Questionnaire.	112

LISTE DES FIGURES

Figure 2.1 Types de maintenance.....	4
Figure 2.2 Processus de PM systématique selon [9].	5
Figure 2.3 Modèle de confiance selon [51] (traduit).....	15
Figure 2.4 Modèle de confiance de [51] divisé selon [53] (annoté, traduit).	16
Figure 4.1 Six key steps in effective maintenance management according to [9].	24
Figure 4.2 Mining KPIs by number of mines (out of 12) found by Lafontaine [69].	25
Figure 4.3 Industry CMMS needs and recommendations based on [27].	28
Figure 4.4 The maintenance process.	33
Figure 4.5 Underground garage diagram.	40
Figure 4.6 Mine operational status by Backlog value.	43
Figure 4.7 CMMS by number of mentions.	44
Figure 4.8 Predictive maintenance opportunities and concerns.	48
Figure 5.1 Key steps of the maintenance process [101].....	61
Figure 5.2 Common maintenance KPIs by number of mines (out of 12) [101].	62
Figure 5.3 VulcanH Architecture Diagram.	67
Figure 5.4 Dashboard view.	68
Figure 5.5 Equipment sheet.....	69
Figure 5.6 Work order prioritization.	70
Figure 5.7 Maintenance flagging.	70
Figure 5.8 Scheduling view.....	71
Figure 5.9 Work order selection.....	72
Figure 5.10 Maintenance KPIs. a) Fleet availability and objectives. b) Equipment stoppages information. c) Bay occupation and workforce availability. d) <i>Schedule Completion</i> KPI for current and past weeks.	73
Figure 5.11 AI explanation levels. 1) No explanation. 2) Confidence score. 3) Confidence score and suggestion. 4) Confidence score, suggestion and visual aid.	77
Figure 5.12 UEQ+ scores for PM and PdM scenarios.	80
Figure 5.13 RIS trust score per participant for the PdM scenario.	81
Figure 5.14 AI explanation rankings (higher score is preferred, maximum 36).	82
Figure 5.15 Debriefing questionnaire responses.	83

Figure A.1 JDEdwards example work order.	107
Figure A.2 GuideTi example work order.	108
Figure E.1 Approbation éthique pour les entrevues d'analyse des besoins.	113
Figure E.2 Approbation éthique pour les tests utilisateur.	114

LISTE DES SIGLES ET ABRÉVIATIONS

AI	Artificial intelligence
BT	Bon de travail
CCU	Conception centrée sur l'utilisateur
CMMS	Computerized maintenance management system
CSUQ	Complex System Usability Questionnaire
FRQ-NT	Fonds de recherche du Québec en nature et technologie
GMAO	Gestion de la maintenance assistée par ordinateur
HMI	Human-Machine Interaction
IA	Intelligence artificielle
IoT	Internet of things
KPI	Key performance indicator
MDMT	Multidimensional Measure of Trust
MTBF	Mean time between failures
MTTM	Mean time between maintenances
PM	Preventive maintenance
PdM	Predictive maintenance
RIS	Reliance Intentions Scale
SUS	System Usability Scale
TiA	Trust in automation
TPS-HRI	Trust-Perception-Scale for Human-Robot Interaction
UI	User Interface
UEQ+	User experience questionnaire Plus
UEQ	User experience questionnaire
UMUX	Usability Metric for User Experience
UX	User experience
XAI	Explainable artificial intelligence

LISTE DES ANNEXES

Annexe A Article 1 – Appendix A.....	107
Annexe B Article 1 – Appendix B	109
Annexe C Article 2 – VulcanH User Requirements	110
Annexe D Article 2 – RIS Questionnaire.....	112
Annexe E Approbations éthiques	113

CHAPITRE 1 INTRODUCTION

L'exploitation minière constitue l'une des plus importantes pratiques au monde et l'une des plus anciennes. En effet, l'extraction de silex et d'ocre, les premières formes d'exploitation minière, datent d'environ 40 000 ans. Sans les outils en cuivre, les Égyptiens de l'Antiquité n'auraient pas pu ciseler les roches du Nile nécessaires pour la création des grandes pyramides. De plus, ce fut pendant l'âge du bronze que l'humanité put stimuler sa culture des sciences et des arts, et pendant l'âge de fer que des avancées militaires importantes eurent lieu. Lors de la première révolution industrielle en Angleterre, c'est l'exploitation massive de charbon qui a fourni l'énergie requise aux industries et aux moyens de transport lorsque les réserves de bois étaient insuffisantes. En somme, l'industrie minière a joué un rôle essentiel dans l'histoire de l'humanité en propulsant ses avancées technologiques et, par conséquent, en catalysant son évolution [1].

Bien que les méthodes d'extraction minière se soient raffinées au fil des années, l'essence du processus demeure la même depuis le 17^{ème} siècle où la poudre à canon fut utilisée pour la première fois dans une mine souterraine. En effet, le processus consiste en le forage, le sautage, le transport et le concassage de la roche [2]. De nombreuses avancées techniques se sont réalisées sur des aspects spécifiques du domaine minier afin d'accroître la productivité. L'un de ces aspects concerne la disponibilité des équipements d'extraction qui, comparativement aux autres industries, est étonnamment faible [2]. Une des causes les plus communes de cet enjeu est l'arrêt non-planifié à la suite du bris d'équipements qui, dans le temps, sont devenus de plus en plus complexes. Dans cette optique, la maintenance des équipements obtient une place considérable dans l'optimisation des pratiques minières du 21^{ème} siècle.

Bien qu'il existe plusieurs types de maintenance pour les équipements miniers, celui le plus couramment utilisé est la maintenance préventive (PM) où un équipement est entretenu à des intervalles fixes dépendamment de son usage [3]. Cependant, la PM est caractérisée par un processus chronophage et ne semble pas réellement améliorer la disponibilité mécanique des équipements [4]. Or, après l'apparition des technologies de l'information et de l'internet des objets (IoT), un nouveau type de maintenance a émergé : la maintenance prédictive (PdM). La PdM a déjà été implémentée avec succès dans plusieurs secteurs tels que l'industrie manufacturière où elle est utilisée activement [5]. Pourtant, elle n'a pas encore été appliquée aux équipements miniers mobiles. Ces équipements sont désormais munis de capteurs intelligents permettant l'enregistrement des données opérationnelles et des infrastructures sans fil, telles que le 4G et les

réseaux LTE, assurent le partage de ces données vers divers systèmes de stockage. Toutefois, bien qu'il soit théoriquement possible de procéder à leur analyse, la pratique indique que 99% des données collectées sur les équipements miniers ne sont pas utilisées [6]. De ce fait, il y a un détachement entre la recherche et la pratique en ce qui concerne l'intégration de la PdM dans les mines. De plus, les systèmes de gestion de la maintenance assistée par ordinateur (GMAOs) offrent peu ou pas de support pour gérer ce type de données et sont souvent compliqués et frustrants à utiliser [7].

Le but de ce mémoire par article est donc de concevoir, développer et évaluer un GMAO facilitant la prise de décision de l'expert en maintenance pour la maintenance préventive et prédictive d'équipements miniers mobiles. Pour ce faire, j'ai cartographié le processus de maintenance appliqué à ce jour dans les mines québécoises dans l'optique d'analyser les tâches et les besoins des experts en maintenance. Puis, ces informations ont permis le développement du GMAO final, nommé VulcanH, qui a été évalué auprès de 9 experts. Ce travail a permis la production de deux articles publiés ou soumis pour publication dans des journaux revus par les pairs.

Le reste de ce mémoire est structuré comme suit. La revue de littérature au chapitre 2 aborde la maintenance d'équipements miniers, les notions sur les GMAOs, l'évaluation de l'utilisabilité de systèmes logiciels et de la confiance en l'automatisation. Le chapitre 3 identifie les manques à la connaissance et les objectifs de recherche de cette maîtrise. Le chapitre 4 présente le premier article où on décrit la cartographie du processus de maintenance ainsi que l'analyse des tâches et des besoins des usagers. Le chapitre 5 contient le second article où est décrit le processus de développement et d'évaluation de VulcanH. Le chapitre 6 offre une discussion permettant de clarifier certains aspects globaux de la recherche et le chapitre 7 conclut le mémoire.

CHAPITRE 2 Revue de littérature

Ce chapitre établit l'état de la littérature scientifique liée à la problématique de recherche à laquelle s'intéresse ce mémoire de maîtrise. Premièrement, elle présente les différents types de maintenance d'équipements, en particulier la maintenance préventive et prédictive, et leurs applications au domaine minier. Deuxièmement, le chapitre revient sur les principales caractéristiques des GMAOs utilisés pour assurer le suivi des activités de maintenance de même que les limitations pour l'ajout de la maintenance prédictive. Troisièmement, le chapitre présente le procédé de conception et d'évaluation de l'expérience utilisateur afin de rendre un système facilement utilisable. Le chapitre se conclut avec une synthèse des principaux résultats sur la confiance des utilisateurs en des systèmes automatisés, qui sera au cœur de la maintenance prédictive.

2.1 Types de maintenance

La maintenance est définie comme l'ensemble des actions techniques et administratives exécutées sur un objet dans le but de le maintenir ou de le réparer pour qu'il accomplisse ses fonctions opérationnelles [8]. Il existe plusieurs types de maintenance et plusieurs façons de les catégoriser mais, dans le cadre de ce mémoire, la maintenance concerne les équipements mécaniques complexes tels que les équipements miniers. La figure 2.1 constitue en un arbre de décision où les types de maintenance sont organisés en fonction de l'état de l'équipement lors de l'exécution des travaux. Cette différenciation est validée par [9] où l'on identifie deux grandes familles de maintenances, soit la maintenance proactive et la maintenance réactive, qui s'effectuent respectivement avant ou après le bris d'un équipement [9].

2.1.1 Maintenance proactive

Le but principal des maintenances proactives est d'entretenir l'équipement avant qu'il n'arrête de fonctionner. Dans cette optique, la maintenance détective vise à trouver des bris ou des défaillances existants qui n'ont pas encore causé l'arrêt de l'équipement. Cependant, sa nature exploratoire engendre des travaux d'une durée notamment élevée. Ainsi, la maintenance détective n'est effectuée que sur des équipements en attente ou pour des enjeux de protection et de sécurité [9]. Plus communément implémentée, la maintenance préventive (PM) a comme but de prévenir les défaillances et de maximiser le taux de bon fonctionnement (MTBF) de l'équipement, soit sa durée de vie moyenne avant nécessiter des réparations [10]. Elle se divise en deux catégories, soit la PM systématique et la maintenance prédictive (PdM).

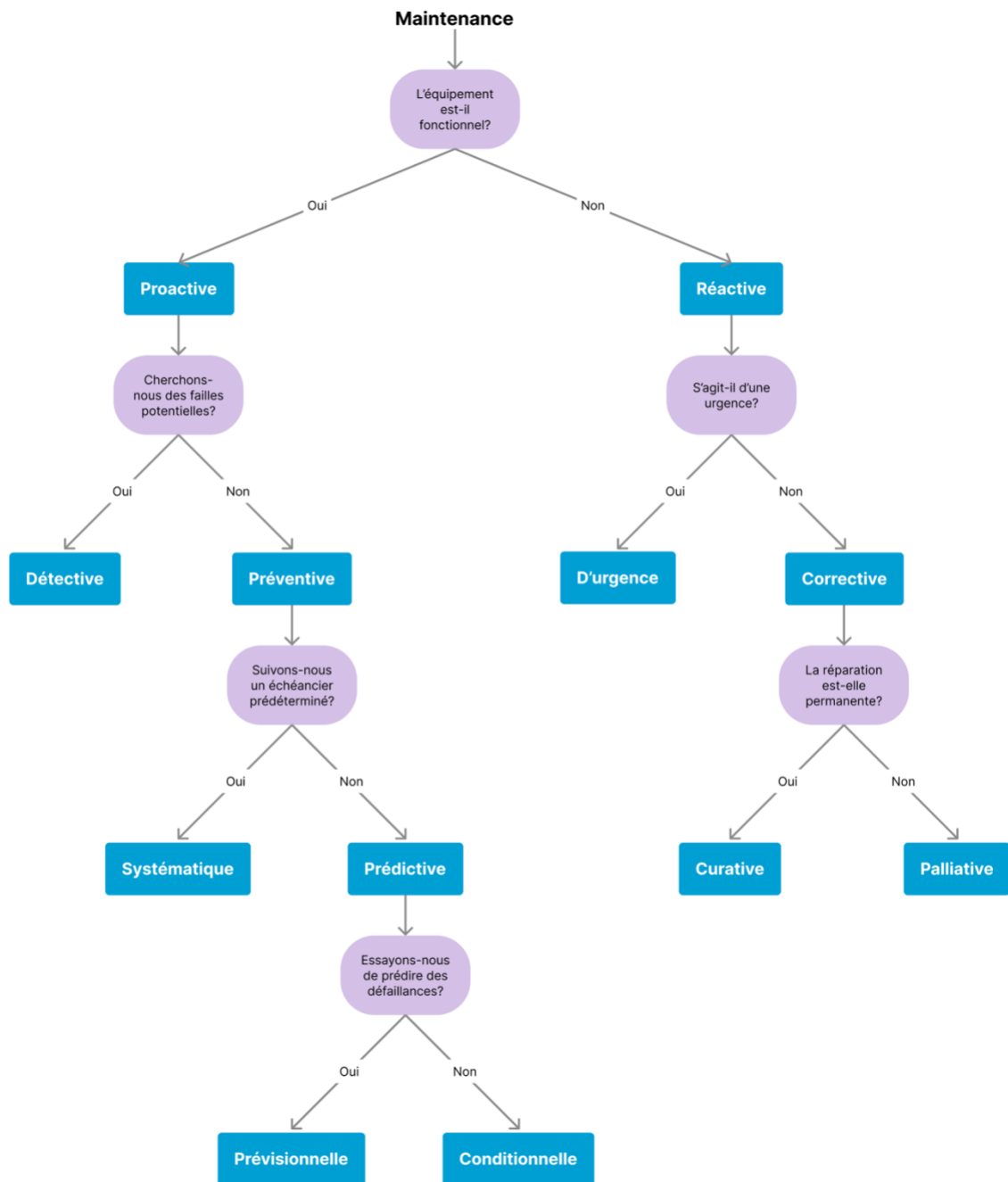


Figure 2.1 Types de maintenance.

2.1.2 Maintenance préventive (PM) systématique

Lors d'une PM systématique, les équipements sont entretenus à des intervalles réguliers et diverses tâches d'entretien sont exécutées de façon périodique dans le but de prévenir les défaillances [10]. Ce type de maintenance comporte des activités telles que l'inspection, la réparation, la maintenance planifiée et le remplacement [11]. Le livre *Uptime* [9] spécifie davantage cette liste d'activités et l'organise en 6 étapes critiques du processus de PM. La figure 2.2 résume ces étapes.

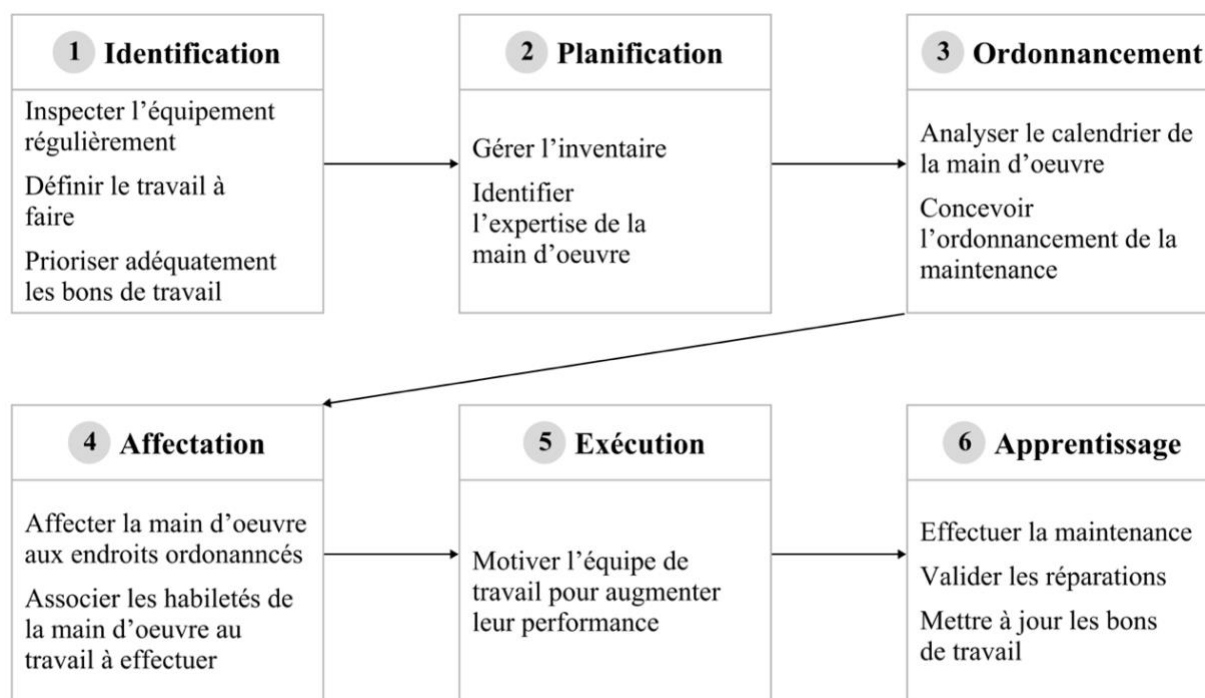


Figure 2.2 Processus de PM systématique selon [9].

La sélection de l'intervalle de temps pour réaliser la maintenance est cruciale pour la PM mais imprécise. En effet, l'intervalle dépend du type d'équipement, des recommandations du fabricant, des pratiques d'autres entreprises, etc. et repose sur la supposition que le MTBF reste constant [12]. Cependant, le MTBF décroît en fonction du vieillissement de l'équipement et risque ainsi d'engendrer des bris prématurés [13]. Au contraire, la constance des intervalles de maintenance amène souvent au remplacement inopportun de composantes en bonne santé [12]. Malgré ces inconvénients, la PM systématique est le type de maintenance le plus utilisé pour l'entretien de systèmes mécaniques [3]. Encore peu de travaux ont exploré le processus réel de PM dans les mines canadiennes.

2.1.3 Maintenance prédictive (PdM)

La PdM est une sous-catégorie de la PM où l'équipement est suivi de façon intelligente pour éviter les défaillances [14]. Auparavant, ce suivi était effectué par un opérateur humain et consistait en l'analyse visuelle et auditive de l'équipement. Maintenant, grâce aux avancées technologiques des dernières années et l'introduction de l'internet des objets (IoT) dans l'industrie, les données propres aux équipements sont désormais analysables de façon informatique [14]. Comparativement à la PM systématique, la PdM vise à optimiser le nombre d'entretiens et le remplacement des pièces pour assurer une diminution des coûts de maintenance [11], [15]. On distingue deux catégories de PdM, soit la PdM conditionnelle et la PdM prévisionnelle [10].

La PdM conditionnelle repose sur la surveillance d'un équipement en temps réel pour détecter des défaillances potentielles et faciliter la planification de la maintenance [16]. Dans ce cas, des données historiques de l'équipement, telles que les mesures d'usure, les résultats de l'analyse d'huile ou de vibration permettent l'établissement de seuils dont le franchissement déclenche une alarme [10]. L'exécution de la maintenance à la suite d'une alarme permet donc d'entretenir l'équipement avant qu'une panne ne survienne [17]. Lorsque la PdM est décrite dans [9], les auteurs font référence à la PdM conditionnelle.

L'ajout d'algorithmes d'analyse statistique à la PdM introduit ce que l'on appelle la PdM prévisionnelle ou statistique [16]. Ce type de PdM a comme but d'estimer la durée de vie résiduelle d'un équipement en s'appuyant sur des méthodes statistiques souvent issues de l'intelligence artificielle (IA) telles que les algorithmes génétiques, les réseaux de neurones, le raisonnement à partir des cas et l'apprentissage machine [11], [18].

Dans ce texte, l'utilisation du terme PdM englobe les deux catégories mentionnées. Cependant, lorsqu'on mentionne l'ajout de pratiques IA, la littérature fait généralement référence à la PdM prévisionnelle.

2.1.4 Maintenance réactive

Lors d'une maintenance réactive, l'équipement est réparé après son arrêt. Pour cela, les maintenances réactives sont souvent connues sous le nom de « réparations » [9]. Leur nature généralement non planifiable les sépare davantage des maintenances proactives. En effet, bien qu'il soit possible, selon l'importance de l'équipement, de planifier les maintenances réactives, elles sont normalement introduites dans la cédule en cours et décalent les travaux subséquents. Si les réparations concernent un équipement critique ou posent un problème imminent de santé ou de sécurité, elles seront alors considérées comme étant des maintenances d'urgence. Sinon, elles constituent des maintenances correctives.

2.1.5 Maintenance corrective

Incorporant l'essence de ce qu'est la maintenance réactive, la maintenance corrective vise à identifier et corriger des défaillances dans le but de restaurer un équipement pour qu'il puisse opérer de façon adéquate [19]. On distingue quatre actions de maintenance corrective [13] :

1. Constatation et identification de la défaillance ;
2. Établissement des causes de la défaillance ;
3. Exécution de la maintenance ;
4. Amélioration continue via la sauvegarde de données historiques.

La maintenance corrective se divise en deux sous-catégories, soit la maintenance palliative et la maintenance curative. Lors d'une maintenance palliative, le seul objectif est de remettre en marche un équipement le plus rapidement possible sans nécessairement assurer un rétablissement complet de toutes ses fonctions opérationnelles. Normalement, ce type de maintenance est suivi par la maintenance curative qui vise à restaurer l'équipement dans une vision plus à long terme [10].

La gestion et l'exécution du processus de maintenance sont facilitées par des outils informatiques qui sont explorés dans la section suivante.

2.2 Systèmes de gestion de la maintenance assistée par ordinateur (GMAO)

Les systèmes de gestion de la maintenance assistée par ordinateur (GMAO) ont été introduits dans les années 1960 sous la forme de systèmes à carte perforée permettant de digitaliser certaines tâches de maintenance. Au fil des années, les GMAOs ont gagné en popularité et ont rapidement été introduits dans plusieurs domaines industriels dont l'industrie minière [8], [20]–[23].

La littérature identifie plusieurs fonctionnalités attendues d'un GMAO par ses utilisateurs : la gestion des actifs d'une compagnie, la gestion de la main d'œuvre et des pièces, le contrôle sur les PM et leur ordonnancement, et la gestion des données de maintenance [8], [9]. Cependant, la plupart des systèmes implémentés réellement dans les entreprises ne jouent que le rôle de bases de données sans système d'aide à la décision pour les utilisateurs [24]. Ce manque d'aide à la prise de décision est une défaillance connue des GMAOs et nuit à leur intégration dans les processus de maintenance [25]. En effet, plusieurs opérateurs partagent l'opinion que ces systèmes n'ajoutent aucune valeur réelle aux entreprises [7], [26].

En 2014, Tretten et Ramin ont organisé des rencontres avec 10 experts en maintenance venant de trois industries différentes (minière, pâte et papier, et fabrication d'avions) dans le but d'évaluer l'utilisabilité des GMAOs [27]. Leurs résultats leur ont permis de compiler une liste de 7 pièges d'utilisabilité auxquels succombent souvent les GMAOs :

1. Accès limité à la documentation ;
2. Incompatibilité avec d'autres systèmes ;
3. Entrée manuelle d'information trop fréquente ;
4. Interface graphique (UI, de l'anglais *User Interface*) difficile à utiliser ;
5. Manque d'orientation menant à une perte d'intérêt ;
6. Manque d'aide à la décision pour les fonctionnalités de maintenance ;
7. Complexité inutilement élevée du système.

Bien que les auteurs fournissent quelques recommandations d'amélioration, aucune solution tangible ou évaluable n'est suggérée. Une opportunité se présente, alors, de fournir un GMAO où l'utilisabilité et l'aide à la prise de décision sont à la base du processus de développement. Pour ce faire, il faut recourir à l'expérience utilisateur et sa sous-catégorie, l'utilisabilité.

2.3 Expérience utilisateur (UX) et utilisabilité

L'expérience utilisateur (UX) est généralement entendue comme étant l'expérience entre un utilisateur et un produit interactif. Cependant, depuis sa première utilisation dans les années 1990 par Donald Norman, sa définition exacte fait encore l'objet de discussion parmi les experts [28]. Selon le *Nielsen-Norman Group*, il s'agit du regroupement de toutes les interactions de l'utilisateur avec la compagnie, ses services et ses produits [29]. Une bonne UX comble, en premier lieu, les besoins de l'utilisateur. Puis, elle offre une élégance et une simplicité capables d'engendrer de la joie dans l'utilisation des services [29]. Une notion importante de l'UX est sa nature temporelle. Effectivement, l'expérience de l'utilisateur ne se limite pas à l'usage du service mais peut survenir avant et après l'usage via des moyens directs (p. ex. : publicité ou démonstrations) et de manière indirecte (p. ex. : suite à une réflexion sur l'usage) [30]. Deux autres aspects communément associés à l'UX sont la subjectivité de l'expérience et son effet sur l'état émotionnel de l'utilisateur. Ces deux dernières notions séparent l'UX de sa contrepartie plus spécifique : l'utilisabilité [28].

Selon la norme ISO 9241-210, l'utilisabilité est le « degré selon lequel un système, un produit ou un service peut être utilisé, par des utilisateurs spécifiés, pour atteindre des buts définis avec efficacité, efficience et satisfaction, dans un contexte d'utilisation spécifié » [31]. Dit simplement, l'utilisabilité réfère à la facilité avec laquelle un utilisateur utilise un système pour réaliser une tâche. L'utilisabilité est donc orientée vers des objectifs pragmatiques, soit d'être orientée vers la tâche, alors que l'UX englobe aussi des notions hédoniques, esthétiques et temporelles.

La conception centrée sur l'utilisateur (CCU) est une démarche de développement de produits interactifs afin d'en assurer leur bonne utilisabilité. Cette démarche est centrale à la réalisation de ce mémoire et est présentée ci-après.

2.3.1 Conception centrée sur l'utilisateur (CCU)

La CCU exige d'impliquer les utilisateurs finaux du produit dans chaque étape du procédé de sa conception [28]. La norme ISO 9241-210 [31] spécifie les 4 étapes principales de la CCU :

- Compréhension et spécification du contexte d'utilisation ;
- Spécification des exigences utilisateurs ;
- Conception de solutions respectant les exigences ;
- Évaluation des solutions face aux exigences.

Ces quatre étapes s'effectuent de manière itérative jusqu'à l'obtention d'une solution respectant les exigences établies [31].

L'étape de compréhension et spécification du contexte d'utilisation permet d'identifier les utilisateurs cibles du produit, leurs tâches à réaliser, leurs procédés de prise de décision, de même que les points de frustration des outils existants où une amélioration est envisageable. Aussi, il est possible d'établir des références de performance et de satisfaction indépendamment de l'originalité du produit.

La spécification des exigences utilisateurs constitue une étape critique de la CCU et ne se limite pas à la définition des exigences purement fonctionnelles. En effet, l'inclusion de toutes les parties prenantes d'une organisation est prévue dans le but de compiler une liste d'exigences qui respectent entièrement le contexte établi dans la première étape [31].

L'étape de conception est l'élaboration d'une solution d'interface afin de réaliser les tâches identifiées. Celle-ci se fait avec une maturité croissante, p. ex. en débutant avec une maquette statique, puis un prototype interactif, puis un prototype de haute fidélité visuelle. Lors de l'établissement des interactions avec le système, il est important d'établir comment l'utilisateur utilise le système pour accomplir ses tâches au lieu de ne définir que le fonctionnement isolé du système. De cette façon, des choix éclairés peuvent être effectués concernant le meilleur moyen de présenter l'information et d'organiser les outils offerts [31].

À l'étape d'évaluation, les utilisateurs finaux utilisent la solution développée à l'étape précédente (maquette, prototype) afin de réaliser leurs tâches. Le degré d'utilisabilité de la solution est évalué à l'aide de différentes métriques p. ex. temps de complétion et des échelles subjectives. Les résultats obtenus sont comparés aux exigences d'utilisabilité définies à l'étape 2.

Les étapes de conception et d'évaluation de solutions sont souvent effectuées en alternance. C'est-à-dire que le produit est en constante évolution et que les choix de conception sont altérés en fonction des rétroactions positives et négatives des utilisateurs afin d'atteindre les exigences ciblées.

L'évaluation de l'utilisabilité et de l'expérience utilisateur est un champ de recherche très actif en littérature auquel nous portons notre attention à la prochaine section.

2.3.2 Techniques d'évaluation UX

L'évaluation d'une solution ou d'un produit peut s'effectuer en implémentant une ou plusieurs méthodes simultanément. Indépendamment des méthodes choisies, lors d'une évaluation, l'utilisateur complète une tâche spécifique qui permet au chercheur de connaître son opinion

concernant l'interaction avec le système. Les techniques d'évaluation les plus couramment utilisées sont les tests utilisateur et les échelles subjectives.

2.3.2.1 Tests utilisateur

Lors de ce type d'évaluation UX, les participants utilisent le système dans le but d'effectuer des tâches prédéfinies [28]. Dû à la nature itérative de la CCU, les tests utilisateur peuvent être effectués pendant toutes les phases de conception d'un produit en utilisant le livrable disponible au moment du test :

- Phase embryonnaire (via une maquette en papier ou statique) ;
- Phase de conception initiale (via une maquette interactive) ;
- Phase de prototypage (via un prototype fonctionnel) ;
- Phase d'amélioration continue (via le produit final).

L'objectif principal des tests utilisateur est d'observer et documenter l'interaction du participant avec le système évalué afin d'identifier les fonctions permettant d'accomplir la tâche et les irritants à améliorer [28]. Normalement, les participants sont invités à penser à haute voix pour expliquer le processus mental leur permettant de compléter la tâche et pour exprimer leurs sentiments face à l'interaction. Cela dit, des questions sont fréquemment posées après chaque tâche ou à la fin du test pour obtenir une évaluation plus ciblée [32]. À ces fins, les échelles subjectives sont communément utilisées pour obtenir des résultats plus significatifs.

2.3.2.2 Échelles subjectives

L'utilisation d'échelles subjectives pour évaluer l'utilisabilité d'un produit est un concept qui existe depuis les années 1980. Ces échelles consistent en des questionnaires, normalement sous forme d'échelles de Likert, qui permettent à l'utilisateur d'exprimer son opinion sur le système évalué [28]. Les échelles le plus communément utilisées sont l'échelle SUS (de l'anglais, *System Usability Scale*) [33], [34], le CSUQ (de l'anglais, *Computer System Usability Questionnaire*) [35], l'échelle UMUX (de l'anglais, *Usability Metric For User Experience*) avec sa variante UMUX-LITE [36], [37], et l'UEQ (de l'anglais, *User Experience Questionnaire*) [38]. Ces questionnaires sont de méthodes d'évaluation subjectives dans lesquelles l'utilisateur indique son niveau d'accord face aux dimensions proposées. Notamment, dans l'échelle SUS, l'utilisateur choisit un chiffre allant de 1 (fortement en désaccord) à 5 (fortement en accord) pour 10 questions portant sur son expérience (p. ex. : « J'ai trouvé ce système inutilement complexe ») [33]. L'avantage principal de ces échelles est la possibilité de calculer des résultats quantifiables qui, grâce aux référentiels

établis en littérature, peuvent être comparés entre diverses études. Généralement, ces méthodes fournissent un indicatif satisfaisant pour évaluer l'UX d'un système mais peuvent être moins applicables à certains contextes où l'UX est défini par des facteurs spécifiques [39]. Dans le but d'offrir une échelle d'évaluation personnalisable, [39] ont transformé l'UEQ en un questionnaire modulaire qu'ils ont appelé UEQ+. Ce questionnaire fournit une liste de 16 dimensions définies dans le tableau 2.1. Chaque dimension contient 4 items à évaluer sur une échelle de Likert, de même qu'une échelle pour évaluer l'importance de cette dimension à l'interaction globale.

Tableau 2.1 Dimensions de l'UEQ+ selon [39].

Dimension	Aspect subjectif évalué
<i>Attractivité</i>	Le niveau d'appréciation générale du système.
<i>Efficacité</i>	La quantité d'effort requise pour compléter les tâches.
<i>Transparence</i>	La facilité d'apprentissage du système.
<i>Maniabilité</i>	Le niveau de contrôle sur l'interaction avec le système.
<i>Stimulation</i>	L'évocation de sentiments captivants ou motivants.
<i>Originalité</i>	L'innovativité du système et sa capacité de capter l'intérêt du participant.
<i>Confiance</i>	Les données entrées dans le système sont sécurisées et ne sont pas utilisées de façon malveillante.
<i>Toucher</i>	La sensation issue d'une interaction tactile avec le système (ou le produit).
<i>Acoustique</i>	Le son ou le bruit provenant du système.
<i>Flexibilité</i>	La facilité de personnalisation du système.
<i>Utilité</i>	La quantité de temps sauvé et la hausse de productivité engendrées par le système.
<i>Valeur</i>	Le niveau de professionnalité et qualité du système.
<i>Esthétique visuelle</i>	L'attractivité esthétique du système.
<i>Utilisation intuitive</i>	Le niveau de formation ou d'aide requis pour utiliser le système.
<i>Crédibilité</i>	La fiabilité et l'exactitude de l'information fournie par le système.
<i>Qualité de contenu</i>	La pertinence de l'information présentée par le système.

Lors de la création du questionnaire personnalisé, il suffit d'identifier les dimensions les plus pertinentes au contexte de recherche et de les inclure dans le questionnaire. Similairement à l'UEQ, l'UEQ+ calcule un indicateur de performance (KPI, de l'anglais *Key Performance Indicator*) qui peut être comparé entre différentes études indépendamment des dimensions choisies [39]. De par sa flexibilité à sélectionner les dimensions pertinentes à l'expérience et sa facilité d'utilisation,

L'UEQ+ est une échelle prometteuse pour évaluer l'expérience utilisateur [40]. Cependant les études précédentes qui l'ont employée l'ont rarement appliquée à des utilisateurs experts et jamais à des tâches de maintenance d'équipements miniers.

Bien que les échelles offrent un aperçu intéressant de l'utilisabilité d'un système, elles sont limitées en termes d'expérience globale d'utilisation. Leur jumelage aux tests utilisateur permet donc d'obtenir une vue plus large de l'utilisabilité du système.

2.3.3 UX et intelligence artificielle (IA)

Dans une industrie où l'automatisation par l'entremise de l'IA prend de plus en plus de place, l'intérêt d'études UX ciblant l'IA est évident. En effet, la littérature a déjà démontré qu'un outil automatisé offrant peu de rétroaction sur son fonctionnement (décrit comme une « boîte noire ») est souvent mal utilisé, inutilisé, ou même abusé par les utilisateurs [41], même chez des experts comme les pilotes d'avions [42]. Dû à leur nature essentiellement opaque, les GMAOs s'insèrent dans cette catégorie [24]. De plus, l'addition de la PdM risque fortement d'augmenter leur complexité par l'ajout d'algorithmes automatisés de prise de décision. Une approche visant à optimiser l'utilisation de ces outils et d'en augmenter l'acceptation est de mise. Cette problématique constitue la base de la recherche en IA explicable (XAI).

L'XAI vise à expliquer le processus de raisonnement d'un modèle IA pour le rendre plus transparent aux yeux des utilisateurs [43]. Pour ce faire, la plupart des méthodes existantes adoptent une approche orientée sur le modèle où l'IA est décortiquée, si possible, dans le but d'expliquer son fonctionnement interne [44]. Cependant, l'augmentation de la transparence d'un système n'en garantit pas la compréhension et peut facilement se montrer accablante pour l'utilisateur. Dans cette optique, [45] ont introduit la notion d'XAI centré sur l'utilisateur. Tout comme la CCU, cette méthode offre des explications actionnables qui permettent aux utilisateurs d'atteindre leurs objectifs dans un contexte défini. Similairement, [46] ont proposé un modèle interactif qui adapte ses explications en fonction des besoins des utilisateurs mais ne l'ont pas encore testé sur le terrain. Malgré son utilité apparente, l'XAI fait face à plusieurs enjeux. Effectivement, la présence d'explications a déjà été associée à une confiance non justifiée en l'IA et en ses capacités [45]. Aussi, la qualité des explications est un sujet peu abordé dans la littérature en XAI et il s'agit d'un sujet très pertinent, notamment lorsqu'elle concerne des utilisateurs experts.

Les travaux de Holzinger en 2017 [44], 2019 [47] et 2020 [48] ont ciblé des médecins dans le but d'évaluer la qualité des explications selon leurs besoins. En effet, les experts adoptent une approche

de justification causale leur permettant d'extrapoler les conditions et les faits nécessaires pour expliquer un évènement. Ainsi, le modèle proposé par Holzinger se concentre sur la « causabilité » des explications au lieu d'en aborder seulement l'explicabilité [44], [47], [48]. En outre, l'on théorise que les utilisateurs experts peuvent être assujettis à des explications plus complexes grâce à leur familiarité du domaine [49] et que, contrairement aux utilisateurs non experts, cette familiarité les rend moins disposés à faire confiance à un système automatisé [50].

À cet égard, l'étude de la confiance en l'automatisation (TiA) prend une place primordiale lors de l'évaluation de systèmes automatisés tels que les GMAOs.

2.4 Confiance en l'automatisation (TiA)

2.4.1 Théorie de la confiance

Bien qu'il n'existe aucun modèle de confiance globalement accepté dans ce champ, la communauté de recherche en TiA a généralement adopté le modèle de confiance interpersonnelle de *Mayer et al.* ([51]) [52], [53]. Selon ce modèle, affiché à la figure 2.3, la confiance est un concept dynamique qui dépend de plusieurs aspects externes précédant ou succédant la décision finale. En premier lieu, la propension des fiduciaires à faire confiance aux fiduciaires est déterminée par trois qualités intrinsèques des fiduciaires, soit leur habileté, leur bénévolence et leur intégrité. Naturellement, on n'entend que la perception de ces qualités aux yeux des fiduciaires leur permettant ultimement de déterminer la fiabilité des fiduciaires. Deuxièmement, vient le choix de faire confiance ou non en la personne. Ce choix dépend du niveau de prise de risque dans la relation ainsi que du risque perçu par les fiduciaires. Ainsi, la notion de vulnérabilité doit être prise en compte, car elle est directement liée à la volonté de prise de risque dans la relation. Troisièmement, les conséquences issues du choix de céder ou non la confiance affectent la propension de faire confiance dans le futur, ce qui explique la nature dynamique du modèle [51].

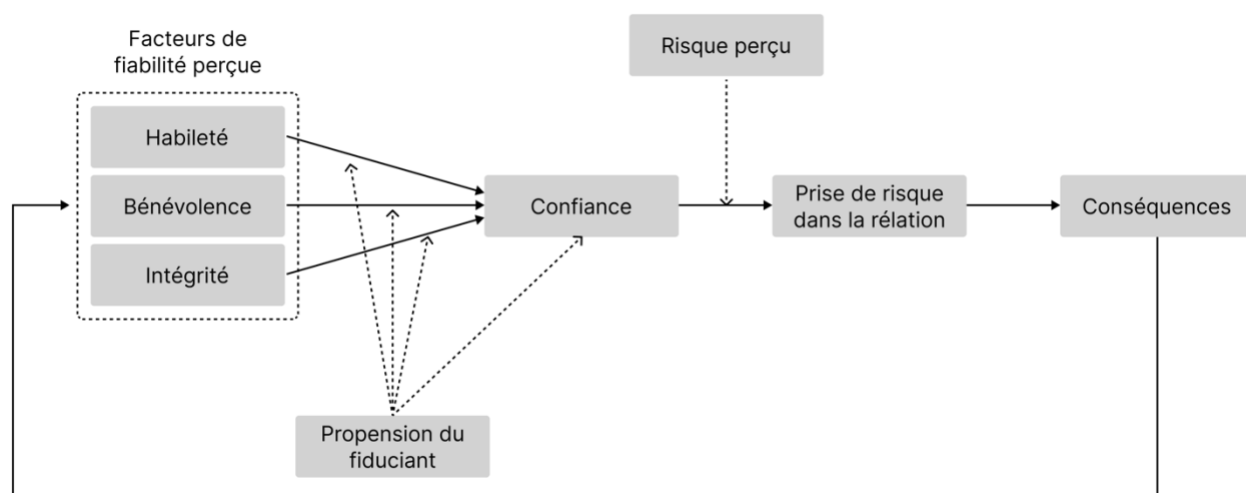


Figure 2.3 Modèle de confiance selon [51] (traduit).

La difficulté de l'évaluation de la confiance telle qu'établie par le modèle de [51] est issue de l'influence exercée par chaque aspect qui module l'interaction humaine au-delà de la confiance elle-même [51].

Quant à la confiance appliquée à l'automatisation, soit la TiA, elle dépend principalement de facteurs propres aux limitations d'une technologie comme sa fiabilité, son utilité, sa robustesse et son taux d'erreur [50]. En effet, lorsque l'humain interagit avec une machine, la tolérance aux erreurs est inférieure que lors d'interactions interpersonnelles [50]. Pour cette raison, la mise en place d'un niveau approprié de TiA est capitale pour l'épanouissement de la relation entre l'humain et la machine [52].

L'évaluation de la TiA est une pratique impliquant plusieurs enjeux et est abordée dans la section suivante.

2.4.2 Évaluation de la TiA

Plusieurs méthodes d'évaluation de la TiA ont été proposées en littérature. Dans leur travail, [53] ont identifié 30 méthodes différentes touchant divers aspects du modèle de confiance proposé par [51]. La figure 2.4 présente la subdivision du modèle selon les catégories identifiées par [53]. Le tableau 2.2 organise les méthodes d'évaluation en fonction des catégories qu'elles évaluent.

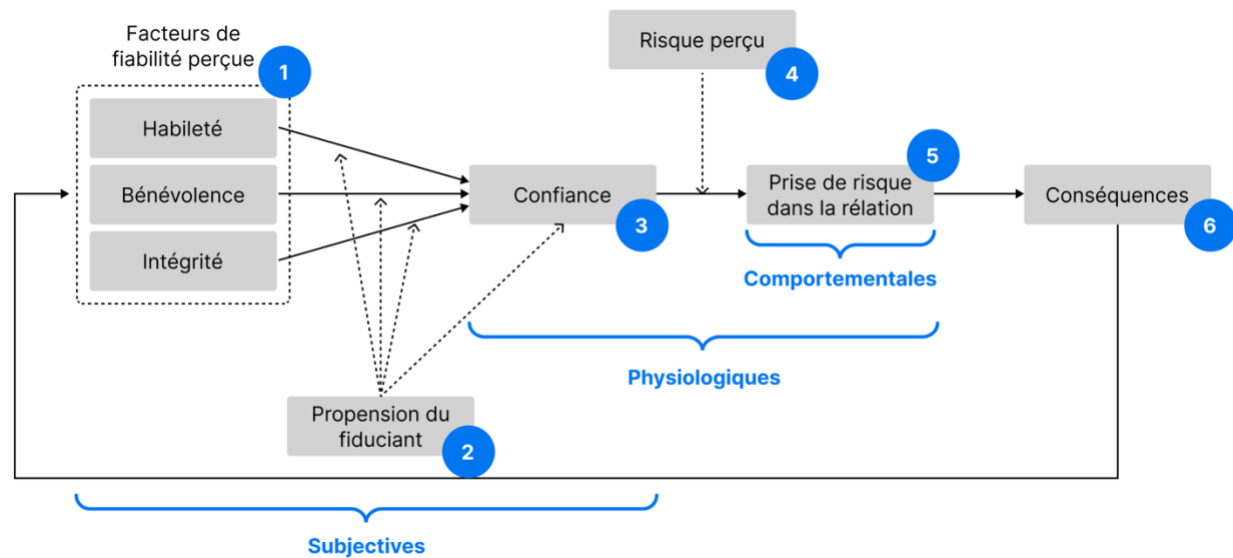


Figure 2.4 Modèle de confiance de [51] divisé selon [53] (annoté, traduit).

Tableau 2.2 Méthodes d'évaluation de la TiA [53].

Méthode	Concepts évalués de Mayer et al. 1995
Subjectives	
Liste de contrôle de la confiance	1 3
Échelle d'évaluation du potentiel de complaisance	2
Échelles personnalisées	3
Déclaration dynamique de la confiance	3
Questionnaire de confiance humain-ordinateur	1 3
Différences individuelles en TiA	2
Modèle intégré de la confiance	3
Mesures de confiance et fiabilité	1 3
<i>Multi-Dimensional Measure of Trust</i> (MDMT)	1 3
Auto-évaluation des qualités de l'automatisation	1
Échelle de confiance et d'assurance	3
<i>Trust in Automated Systems Test</i> (TOAST)	1
Échelle de TiA	1 3
Échelle de perception de la confiance pour l'interaction humain-robot	1 3
Échelle de confiance, Lee & Moray	3
Échelle de confiance, Merritt	1 3
Comportementales	
Performance d'équipe combinée	6
Taux de conformité/accord	5
Temps de décision	5
Délégation	5
Jeu de confiance économique	5
Intervention	5
Dépendance	5
Temps de réponse	N/A
Vérification	5
Physiologiques	
Activité électrodermale	3 4
Suivi du regard	3
Variation et variabilité de la fréquence cardiaque	3 4
Mesures neurales	1 3

Comme indiqué par la figure 2.4, les méthodes d'évaluation de la TiA se divisent en 3 catégories, soit les méthodes subjectives (ou d'auto-évaluation), les méthodes physiologiques et les méthodes comportementales. De ces catégories, la plus populaire est celle de l'auto-évaluation où figurent 16 méthodes sur 30 (voir le tableau 2.2). Parmi les méthodes subjectives, l'utilisation de questionnaires personnalisés est la pratique la plus commune [53]. Cependant, ces questionnaires ont tendance à traiter la confiance comme un concept isolé et respectent rarement le modèle de *Mayer et al.* ([51]) [53]. Constituant une exception à cette observation, l'échelle RIS (de l'anglais *Reliance Intentions Scale*), développée par [54], tient compte de la nature complexe du modèle en question tout en l'adaptant aux notions propres à la TiA [54]. RIS possède 10 items sur une échelle de Likert allant de 1 à 7 dont l'objectif est d'analyser la propension des utilisateurs à être dépendants d'un système automatisé sans en avoir le contrôle [54]. La notion de vulnérabilité intentionnelle est donc couverte par l'échelle. Cette dernière a été comparée à d'autres méthodes d'évaluation subjective de systèmes robotiques, telles que l'échelle de perception de la confiance pour l'interaction humain-machine (TPS-HRI, de l'anglais *Trust-Perception-Scale for Human-Robot Interaction*) et la mesure multidimensionnelle de confiance (MDMT, de l'anglais *Multidimensional Measure of Trust*), et constitue un moyen fiable et efficace d'évaluer la TiA [55]. Toutefois, elle n'a pas souvent été appliquée aux systèmes purement logiciels et son utilisation auprès d'experts reste rare.

Les notions nécessaires pour comprendre ces travaux de recherche et les travaux existants dans chaque domaine ont été détaillés, ce qui met fin à la revue de littérature. Le prochain chapitre résume ces concepts ainsi que les opportunités de recherche identifiées. De plus, les objectifs du mémoire sont présentés.

CHAPITRE 3 OBJECTIFS DE RECHERCHE

3.1 Problématiques

La revue de littérature a permis d'identifier plusieurs opportunités de recherche dans l'ensemble des sujets abordés. Premièrement, peu d'information existe concernant le processus réel de maintenance dans les mines canadiennes. Bien que le processus théorique soit clair, la réalité du terrain joue un impact non-négligeable sur son implémentation et il s'agit d'un enjeu rarement pris en compte dans les travaux existants. De plus, l'arrivée de la PdM a motivé la réalisation de plusieurs travaux de recherche sur son application auprès des mines. Toutefois, ces travaux proposent des modèles théoriques qui ne tiennent pas nécessairement compte de l'impact de ces nouvelles pratiques sur les experts en maintenance. Des études centrées sur l'utilisateur, dont l'objectif est de connaître l'opinion, les soucis et les conseils des experts concernant la PdM et son intégration, pourraient réduire l'écart toujours croissant entre l'industrie et la recherche.

Quant aux GMAOs, leurs lacunes en termes d'utilisabilité sont connues. En effet, plusieurs travaux ont soulevé le besoin d'un développement centré sur l'utilisateur pour la conception de GMAOs capables de répondre autant aux besoins courants en PM qu'aux besoins futurs en PdM. Cependant, peu de chercheurs ont répondu à l'appel et il y a un manque de solutions tangibles et évaluables.

Finalement, l'automatisation issue de l'intégration de la PdM dans les mines souterraines met en évidence le besoin d'études en TiA ciblant les experts en maintenance. Bien que plusieurs études aient ciblé des experts, ce champ de recherche a rarement été appliqué aux GMAOs. Quant à l'évaluation de la TiA, l'échelle RIS constitue un moyen intéressant et fiable, mais a rarement été appliquée aux solutions logicielles, dont les GMAOs.

3.2 Objectifs

L'objectif principal de ces travaux de recherche était de concevoir et développer un GMAO axé sur les pratiques actuelles de PM et les pratiques futures de PdM pour les équipements miniers mobiles souterrains. Pour atteindre cet objectif, nous avons réalisé les tâches suivantes :

1. Analyse des besoins utilisateurs via des entrevues avec des experts en maintenance ;
2. Conception et développement d'une solution logicielle ;
3. Évaluation de la solution auprès des utilisateurs.

L'analyse des besoins a fait l'objet du premier article dont l'objectif principal était de cartographier les processus de maintenance actuellement implémentés dans les mines canadiennes. Cet article a aussi atteint des deux sous-objectifs suivants :

- Documenter les soucis et les recommandations d'experts concernant l'intégration de la PdM dans les mines du 21^{ème} siècle ;
- Compiler une liste de requis centrés-utilisateur permettant de guider la conception de systèmes de GMAO.

La conception, le développement et l'évaluation du GMAO ont fait l'objet du deuxième article. L'objectif principal de cet article correspondait avec celui du présent document, soit le développement et l'évaluation du livrable final. En même temps, les 3 sous-objectifs étaient :

- Étudier l'effet de l'intégration de la PdM dans les processus actuels de maintenance ;
- Quantifier et analyser la confiance de l'expert en l'automatisation amenée par la PdM ;
- Évaluer le niveau d'explicabilité des techniques de PdM espéré par l'utilisateur expert.

CHAPITRE 4 ARTICLE 1: 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

4.1 Introduction

Equipment maintenance costs are estimated to constitute from 30% to 50% of a mining operation's annual budget [56], [57]. 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. [58] 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 [58]. 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 [59]. They were proven to be a valuable tool to evaluate the effect of component failures on a mine's development cycle [59] and as means to optimize cost reduction via opportunistic maintenance [60]. Additionally, a recent study showed how mines can make use of these technologies to conduct dynamic simulations that offer insightful decision support [61]. Alas, as most research focuses on mathematical models, simulations, and data-driven approaches [62], 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 [63]. 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 4.2 reviews related work on maintenance best practices, active work on predictive maintenance and usability studies on CMMS. Section 0 presents the methodology used to conduct interviews. Section 4.3.1 presents the maintenance process in Canadian mines along with Key Performance Indicators (KPIs) and expert feedback and comments. Section 4.3.2 documents expectations and concerns for predictive maintenance, and Section 4.3.3 presents user interface (UI) guidelines for mining CMMS. Section 4.4 puts into perspective our findings with the current state of the art and Section 4.5 concludes the work.

4.2 Related Work

4.2.1 Maintenance Background

According to Introduction to Maintenance Engineering [8], “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” [8]. 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 [9]:

- *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 [9], [64]–[66]. 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 [9] is presented in Figure 4.1. Notice how, despite there being 6 steps, the 4 core steps are present.

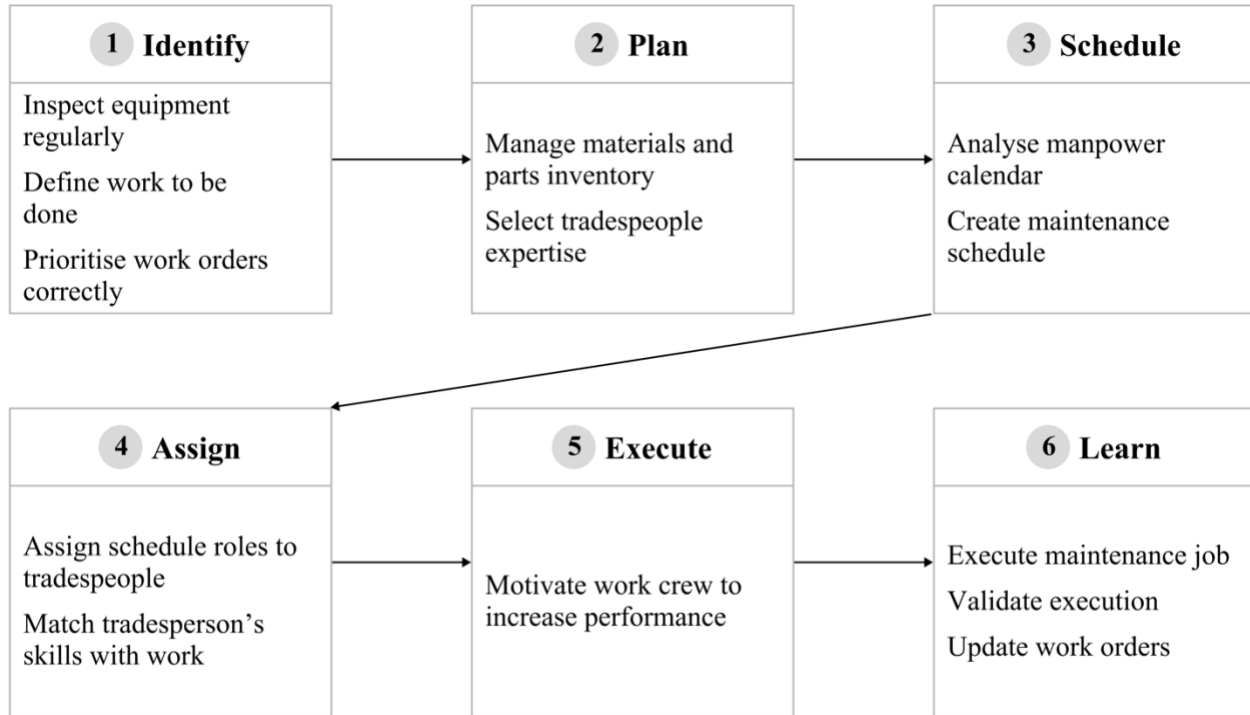


Figure 4.1 Six key steps in effective maintenance management according to [9].

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 [7], [25], [67].

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 [68]. This methodology was then found to improve maintenance planning and scheduling while reducing costs [68]. Later work from Lafontaine in 2006 queried 12 underground mines in Québec, Canada and highlighted the most used KPIs at the time [69]. Figure 4.2 summarizes her results.

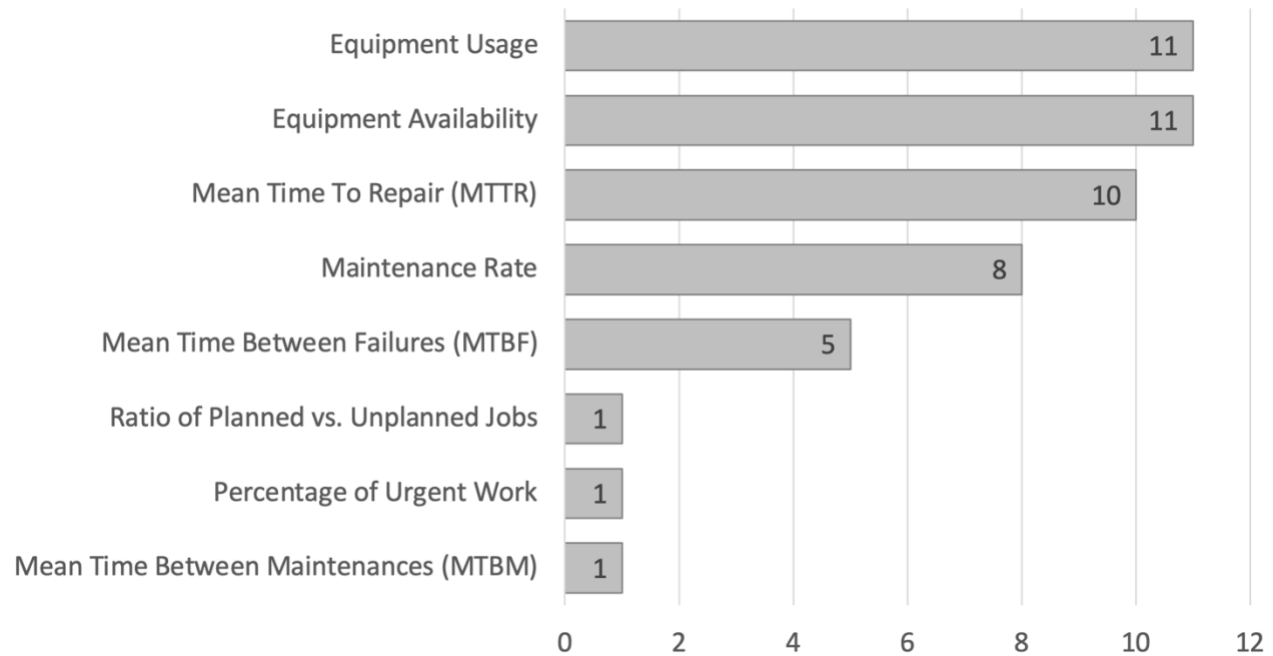


Figure 4.2 Mining KPIs by number of mines (out of 12) found by Lafontaine [69].

Figure 4.2 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

4.2.2 Preventive Maintenance

Preventive maintenance (PM) is a subject greatly discussed in industries such as manufacturing [70], [71], maritime [3] and mining [72]. In fact, when it comes to mechanical systems, PM is the

predominantly employed form of maintenance [3]. Concerning research, however, most PM planning studies focus on mathematical algorithms and simulations instead of targeting concrete problems in the industry [70]. 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 [70]. 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 [10]. His findings concerning the steps executed in the PM process at the LaRonde Complex respect the general steps identified in Section 4.2.1 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.

4.2.3 Predictive Maintenance

Predictive maintenance, oftentimes called condition-based maintenance, refers to the “intelligent monitoring of equipment to avoid future failures” [14]. 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 [14]. Predictive maintenance practices have been linked to cost reduction and increase of equipment reliability [73], [74] as well as a reduction of equipment environmental impacts [17]. Research in predictive maintenance is active in the manufacturing and process industry where fixed equipment is predominant. Paolanti et al. [14] proposed a predictive maintenance architecture for the process industry that offers a cloud-based solution obtaining a 95% accuracy in machine state prediction [14]. Similarly, Alves et al. [18] deployed a predictive maintenance system in a manufacturing plant which achieved a prediction accuracy of 99% despite a time range limitation of 5 min [18]. 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 [75]. 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 [76], Baker Hughes [77] and ABB [78]. Yet, industrial articles who present its integration in different mines do not actually document the implementation process [79]–[81]. Concerning research, most studies focus on theoretical literature reviews of predictive maintenance technologies (i.e., [82]), and potential issues and challenges linked to its adoption (i.e., [5]). At the same time, other studies propose architectural solutions that remain unimplemented as of the writing of this article (i.e., [83], [84]). 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 [85]. On actual implementation, technical guidelines have been proposed as early as 2002 [86], 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.

4.2.4 CMMS Usability

CMMS have existed for a long time and have, since the beginning of user-centered studies, been linked to usability issues [25]. One study highlighted the need for a user-oriented design in a world where automation gains increasingly more traction [87]. When visiting specific issues with CMMS design, Tretten and Ramin [27] offered an insight on actual personnel needs and suggestions for improvement [27]. Their results were obtained from interviews with expert personnel in the paper and pulp, mining and airplane manufacturing industries and are summarized in Figure 4.3.



Figure 4.3 Industry CMMS needs and recommendations based on [27].

Figure 4.3 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 [25]. 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.

4.2.5 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.

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 [88]), Lamaque (Gold, 4.9 tons/year [89]), Éléonore (Gold, 7.7 tons/year [90]), Westwood (Gold, 3.1 tons/year [91]) and Renard (Diamond, 1.6 million carats/year, [92]), one mining site in the Nunavut territory: Méliadine (Gold, 11.9 tons/year [93]), and one open-pit site in Ontario: Côté Gold (Gold, site in construction [94]).

4.2.6 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-2122-04D), and all participants signed an informed consent form.

4.2.7 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.

4.2.8 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.

4.2.9 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.

4.3 Results

We structured the main findings from our interviews into 6 categories (see Table 4.1) that will be described in detail in the following subsections.

Table 4.1 Categories extrapolated from the interviews.

Category	Definition
1. Maintenance Process (Section 4.3.1)	The maintenance management process and its challenges along with participants' opinions and comments.
2. Maintenance Planner (Section 4.3.1.3)	List of tasks and responsibilities of a maintenance planner.
3. KPIs (Section 4.3.1.6)	An exhaustive list of KPIs used to plan maintenance.
4. Tools (Section 4.3.1.7)	Overview of the suite of tools used to plan maintenance along with participants' feedback.

Table 4.1 Categories extrapolated from the interviews (Continued).

Category	Definition
5. Predictive maintenance Analytics (Section 4.3.2)	Requirements and issues to be considered for predictive maintenance Analytics according to participants.
6. Decision Support System (Section 4.3.3)	List of guidelines for a decision support system aimed at maintenance personnel.

The following subsections describe the 6 categories in detail. Section 4.3.1 gives an in-depth summary of the maintenance process currently implemented in East-Canadian mines and recorded best practices. Section 4.3.1 also includes findings on KPIs (Section 4.3.1.6), the role of the maintenance planner (Section 4.3.1.3) and the suite of tools used to manage maintenance (Section 4.3.1.7). We made this decision due to their close relationship to the maintenance process. Section 4.3.2 presents participants' thoughts and fears concerning predictive maintenance Analytics and Section 4.3.3 defines a series of guidelines for a decision support system used to assist experts in maintenance planning.

4.3.1 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 4.4). 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.

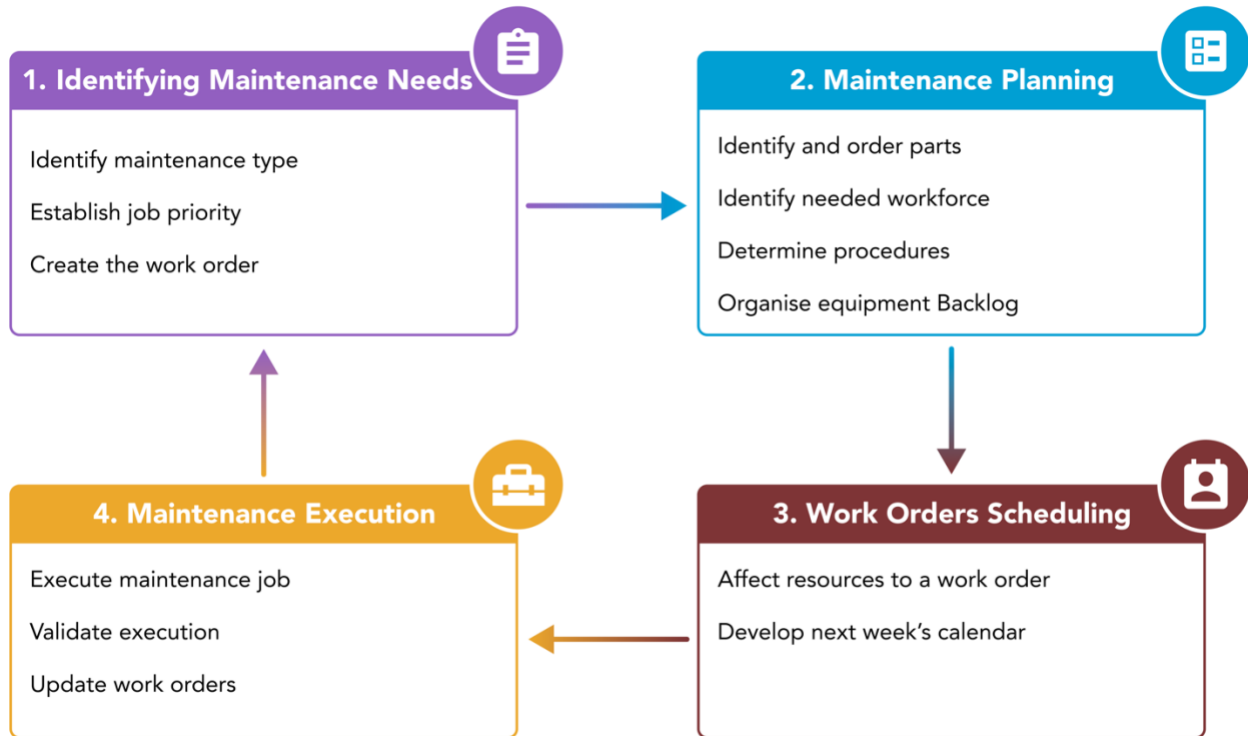


Figure 4.4 The maintenance process.

4.3.1.1 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 4.3.1.3.

- **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.

4.3.1.2 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 4.2 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 4.2 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 4.3 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 4.3 Work order life cycle states and description.

State	Description
<i>Registered</i>	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.
<i>Ready for Planning</i>	The work order was revised and approved. The required material and manpower have been established.
<i>Waiting for Parts</i>	Material to execute the work order was ordered but is not available yet.
<i>Ready for Scheduling</i>	The work order has been validated by personnel in charge and materials needed are available. The work order can be added to the calendar.
<i>Scheduled</i>	The work order is set to be executed on a specific date.
<i>Completed</i>	The work order was executed by a tradesman.
<i>Closed</i>	The finished work order was validated by the maintenance planner and can be safely considered as done.

4.3.1.3 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
- Re-evaluate 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.

4.3.1.4 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 4.5 presents the diagram of an underground garage belonging to one of the interviewed mines.

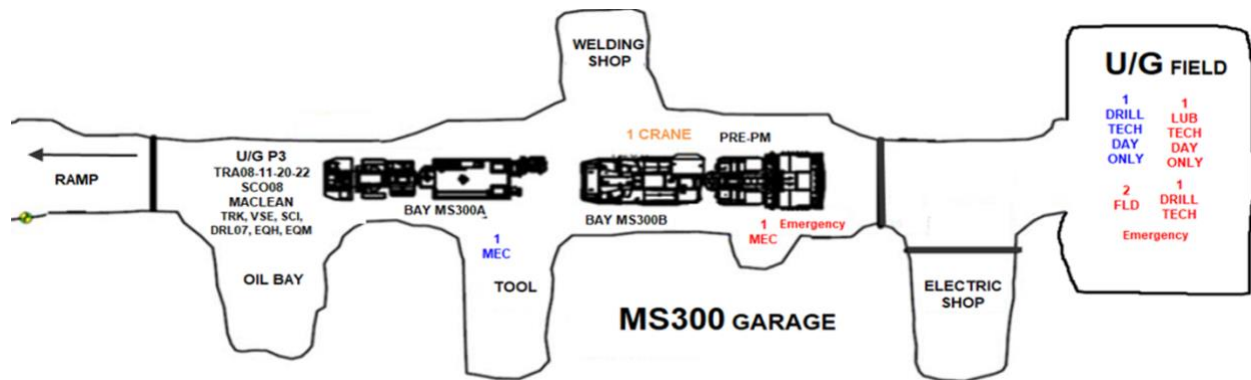


Figure 4.5 Underground garage diagram.

As can be seen by Figure 4.5, 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 ($12 \text{ h shifts} \times \text{day \& night shifts} \times 2 \text{ workers per shift} \times 7 \text{ days a week}$) 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.

4.3.1.5 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.

4.3.1.6 KPIs

Members of the maintenance team base their decisions on an array of KPIs which allow them to maximize maintenance efficiency. Table 4.4 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 4.6.

Table 4.4 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.

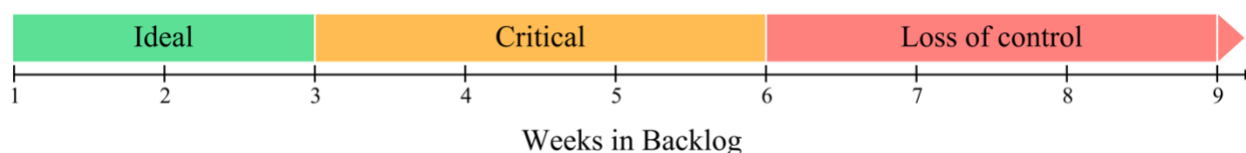


Figure 4.6 Mine operational status by Backlog value.

Figure 4.6 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.

4.3.1.7 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 4.7 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.

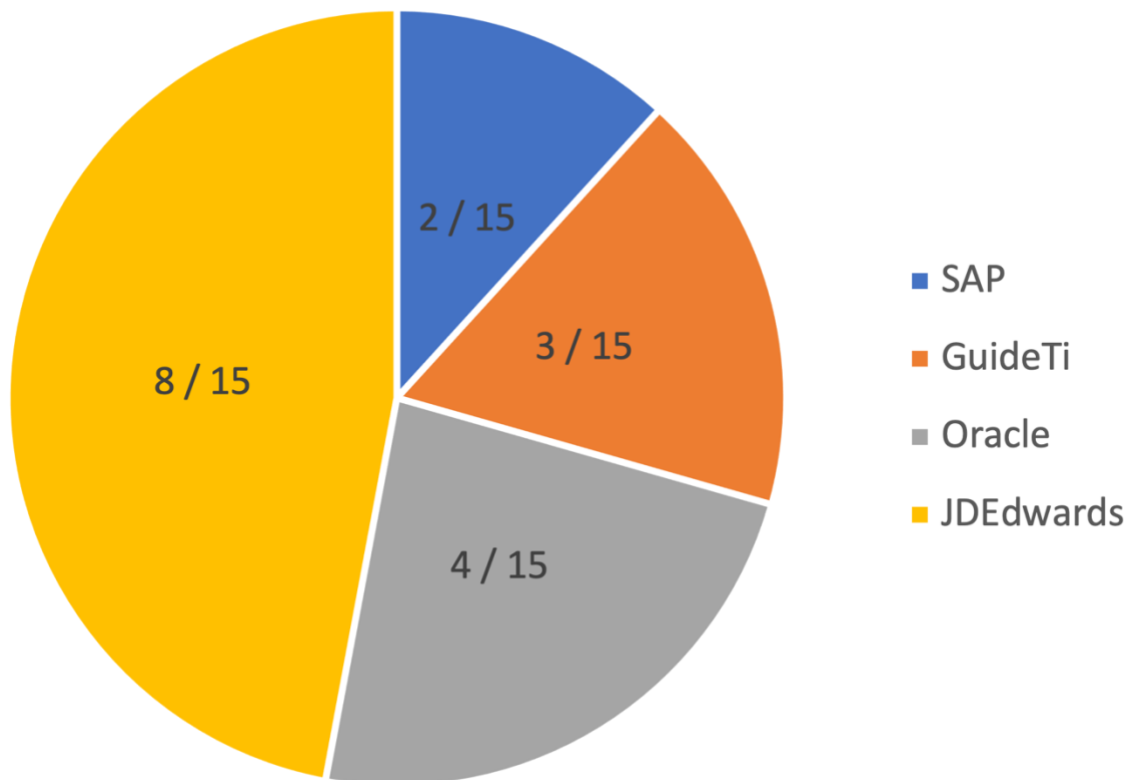


Figure 4.7 CMMS by number of mentions.

Screenshots of a work order as defined in JDEdwards and GuideTi are presented in Figures A.1 and A.2, respectively. Following, Table 4.5 records participants' most frequent feedback on the used CMMS.

Table 4.5 Participants' feedback on CMMS.

Positive	Negative
<i>JDEdwards</i>	
• 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
<i>GuideTi</i>	
• 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
<i>SAP</i>	
• Automatic work order creation • Offers many options	• Scheduling maintenance is very complicated • Constant importing / exporting of data
<i>Oracle</i>	
• 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 state 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 B.1.

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 4.3.1.4. 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.

4.3.1.8 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.

4.3.2 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 4.8.

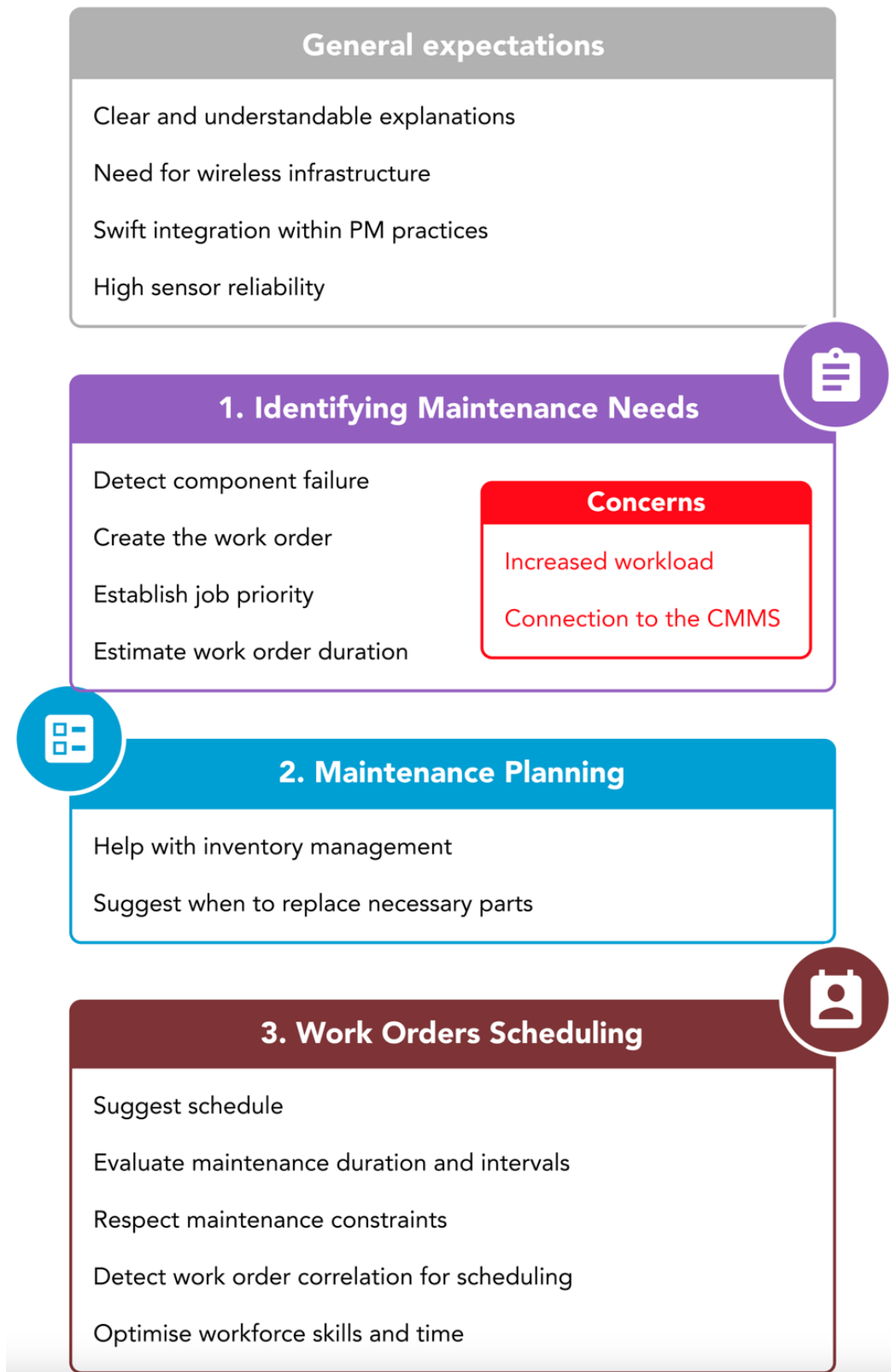


Figure 4.8 Predictive maintenance opportunities and concerns.

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 Analytics' solutions 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 result 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 Analytics' solutions 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 optimize mechanics' 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.

4.3.3 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 4.6 shows the UI requirements and guidelines.

Table 4.6 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

Table 4.6 Requirements and guidelines for a decision support system (Continued).

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 4.3.1.6, 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.

4.4 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 non-functional 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 [70] 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 [10], 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 [9], 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 [66] study where it was stipulated that the transfer of best practices can hinder creativity [66]. 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 [9], [10] and are used to quantify goals and objectives at every step of the process [69], [95]. Most of the maintenance KPIs collected in this study overlapped with best practices in the mining [10], [69] and industrial sectors [9], [95]. 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 [15]), 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 ([79], [80]) that are hardly usable by maintenance personnel. Predictive maintenance AI usability is hindered by the lack of explanation [96]. 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 [97]. 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 tools and interfaces offer 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 [27]. 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 [25], [67]. 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 Ramin [27] where system designers develop a system based on their conception on how maintenance is conducted as opposed to what expert personnel truly needs [27].

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 [98]. In manufacturing, XAI applications are numerous and are linked to an increase in trust [43]. 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.

4.5 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.

CHAPITRE 5 ARTICLE 2: DEVELOPMENT AND USABILITY EVALUATION OF VULCANH, A CMMS PROTOTYPE FOR PREVENTIVE AND PREDICTIVE MAINTENANCE OF MOBILE MINING EQUIPMENT

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Structured Abstract

Purpose This paper details the design, development and evaluation of VulcanH, a computerized maintenance management system (CMMS) specialized in preventive maintenance (PM) and predictive maintenance (PdM) management for underground mobile mining equipment. At the same time, it aims to expand knowledge on trust in automation (TiA) for PdM as well as contribute to literature on explainability requirements of a PdM-capable artificial intelligence (AI).

Design/methodology/approach The paper adopted an empirical approach through the execution of user tests with 9 maintenance experts from 5 East-Canadian mines. UEQ+ and RIS were implemented to evaluate usability and TiA, respectively.

Findings The paper found that the usability and efficiency of VulcanH were satisfactory for expert users and encouraged the gradual transition from PM to PdM practices. Quantitative and qualitative results documented participants' willingness to rely on PdM predictions as long as suitable explanations are provided. Graphical explanations covering the full spectrum of the derived data were preferred.

Research limitations/implications Due to the prototypical nature of VulcanH, relevant aspects of maintenance planning, such as workforce and parts management, were not considered. Researchers are encouraged to include these notions into the evaluation of future CMMS proposals.

Practical implications The paper suggests a harmonious integration of both preventive and predictive maintenance practices in the mining industry. Also, this study may guide future research in PdM to select an analytical algorithm capable of supplying adequate and causal justifications for informed decision making.

Originality/value This study fulfills an identified need to adopt a user-centered approach in the development of CMMSs in the mining industry. Hence, both researchers and industry stakeholders may benefit from the findings.

Keywords Preventive maintenance, Predictive maintenance, Computerized maintenance management system, Usability, Trust in automation, Explainability

Paper type Research paper

5.1 Introduction

Initially introduced in the 1960s, Computerized Maintenance Management Systems (CMMSs) offered a punch-card-based approach to digitalize routine maintenance tasks. They were, however, limited to the large and profitable enterprises that could afford them. Advancements in technology throughout the subsequent decades increased CMMSs' affordability, functional usefulness, and, incidentally, their popularity. CMMSs proved to be an indispensable tool in industries such as manufacturing, aeronautics, power, and mining. In the 2000s, CMMSs experienced another evolution, engendered by the Internet's increasing availability. By then, these systems supported multimedia assets and Web-based communication, and offered an overall improved set of functionalities and computational capabilities [8], [20]–[23], [99]. However, CMMSs have shown to be poor decision-support systems (DSSs) for equipment maintenance because of their “black-box” nature, complexity and general lack of user-friendliness [24]. In fact, the most commonly cited drawback of CMMSs are their “Black Hole” nature [24] meaning that, similarly to black holes, they ingest data at high rates without returning information on their decision-support capabilities. Even to this day, their usability constitutes a major hindrance to their successful integration in the maintenance workflow [25]. As a result, CMMS are mostly used as databases to store equipment and maintenance information, and external solutions are implemented for data analysis and decision making [24], [100], [101]. In the mining industry, the addition of sensors on underground equipment and the installation of wireless infrastructure into the mine has introduced Internet-of-Things (IoT) to the industry, which drives the approach of predictive maintenance (PdM) for mobile mining equipment [101]. However, available CMMSs are not equipped to handle such practices [102] and a transition to human-oriented CMMS development and design is direly needed [101].

In this paper, we developed and tested VulcanH, a new type of CMMS built primarily as a decision support system (DSS) specialized in preventive and predictive maintenance management for underground mobile mining equipment. The main contributions of our study were to evaluate the usability of the proposed CMMS prototype and to analyze the level of explainability in a PdM-capable artificial intelligence (AI).

The rest of this article is structured as follows. Section 5.2 reviews background knowledge on maintenance and CMMSs, usability and trust in automation. Section 5.3.1 presents the developed CMMS prototype while section 5.3.2 details the methodology used to conduct user tests and section 5.4 the main results found. Section 5.5 puts our findings into perspective with the current state of the art and Section 5.6 concludes the work.

5.2 Background and Related Work

5.2.1 Maintenance

Maintenance constitutes the combination of a diverse set of actions aimed at restoring or maintaining an equipment into a state in which it may perform its required function [8]. Even though many types of maintenance exist [9], preventive maintenance (PM) and predictive maintenance (PdM) are the most relevant for this study. PM relies on a maintenance plan, where intervals for maintenance scheduling and execution are detailed based on predetermined equipment-related, time-related or cost-related factors [9], [70]. During maintenance execution, components are replaced or repaired regardless of their condition. On the other hand, PdM, also known as condition-based maintenance or statistical maintenance, comprises jobs dependent on equipment status [9], [16]. PdM relies on wireless sensors on the equipment and an IoT infrastructure to provide consistent streams of data. Then, algorithms are used to analyze the data to predict when the equipment may require servicing. The use of machine learning or artificial intelligence (AI) to achieve this goal is most common [96] and PdM practices have already been associated with a reduction of maintenance-related costs [66], [85].

PM is the predominantly implemented type of maintenance for mechanical systems and has ensured the implementation of a constant workflow in many industries [3], [71]. In the mining industry, maintenance-related costs constitute between 30% and 50% of a company's expenditures [56], [57], [103]. Thus, an efficient maintenance process is crucial. Maintenance literature identifies 4 key steps in a successful maintenance implementation (see Figure 5.1).

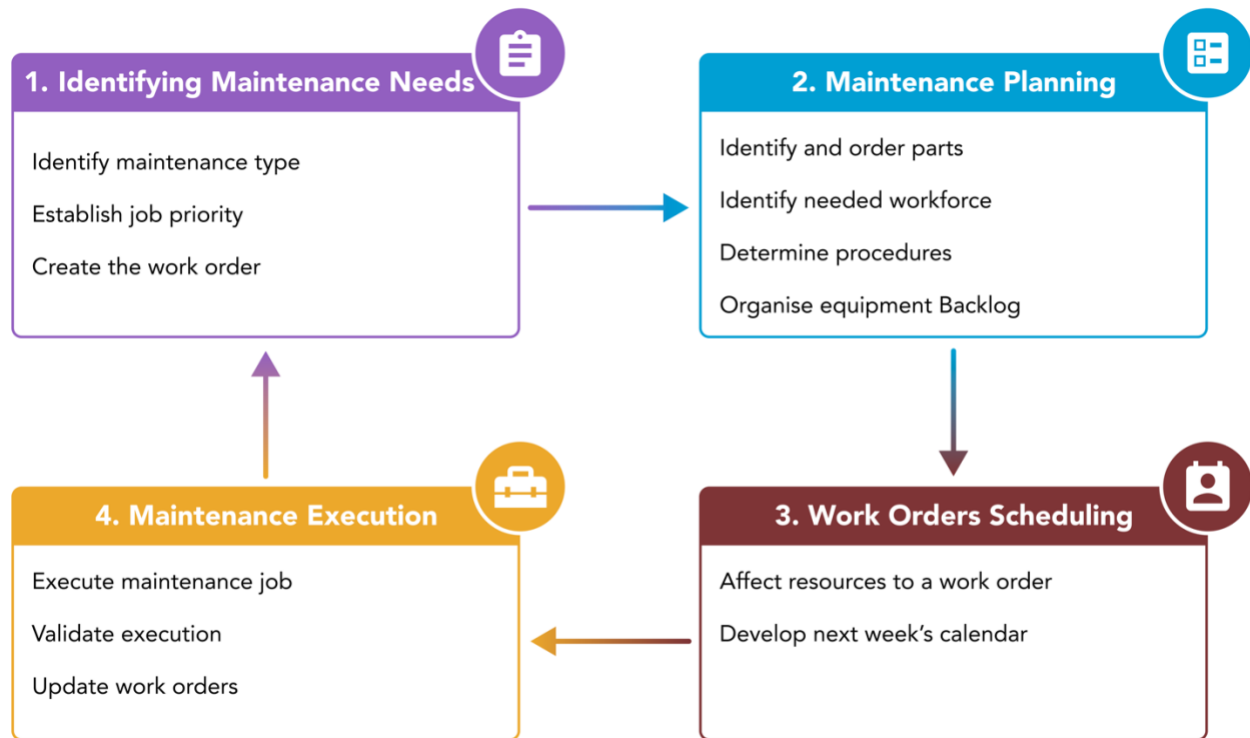


Figure 5.1 Key steps of the maintenance process [101].

The first step of the process is the identification of maintenance needs. This is the process by which members of the workforce pinpoint servicing jobs in need to be executed on an equipment and catalog them in a document known as a “Work order”. Work orders are the main transaction document in a maintenance process and contain useful information pertaining to the job, such as its description, its priority, the targeted equipment and the expected date of execution. A work order’s priority is a number critical to the establishment of the work order’s life cycle. Table 5.1 highlights the most common priorities and their meaning.

Table 5.1 Common work order priorities, adapted from [101].

<i>Code</i>	P1	P2	P3
<i>Description</i>	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.

From Table 5.1, the most important priority for maintenance planning is P3 due to the fact that P1 and P2 represent unplanned jobs. The second step of the maintenance process is the planning of maintenance. A maintenance planner is mainly responsible for validating the active work orders, ordering and managing required parts and establishing the workforce needed to complete the maintenance job. In many cases, the planner is also responsible for the third step of the process: Maintenance Scheduling. During the scheduling phase, necessary work orders are identified by maintenance stakeholders and the equipment in need of servicing is assigned to a garage's bay. Assignment of individual tradesmen is generally not a concern of the planner but is, instead, done by the general supervisor on-site. For an in-depth overview of the maintenance management process in East-Canadian mines, see [101].

Once the job is executed, the tracking of maintenance Key Performance Indicators (KPIs) is an essential step to ensure continuous improvement of the maintenance process. Figure 5.2 showcases some commonly used KPIs along with their definition. Lafontaine [69] queried 12 mines and compiled a list of maintenance KPIs, most of which are still relevant to this day.

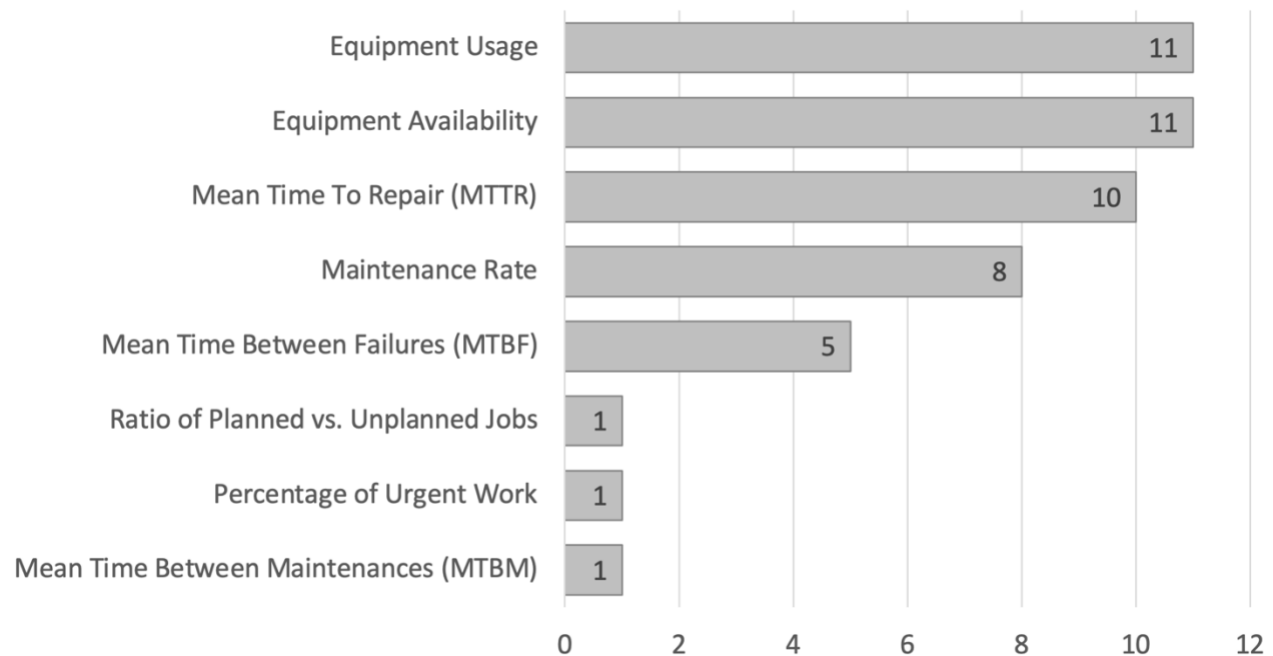


Figure 5.2 Common maintenance KPIs by number of mines (out of 12) [101].

With the digitalization of mining operations, work orders, calendars, maintenance information, KPIs, and more are stored in specialized software known as a CMMS. A CMMS is a collection of integrated programs aimed at assisting with maintenance management activities [8]. While there is

no explicit standard on CMMS functional requirements, maintenance literature commonly identifies their most-expected features [8], [9]:

- Manage the company's assets
- Provide a level of automation for jobs and inventory management
- Manage human resources
- Manage maintenance transaction data such as work orders
- Handle accounting and finance
- Control and schedule PM routines
- Manage data for process improvement (reliability analysis)
- Integrate with other systems

Of the listed features, however, only those related to data management are generally implemented by most CMMS providers leaving control for scheduling and maintenance decision support to the buyer [24]. Hence, CMMSs' main purpose being that of a database. A concrete example can be studied from an underground mine in Québec, Canada, where 3 custom software solutions were developed, besides the CMMS, to satisfy their maintenance needs [101]. Different in-house tools were needed to collect equipment data for reliability analysis, to generate reports from real-time equipment data streams, and to create and update the maintenance schedule. The creation of custom scripts to fulfill specific maintenance needs serves as an indicator of the disconnect between maintenance service providers and the users of these systems [24]. In fact, in an attempt to benchmark CMMS development, [102] noticed how CMMSs were not able to adequately support both PM and PdM. Therefore, a human-oriented approach is greatly needed to optimize CMMSs' usage for current PM practices and future PdM approaches. Usability evaluation constitutes a crucial step in the application of a human-oriented approach.

5.2.2 Usability Evaluation

Usability is defined in ISO 9241-210 as the “extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use” [31]. Multiple means to evaluate subjective usability have been proposed in the past. The most popular methods include the System Usability Scale (SUS) [33], [34], Computer System Usability Questionnaire (CSUQ) [35], Usability Metric for User Experience (UMUX) and its variants [36], [37], and the User Experience Questionnaire (UEQ) [38]. These standard evaluation methods evaluate usability by leveraging a predetermined list of

scales and propose a standardized result which allows for a facilitated analysis and comparison with existing literature. However, such methods are not specific to a particular research context and may not be suitable for the objectives of a particular study [39]. To solve this problem, [39] have developed a modular extension of UEQ, known as UEQ+. Similar to UEQ, each UEQ+ scale contains four Likert items that analyze the user's perception of the scale's prominence in the tested product. This method allows researchers to construct a custom questionnaire that concentrates on aspects that users consider important without sacrificing clarity or concision. A key performance indicator (KPI) is calculated to obtain a score for the final usability of the product and to display users' overall satisfaction. Unfortunately, due to UEQ+'s novelty and modular design, no benchmarks have been established at the time of writing. Nevertheless, UEQ+'s authors stipulate that it may be possible to develop KPI benchmarks that are independent of the selected scales [39]. When it comes to complex systems, ease-of-use and usefulness have been studied more extensively [104] but are incomplete when conducting a proper and detailed evaluation of these systems [105]. Adequacy, adaptability and core-task orientedness were highlighted as the basis of the usability evaluation technique proposed by [106]. Studies that analyzed the usability of complex systems often used SUS [18], [107], [108] or implemented a custom questionnaire [109]. However, their usability evaluations are limited to the overall SUS score (or the respective custom score) and its benchmark interpretation. We believe that the use of UEQ+ will allow for a more in-depth analysis of usability results and that it is the best fit due to the comparative nature of our study [39].

CMMS usability issues are well documented in research. Tretten and Ramin interviewed 10 industry experts to document CMMS usability issues and compiled a list of 7 pitfalls of CMMSs: hard-to-access documentation; incompatibility with other systems; lack of input automation; unintuitive User Interface (UI); lack of guidance; poor decision support; and high complexity [27]. Interestingly, even though the interviewed experts worked in different industries and used different CMMSs, the usability issues mentioned were similar amongst the respondents. Similarly, [110] surveyed 133 maintenance personnel in the petrochemical industry and recorded a feeling of dissatisfaction in regards to the CMMS used. Results from [25], [67], [111], [112] further affirm the unacceptable level of usability in current CMMSs. CMMSs are regarded among operators as systems that rarely provide value to the company and, in some cases, even hinder efficiency and productivity [7], [26], [113].

5.2.3 Trust in Automation

Practices in PdM require that the expert user relies on an automated system. Whether it be in the selection of an automatically generated schedule or in the review of automatically generated and prioritized work orders, automation plays an essential role in PdM. However, most CMMSSs lack transparency when it comes to exploring and understanding the system's decisions and are most often regarded as "black boxes" [24]. Wickens expresses how the opaque or "black-box" nature of a complex automated system may reduce the operator's ability to understand its decisions [42]. This lack of understanding may lead to disuse, misuse or even abuse of the system. In a similar fashion, [114] indicated that AI recommendations should be accompanied by the logic from which they were derived. The field of eXplainable AI (XAI) has also made a point of targeting expert users. Bayer *et al.* showed how expert chess players would rely more in the system when explanations were provided [97]. Similarly, [44] documented medical doctors' higher trust in medical applications that offered more transparent AI suggestions. The paper stipulates that XAI may facilitate implementation of AI systems in medical-related contexts. In later studies, the same author introduced and explored the concept of "causability" where it is proposed that medical-related AI should understand the current context and offer actionable and causal explanations [47], [48]. Such causal explanations are more closely related to real human-to-human or, more specifically, expert-to-expert communication and may help shift the explainability paradigm from system-oriented to human-oriented [47], [115]. All in all, explanations have proven to be necessary when interacting with complex systems and constitute a means of increasing trust and reliance on automation.

Trust in automation (TiA) and its evaluation are highly active subjects in Human-Machine Interaction (HMI) research. While the exact model for trust is still being debated by researchers, the TiA community has generally adopted the model proposed by Mayer *et al.* in 1995 ([51]) [52]. This model makes a point of differentiating between factors that cause trust, trust itself, and the consequences of trust which need to be measured collectively [51]. To enlighten researchers on means to measure trust, a recent study conducted a comprehensive narrative review and found that 3 types of trust-related measures were used: Self-Report, Behavioral and Physiological [53]. Self-Report measures seemed to be the most popular method with custom scales being the most frequently used means to analyze TiA. However, it was found that custom scales rarely accounted for trust model theory and, instead, treated trust as a single global construct [53].

Building on self-report measures, [54] validated the Reliance Intentions Scale (RIS), a 10-item scale targeting the user's intention to rely on an automated system to perform its tasks. This scale has been consistently used by researchers to evaluate TiA for unmanned ground vehicles [116], security checkpoint robots [117], and other robotic systems (i.e. [118]–[120]). In fact, results from [55] showed that RIS is an effective and reliable way to evaluate TiA in robotic systems after comparison with other popular methods like Trust-Perception-Scale for Human-Robot Interaction (TPS-HRI) [121] and the Multidimensional Measure of Trust (MDMT) [122]. As per its usage in complex software systems, however, this scale has yet to be applied to maintenance solutions such as CMMS and to expert participants, due to most papers having tested the scale on students (i.e. [116]–[119]).

5.2.4 Synthesis and Research Objectives

Both scholarly and industrial sources indicate that PdM for mobile mining equipment is just around the corner. However, few CMMSs offer support for PdM integration and are commonly associated with an unsatisfactory user experience. Our literature review highlighted the pressing need for user-centered CMMSs whose primary concern is usability.

The nearing of PdM also implies an increased reliance on automation. Notions of TiA are therefore critical to the correct integration of PdM in the mining industry but, at the time of writing, few papers are available on the subject. A research opportunity is therefore that of evaluating TiA in CMMSs. On this topic, the literature review has shown how the RIS may be a reliable method of evaluating TiA.

Closely coupled with trust is explainability. Our review has pointed out the link between causal explanations and increases in trust but has offered no insights on the types of explanations necessary for expert CMMS users. Hence, an opportunity arises in the study of PdM algorithms explainability and the level of detail required.

The main objective of our study was to evaluate the usability of VulcanH, a CMMS capable of assisting the user in maintenance planning and scheduling for both PM and PdM practices. Concurrently, we analyzed the impact of PdM on the maintenance process where we hypothesized that PdM integration would not lead to a significant disruption of current PM practices. We also focused on the evaluation of experts' TiA where we tested RIS's applicability to expert users' trust towards CMMSs, and the analysis of the level of details expected in PdM explanations.

5.3 Method

The method is separated in two sections. First, we present VulcanH and its features for maintenance planning and scheduling. Second, we present the test plan for its usability evaluation.

5.3.1 VulcanH¹

We implemented the prototype as a Web Application operating on a browser. Figure 5.3 shows our architecture's UML diagram. User requirements constituting the basis of our design choices are identified in Table C.1 of Appendix C.

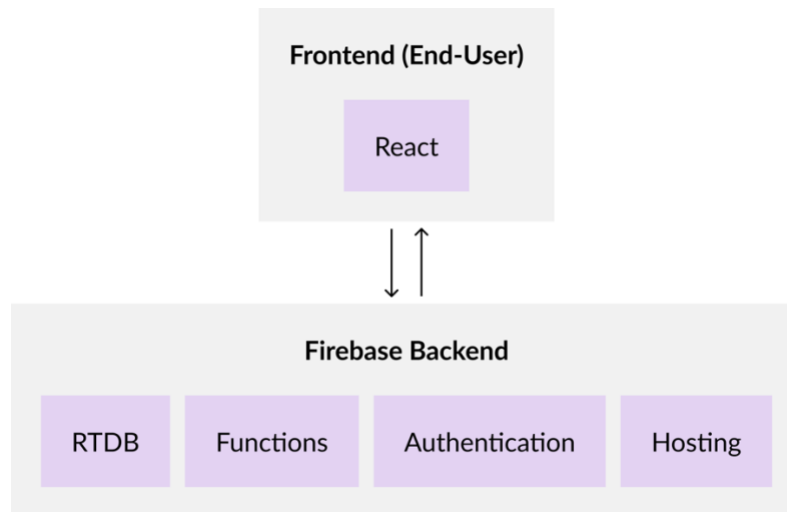


Figure 5.3 VulcanH Architecture Diagram.

We divided our solution into two main views (one for planning and one for scheduling) each presenting contextual panels offering additional actions and information. Figure 5.4 shows the planning dashboard that offers an overview of the current state of the fleet. It lists all the mobile equipment of the mine, grouped by categories. Each equipment is presented as a card with its identification number, status (available, broken, or in maintenance), remaining time before next planned maintenance, and whether the equipment is marked for maintenance. The right panel presents the current week's KPIs for fleet management, garage occupation and planning evaluation, with the acceptable range for each value. The left panel offers organizational actions on the equipment list, such as searching and filtering.

¹ We named our application VulcanH in tribute to Vulcan, the Roman god of fire and inventor of smithing and metal working, and his Greek equivalent Hephaestus.

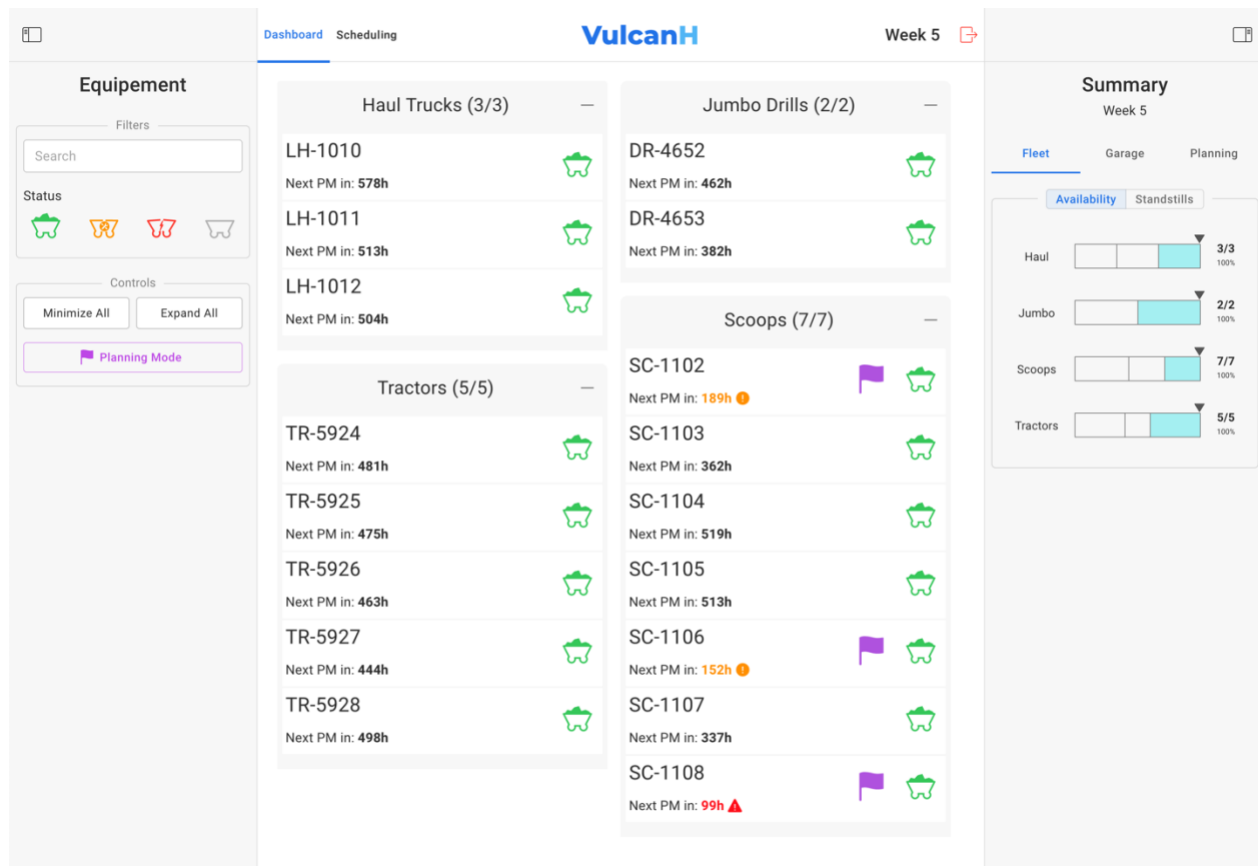


Figure 5.4 Dashboard view.

Additional information is presented by clicking on the equipment card. This opens the equipment sheet (Figure 5.5), where users can evaluate the state of the equipment, obtain information on previous maintenance jobs or indications for future maintenance jobs, and can assess the remaining maintenance workload by analyzing the work orders table. The table is split between work orders for the next preventive maintenance and the backlog.

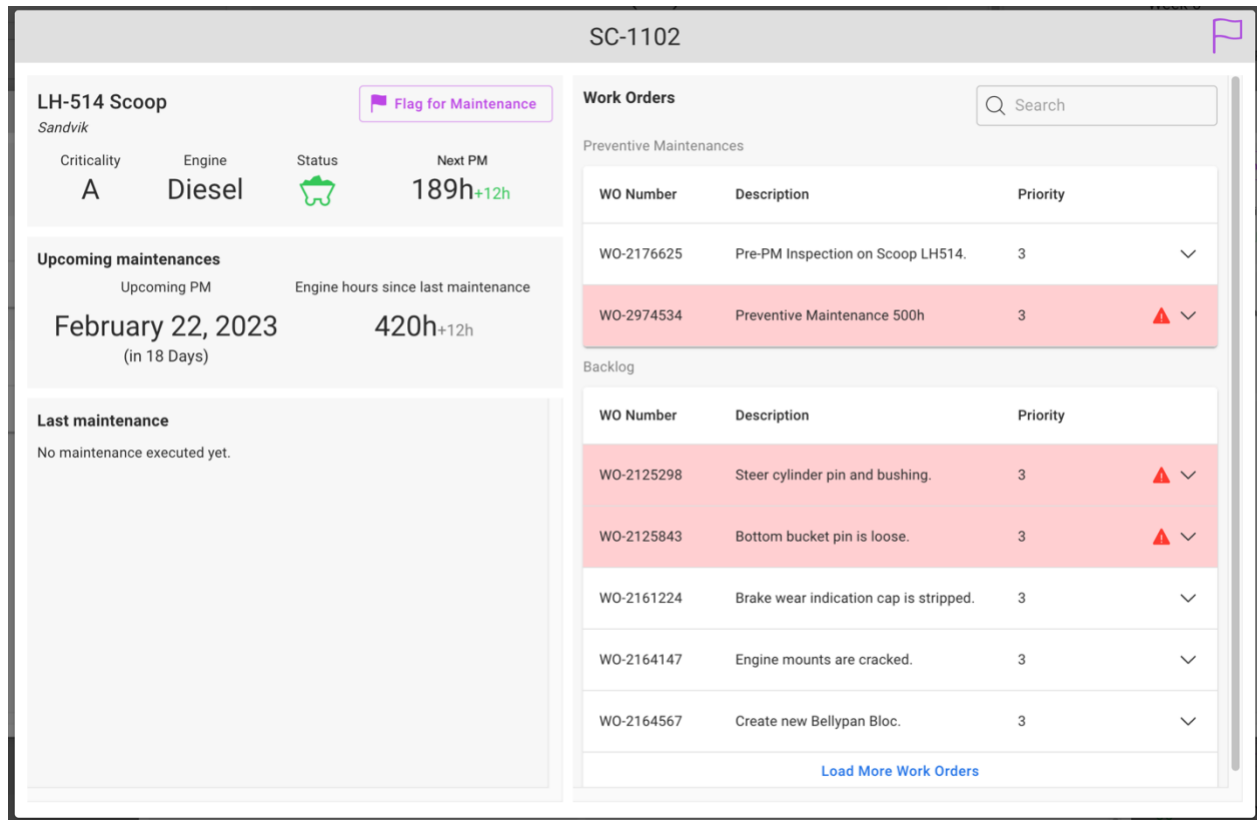


Figure 5.5 Equipment sheet.

Work orders can be prioritized by clicking on the prioritization icon and selecting the planning priority desired (Figure 5.6). The planning priority constitutes a sub-priority which differs from a work order's actual priority. Whereas a work order's priority determines the lifecycle of the work order, its planning priority indicates when a work order should be scheduled. Some mines have implemented their own work order sub-priorities, for example by labeling a work order P3.1 to indicate a priority 3 work order with level 1 sub-priority. In the prototype, users have access to three planning priority levels:

- Level 0: No planning priority.
- Level 1: To be scheduled for next week.
- Level 2: To be scheduled in 2 to 3 weeks.

This reflects the common practices observed in Canadian Mines [101].

Work Orders

Preventive Maintenances

WO Number	Description	Priority
WO-2176625	Pre-PM Inspection on Scoop LH514.	3
WO-2974534	Preventive Maintenance 500h	3

Backlog

WO Number	Description	Priority
WO-2125298	Steer cylinder pin and bushing.	3

Priority Selection:

- No selection: 0
- In 1 week: 1
- In 2-3 weeks: 2

Figure 5.6 Work order prioritization.

A user can flag an equipment for maintenance by clicking on the respective button or on the purple flag on the sheet's header (Figure 5.7).

LH-514 Scoop

Sandvik

Flag for Maintenance

Criticality: **A**

Engine: **Diesel**

Status:

Next PM: **189h+12h**

Figure 5.7 Maintenance flagging.

Figure 5.8 shows the scheduling calendar. From there, the user can view a maintenance's work orders by clicking on the equipment header's arrow (left panel) or change an equipment's bay by dragging the calendar's entry header on the wanted bay (right panel). The same action is used to remove an equipment from the calendar if the equipment is dragged towards the initial left panel. Additionally, the user can modify the maintenance's start time by dragging horizontally on the calendar entry.

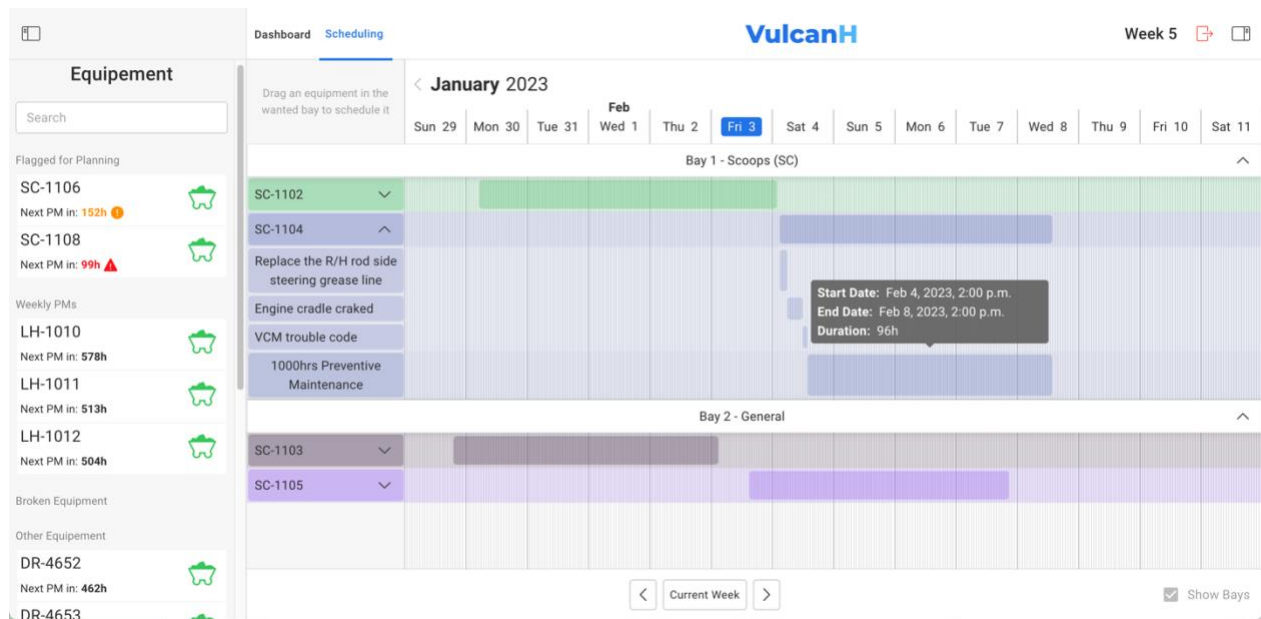


Figure 5.8 Scheduling view.

All equipment is shown on the left panel which is divided into 4 sections:

1. Equipment flagged for maintenance planning
2. Equipment whose preventive maintenance is expected for next week
3. Equipment with “DOWN” status
4. All other equipment

Dragging an equipment on a bay inside the calendar opens the work orders selection screen (Figure 5.9).

Dashboard
Scheduling
Week 5

Equipment

Flagged for Planning

SC-1106
 Next PM in: 152h ⚠️

SC-1108
 Next PM in: 99h ⚠️

Weekly PMs

LH-1010
 Next PM in: 578h

LH-1011
 Next PM in: 513h

LH-1012
 Next PM in: 504h

Broken Equipment

Other Equipment

DR-4652
 Next PM in: 462h

DR-4653
 Next PM in: 382h

SC-1107
 Next PM in: 337h

TR-5924
 Next PM in: 481h

TR-5925
 Next PM in: 475h

TR-5926
 Next PM in: 463h

TR-5927
 Next PM in: 444h

TR-5928
 Next PM in: 498h

Bay
Bay 1

Word Order Selection

SC-1108

🔍

Preventive Maintenances

	WO Number	Description	Priority	
☒	WO-0488225	2000hrs preventive maintenance	3	⚠️ ▼

Backlog

	WO Number	Description	Priority	
☒	WO-1046615	T/S ride control not working	3	⚠️ ▼
☒	WO-1798452	Replace wiper blades and nozzle	3	⚠️ ▲

Detailed Description

Replace wiper blades and nozzle

Date Added

2022-08-07

Comment

No comment

Workforce Hours

Mechanic 2

Total Estimated Time

2

☐	WO-2344911	Cradle craked	3	▼
☐	WO-2934962	T/S bucket counter NF	3	▼
☒	WO-3338148	Replace tilt cylinder guard pin	3	▼

Selected work orders: 4

Total maintenance time: 115h

Choose Later

Cancel

Schedule

Figure 5.9 Work order selection.

Users can select work orders to add to the schedule and information on total stoppage time is presented on the bottom left corner of the screen. Clicking on the blue “Schedule” button will add the maintenance to the calendar.

A list of maintenance KPIs is accessible from the right informational panel. The first tab (Figure 5.10.a) presents equipment availability compared to weekly operational objectives. Also presented are types and durations of active stoppages (Figure 5.10.b), garage information (Figure 5.10.c) and a graphical representation of the *Schedule Completion* KPI (Figure 5.10.d).



Figure 5.10 Maintenance KPIs. a) Fleet availability and objectives. b) Equipment stoppages information. c) Bay occupation and workforce availability. d) *Schedule Completion* KPI for current and past weeks.

A variant of the prototype was created to simulate the introduction of PdM. Table 5.2 summarizes the changes introduced in the variant.

Table 5.2 VulcanH changes due to the addition of PdM.

Change	Description
Estimated residual lifetime of equipment	Instead of displaying the upcoming preventive maintenance date, PdM will predict the number of engine-hours remaining before the equipment will need to be serviced. A confidence score is given to indicate the prediction's reliability.
Equipment maintenance suggestions	Actionable suggestions in the left panel to allow for quick flagging of an equipment according to the AI predictions.
Work order suggestions	Whereas, in PM, the work orders table organizes work orders into preventive and Backlog, the PdM variant will spotlight critical work orders from the Backlog. A complete shift from preventive to predictive implies the removal of preventive maintenance work orders. Thus, the variant will not show preventive work orders.
Schedule optimization	From the interactive calendar, users may choose to automatically generate a schedule. Once this option is selected, the user enters hard constraints such as mandatory garage exit/entry times for specific equipment and clicks on "Generate". In our test, the scheduler outputted a predetermined schedule that overwrote the calendar for the current week.

5.3.2 Usability Evaluation

5.3.2.1 Philosophy

Our methodology is based on ISO 9241-210:2019 [31]. The standard describes four steps in a successful implementation of human-centered design. These steps are the specification of the usage context, the designation of user requirements, the production of design solutions and the evaluation of said solutions. The first two steps were completed in [101]. In this study, we developed VulcanH as a working prototype and evaluated its usability with expert maintenance personnel from 5 mining sites across East-Canada : LaRonde Complex (Gold, 11.9 tons [88]), Westwood (Gold, 1.1 tons [123]) and Renard (Diamond, 1.6 million carats/year [92]), one mining site in the Nunavut province: Méliadine (Gold, 12.2 tons [93]), and one open-pit site in Ontario: Côté Gold (Gold, site in construction [94]).

5.3.2.2 Participants

9 participants (7 male, 2 female) took part in this study. Participants' ages were 39 years old on average, with 30 being the youngest and 50 the oldest. Most participants had more than 13 years of experience in the mining sector and their expertise was distributed as follows: 5 General Supervisors (or any supervisor role associated with maintenance), 1 Maintenance Planner, 1 Maintenance Assistant Specialist, and 2 Maintenance Data Managers. The study received the approval of Polytechnique Montréal Ethics Research Board (CER-2223-32-D) and all participants verbally agreed to an informed consent form prior to the test.

5.3.2.3 Materials

User tests were conducted remotely via Zoom or MS Teams, depending on participants' preferences. The tests were recorded to facilitate notetaking throughout the test.

5.3.2.4 Procedure

We conducted VulcanH user tests with and without PdM. The version without PdM constituted the baseline while the version with PdM was considered as the dependent variable. The PdM analytics showcased for the dependent variable were hard-coded by leveraging a non-real-time Wizard of Oz method [28] and present an automation system whose suggestions are reliable. The test was divided into 4 sections. Section 1 was the demographics questionnaire asking 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.

Section 2 was the execution of two scenarios: PM or PdM planning. Participants were instructed that they needed to schedule next week's maintenance for the loaders' fleet from a fictitious mine composed of 17 pieces of equipment, as shown in Table 5.3.

Table 5.3 Equipment count by equipment family.

	Equipment Count
Loaders (Scoops)	7
Tractors	5
Haul Trucks	3
Jumbo Drills	2

In the PM scenario, participants used VulcanH for PM planning. In this scenario, participants had to manually identify the equipment for maintenance, select its relevant work orders, and schedule the maintenance on the calendar view. It established the baseline performance for the prototype as PM is the maintenance type most implemented in mining. In the PdM scenario, participants used VulcanH for predictive maintenance planning. In this case, the predictive algorithm automatically selected the equipment for maintenance and highlighted the work orders that should be done in priority. Users could review the selection and modify it, if needed. Then, the scheduler would optimize the maintenance sequence in the calendar view. Once again, users could adjust the schedule if needed.

In both scenarios, participants had a familiarization stage to introduce the different features of the CMMS. Then, they were asked to execute the same 3 tasks:

- Identify 3 Scoops for maintenance in the next week
- Prioritize 4-5 work orders for each equipment identified for maintenance
- Schedule the equipment into the maintenance calendar

To prevent a learning effect, the order of presentation of the PM and PdM scenarios was inverted between participants. Work orders were shuffled between scenarios such that a user would be exposed to a different set of work orders every time.

Once the execution was completed, the participant filled 2 questionnaires. First, was the UEQ+ for which we selected the following dimensions: Efficiency, Perspicuity (ease-of-use),

Trustworthiness of Content and Usefulness. Second, was a questionnaire adapted from the RIS [54] to fit the needs of our study. The adapted RIS consisted of 10 questions evaluating participant's tendency to rely on the system. The questionnaire is displayed in Appendix D.

Section 3 of the test was the ranking of different levels of explanation of the PdM algorithm. Figure 5.11 shows the AI explanation levels numbered from 1 to 4 which the user was asked to rank by preference. Level 1 showed the estimated remaining lifetime of the equipment in engine-hour. Level 2 added the confidence interval of the remaining lifetime prediction. Level 3 gave a plain English description of the remaining lifetime and confidence interval. Level 4 presented the normal distribution of the equipment's residual lifetime and a timeline for the expected maintenance scheduling. In the prototype, we implemented level 2 for the PdM scenario. However, for the ranking, we hypothesized that level 3 would be the most popular among our participants due to its concise, actionable instructions and easily understandable presentation.

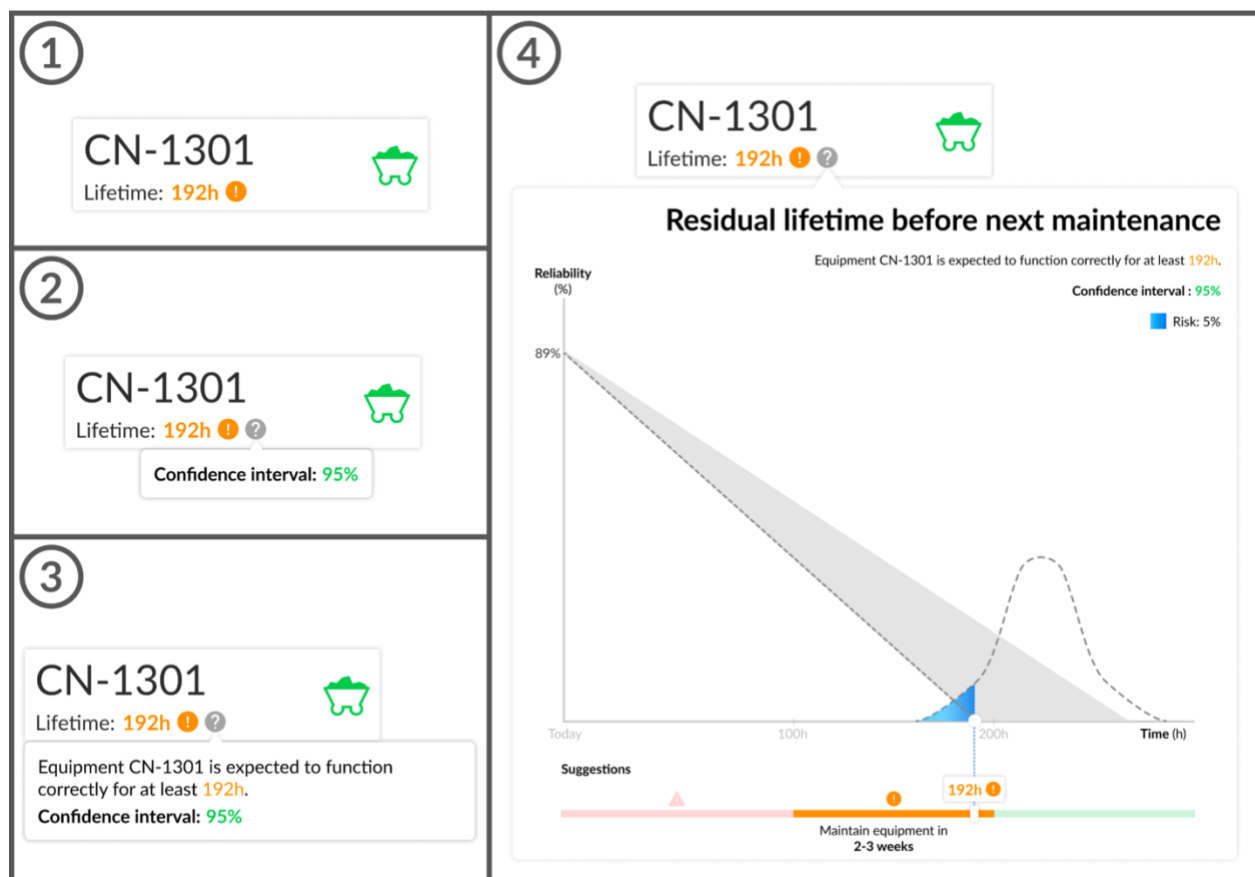


Figure 5.11 AI explanation levels. 1) No explanation. 2) Confidence score. 3) Confidence score and suggestion. 4) Confidence score, suggestion and visual aid.

Section 4 was the debriefing questionnaire containing questions to evaluate the overall experience and scenario preferences. We also asked participants to state aspects of the DSS that helped in their decision-making and aspects that could be improved. Finally, we invited participants to ask questions or to share additional commentary on the test.

5.3.2.5 Data Analysis

We analyzed UEQ+ responses by using the sheet provided by [39]. The analysis tool provided methods to establish means, variances and confidence intervals for each scale. Once transcribed, the original 1 to 7 scores are transformed into a -3 to 3 interval to mimic the original UEQ's data format. A global KPI was calculated by averaging the score of all responses among participants. We surmised participants' understanding of each questionnaire item by using Cronbach's Alpha-Coefficient. However, due to the Alpha-Coefficient's acute sensitivity to low sample sizes ($N < 20$), no final interpretations were made [124], [125]. We used similar analysis methods for the RIS. Although participants provided answers for both scenarios, we only document RIS answers for the PdM scenario. This is due to participants' confusion regarding automation questions for a scenario where explicit automation was not provided. Regarding AI explanation ranking, we organized the results by popularity. Each rank (1 most appreciated, 4 least appreciated) was given a unique value where the value for rank R equals $5 - R$. We multiplied the number of occurrences of an explanation level by the respective ranking's value for all ranks. Then, we calculated the cumulative sum, which resulted in the final score. For the debriefing questionnaire, we transcribed the key moments of each recording and divided our notes into 3 categories. Category 1 consisted of aspects that were appreciated by users. Category 2 consisted of suggestions to improve the prototype. Category 3 comprised all the general comments concerning the experience of the participant. The mentioned categories respect those identified in the debriefing questionnaire.

5.4 Results

We organized our results into 4 sections directly derived from the user tests' format. Sections 5.4.1 and 5.4.2 display user responses to the UEQ+ and RIS respectively. Section 5.4.3 presents the rankings of different levels of AI explanation. Section 5.4.4 summarizes participants' responses during the debriefing questionnaire.

5.4.1 UEQ+

Table 5.4 presents the consistency for all scales among both scenarios. Consistencies are generally strong ($\alpha > 0.70$) except for the Trustworthiness of Content scale in the PM scenario, which obtained a poor alpha coefficient of 0.49. Further evaluation of this scale is shown in Table 5.5.

Table 5.4 Alpha-Coefficient per UEQ+ Scale.

Scale	Alpha-Coefficient	
	PM Scenario	PdM Scenario
Efficiency	0.89	0.85
Perspiciuity	0.89	0.91
Trustworthiness of Content	0.49	0.98
Usefulness	0.79	0.92

Table 5.5 Item-Correlation of the scale “Trustworthiness of Content” for the PM scenario.

Item 1–Item 2	Item 1–Item 3	Item 1–Item 4	Item 2–Item 3	Item 2–Item 4	Item 3–Item 4
0.42	0.15	-0.12	-0.18	0.31	0.55

Table 5.5 suggests the presence of two subgroups in the targeted scale, namely a subgroup composed of items 1 (useful) and 2 (plausible), and another with items 3 (trustworthy) and 4 (accurate). The corresponding data validates this claim in that some participants tended to assign high values to data usefulness and plausibility but assigned lower values to data trustworthiness and accuracy.

Figure 5.12 shows the UEQ+ means score and 95% confidence interval for both scenarios. Usual UEQ+ results range from -3 to 3 but, due to the absence of negative results, we limited the interval to only display positive numbers.

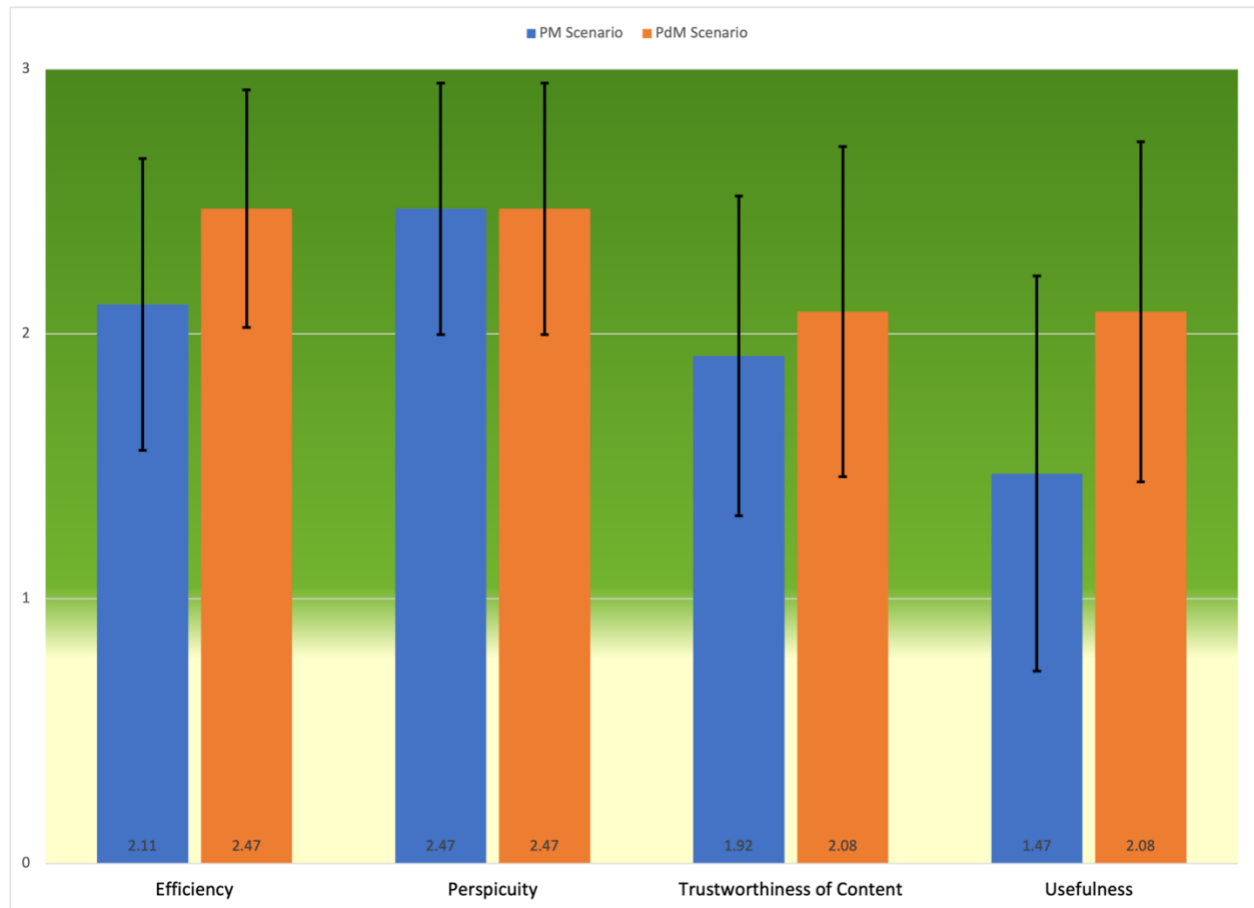


Figure 5.12 UEQ+ scores for PM and PdM scenarios.

Perspicuity was unchanged between the two scenarios while the other three scales presented slight differences. For the PM scenario, the Perspicuity scale scored highest with items “easy to learn” and “easy” obtaining 2.56. For the PdM scenario, the Efficiency and Perspicuity scales obtained similar results with the item “organized”, of the Efficiency scale, scoring 2.67. Regarding scale importance, the difference between the PM and PdM scenarios was minimal with importance for all scales being 2.56 on average. Finally, the KPI for the overall UX impression of the product was 2.00 ± 0.43 for the PM scenario and 2.28 ± 0.61 for the PdM scenario.

5.4.2 RIS

Consistency for the PdM scenario was $\alpha=0.69$, which is hardly inferior to the accepted value of 0.7. Trust scores per participant for the RIS are shown in Figure 5.13. Scores were calculated according to [54]. Questions Q1 and Q3 were reverse-coded and, therefore, adapted accordingly.

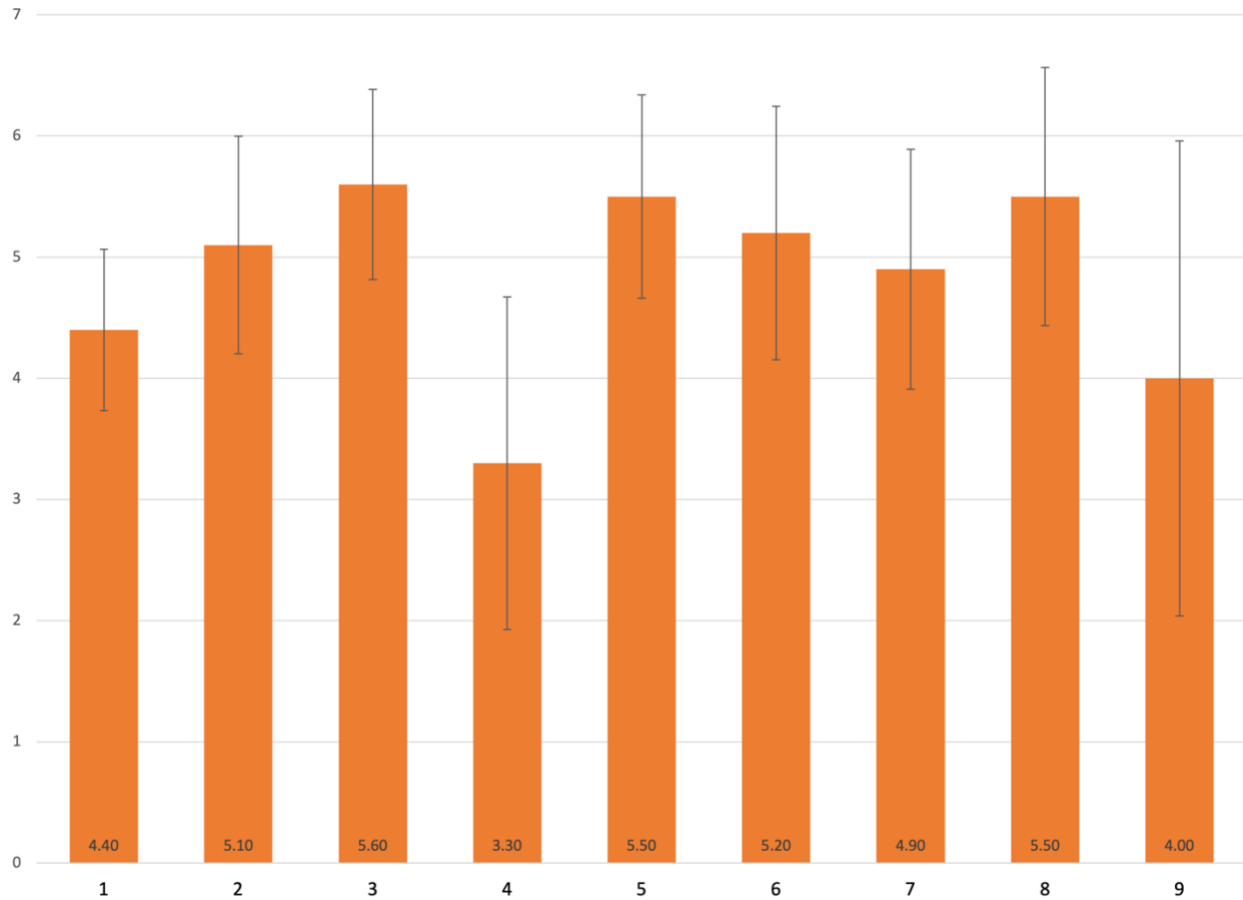


Figure 5.13 RIS trust score per participant for the PdM scenario.

As highlighted by Figure 5.13, the PdM scenario displays an elevated reliance tendency with an average score of 4.83 ± 1.07 out of 7.

5.4.3 AI Explanation Ranking

The ranking of AI explanation levels is shown in Figure 5.14. A higher score is desirable.

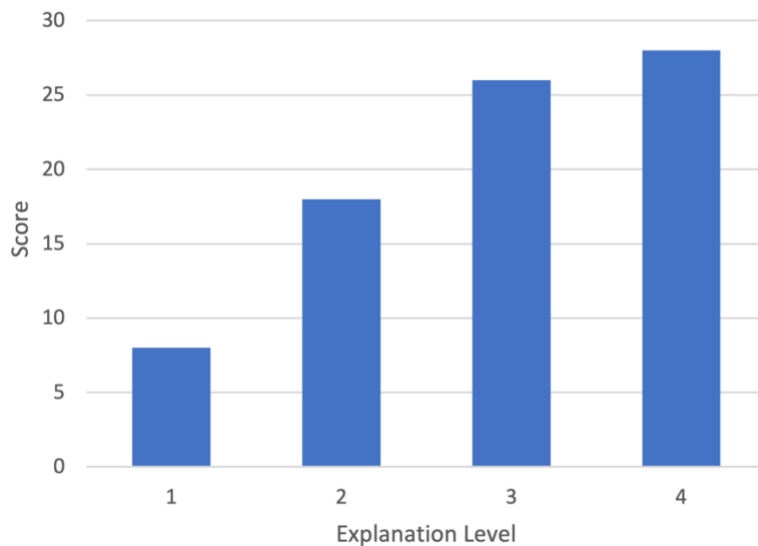


Figure 5.14 AI explanation rankings (higher score is preferred, maximum 36).

The most popular explanation levels were levels 3 and 4. The highest score was attributed to level 4, having been placed in first place by 6 out of 9 participants. The main reason for this choice is that level 4 presented the most detailed explanation. In fact, according to participants, the more information the system is able to provide, the more enlightened their decision making. Additionally, the visual aid was greatly appreciated by participants, who commented that it was a necessary addition to the explanation. Level 3 was selected as the second preferred explanation by 5 out of 9 participants, as it indicated both a confidence score and a suggested action. Level 2 was selected in third place by 7 out of 9 participants as it did not display the information required for sound decision making. In last place can be found explanation level 1 which shows that a minimal amount of explanation is required by experts. Concerning outliers, two participants stated that the visual aid in explanation level 4 was hard to understand and therefore useless to them. This sentiment was voiced mostly by participants who did not occupy a managerial job. In fact, participants occupying a non-supervisory role preferred level 3. Two participants stated that level 3 added redundant information claiming that an expert user would not need action suggestions. Hence, they prioritized level 2 above level 3 mainly due to its conciseness.

5.4.4 Debriefing Questionnaire

We divided debriefing responses into 4 themes issued from those highlighted in the questionnaire: the preferred scenario, the effect of PdM on decision-making, suggestions and comments to improve the prototype, and participants' willingness to integrate the prototype in their mine. Figure 5.15 displays a summary of participants' responses to these 4 themes.

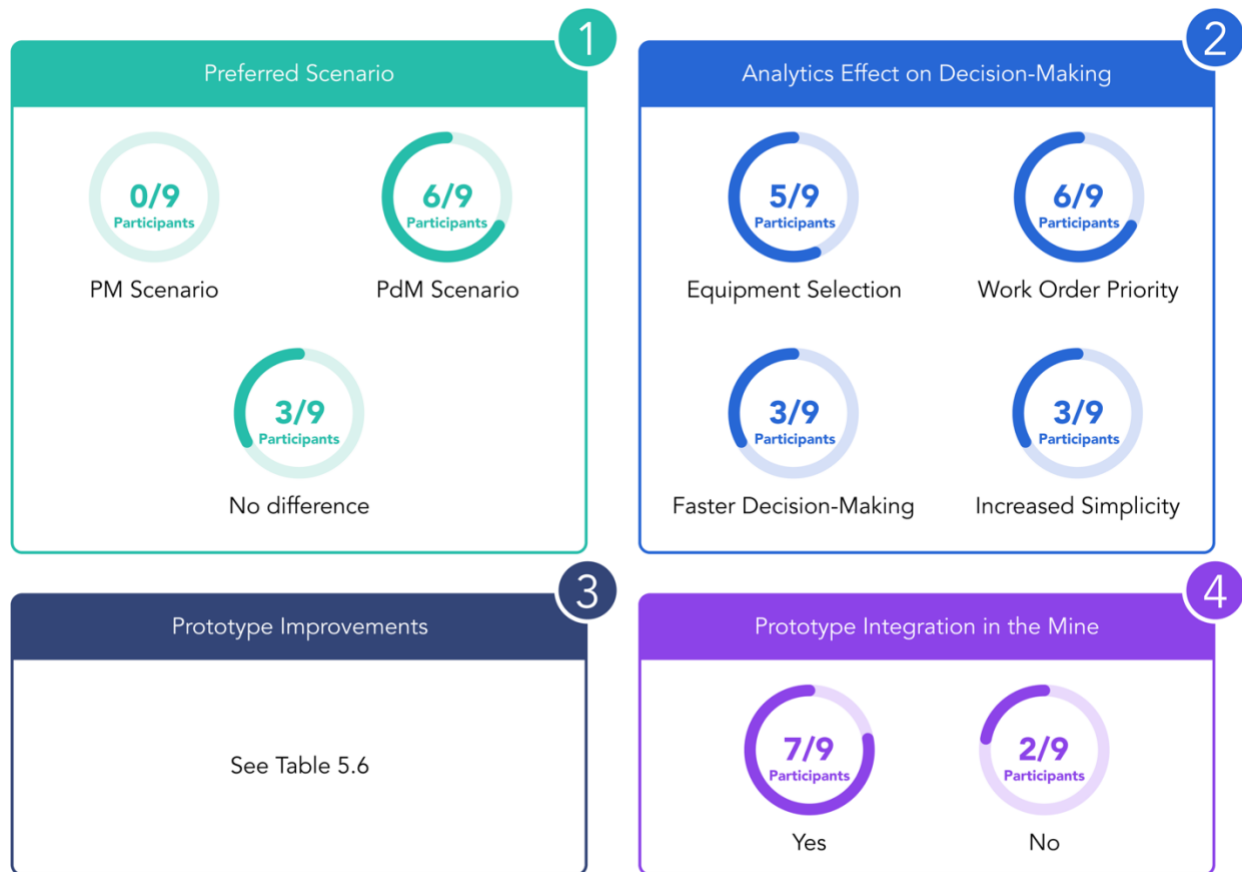


Figure 5.15 Debriefing questionnaire responses.

As shown in Figure 5.15, most participants (6/9) preferred the PdM scenario over PM for maintenance planning. According to participants, the advantages of PdM on decision making were most notable during equipment selection and work order prioritization, and it was linked to a faster and simpler decision-making process. On the prototype's integration in the participants' mines, 7 out of 9 participants answered positively. Participants' comments on this choice mentioned the prototype's great user-friendliness (5/9), UI cleanliness (4/9) and high learnability (3/9). On the other hand, one participant stated that the prototype may not be optimized for larger mining operations, while another participant did not give a definitive answer. We organized participants'

responses concerning prototype improvements into 4 categories: Missing Information, Feature Requests, UI improvements, and software bugs or coding artifacts. Table 5.6 summarizes the most common responses.

Table 5.6 Participants' suggestions and comments on prototype improvement.

	Frequency*
Missing Information	
Manpower, costs and materials management. Equipment maintenance is prioritized based on manpower availability, the cost of having the equipment inoperative and whether parts are available. In our test, we told participants to assume that all resources were available.	5
Work order's "Expected Execution" date. This value helps guide maintenance planners to create the schedule. This information was not available in VulcanH.	3
Feature Requests	
Work order reordering in the scheduling calendar. Participants mentioned how the order of work orders in the scheduling calendar is used to indicate the priority of individual job execution during maintenance.	7
Support for parallel work orders. Depending on the job and on the maintenance team, some work orders can be executed at the same time and should, therefore, be scheduled in parallel.	2
Maintenance splitting (pausing and resuming) in the same week. Spreading maintenance for the same equipment throughout different days is common for multiple reasons (e.g., accounting for the day/night shift changes).	2

Table 5.6 Participants' suggestions and comments on prototype improvement (Continued).

Frequency*	
UI Improvements	
Work orders table column for “Estimated Duration”. Despite this information being available when expanding a work order's table row, participants noted how having this information on the top level would be desirable.	5
Better indicators and actions for prioritized work orders. A common pitfall of VulcanH, according to participants, was the lack of indication for equipment whose work orders had been prioritized for the week. A visual indicator on the equipment card, along with the maintenance planning flag, was requested.	6
UI customization (Equipment display and KPIs). Most commercially available CMMSs allow users to fully customize the information displayed on the Dashboard. Some participants pointed out the lack of UI customization in our prototype.	3

Legend: * - Out of 9 participants

5.5 Discussion

The main objective of this study was to evaluate the usability of VulcanH. At the same time, we clarified TiA constraints related to PdM through the analysis of reliance intentions and level-of-detail recommendations of explainability via rankings of PdM suggestions. From our results, we concluded that VulcanH shows great potential in terms of usability, with intuitiveness and ease-of-use being among the most appreciated aspects. Concerning participants' tendency to rely on automation, our results displayed a generally acceptable level of trust towards PdM. As for explainability ranking, we recommend the implementation of complete and actionable suggestions related to the context at hand with emphasis on graphical means to convey information.

The overall UEQ+ score for the PM scenario was 2.00 ± 0.43 whereas it was 2.28 ± 0.61 for the PdM scenario. This shows that the prototype had good usability for both preventive and predictive

maintenance. Indeed, [39] correlated general satisfaction of products to the KPI to demonstrate its effectiveness. The portrayed values seem to indicate that KPIs between 0 and 1 offer an acceptable user experience, while values above 1 are satisfactory. For purposes of comparison, Netflix's and Amazon Prime's KPIs were 1.73 ± 0.74 and 1.35 ± 0.87 respectively. Similarly, a recent study concluded that a KPI value of 1.53 reflected a positive usability of the system [126]. This value was accompanied by a SUS score of 69% which can be considered slightly above average according to SUS benchmarks [127]. In the same vein, a recent thesis evaluated the usability of online management systems for university students and associated KPI values between 0.48 and 0.99 to an average experience [128]. Our results on UEQ+ scale importance were considerably elevated (2.56/3) and consistent. Hence, we believe that the chosen scales correctly represent users' usability expectations towards a CMMS. Overall, the usability of our prototype may be deemed more than satisfactory, which consolidates the primary objective of our study.

The expected method of evaluating UEQ+ responses is by product comparison [39]. However, our usability results are too similar to identify a superior solution between PM and PdM. This similarity may be due to two factors. First, we previously found the user experience of participants' maintenance management tools to be noticeably improvable [101]. We suppose this had an impact on participants' perception of our prototype's usability although a formal comparison is required to effectively prove this hypothesis. Second, the integration of PdM in our design seemed to have had little impact on participants' decision making with 3 of 9 participants noticing no difference between the proposed scenarios. Yet, most participants (6/9) preferred being aided by the PdM analytics.

Alpha coefficients for UEQ+ responses were generally above the expected threshold of 0.7 [39]. As stated, due to our low sample size ($N=9$), we did not extract any final conclusions regarding each scale's consistency [125]. Cronbach's coefficient was used mainly to validate participants' understanding of the measured items and comment on unexpected results, as was the case for the scale of Trustworthiness of Content for the PM scenario. Addressing this scale's low alpha coefficient, we suspect it to be related to the prototyped nature of the test. In fact, some participants (3/9) stated that contextual information was missing from the scenarios to realistically ascertain the content's trustworthiness or accuracy, most importantly manpower, costs and materials availability. This was the case even if participants felt that the content was useful for their decision making and plausible in the given picture.

On a per-scale basis, participants' comments concerned mostly Perspicuity and Efficiency. Perspicuity was appreciated by all participants. During the debriefing phase, all participants commented on the prototype's ease-of-use and clarity, with one participant stating that the tool he or she used for maintenance planning was less user-friendly than our prototype. Additionally, this participant mentioned that, compared to the evaluated prototype, the aforementioned tool offered little visual aid to help in decision making. Another participant commented on the efficiency and simplicity of the prototype stating their enjoyment of the "Drag&Drop" feature for equipment scheduling and expressing a feeling of wonder towards the visual aspect of our solution. Efficiency-wise, all participants appreciated the prototype's speed during task execution as well as the practical way in which information was presented. However, one of the most mentioned improvements concerned the practicality aspect. In fact, 7 participants noted how the work orders table could offer functions such as sorting or filtering to better aid in task completion.

We measured TiA for the PdM scenario using Lyon and Guznov's RIS and obtained a score of 4.83 ± 1.07 (out of 7). The alpha value for our measurement was 0.69 which is close to the accepted threshold of 0.7 [125]. Previous literature associated a score of 3.61 ± 1.05 to a moderate amount of trust [129]. This association is supported by [54] where values between 3 and 4 were portrayed as being acceptable, albeit the authors making no explicit comments regarding absolute trust. Hence, based on score alone, we concluded that participants generally trusted VulcanH. Our study adds to the body of knowledge on expert users' trust on automation.

Qualitative results from participants' comments throughout the test or during the debriefing phase consolidated our conclusion. One participant stated that it would be pointless to implement PdM if one were not ready to trust it. Additionally, almost all participants (7/9) based their decisions on the system's suggestions without questioning it. We believe that this may be due to the analytics' elevated confidence score, the complex nature of the task, and the confined amount of contextual information. On the other hand, one participant expressed needing to thoroughly test the system before a trusted relationship may be established, while another stated that the PdM suggestions were too unclear to be able to rely on them.

Our results highlighted a common trend among participants, who generally trusted the system, to select a high value for the reverse-coded question: "I really wish I had a good way to monitor the decisions of the system." Admittedly, participants tended to rely on the system but expressed a need for explanation before committing to it. This result respects current findings on TiA research

targeting expert users [42] and findings in expert-related XAI studies [44], [47], [48], [97]. We believe that accountability plays an important role in the expert's interaction with automated systems. In fact, the creation of a poor maintenance schedule may lead to the loss of millions of dollars in unplanned equipment breakage or production downtime, and maintenance experts are responsible to ensure the quality of said schedule [101].

On the topic of explanations, we found that the more information is presented to the expert users, the better. This finding contradicted our initial hypothesis that expected explanation level 3 to be the most popular. When commenting on their choices, participants mentioned how the residual lifetime graph was preferable even if they did not understand it entirely at first glance. It was stated multiple times that a graphical approach would be more appreciated than a textual one. This finding suggests that explanations should be conveyed to the maintenance expert by leveraging graphical means as opposed to explaining recommendations through text.

During the debriefing phase we were able to ascertain that 6 out of 9 participants preferred the PdM scenario. These participants were greatly satisfied by the increase in decision-making speed considering AI suggestions. Admittedly, one participant stated that this kind of system is exactly what the industry needs for the future. The remaining 3 participants did not find enough difference between the proposed scenarios to soundly express their preference. Similarity between scenarios was an aspect of our tests that all participants highlighted. This was surprising, as it was the first time that participants were exposed to PdM whereas they were all familiar with PM. In our previous study, maintenance planners stated that the passage from PM to PdM needed to be done in an exclusive manner [101]. Our results suggest that a gradual adaptation of the process is possible. Indeed, the high level of usability and trust towards VulcanH suggest an overlap between PM and PdM practices. It is also plausible that the similarity between the two scenarios is due to limitations in our methodology, specifically concerning the absence of workforce management and schedule proposition. The inclusion of these aspects in future studies may offer insights into the issue of PdM integration. Overall, our results validated our objective to integrate PdM into the current maintenance workflow while ensuring minimal disruption of active PM practices.

There are three main limitations to this study. First, our choice to ignore workforce availability and parts management removed a substantial portion of the planning phase. The choice ensured that all participants completed the test regardless of their familiarity with maintenance planning but sacrificed the realism of the experience. Thus, participants' decisions were oftentimes less rigorous

than expected in real circumstances. Future studies should conduct user tests including these aspects of the planning phase. Second, since this study focused on the usability evaluation of VulcanH, we developed test-cases that did not account for the quality of the final schedule. To analyze a CMMS's usefulness, measures for performance and error-rate are essential [105]. Hence, future research should establish a baseline for performance analysis through error detection for complex systems such as CMMSs and compare the user's schedule to this baseline. Third, our evaluation was limited to the prototype stage. An actual implementation of the system within the maintenance process would allow for a clearer understanding of the prototype's capabilities for maintenance planning and scheduling on the field. Furthermore, evaluating the system's usage in a high-stakes scenario would most likely yield more accurate results from which researchers may better identify avenues for improvement.

5.6 Conclusions and future research

In this study, we conducted user tests with 9 participants from 5 mining sites to evaluate the usability of our PM and PdM CMMS prototype, VulcanH. Simultaneously, we measured experts' TiA through the analysis of their reliance intentions and explored user-dictated constraints regarding the level of detail of PdM explanations. Our main contribution is the proposal and development of a CMMS prototype aimed at providing improved decision support for current PM and future PdM practices for mobile equipment in the mining industry. We found that the usability and efficiency of VulcanH were satisfactory for expert users and encouraged the gradual transition from PM to PdM practices, with participants appreciating the prototype's learnability and ease-of-use. Concerning TiA, our results indicated an elevated tendency to rely on the PdM's suggestions. Quantitative and qualitative results allowed us to conclude that the participants were willing to rely on predictions if suitable explanations are provided. On PdM explanations, most participants preferred graphical explanations covering the full spectrum of the derived data. This finding may guide future research in PdM to select an analytical algorithm capable of supplying adequate and causal justifications for informed decision making preferably leveraging graphical means.

The nearing of PdM practices into the everyday mine emphasizes the need for user-oriented research. CMMSs capable of providing an exciting user experience will generate an increased level of productivity, a reduction of human-related error, and an overall greater symbiosis between the expert and the automated system. This work has shown how to bring this vision into practice.

CHAPITRE 6 DISCUSSION GÉNÉRALE

La CCU a facilité la subdivision des tâches à compléter pour atteindre l'objectif principal du mémoire. En effet, les deux articles scientifiques présentés découlent directement des étapes proposées par la norme ISO 9241-210. L'artéfact consolidant le lien entre le premier et le deuxième article est la liste des requis centrés sur l'utilisateur créée à partir des entrevues avec les experts. Cette liste a guidé les choix de conception de VulcanH avant et pendant le développement.

Lors des tests utilisateur, aucune IA n'a été utilisée pour le scénario de PdM. Ce choix a été imposé par l'absence d'algorithmes intelligents appliqués à la PdM d'équipements miniers mobiles. En conséquence, aucun algorithme d'XAI n'a été utilisé lors de l'évaluation de VulcanH. La pertinence de l'XAI réside dans les résultats disponibles en littérature, notamment ceux concernant l'utilisabilité des explications fournies à l'utilisateur expert. Ces concepts ont joué un rôle capital dans la création des niveaux d'explicabilité et dans l'analyse des résultats des entrevues du premier article et des tests utilisateur du deuxième article. De plus, mes résultats s'insèrent dans la recherche XAI appliquée aux experts en mettant en évidence l'utilité d'explications contextuelles et utilisables préférentiellement sous forme graphique.

Concernant l'évaluation de VulcanH, celle-ci reposait principalement sur un seul KPI, soit le temps avant l'exécution suggérée d'une maintenance. Dans le scénario de PM, ce temps constituait en les heures-moteur de l'équipement selon l'intervalle de PM alors que dans le scénario de PdM le temps était estimé par une IA fictive. L'utilisation d'un seul KPI pour faciliter les décisions en maintenance est justifiée par les résultats du premier article où l'on identifie le besoin de connaître la date espérée pour exécuter une maintenance. Cette information a guidé les participants dans la complétion des tests utilisateur en leur permettant de déterminer rapidement quels équipements nécessitaient un entretien. Cependant, la maintenance dépend de plusieurs facteurs autant propres aux données internes qu'aux conditions externes d'opération ou de logistique. Le choix de ne cibler qu'un KPI a potentiellement impacté la prise de décision des participants et constitue une limitation de cette recherche. Les études futures devraient intégrer d'autres KPIs pour explorer davantage l'impact de chacun sur la prise de décision.

CHAPITRE 7 CONCLUSION ET RECOMMANDATIONS

7.1 Synthèse des travaux

La revue de littérature a permis d'identifier plusieurs opportunités de recherche concernant le processus de maintenance, l'utilisabilité des GMAOs et les études en TiA. En effet, peu d'études ont abordé le processus de maintenance implémenté dans les mines canadiennes du 21^{ème} siècle et les travaux abordant les problèmes d'utilisabilité des GMAOs offrent rarement des solutions tangibles aux limitations identifiées. Quant à la TiA, son application aux systèmes complexes tels que les GMAOs est un champ suscitant l'intérêt de scientifiques et industriels mais peu de travaux sur ce sujet ont ciblé les utilisateurs experts dans le domaine de la maintenance.

Se basant sur ces manques de connaissance, l'objectif principal de ces travaux était de concevoir et évaluer un GMAO axé sur les pratiques de PM et de PdM pour les équipements mobiles des mines souterraines canadiennes. La CCU telle qu'entendue par la norme ISO 9241-210 dicte l'exécution de quatre activités de conception qui ont fait l'objet de deux articles publiés ou soumis dans des journaux revus par les pairs.

Le premier article a établi le contexte d'utilisation et les besoins des utilisateurs en effectuant des entrevues avec 15 experts en maintenance provenant de 7 mines au Canada. Les résultats obtenus ont permis de cartographier le processus de maintenance d'équipements miniers et d'identifier les KPIs essentiels à la planification de la maintenance. Aussi, grâce à la documentation des avantages et des irritants des GMAOs utilisés, il a été possible de compiler une liste de requis centrés sur l'utilisateur dont le but était de guider la conception future de GMAOs.

Le deuxième article a abordé la conception d'un GMAO et son évaluation auprès des utilisateurs. Le prototype proposé par cette étude a été nommé VulcanH et a été évalué par 9 experts provenant de 5 mines canadiennes via la participation à des tests utilisateur. Les résultats de ces tests ont permis de conclure que l'utilisabilité de VulcanH était satisfaisante pour la planification de la PM ($UEQ+ = 2,00 \pm 0,43$) et de la PdM ($UEQ+ = 2,28 \pm 0,61$). Aussi, les tendances des experts à dépendre de l'automatisation issue de la PdM étaient élevées ($RIS = 4,83 \pm 1,07$ sur 7) et témoignaient une confiance acceptable en VulcanH. Cependant, les experts exigeaient une IA fournissant des explications claires et détaillées concernant les décisions de planification et d'ordonnancement. La complexité des explications ne semblait pas poser un problème pour la plupart des participants.

7.2 Limitations de la recherche

Comme mentionné auparavant, cette recherche comporte quelques limitations. En premier lieu, la collecte de données a été limitée aux mines canadiennes et, bien que la littérature semble suggérer que les pratiques de maintenance soient similaires ailleurs dans le monde, plus d'études sont requises pour s'en assurer. En deuxième lieu, lors des entrevues avec les experts, les participants mentionnaient souvent le processus théorique au lieu de se baser sur le processus implémenté réellement sur le terrain. Afin de limiter l'impact de cet enjeu, les questions ont été reformulées pour interpeller davantage le participant. En troisième lieu, lors de la conception du GMAO, la gestion de la main d'œuvre et des pièces était absente et les participants pouvaient présumer que ces limitants étaient toujours disponibles. Cette décision a été prise en fonction des résultats des entrevues avec les experts où les irritants les plus communs du processus de maintenance concernaient souvent l'ordonnancement des équipements (p.ex. : sélection des équipements devant être entretenus et création de la cédule). Cependant, ce choix a intensifié la nature prototypique du test et a potentiellement diminué la rigueur de la cédule développée par les participants. En quatrième lieu, les analyses de performance (exactitude de la cédule finale) et du taux d'erreur n'étaient pas prévues par les tests utilisateur. Bien que leur importance soit non négligeable pour l'établissement de l'utilité d'un GMAO, les efforts pendant ces travaux de recherche étaient concentrés sur les aspects d'utilisabilité évalués par l'UEQ+. Finalement, VulcanH n'a pas été intégré dans le processus d'une mine réelle. Les systèmes complexes, tels que les GMAOs, sont composés de plusieurs composantes qui interagissent et impactent d'autres composantes du même système. Pour valider l'utilité et l'UX concrètes du prototype, une installation auprès d'une mine partenaire est de mise.

7.3 Implications et recommandations

Les travaux documentés dans ce mémoire touchent plusieurs domaines de recherche. En maintenance, ces travaux permettront aux chercheurs de mieux connaître le processus de maintenance d'équipements miniers afin de réduire l'écart grandissant entre la recherche et l'industrie. Aussi, ces travaux indiquent qu'une intégration harmonieuse des pratiques de PdM dans le processus actuel de PM est possible. En termes d'utilisabilité, les résultats démontrent l'utilité de la CCU pour développer des GMAOs et, en TiA, RIS est une méthode valide et efficace d'évaluer la confiance d'utilisateurs experts. Finalement, en XAI, les chercheurs voulant appliquer l'IA aux outils de PdM sont encouragés à sélectionner des algorithmes pouvant fournir des explications pertinentes et utilisables par l'expert.

Ces travaux de recherche font partie du projet « Analyse des données pour la maintenance préventive et prédictive des équipements miniers » subventionné par les fonds de recherche du Québec en nature et technologie (FRQ-NT). Ce projet est divisé en plusieurs sous-projets dont l'objectif est d'optimiser les pratiques de PM et d'étudier l'introduction de la PdM dans l'industrie minière. Dans le futur, les outils d'analyse de données issus des projets en question seront intégrés dans VulcanH pour fournir un outil centralisé d'aide à la décision pour la PM et la PdM.

Dans une optique plus à court terme, les travaux futurs en utilisabilité de GMAOs devraient cibler des mesures de performance, de taux d'erreur et de conscience de la situation pour mieux analyser l'efficacité et l'utilité du système. Aussi, l'inclusion de participants situés à l'extérieur du Canada aiderait à généraliser le processus de maintenance. Enfin, les études en TiA devraient évaluer la confiance en utilisant une IA existante au lieu de la simuler, comme ce fut le cas dans cette étude. Le domaine minier est l'un des piliers des civilisations depuis le Paléolithique et a catalysé l'évolution des technologies qui ont permis de mettre en place la société telle qu'on la connaît aujourd'hui. La complexité toujours grandissante des outils de gestion des activités minières, dont la maintenance, requiert une réorientation des méthodes de conception de GMAOs vers une approche orientée sur l'utilisateur. Ce besoin est mis en évidence par l'arrivée prochaine de la PdM dans les mines souterraines qui permettra à l'industrie minière d'améliorer les niveaux d'extraction de manière efficace, sécuritaire et durable pour le bénéfice du monde entier.

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ANNEXE A ARTICLE 1 – APPENDIX A

Figures A.1 and A.2 display work orders as they are presented in JDEdwards and GuideTi respectively. Please note that some information was redacted to guarantee anonymity.

BT Correctif - Bon travail - Gestion MODIFIER VALVE (719066) Ecran personnel : (Aucune personnalisation) Mise en pages: (Aucune mise en pages)

Bons travail | Pièces | Main-d'oeuvre | Historique statut | Actions associées

Détail | Liens associés | Historique client

Enreg. modif. (V) | Annuler modif. | Fermer (L) | Imprimer BT | Update Status To 70 | Update Status To 80 | Contrats service

N° commande: 719066 WO Type: 4 BT MODIFICATION

N° unité: TRACTEUR M8540 KUBOTA

AVEC HIAB OK (O) SOUS-TERRE

Modèle produit: M8540DT1 M8540DT1 N° dossier:

Famille produits: TRA TRACTEUR N° réf. client:

Description: MODIFIER VALVE N° site: 11

Desc. échec: 2 VALVES A CONVERTIR EN ACTUEE PAR AIR

Planification | Detail commande | Classement | Comptabilité | Annexes

Statut

Statut	65	Ordonnancer	Heures réelles	
Heures estimées		Date Créat... 2012-11-0€	Temps arrêt réel	
Temps arrêt estimé			Temps réponse garanti	.00
Date fin demandée		00:00:00	réalisation	
Date début planifié	2020-11-13	00:00:00	N° bon travail principal	719066
Date fin planifiée	2020-11-13	00:00:00	Priorité	3

Figure A.1 JDEdwards example work order.

Gestion des bons de travail (CRBT)
 Fichier Paramètres Affichage Pages Aide

Bon de travail: BT-158806
 État: Ouvert

1 - 001-Alécanien Équipement Mobile

BON DE TRAVAIL	INFORMATION DE L'ACTIF	PIECES REQUISE - REQUISITION								
Bon de travail: BT-158806 État: Inactif → ACTIVER MACLEAY BOULONNEUSE MEHA-828 Composante:	Secteur: 1000 Mine Sous-secteur: 1112 Équipement Mobile Mine Sous-Terre No de série: 1 Manufacture: 1 Modèle: MEHA-828 Année: 2014 Valeur lue (compteur): 2 748 heures d'opération	→ PIECES REQUISES → REQUISITIONS DE PIECES ASSOCIEES AU BT → LOGS DE PIECES PLANTES SUR L'ACTIF → PRELEVEMENT EN LOGS								
DEMANDEUR	DESCRIPTION DES TRAVAUX	INFORMATION DES BT								
Demandeur: (234958) Département (BT): 01-Entretien Mine Date inscrite: 2022-02-11 14:16:21	Description des travaux:	Composante de BT: Système électrique Problématique de BT: Endommagé Cause de BT: Pièce défectueuse								
PARAMETRES DU BT	RESERVE AUX PLANNIFICATEURS CONTRACTUALISES	DECLARATION COMPTABLE								
Modèle de bon: Type d'entretien: Correctif panne Mode d'exécution: Arrêt de secteur Priorité: 23 - Faible Contrainte: Contrainte: Maintenance Mine (C380) Compétence requise: 001-Alécanien Équipement Mobile	Structure: Non-classé Responsable: Date de début: Date de fin d'ordonnancement:	→ FICHE UN BOUTON DE COMPTAGE Déclaration comptable: Inter en 90:								
TEMPS D'AVANCEMENT	TEMPS ESTIMÉ POUR LES TRAVAUX REQUIS	INTERVENTIONS								
Date d'arrêt: Date de remise en fonction:	Temps estimé: 3.00 Nb d'employés requis: 1 Temps estimé total: 3.00	Intervenant: Destinataire: Entretien Planificateur Usine → RELANCE DE L'INTERVENTION → CHANGEMENT DE BT								
LISTES D'ACTIVITES	DOCUMENTS LIES	COÛTS DU BON DE TRAVAIL								
→ AJOUTER → SUIVRE → AJOUTER UN FORAAT → SUIVRE UN FORAAT	→ AJOUTER UN FORAAT	→ AJOUTER UN FORAAT								
Étape	Activité	Sous-activité	Note	Temps estimé	Réponse	Compétence	Compteur	Information	État	Paramètres

☒ Permettre les transactions de pièces
☒ Permettre d'inscrire du temps travaillé
☒ Permettre d'inscrire des autres dépenses

Figure A.2 GuideTi example work order.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM	DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX	DY	DZ	EA	EB	EC	ED	EE	EF	EG	EH	EI	EJ	ЕК	EL	EM	EN	EO	EP	EQ	ER	ES	ET	EU	EV	EW	EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ	FK	FL	FM	FN	FO	FP	FQ	FR	FS	FT	FU	FV	FW	FX	FY	FZ	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ	GK	GL	GM	GN	GO	GP	GQ	GR	GS	GT	GU	GV	GW	GX	GZ	HA	HB	HC	HD	HE	HF	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	HV	HW	HX	HY	HA	IB	IC	ID	IE	IF	IG	IH	II	IJ	IK	IL	IM	IN	IO	IP	IQ	IR	IS	IT	IU	IV	IW	IX	IY	IZ	JA	JB	JC	JD	JE	JF	JG	JH	JI	JJ	JK	KL	KM	KN	KO	KP	KQ	KR	KS	KT	KU	KV	KW	KX	KY	KZ	LA	LB	LC	LD	LE	LF	LG	LH	LI	LJ	LK	LM	LN	LO	LP	LQ	LR	LS	LT	LU	LV	LW	LX	LY	LZ	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	ML	MM	MN	MO	MP	MQ	MR	MS	MT	MU	MV	MW	MX	MY	MZ	NA	NB	NC	ND	NE	NF	NG	NH	NI	NJ	NK	NL	NM	NN	NO	NP	NQ	NR	NS	NT	NU	NV	NW	NX	NY	NZ	OA	OB	OC	OD	OE	OF	OG	OH	OI	OJ	OK	OL	OM	ON	OO	OP	OQ	OR	OS	OT	OU	OV	OW	OX	OY	OZ	PA	PB	PC	PD	PE	PF	PG	PH	PI	PJ	PK	PL	PM	PN	PO	PP	PQ	PR	PS	PT	PU	PV	PW	PX	PY	PZ	QA	QB	QC	QD	QE	QF	QG	QH	QI	QJ	QK	QL	QM	QN	QO	QP	QQ	QR	QS	QT	QU	QV	QW	QX	QY	QZ	RA	RB	RC	RD	RE	RF	RG	RH	RI	RJ	RK	RL	RM	RN	RO	RP	RQ	RR	RS	RT	RU	RV	RW	RX	RY	RZ	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ	SK	SL	SM	SN	SO	SP	SQ	SR	SS	ST	SU	SV	SW	SX	SY	SZ	TA	TB	TC	TD	TE	TF	TG	TH	TI	TJ	TK	TL	TM	TN	TO	TP	TQ	TR	TS	TT	TU	<th>TW</th> <th>TX</th> <th>TY</th> <th>TZ</th> <th>UA</th> <th>UB</th> <th>UC</th> <th>UD</th> <th>UE</th> <th>UF</th> <th>UG</th> <th>UH</th> <th>UI</th> <th>UJ</th> <th>UK</th> <th>UL</th> <th>UM</th> <th>UN</th> <th>UO</th> <th>UP</th> <th>UQ</th> <th>UR</th> <th>US</th> <th>UT</th> <th>UU</th> <th>UV</th> <th>UW</th> <th>UX</th> <th>UY</th> <th>UZ</th> <th>VA</th> <th>VB</th> <th>VC</th> <th>VD</th> <th>VE</th> <th>VF</th> <th>VG</th> <th>VH</th> <th>VI</th> <th>VJ</th> <th>VK</th> <th>VL</th> <th>VM</th> <th>VN</th> <th>VO</th> <th>VP</th> <th>VQ</th> <th>VR</th> <th>VS</th> <th>VT</th> <th>VU</th> <th>VV</th> <th>VW</th> <th>VX</th> <th>VY</th> <th>VZ</th> <th>WA</th> <th>WB</th> <th>WC</th> <th>WD</th> <th>WE</th> <th>WF</th> <th>WG</th> <th>WH</th> <th>WI</th> <th>WJ</th> <th>WK</th> <th>WL</th> <th>WM</th> <th>WN</th> <th>WO</th> <th>WP</th> <th>WQ</th> <th>WR</th> <th>WS</th> <th>WT</th> <th>WU</th> <th>WV</th> <th>WW</th> <th>WX</th> <th>WY</th> <th>WZ</th> <th>XA</th> <th>XB</th> <th>XC</th> <th>XD</th> <th>XE</th> <th>XF</th> <th>XG</th> <th>XH</th> <th>XI</th> <th>XJ</th> <th>XK</th> <th>XL</th> <th>XM</th> <th>XN</th> <th>XO</th> <th>XP</th> <th>XQ</th> <th>XR</th> <th>XS</th> <th>XT</th> <th>XU</th> <th>XV</th> <th>XW</th> <th>XX</th> <th>XY</th> <th>XZ</th> <th>YA</th> <th>YB</th> <th>YC</th> <th>YD</th> <th>YE</th> <th>YF</th> <th>YG</th> <th>YH</th> <th>YI</th> <th>YJ</th> <th>YK</th> <th>YL</th> <th>YM</th> <th>YN</th> <th>YO</th> <th>YP</th> <th>YQ</th> <th>YR</th> <th>YS</th> <th>YT</th> <th>YU</th> <th>YV</th> <th>YW</th> <th>YX</th> <th>YZ</th> <th>ZA</th> <th>ZB</th> <th>ZC</th> <th>ZD</th> <th>ZE</th> <th>ZF</th> <th>ZG</th> <th>ZH</th> <th>ZI</th> <th>ZJ</th> <th>ZK</th> <th>ZL</th> <th>ZM</th> <th>ZN</th> <th>ZO</th> <th>ZP</th> <th>ZQ</th> <th>ZR</th> <th>ZS</th> <th>ZT</th> <th>ZU</th> <th>ZV</th> <th>ZW</th> <th>ZX</th> <th>ZY</th> <th>ZZ</th> <th>AA</th> <th>AB</th> <th>AC</th> <th>AD</th> <th>AE</th> <th>AF</th> <th>AG</</th>	TW	TX	TY	TZ	UA	UB	UC	UD	UE	UF	UG	UH	UI	UJ	UK	UL	UM	UN	UO	UP	UQ	UR	US	UT	UU	UV	UW	UX	UY	UZ	VA	VB	VC	VD	VE	VF	VG	VH	VI	VJ	VK	VL	VM	VN	VO	VP	VQ	VR	VS	VT	VU	VV	VW	VX	VY	VZ	WA	WB	WC	WD	WE	WF	WG	WH	WI	WJ	WK	WL	WM	WN	WO	WP	WQ	WR	WS	WT	WU	WV	WW	WX	WY	WZ	XA	XB	XC	XD	XE	XF	XG	XH	XI	XJ	XK	XL	XM	XN	XO	XP	XQ	XR	XS	XT	XU	XV	XW	XX	XY	XZ	YA	YB	YC	YD	YE	YF	YG	YH	YI	YJ	YK	YL	YM	YN	YO	YP	YQ	YR	YS	YT	YU	YV	YW	YX	YZ	ZA	ZB	ZC	ZD	ZE	ZF	ZG	ZH	ZI	ZJ	ZK	ZL	ZM	ZN	ZO	ZP	ZQ	ZR	ZS	ZT	ZU	ZV	ZW	ZX	ZY	ZZ	AA	AB	AC	AD	AE	AF	AG</
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Figure B.1 Excel Schedule.

ANNEXE C ARTICLE 2 – VULCANH USER REQUIREMENTS

Table C.1 displays the respected requirements adapted from [101]. The items that were not selected are preceded by an asterisk (*).

Table C.1 User requirements for VulcanH.

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 - Allow to mark equipment for maintenance.

Table C.1 User requirements for VulcanH (Continued).

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

ANNEXE D ARTICLE 2 – RIS QUESTIONNAIRE

Table D.1 displays the questions adapted from the original RIS [54] to fit the needs of our study.

Table D.1 RIS Questionnaire.

#	Question
1	If I had my way, I would NOT let the system have any influence over important scheduling issues. (Reverse-coded)
2	I would be comfortable giving the system complete responsibility for the planning of maintenance.
3	I really wish I had a good way to monitor the decisions of the system. (Reverse-coded)
4	I would be comfortable allowing the system to implement the schedule, even if I could not monitor it.
5	I would rely on the system without hesitation.
6	I think using the system will lead to positive outcomes.
7	I would feel comfortable relying on the system in the future.
8	When the task was hard, I felt like I could depend on the system.
9	If I were facing a very hard task in the future, I would want to have this system with me.
10	I would be comfortable allowing this system to make all decisions.

ANNEXE E APPROBATIONS ÉTHIQUES

CER-2122-04-D



Montréal, le 15 octobre 2021

Objet: Approbation éthique – « Outil de visualisation et d'aide à la décision pour la maintenance prédictive des équipements miniers » - Projet CER-2122-04-D

M. Simon Robatto Simard,

J'ai le plaisir de vous informer que le Comité d'éthique de la recherche, selon les procédures en vigueur, en vertu des documents qui lui ont été fournis, a examiné le projet de recherche susmentionné et conclu que ce dernier répond aux normes en vigueur au chapitre de l'éthique de la recherche énoncées dans la *Politique en matière d'éthique de la recherche avec des êtres humains* de Polytechnique Montréal.

Veuillez noter que le présent certificat est valable pour une durée d'un an, soit du 15 octobre 2021 au 16 octobre 2022, pour le projet tel qu'approuvé au Comité d'éthique de la recherche avec des êtres humains.

Veuillez noter que conformément aux exigences auxquelles l'institution et son personnel sont assujettis afin d'être admissibles aux fonds des organismes subventionnaires, il est de votre responsabilité de déposer au CER un rapport annuel ou un rapport final avant l'expiration de la présente approbation éthique afin de l'informer de l'avancement de vos travaux. Le formulaire à remplir est disponible à l'adresse suivante : (<http://www.polymtl.ca/recherche/formulaires-et-guides>).

De plus, il est de votre responsabilité d'informer le CER de toute modification importante qui pourrait être apportée au protocole expérimental avant sa mise en œuvre, de même que de tout élément ou événement imprévu pouvant avoir une incidence sur le bien-être ou l'intégrité des participant(e)s impliqué(e)s dans le projet de recherche. Nous vous invitons aussi à nous signaler tout problème susceptible d'avoir une incidence sur les membres de l'équipe de recherche.

Je vous souhaite bonne chance dans la poursuite de vos travaux.

Nous vous prions d'agréer, Monsieur, l'expression de nos sentiments les meilleurs,

Farida Cheriet, présidente
Comité d'éthique de la recherche
Polytechnique Montréal

c.c. Direction de la formation et de la recherche; Service des Finances
Philippe Doyon-Poulin, Professeur adjoint, Département de mathématiques et de génie industriel
Michel Gamache, professeur titulaire, Département de mathématiques et de génie industriel
p.j. Certificat # CER-2122-04-D

Comité d'éthique de la recherche
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Figure E.1 Approbation éthique pour les entrevues d'analyse des besoins.

CER-2223-32-D



Montréal, le 29 septembre 2022

Objet: Approbation éthique – « Outil de visualisation et d'aide à la décision pour la maintenance prédictive des équipements miniers (Projet 4) » - Projet CER-2223-32-D

M. Simon Robatto Simard,

J'ai le plaisir de vous informer que le Comité d'éthique de la recherche, selon les procédures en vigueur, en vertu des documents qui lui ont été fournis, a examiné le projet de recherche susmentionné et conclu que ce dernier répond aux normes en vigueur au chapitre de l'éthique de la recherche énoncées dans la *Politique en matière d'éthique de la recherche avec des êtres humains* de Polytechnique Montréal.

Veillez noter que le présent certificat est valable pour une durée d'un an, soit du 29 septembre 2022 au 30 septembre 2023, pour le projet tel qu'approuvé au Comité d'éthique de la recherche avec des êtres humains.

Veillez noter que conformément aux exigences auxquelles l'institution et son personnel sont assujettis afin d'être admissibles aux fonds des organismes subventionnaires, il est de votre responsabilité de déposer au CÉR un rapport annuel ou un rapport final avant l'expiration de la présente approbation éthique afin de l'informer de l'avancement de vos travaux. Le formulaire à remplir est disponible à l'adresse suivante : (<http://www.polymtl.ca/recherche/formulaires-et-guides>).

De plus, il est de votre responsabilité d'informer le CER de toute modification importante qui pourrait être apportée au protocole expérimental avant sa mise en œuvre, de même que de tout élément ou événement imprévu pouvant avoir une incidence sur le bien-être ou l'intégrité des participant(e)s impliqué(e)s dans le projet de recherche. Nous vous invitons aussi à nous signaler tout problème susceptible d'avoir une incidence sur les membres de l'équipe de recherche.

Je vous souhaite bonne chance dans la poursuite de vos travaux.

Nous vous prions d'agréer, Monsieur, l'expression de nos sentiments les meilleurs,

L'Hocine Yahia, vice-président
Comité d'éthique de la recherche
Polytechnique Montréal

c.c. Direction de la formation et de la recherche; Service des Finances
Philippe Doyon-Poulin, Professeur adjoint, Département de mathématiques et de génie industriel
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Figure E.2 Approbation éthique pour les tests utilisateur.