POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Guider la transformation numérique des mines souterraines vers la Mine Intelligente : une approche de gestion de portefeuille de projets

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Cette thèse intitulée :

Guider la transformation numérique des mines souterraines vers la Mine Intelligente : une approche de gestion de portefeuille de projets

présentée par **Marine ECHTERNACH-JAUBERT**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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DÉDICACE

À mon mari, pour sa patience, ses idées et son soutien dans cette longue aventure.

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RÉSUMÉ

La transformation numérique (TN) représente un tournant inévitable et stratégique pour le secteur minier, en particulier pour les opérations d'extraction souterraine. L'adoption progressive des technologies issues de l'Industrie 4.0 transforme la manière dont les mines sont perçues, conçues, exploitées et gérées. Ce mouvement conduit à l'émergence du concept de Mine Intelligente, incarnant la vision d'une exploitation durable, autonome, connectée et centrée sur l'humain.

Cependant, malgré la multiplication des initiatives technologiques, peu d'entreprises minières disposent d'un cadre structuré pour planifier ces projets selon une logique de portefeuille de projets. Cette recherche s'inscrit dans cette perspective et vise à guider la gestion de portefeuille de projets (GPP) de TN pour les mines souterraines.

La méthodologie adoptée repose sur une approche mixte combinant étude de terrain, analyse documentaire et validation empirique. Une immersion de six mois en milieu industriel a permis d'observer directement les opérations et de collecter des données empiriques sur les réalités organisationnelles, les contraintes techniques et les besoins spécifiques des mines souterraines. Un cadre conceptuel clarifiant le concept de Mine Intelligente, tel que défini par les praticiens, a été développé et ensuite confronté à la littérature scientifique afin d'identifier les convergences et écarts entre la vision industrielle et la recherche universitaire. À la suite de cela, les approches de TN employées dans le secteur minier et les bonnes pratiques issues de l'Industrie 4.0 sont identifiées et évaluées au moyen de dix entretiens semi-dirigés menés auprès d'experts canadiens en gestion de projets miniers. Sur cette base, un modèle de GPP adapté au contexte minier souterrain est développé et validé par l'application à un cas de test d'une mine de roche dure.

Les résultats de cette recherche apportent plusieurs contributions. Premièrement, ils clarifient le concept de la Mine Intelligente pour les opérations d'extraction minières souterraines en termes d'objectifs, de solutions et de processus d'affaires. Deuxièmement, ils offrent une meilleure compréhension des pratiques de TN dans le secteur minier et de l'adaptation des pratiques de GPP, reflétant les réalités opérationnelles et les défis propres à cette industrie. Troisièmement, ils définissent un modèle opérationnel et contextualisé permettant aux entreprises minières de développer leur portefeuille de projets de TN aligné avec la vision de la Mine Intelligente et leur vision stratégique. Ce modèle s'appuie sur une approche ascendante et descendante et inclut la gestion du risque, du changement, de la communication et des parties prenantes, tout en proposant des outils et des techniques pour en assurer la mise en œuvre.

La recherche présente toutefois certaines limites ; elle se concentre sur les opérations d'extraction souterraine et repose sur un échantillon limité d'experts et sur un seul cas de test. Les perspectives de recherche incluent l'élargissement du cadre conceptuel à l'ensemble de la chaîne de valeur minière, l'application du modèle à d'autres contextes miniers, ainsi que sa transposition à d'autres secteurs caractérisés par des cycles de production complexes et temporaires.

ABSTRACT

Digital transformation (DT) represents an inevitable and strategic shift for the mining sector, particularly for underground extraction operations. The progressive adoption of Industry 4.0 technologies is reshaping how mines are perceived, conceived, operated, and managed. This evolution drives the emergence of the Smart Mine concept, reflecting a vision of sustainable, autonomous, connected, and human-centered mining.

However, despite the growing number of technological initiatives, few mining companies have a structured framework to plan these projects using a portfolio-based approach. This research aligns with this perspective and aims to guide project portfolio management (PPM) for DT in underground mines.

The methodology relies on a mixed approach combining field study, document analysis, and empirical validation. A six-month industrial immersion enabled direct observation of operations and the collection of empirical data on organizational realities, technical constraints, and the specific needs of underground mining. A conceptual framework clarifying the Smart Mine concept as defined by mining practitioners was developed and then compared with scientific literature to identify convergences and discrepancies between industry vision and academic research. Subsequently, DT approaches employed in the mining sector and best practices drawn from Industry 4.0 were identified and evaluated through ten semi-structured interviews with Canadian mining experts in project management. Based on these findings, a PPM model adapted to the underground mining context was developed and validated through application to a hard-rock mining test case.

This research provides several contributions. First, it clarifies the Smart Mine concept for underground extraction operations in terms of objectives, solutions, and business processes. Second, it enhances the understanding of DT practices in the mining sector and the adaptation of PPM practices to reflect operational realities and industry-specific challenges. Third, it defines an operational and contextualized model enabling mining companies to develop DT project portfolios aligned with the Smart Mine vision and their strategic objectives. The model draws on both top-down and bottom-up approaches, integrating risk, change, communication, and stakeholder management as continuous components, while offering tools and techniques to support implementation.

Some limitations must be acknowledged: the research focuses on underground extraction operations, involves a limited sample of experts, and is validated using a single test case. Future research directions include extending the conceptual framework to the entire mining value chain, applying the model in other mining contexts, and adapting it to other sectors characterized by complex and temporary production cycles.

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LISTE DES SIGLES ET ABRÉVIATIONS

La liste des sigles et abréviations présente, dans l'ordre alphabétique, les sigles et abréviations utilisés dans la thèse ainsi que leur signification.

CAPEX	Dépenses en capital
ESG	Environnement, social et gouvernance
GPP	Gestion de portefeuille de projets
IT	Technologie de l'information
KPI	Indicateurs de performance
OPEX	Dépenses opérationnelles
PMI	Project Management Institute
ROI	Retour sur investissement
TN	Transformation numérique
TRL	Niveau de préparation technologique

CHAPITRE 1 INTRODUCTION

Selon le Larousse, une mine est une cavité creusée dans le sol pour extraire le minerai, ainsi que l'ensemble des installations nécessaires à l'exploitation d'un gisement. Elle peut être à ciel ouvert, lorsque l'exploitation se fait depuis la surface par gradins successifs, ou souterraine, lorsque l'accès au gisement se fait par puits, rampes ou galeries. La présente recherche se focalise sur les mines souterraines existantes et en opération, qui présentent des contraintes techniques, environnementales et organisationnelles particulières, notamment en matière de santé et sécurité, de connectivité, de réglementation, d'espace restreint, d'expansion continue des galeries et de conditions géologiques.

De manière générale, une mine suit un cycle de vie composé de plusieurs étapes :

1. Exploration, visant à identifier et caractériser les gisements minéraux;
2. Développement, comprenant la conception, la planification et la construction des infrastructures nécessaires;
3. Exploitation, soit la phase de production où le minerai est extrait, transporté et traité; et
4. Fermeture et réhabilitation, où les opérations cessent et le site est remis en état afin de limiter son impact environnemental.

Ce cycle de vie s'inscrit dans une chaîne de valeur plus large allant de l'exploration géologique à la commercialisation des produits finis. Toutefois, ce projet se concentre spécifiquement sur la phase de développement et d'exploitation des mines souterraines à accès par rampe ou puits, sans couvrir l'ensemble de la chaîne de valeur minière. Étant donné que notre étude se concentre sur les mines souterraines, la littérature portant sur les mines à ciel ouvert a été exclue. En effet, ces dernières ont un environnement plus stable, sont moins contraintes physiquement et plus facilement instrumentables. De plus, les mines d'exploitation in situ utilisant la dissolution n'ont pas été considérées, puisqu'elles n'impliquent pas d'intervention humaine directe en milieu souterrain. De même, les travaux relatifs aux mines de charbon et à l'exploitation par longue taille, une méthode continue et largement automatisée, qui se distingue des modes d'exploitation étudiés dans le cadre de ce projet, ont été écartés des résultats de recherche, conformément à l'ontologie formelle de classification des types de mines proposée par Cheng, G. et al. (2011). Ces choix d'exclusions se justifient par les spécificités techniques, organisationnelles et sociotechniques en environnement

souterrain qui sont transférables à des contextes caractérisés par une forte complexité opérationnelle, des contraintes spatiales et d'expansion continue avec une dépendance critique aux systèmes de connectivité et de sécurité. Cette contextualisation préalable permet de tenir compte des différences de maturité technologique et d'échelle.

L'industrie minière est aujourd'hui engagée dans un processus de TN qui redéfinit en profondeur ses pratiques opérationnelles et managériales. L'objectif de cette transformation est de favoriser la performance, la sécurité, la durabilité et le développement des compétences de la main-d'œuvre, tout en préparant le passage vers le concept émergent de la Mine Intelligente ou Mine 4.0 (Institut National des Mines, 2021; Merma, 2023). La Mine 4.0 fait référence au concept de l'I4.0,fondée sur l'intégration de technologies avancées, d'infrastructures intelligentes, de processus interconnectés et de systèmes de gestion intégrés (Morisse & Prigge, 2017). L'I 4.0 a plus de 100 définitions différentes faisant référence à l'utilisation d'un ensemble de technologies, qui varient selon les auteurs, mais la majorité s'accorde à dire que l'I 4.0 exploite et supporte la prise de décision en temps réel (Moeuf et al., 2018). L'I4.0 est ainsi un sous-ensemble restrictif de la TN qui désigne de façon générale l'adoption des technologies de l'information. La TN englobe la dimension stratégique et organisationnelle nécessaire pour le déploiement des technologies (Ji & Li, 2022).

Dans ce cadre, la TN est envisagée comme un cycle de développement progressif. Le point de départ, ou temps zéro (t_0), correspond à la création initiale du portefeuille de projets numériques, où sont définies les premières initiatives nécessaires au virage technologique. Le temps n (t_n) correspond, quant à lui, à l'état futur où la mine peut être considérée comme autonome, connectée et intelligente. L'objectif de cette recherche n'est pas d'étudier en détail l'atteinte de cet état final, mais bien le cheminement progressif vers cet état, notamment en matière de gestion et de coordination des projets numériques.

Cependant, contrairement au secteur manufacturier qui a largement bénéficié des approches structurées de l'Industrie 4.0, l'industrie minière reste en retard dans son adoption du numérique et demeure l'un des derniers secteurs industriels à se numériser (Young & Rogers, 2019). La lenteur de ce virage s'explique principalement par l'apparition tardive de la connectivité souterraine (Rogers et al., 2019). En effet, la transformation numérique dépend grandement de la connectivité et l'apparition et le déploiement de solutions de communication pour l'exploitation souterraine ont

commencé en 2017 (GMSG, 2017). Plusieurs autres spécificités du contexte minier souterrain retardent la numérisation du domaine comme la durée de vie limitée des sites, le retour sur investissement incertain (Institut National des Mines, 2021), les conditions de travail souterraines difficiles (poussière, humidité, instabilité géologique), les contraintes environnementales et réglementaires (Gao, S. et al., 2019; Sánchez & Hartlieb, 2020), ainsi que la complexité liée à l'expansion continue des galeries souterraines (Yendamuri et al., 2021). Ces facteurs rendent l'intégration des technologies non seulement coûteuse mais aussi hautement incertaine, ce qui distingue fortement le secteur minier de l'environnement plus stable des usines manufacturières. De plus, les répercussions négatives que l'adoption des technologies peut avoir sur la production pèsent sur l'acceptation des innovations (Ediriweera & Wiewiora, 2021).

À ces contraintes s'ajoutent des défis organisationnels : une main-d'œuvre vieillissante, un manque de compétences numériques (Dragičević & Bošnjak, 2019), des visions stratégiques souvent floues de la TN (Barnewold & Lottermoser, 2020), une terminologie hétérogène, et une adoption des technologies davantage réactive et fragmentée que proactive et planifiée (Wael et al., 2022; Yaqot & Menezes, 2022). Étonnamment, la localisation du site n'est pas un critère impactant la volonté de la maison-mère d'implanter des solutions technologiques (Sörensen & Clausen, 2022).

Plusieurs études de cas (Benzane, 2019; Gao, S. et al., 2019; Merma, 2023; Nyström Eklund & Adelgren, 2021) confirment que la plupart des projets numériques en contexte minier sont isolés et centrés sur une technologie précise, négligeant la nécessité de coordonner simultanément plusieurs initiatives numériques aux résultats interdépendants. De plus, les objectifs stratégiques liés à la TN sont généralement définis par la maison-mère et chaque site minier conserve une certaine marge de manœuvre dans la sélection et la mise en œuvre des projets. Cette approche crée parfois des tensions dues à la réalité opérationnelle du site minier et à l'organisation en silo.

Le concept de Mine Intelligente illustre ces défis. Dans la littérature et la pratique, ce concept est encore sujet à interprétation et regroupe diverses appellations : « Mine Intelligente », « mine numérique », « mine 4.0 » (Sörensen & Clausen, 2021). Alors que certains acteurs industriels définissent la Smart Mine comme une mine autonome, électrifiée, connectée et durable (ABB, 2022; Hillal, 2022), d'autres l'envisagent comme une vision à long terme, où l'intégration numérique permet de réduire la complexité croissante des opérations, d'améliorer la prise de

décision en temps réel et de renforcer la sécurité et la productivité tout en minimisant l'impact environnemental (Sörensen & Clausen, 2021).

Selon Geraldi et al. (2011), la complexité des projets ne se limite pas à la dimension technique, mais inclut également les dimensions organisationnelles, systémiques et décisionnelles. Concernant le domaine minier souterrain, les projets font face aux défis techniques liés aux conditions souterraines et environnementales, ainsi qu'aux défis organisationnels exigeant la collaboration entre plusieurs départements et acteurs externes, tels que les investisseurs et les fournisseurs. Des défis systémiques s'ajoutent par l'interaction des systèmes dans un environnement contraint et la complexité décisionnelle due à la durée de vie, à l'implication des parties prenantes, aux facteurs de sécurité, de productivité et de coût.

Dans ce contexte, la mise en œuvre de la TN dans les mines ne se limite pas à l'intégration de nouvelles technologies, mais signifie l'intégration de technologies dans les processus, et nécessite une stratégie organisationnelle pour soutenir les objectifs de performance et d'adaptation avec une gestion du changement centrée sur l'humain. La gouvernance organisationnelle fournit les structures décisionnelles et les mécanismes de coordination stratégique à travers plusieurs niveaux organisationnels pour gérer plusieurs projets simultanés, chacun présentant un haut degré d'incertitude et des résultats interdépendants, et allouer les ressources (Ali & Fripomg, 2020; Sanchez & Hartlieb, 2020; Yendamuri et al., 2021; PMI, 2016). C'est précisément le rôle de la GPP, qui vise à aligner les initiatives sur les objectifs stratégiques, en s'assurant que les investissements ne sont pas des initiatives isolées et qu'ils contribuent à la création de valeur (PMI, 2016).

Dans le secteur manufacturier, la GPP constitue déjà un levier mature pour orienter les initiatives numériques, assurer la cohérence des investissements et éviter le « paradoxe de la productivité » (application non sélective de nouvelles technologies qui augmente la complexité du système et diminue la production (Dragičević & Bošnjak, 2019)). En revanche, dans le secteur minier, de telles approches demeurent largement absentes (Kutnjak et al., 2019). Le manque d'une perspective GPP adaptée au contexte minier se traduit par une fragmentation des initiatives, une dépendance excessive envers les fournisseurs de technologies externes pour créer les feuilles de route de transformation numérique (GMG, 2021; Harris, J., 2023; Rockwell Automation, 2019) et une difficulté à planifier la scalabilité et la pérennité des projets numériques.

Alors que de nombreux cadres et bonnes pratiques de TN existent dans d'autres secteurs, la littérature révèle un vide empirique quant à la manière dont les entreprises minières structurent, priorisent et gèrent leurs portefeuilles d'initiatives numériques. Cette lacune laisse les organisations sans cadre clair pour naviguer dans la complexité des projets simultanés, interdépendants et à forte incertitude. **L'objectif général de cette thèse est ainsi d'améliorer la GPP afin de guider la TN des mines souterraines.**

Pour répondre à cet objectif général, cette thèse par articles est structurée comme suit. Le chapitre 2 présente une brève revue de la littérature sur les approches de TN dans l'Industrie 4.0 et dans le secteur minier. Le chapitre 3 présente la démarche de recherche employée, la méthodologie générale utilisée et définit les objectifs spécifiques. Suite à cela, chaque objectif spécifique est traité dans un chapitre. Le chapitre 4 présente le premier article publié et combine une revue de la littérature académique et non académique sur le concept de la Mine Intelligente ainsi que les initiatives de TN pour les mines souterraines pour créer un cadre de référence. Le chapitre 5 présente le deuxième article publié, portant sur l'analyse des pratiques de TN dans le secteur minier canadien. Le chapitre 6, constitué d'un troisième article soumis pour publication, propose le développement d'un modèle opérationnel de GPP adapté à l'industrie minière, synthétisant les enseignements de la littérature et les recommandations issues des praticiens. Ce modèle est ensuite appliqué et validé dans le cadre d'une étude de cas en mine souterraine de roche dure permettant d'évaluer son applicabilité pratique et d'illustrer la coordination de multiples initiatives de TN simultanées. Enfin, le chapitre 7 discute des résultats au regard des principales contributions, mettant en évidence les écarts entre la vision académique et la pratique industrielle, et les opportunités pour améliorer la GPP des initiatives numériques, ainsi que les limites et les perspectives associées à cette recherche. Finalement, le chapitre 8 conclut notre thèse en ouvrant les perspectives de recherche futures pour soutenir la transition vers la Mine Intelligente.

CHAPITRE 2 BRÈVE REVUE DE LITTÉRATURE

Ce chapitre apporte une brève revue de la littérature pour mettre en contexte notre recherche, comprendre l'état actuel des connaissances en matière de TN dans le secteur minier et identifier les pistes de solutions potentielles permettant d'atteindre l'objectif général de cette thèse. La littérature spécifique à la TN des mines reste limitée, pour cette raison, nous avons recherché des publications sur l'I4.0, plus documentées dans la littérature. Puisque nous cherchons à améliorer la GPP pour guider la TN des mines souterraines, notre revue de la littérature est divisée en trois sections. Premièrement, une revue des revues de littérature portant sur la TN dans l'Industrie 4.0 est présentée afin de situer notre recherche. Deuxièmement, une revue portant sur la TN et la Mine Intelligente pour comprendre l'état actuel des connaissances dans le secteur minier. Troisièmement, une revue des pratiques de GPP dans l'Industrie 4.0 est présentée. Finalement, le chapitre se conclut par une analyse critique de la littérature.

2.1 Revue de littérature de la TN dans l'Industrie 4.0

Cette section aborde le statut de la littérature sur la TN dans l'Industrie 4.0, en s'appuyant sur les revues de littérature issues de la base de données Web of Science abordant le statut de la TN dans l'Industrie 4.0 ainsi que son déploiement selon les mots-clés « Digital transformation », « Industrie 4.0 », « review ».

À partir de cette démarche, sept revues de littérature ont été retenues et regroupées en trois groupes permettant de comprendre l'état actuel des connaissances en matière de TN dans l'Industrie 4.0. Un premier groupe de travaux se concentre sur les revues générales portant sur l'Industrie 4.0 et la TN dans le secteur manufacturier. Sony et Naik (2020) identifient les facteurs critiques de succès pour l'implantation de l'Industrie 4.0, tandis qu'Ortt et al. (2020) évaluent le degré actuel de mise en œuvre de l'Industrie 4.0. L'implémentation de l'Industrie 4.0 repose sur un processus en plusieurs étapes : l'analyse du processus actuel, le développement d'une vision pour le futur processus, le développement d'un plan d'action et l'implémentation du processus. L'analyse du processus se fait au travers de l'évaluation de la maturité ou de la préparation et inclut les changements organisationnels, la culture du changement et la dimension humaine. De manière complémentaire, Ghobakhloo et al. (2022) présentent une revue de littérature systématique de l'adoption des technologies de l'Industrie 4.0 par les petites et moyennes entreprises (PME). Ces

trois revues dressent un état des lieux centré sur le secteur manufacturier, confirmant la prépondérance des recherches sur l'Industrie 4.0 dans ce domaine.

Le deuxième ensemble de publications met l'accent sur les approches stratégiques et méthodologiques de la TN. Khoshroo et Talari (2022) présentent une analyse bibliométrique des recherches portant sur les stratégies de TN dans l'Industrie 4.0 d'un point de vue des affaires et du management et démontrent que les publications portent surtout sur les PME et le secteur manufacturier. Iribarren et al. (2024) proposent une revue de littérature systématique sur les instruments permettant d'évaluer le degré de déploiement de l'Industrie 4.0 dans les entreprises. Ils démontrent que les études portent presque exclusivement sur le domaine manufacturier en 2017, mais s'étendent à d'autres domaines avec les années, excepté le secteur minier. Enfin, Galizia et al. (2023) adoptent une perspective intersectorielle en passant en revue les meilleures pratiques de l'Industrie 4.0. Leur étude révèle que les cas d'étude portent sur le domaine du transport et du génie mécanique, confirmant le manque d'analyse dans l'industrie minière.

Enfin, le troisième angle met en lumière la faible représentation du secteur minier dans les recherches de TN. Kutnjak et al. (2019) effectuent une revue de la littérature sur la TN, basée sur des études de cas multisectorielles d'application de technologies numériques, et soulignent qu'aucun cas analysé n'implique l'industrie minière à la période étudiée. Cette observation souligne un retard initial de prise en compte du secteur minier dans la littérature sur la TN comparativement à d'autres industries, mettant en évidence la nécessité d'examiner l'évolution récente des recherches et de mieux comprendre la TN de ce secteur.

Un résumé des revues de littérature est présenté dans le Tableau 2.1 ci-dessous. De manière générale, la littérature scientifique montre que les recherches sur la TN et l'Industrie 4.0 se concentrent sur le secteur manufacturier et les PME, avec une marginalisation de l'industrie minière et de la TN dans ce contexte.

Tableau 2.1 Revue de littérature de TN dans l'Industrie 4.0

Auteur	Domaine	Thématique
Kutnjak et al. (2019)	Multi-sectoriel	Cas d'étude de TN – application de technologies numériques
Ortt et al. (2020)	Manufacturier	Degré de mise en œuvre de l'Industrie 4.0
Sony et Naik (2020)	Manufacturier	Facteurs critiques de succès
Ghobakhloo et al. (2022)	PME Manufacturière	Adoption des technologies de l'Industrie 4.0
Khoshroo et Talari (2022)	PME Manufacturière	Analyse bibliométrique des stratégies de TN dans l'Industrie 4.0
Galizia et al. (2023)	Intersectoriel	Meilleures pratiques de l'Industrie 4.0
Iribarren et al. (2024)	Intersectoriel	Outils pour évaluer le degré de déploiement de l'Industrie 4.0

2.2 TN et Mine Intelligente

Cette section démontre que, depuis 2019, plusieurs articles se sont intéressés à la TN du secteur minier, abordant le concept de Mine 4.0, aussi appelée Mine Intelligente.

Young et Rogers (2019) notent que malgré l'intérêt des chercheurs pour l'adaptation des compagnies minières aux changements technologiques depuis près de 70 ans, l'industrie demeure en retard par rapport aux autres secteurs. De même, Dragičević et Bošnjak (2019), Sánchez et Hartlieb (2020) et Kalenov et Kukushkin (2021) montrent que le secteur minier est le moins avancé en matière de TN et de digitalisation.

Sörensen et Clausen (2021) soulignent que malgré l'acceptation du concept de Mine Intelligente, sa signification est floue. Le concept de Mine Intelligente ou Mine 4.0 est défini par Clausen et Sörensen (2022) comme l'intégration et la connexion intelligentes des équipements miniers avec les technologies de l'information et de la communication pour former ce que l'on appelle des

systèmes cyber-physiques, où l'échange et la transmission de données et d'informations s'effectuent via une plateforme, l'Internet industriel des objets (IIoT).

De plus, en raison des divergences entre les entreprises quant à leur vision de l'industrie 4.0, Suleiman et al. (2022) soulignent l'absence d'une vision unifiée et d'une approche pour la mise en œuvre des feuilles de route. Quelques travaux se sont néanmoins intéressés plus directement au secteur minier. Faz-Mendoza et al. (2020) établissent un lien entre les concepts d'Industrie 4.0 et de Mine 4.0 en identifiant les défis, les opportunités et les tendances technologiques nécessaires pour atteindre la Mine Intelligente. Qassimi et Abdelwahed (2021) examinent le rôle des technologies disruptives dans cette transition. Sishi et Telukdarie (2020) se concentrent sur l'application des technologies de l'industrie 4.0 dans le secteur minier, tandis que Wael et al. (2022) mettent en évidence les principaux défis liés aux projets de TN et proposent des solutions axées sur les données et la cybersécurité, mais n'offrent pas de modèle opérationnel pour guider les initiatives. D'un autre côté, Dragičević et Bošnjak (2019) constatent un manque de recherche dans le secteur minier et cherchent à comprendre les facteurs de réussite et d'échec des initiatives, sans toutefois proposer d'approche structurée pour les piloter. Pour finir, Smith et Sepasgozar (2022) analysent le secteur de la construction et des mines sous l'angle de la règlementation de l'industrie 4.0 afin de définir des normes.

Les articles et leurs constats sont résumés dans le Tableau 2.2 ci-dessous.

Tableau 2.2. TN dans le secteur minier

Auteur	Thématique	Constat
Dragičević et Bošnjak (2019)	TN des entreprises minières	L'état actuel de la TN est faible. Identifie les défis et facteurs critiques de succès.
Young et Rogers (2019)	TN minière	L'industrie minière est en retard par rapport aux autres secteurs.
Faz-Mendoza et al. (2020)	Mine 4.0	Identifie les défis, les opportunités et les tendances technologiques pour arriver à la Mine Intelligente.
Sánchez et Hartlieb (2020)	Innovation et tendance technologique dans l'industrie minière	Le niveau de numérisation est bas et le potentiel de TN est élevé.
Sishi et Telukdarie (2020)	Technologies 4.0	Application des technologies 4.0 dans l'industrie minière
Kalenov et Kukushkin (2021)	TN des entreprises minières	L'industrie minière se transforme plus lentement que d'autres secteurs.
Sörensen et Clausen (2021)	Le futur du secteur minier	Le concept de Mine Intelligente est répandu, mais sa signification est floue.
Qassimi et Abdelwahed (2021)	TN minière	Technologies disruptives dans la TN minière
Clausen et Sörensen (2022)	Futur de l'extraction des minéraux	Définition de la Mine 4.0 et manque d'une vision générale pour la digitalisation
Smith et Sepasgozar (2022)	Régulation minière	Régulation de l'Industrie 4.0 pour définir des standards aidant la TN
Suleiman et al. (2022)	Industrie 4.0	Manque d'une vision unifiée et d'une approche pour le déploiement de l'Industrie 4.0
Wael et al. (2022)	TN minière	Principaux défis des projets de TN

2.3 Pratiques de GPP dans le secteur minier, l'Industrie 4.0 et la TN

Cette section présente les pratiques de GPP dans le secteur minier et dans le contexte de l'Industrie 4.0 et la TN. Les mots-clés et leurs synonymes « portfolio », « mining », « Industrie 4.0 », « digital transformation » ont été utilisés dans la base de données Web of Science.

La TN remodèle la manière dont les organisations fonctionnent en impliquant des changements comportementaux, stratégiques et institutionnels (Chen et al., 2025). Ces transformations sont gérées par le biais de projets et de programmes, ainsi la gestion de projet joue un rôle central. Cependant, la relation entre la TN et la gestion de projet reste fragmentée dans la littérature. Chen et al. (2025) identifient la GPP, la gouvernance et le leadership comme facteurs clés de réussite des initiatives de TN. Plusieurs travaux se sont intéressés à la GPP dans le contexte de l'Industrie 4.0 et de la TN. Richard et al. (2021) proposent une approche de GPP destinée aux PME du secteur manufacturier, articulée autour des neuf phases recommandées par le Project Management Institute (2008). Tandis que Francisco da Silva et al. (2022) analysent les pratiques de GPP de l'Industrie 4.0 et soulignent plusieurs limites nuisant à la création de portefeuilles de projets, notamment le manque de balancement des projets, l'absence d'évaluation continue du portefeuille et une sélection principalement fondée sur le financement plutôt que sur les caractéristiques des projets. Dans le secteur minier, Visser (2020) propose un système visant à améliorer la GPP en déterminant, à l'échelle organisationnelle, les responsabilités liées aux projets de TN dans le secteur minier.

Sur le plan théorique, Ellström et al. (2021), en s'appuyant sur la théorie des capacités dynamiques, montrent que la TN repose sur la capacité des organisations à détecter les opportunités technologiques (*sensing*), à les exploiter stratégiquement (*seizing*) et à reconfigurer leurs ressources et structures organisationnelles (*transforming*). Dans ce cadre, la gouvernance et la GPP constituent des mécanismes clés de la capacité *transforming*, en permettant l'alignement stratégique. Néanmoins, la littérature reliant explicitement TN et GPP demeure limitée, avec un nombre restreint de contributions issues du secteur minier.

Le Tableau 2.3 ci-dessous résume les références.

Tableau 2.3. GPP dans l'Industrie 4.0

Auteurs	Domaine	Résumé
Visser (2020)	Minier	Amélioration de la GPP en proposant un système pour déterminer le responsable des projets
Ellström et al. (2021)	Management	Les capacités dynamiques forment un cadre théorique pour la TN
Richard et al. (2021)	PME manufacturière	Approche opérationnelle suivant neuf phases pour construire un portefeuille de projets de TN
Francisco da Silva et al. (2022)	Industrie 4.0	Identifie les lacunes des entreprises dans la GPP de projets de l'Industrie 4.0
Chen et al. (2025)	Intersectoriel	GPP comme facteur clé de réussite de TN

2.4 Revue critique

Les revues de littérature montrent que les recherches portant sur la TN se concentrent principalement sur le secteur manufacturier, tandis que l'industrie minière demeure largement marginalisée. Ces travaux portent majoritairement sur les technologies (Ghobakhloo et al., 2022; Kutnjak et al., 2019), le niveau d'implémentation de ces technologies (Ortt et al., 2020), les facteurs critiques de succès (Sony & Naik, 2020), ou encore les outils pour évaluer le niveau actuel de numérisation des opérations (Iribarren et al., 2024). De leur côté, Galizia et al. (2023) recensent les meilleures pratiques de l'Industrie 4.0 à partir d'études de cas, sans mentionner les approches pour identifier et sélectionner les projets. Khoshroo et Talari (2022), à travers une analyse des mots-clés liés à la TN, montrent que la GPP n'est pas un concept couramment associé à la TN. Globalement, les travaux ne proposent pas d'approches pour guider la TN des entreprises.

Notre objectif général étant d'améliorer la GPP pour guider la TN des mines souterraines, nous cherchons à établir un lien entre les pratiques de l'Industrie 4.0 et celles de la Mine 4.0. Or, la notion de Mine 4.0 demeure peu définie dans la littérature. Sörensen et Clausen (2021) proposent une brève description sans préciser les objectifs, les solutions ni les processus d'affaires qui soutiennent la transition. Faz-Mendoza et al. (2020) établissent un parallèle entre les deux concepts en termes d'opportunités, de défis et de tendances technologiques associés à la transition vers la Mine Intelligente, mais ne définissent pas le concept en lui-même. D'un autre côté, Kalenov et

Kukushkin (2021) se limitent à identifier les opportunités et les menaces liées à l'intégration des technologies, sans aborder les aspects organisationnels de la transformation. Plusieurs travaux, tels que ceux de Sishi et Telukdarie (2020), Sánchez et Hartlieb (2020), ainsi que Qassimi et Abdelwahed (2021), se concentrent principalement sur les technologies, ne couvrant qu'une dimension partielle des solutions pour arriver à la Mine Intelligente. Wael et al. (2022) s'intéressent davantage aux projets de TN, mais leurs propositions se limitent à des solutions techniques axées sur les données et la cybersécurité. De même, Dragičević et Bošnjak (2019) examinent les facteurs de réussite et d'échec liés à la mise en œuvre des initiatives, sans proposer d'approche structurée pour piloter ces initiatives à l'échelle du portefeuille. Enfin, Smith et Sepasgozar (2022) traitent des standards du côté des régulations destinés à soutenir la TN, sans aborder en détail le concept de la Mine Intelligente. L'ensemble de ces travaux contribue à une compréhension technique fragmentée et partielle de la Mine Intelligente, mais la littérature ne propose pas de cadre conceptuel permettant de clarifier le concept de la Mine Intelligente.

Le concept de la Mine Intelligente n'étant pas défini et les travaux ne proposant pas d'approches pour guider la TN des mines, nous cherchons plus précisément des travaux sur la GPP dans l'Industrie 4.0 la TN et le secteur minier, indiqué comme facteur clé de réussite pour les initiatives de TN par Chen et al. (2025) et Ellström et al. (2021). Richard et al. (2021) et Francisco da Silva et al. (2022) abordent la GPP dans le secteur manufacturier. Le premier propose un modèle opérationnel en neuf phases, mais ne tient pas compte des défis et de la complexité du secteur minier, tandis que le dernier ne traite que des lacunes au sein des entreprises menant une GPP. Seul, Visser (2020) est une référence provenant du secteur minier, mais ne propose qu'un système pour déterminer le responsable des projets sans s'intéresser à la TN ni à la conception du portefeuille de projets. Le Tableau 2.4 ci-dessous résume la revue critique des articles.

Tableau 2.4. Revue critique des articles

Auteur	Domaine	Mine Intelligente	GPP	TN
Dragičević et Bošnjak (2019)	Minier	-	-	Facteurs de réussite et d'échec de mise en place d'initiatives
Kutnjak et al. (2019)	Multi-sectoriel	-	-	Application des technologies
Young et Rogers (2019)	Minier	-	-	Besoin de l'industrie minière
Faz-Mendoza et al. (2020)	Minier	Lien entre Industrie 4.0 et Mine 4.0	-	Défis, opportunités, tendances technologiques
Ortt et al. (2020)	Manufacturier	-	-	Étape de mise en œuvre
Sánchez et Hartlieb (2020)	Minier	-	-	Tendance technologique
Sishi et Telukdarie (2020)	Minier	-	-	Application des technologies 4.0 au secteur minier
Sony et Naik (2020)	Manufacturier	-	-	Facteurs critiques de succès
Visser (2020)	Minier	-	Système pour déterminer le responsable de projets	-
Ellström et al. (2021)	Management	-	Capacités dynamiques	Gouvernance et GPP mécanismes clé de la TN
Kalenov et Kukushkin (2021)	Minier	-	-	Opportunités et menaces liées à l'intégration des technologies
Richard et al. (2021)	PME manufacturière	-	Processus opérationnel en neuf phases	Gestion de portefeuille de projets de TN
Sörensen et Clausen (2021)	Minier	Concept de la Mine Intelligente	-	Technologies
Qassimi et Abdelwahed (2021)	Minier	Impact des technologies sur la Mine 4.0	-	Rôle des technologies disruptives
Clausen et Sörensen (2022)	Minier	Concept de la Mine Intelligente		Solutions pour atteindre la Mine Intelligente
Francisco da Silva et al. (2022)	Manufacturier	-	Lacunes des entreprises en GPP	GPP de TN
Ghobakhloo et al. (2022)	PME Manufacturière	-	-	Adoption des technologies
Khoshroo et Talari (2022)	PME Manufacturière	-	-	Stratégie d'adoption des technologies
Smith et Sepasgozar (2022)	Minier	-	-	Régulations et standards
Suleiman et al. (2022)	Manufacturier	-	-	Caractéristique et technologie de l'Industrie 4.0
Wael et al. (2022)	Minier	-	-	Défis liés aux projets de TN
Galizia et al. (2023)	Intersectoriel	-	-	Meilleures pratiques de l'Industrie 4.0
Iribarren et al. (2024)	Intersectoriel	-	-	Outils d'évaluation du niveau actuel de numérisation
Chen et al. (2025)	Intersectoriel	-	TN en gestion de projets	GPP facteur clé de TN

Pour finir, les recherches effectuées jusqu'à présent ne permettent pas de répondre à la question suivante : Comment améliorer la GPP pour guider la TN des mines souterraines vers la Mine Intelligente? En effet, la littérature ne donne pas de cadre conceptuel du concept de la Mine Intelligente, ni n'associe la GPP à la TN des mines. Les recherches ont permis de démontrer que le concept de la Mine Intelligente est encore flou et pourrait être éclairci. De même, le lien entre

l'Industrie 4.0 et la Mine 4.0 ainsi que l'applicabilité des technologies 4.0 à celle-ci ont été démontrés et les pratiques de GPP appliquées à l'Industrie 4.0 peuvent possiblement être adaptées à la Mine 4.0.

2.5 Conclusion

Les revues de littérature citées précédemment, ainsi que les travaux portant sur l'industrie minière et la GPP, mettent en évidence que les connaissances actuelles sur la TN s'appuient principalement sur le domaine manufacturier, alors que l'industrie minière reste peu étudiée. Ce constat justifie l'objectif général de cette recherche, qui vise à améliorer la GPP afin de guider la TN des mines souterraines. Le chapitre suivant présente les questions de recherche formulées ainsi que la méthodologie visant à répondre à notre objectif général.

CHAPITRE 3 MÉTHODOLOGIE DE RECHERCHE

Ce chapitre présente les objectifs de recherche de cette étude et décrit la méthodologie adoptée pour y répondre. Premièrement, nous préciserons les questions de recherche, la démarche générale de recherche et les objectifs spécifiques visés par cette recherche en lien avec les limitations discutées dans la revue de la littérature. Ensuite, la méthodologie de recherche préconisée y est présentée.

3.1 Démarche générale de recherche

La problématique de cette recherche repose sur la difficulté des compagnies minières à planifier la TN des mines souterraines. Nous avons démontré précédemment que les approches pour guider la TN étaient peu présentes, voire absentes, pour le secteur minier. **L'objectif général de cette thèse est ainsi d'améliorer la GPP afin de guider la TN des mines souterraines.** Pour atteindre notre objectif de recherche, cette thèse vise à répondre aux questions de recherche suivantes:

1. **Quels sont les objectifs associés au concept de Mine Intelligente?**
2. **Quels moyens et processus d'affaires permettent d'atteindre ces objectifs, en tenant compte des spécificités des opérations minières souterraines?**
3. **Quel est le statut actuel des pratiques de TN dans l'industrie minière canadienne, en termes de mise en œuvre, de fréquence d'application et de valeur perçue?**
4. **Comment les entreprises minières peuvent-elles structurer efficacement un portefeuille d'initiatives de TN afin de soutenir la transition vers la Mine Intelligente, tout en tenant compte de la complexité et de l'incertitude propres à leur contexte?**

Afin de répondre à ces questions, nous avons défini les sous-objectifs (SO) spécifiques suivants :

- **SO1 : Caractériser le concept de la Mine Intelligente en précisant les objectifs recherchés, les solutions et le processus d'affaires;**
- **SO2 : Identifier le statut actuel des pratiques de TN dans l'industrie minière canadienne, en termes de mise en œuvre, de fréquence d'application et de valeur perçue; et**
- **SO3 : Développer un modèle de GPP de TN adapté à l'industrie minière et valider le modèle en le confrontant à un cas pratique.**

3.2 Méthodologie de recherche

La Figure 3.1 illustre la méthodologie de recherche adoptée pour atteindre les SO. Chaque SO correspond à une étape de recherche menant à un article. Nous établissons une approche de recherche afin d'ancrer nos recommandations dans la réalité industrielle, tout en tenant compte des caractéristiques propres à l'industrie minière.

Cette recherche a débuté par un stage de recherche MITACS *in situ* en partenariat avec le groupe MISA (pôle d'excellence en exploration et exploitation minière au Québec). Ce stage, s'étalant sur six mois, combinant une étude de terrain et des observations directes, a permis de collecter des données empiriques et de clarifier les SO ainsi que les spécificités des mines souterraines qui seront prises en compte par la suite.

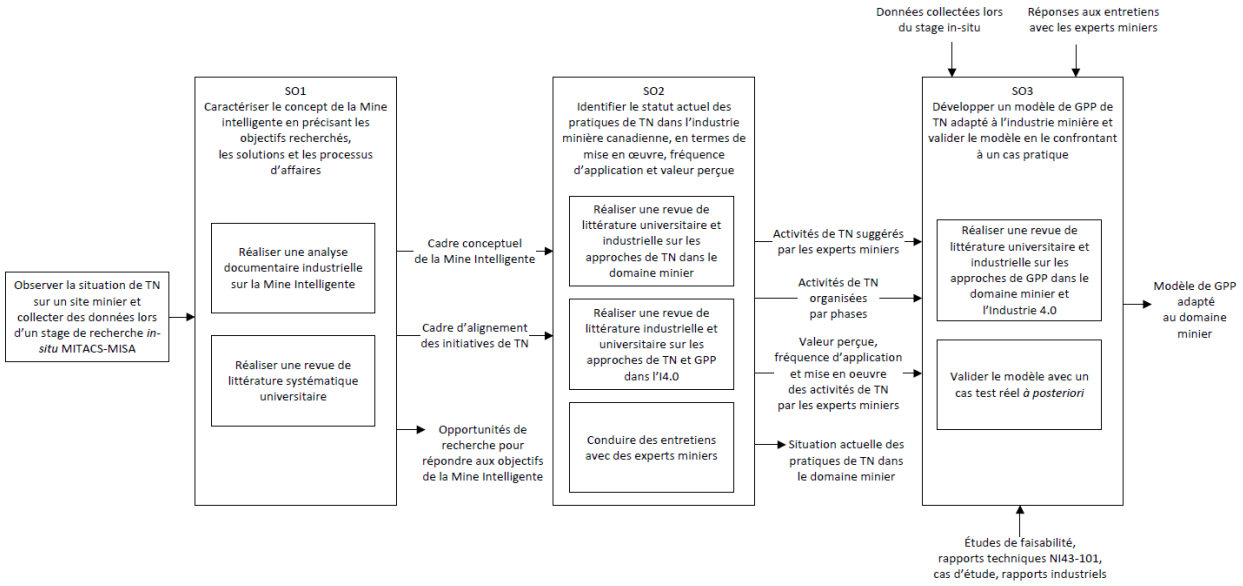

Figure 3.1. Méthodologie de recherche

3.2.1 Article 1

Dû au critère émergent de la Mine Intelligent, l'article 1 s'appuie sur une analyse documentaire issue du milieu industriel pour clarifier le concept de Mine Intelligente appliqué aux opérations d'extraction souterraine, en termes d'objectifs, de solutions et de processus d'affaires, tels que définis par les praticiens de l'exploitation minière. Les sources industrielles proviennent de rapports internes, de livres blancs ou de présentations de fournisseurs de solutions technologiques permettant de décrire les pratiques réelles et tendance émergente. Pour s'assurer de la fiabilité nous

avons recoupé les informations entre plusieurs sources. Cependant, leur portée reste limitée à certaines compagnies ou technologies spécifiques, ce qui peut restreindre la représentativité de l'industrie. Elles peuvent présenter des biais potentiels en se focalisant sur leurs succès plutôt que leurs échecs. Ces éléments ont été pris en compte lors de la construction du cadre conceptuel. Lors de l'analyse des publications industrielles, il est apparu que plusieurs thèmes étaient abordés, de manière fragmentée, touchant tant aux objectifs stratégiques qu'aux solutions technologiques ou aux processus d'affaires. Pour structurer cette diversité d'informations, les chercheurs ont regroupé les thèmes identifiés dans un cadre conceptuel organisé autour de ces trois dimensions : objectifs, solutions et processus d'affaires.

Les sous-catégories proposées pour la dimension « solution » et plus particulièrement « technologies » du cadre d'analyse ne correspondent pas directement aux classifications déjà établies par les communautés travaillant sur la transformation numérique. Cette décision méthodologique a été motivée par la volonté de refléter la diversité des solutions observées spécifiquement dans le contexte minier souterrain, où les technologies sont appliquées de manière très pratique et intégrée aux opérations. Nous avons choisi de regrouper les solutions selon les mentions faites dans les publications industrielles pour rester ancrer dans les réalités du secteur minier, donnant six catégories pour le cadre conceptuel. Du côté des technologies identifiées dans les publications et rapports industriels, l'objectif était de créer un langage analytique commun permettant de comparer, structurer et analyser les technologies utilisées dans le secteur minier. Ce choix vise donc moins à reproduire les classifications générales de la littérature sur la transformation numérique que d'adapter le cadre aux spécificités opérationnelles et technologiques du contexte étudié.

Le cadre conceptuel obtenu sert de base à une revue systématique de la littérature scientifique, selon la stratégie proposée par Tranfield et al. (2003), afin de comparer la vision industrielle aux travaux universitaires récents (SO1). Une requête a été créée pour chaque terme apparaissant dans le cadre conceptuel. La requête est la suivante : « Terme du cadre conceptuel » AND ("Smart Mine" OR "digital mine" OR "intelligent mine" OR "mine 4.0") AND "underground", dans le titre, le résumé et les mots-clés. Les publications dans une autre langue que le français et l'anglais ont été exclues ainsi que les articles sur les mines à ciel ouvert, de dissolution, de charbon et en longue taille ont été exclus par lecture des résumés et du texte intégral au besoin.

L'analyse croisée des publications scientifiques visant à identifier les solutions liées aux objectifs a été réalisée selon une démarche de validation par échantillonnage en binôme. Un échantillon de 10% du corpus total, soit 16 articles sélectionnés aléatoirement, a été analysé indépendamment par deux chercheurs. Chacun a procédé à l'association des solutions aux objectifs, puis les résultats ont été comparés. La convergence des résultats a confirmé les critères d'inclusions et d'exclusions retenus. Suite à cette validation, la chercheuse principale a poursuivi l'analyse de l'ensemble du corpus.

Basé sur le cadre conceptuel de la Mine Intelligente, nous établissons un cadre d'alignement des initiatives TN pour aider les compagnies minières à sélectionner leurs initiatives de TN selon les travaux publiés sur la TN des entreprises.

3.2.2 Article 2

L'article 2 évalue les approches de TN employées dans le secteur minier souterrain canadien et identifie les bonnes pratiques issues de l'Industrie 4.0, afin d'établir les activités recommandées et jugées utiles par les praticiens de l'exploitation minière afin de créer un portefeuille de projets (SO2). Pour cela, une première revue de littérature universitaire et industrielle a été conduite pour positionner notre recherche selon l'état actuel des pratiques de TN dans le domaine minier. La base de données Web of Science a été utilisé avec les mots-clés « Digital transformation » AND (« approach » OR « Roadmap » OR « assess » OR « framework » AND (« mining » OR « mine »). Les résultats abordant les approches utilisées dans le secteur minier souterrain ont été sélectionné.

Pour construire notre cadre analytique des bonnes pratiques, nous établissons une revue de la littérature universitaire et industrielle sur les approches de TN en gestion de projets et en GPP dans le domaine minier et dans l'Industrie 4.0. La requête suivante a été utilisée dans les bases de données Scopus, Web of Science, IEEE, Mining, Metallurgy and Exploration Journal ainsi que Google Scholar : Titre, résumé et mots-clés ("project portfolio" OR "model" OR "framework" OR "canva" OR "roadmap") AND "digital transformation" AND ("mining OR mine OR Industry 4.0)"

Les publications sélectionnées adressent la GPP ou des pratiques de TN, rédigées en français ou en anglais, publiées après 2011 (émergence du concept de l'Industrie 4.0). Les références des articles sélectionnés ont été lues. Au total sept publications sont sélectionnées. Pour la revue de littérature industrielle, nous avons consulté les rapports publiés sur les sites internet des firmes de génie-

conseil et fournisseurs de solutions technologiques qui donnent des pratiques de TN pour les compagnies minières. Onze documents ont été incorporés.

L'évaluation des phases et activités recommandées s'appuie sur dix questionnaires suivis d'entretiens semi-dirigés menés entre janvier et septembre 2024 auprès d'experts en gestion de projets dans le secteur minier. Ces experts représentent différents niveaux organisationnels d'entreprise minière canadienne (deux directeurs ayant 10 et 15 ans d'expérience, trois gestionnaire de projets ayant entre 8 et 17 ans d'expérience, deux gestionnaires de portefeuille de projets ayant 15 et 25 ans d'expérience et un gestionnaire de mine ayant 8 ans d'expérience), un gestionnaire de projet de génie-conseil ayant 12 ans d'expérience et un gestionnaire de projet de fournisseurs de solutions technologiques ayant 5 ans d'expérience dans le secteur minier. Au Canada, une centaine de mines souterraines sont recensées et exploitées par un nombre limité de grandes et moyennes entreprises minières canadiennes, au nombre de treize. Dans ce contexte, l'échantillon constitué de dix experts issus de compagnies différentes permet de couvrir une diversité de perspectives organisationnelles et opérationnelles, contribuant ainsi à une représentativité raisonnable des pratiques et enjeux associés au secteur minier souterrain canadien.

Conformément aux recommandations méthodologiques de Yin (2018), la collecte de données repose sur un questionnaire structuré, combinant des questions fermées (oui/non), des échelles de Likert et des classifications. Cette structure permet d'assurer la comparabilité des réponses entre les participants, de standardiser le recueil d'information et de minimiser les biais liés à l'interprétation de l'enquêtrice. Les experts ont été sélectionnés en fonction de leur expertise et contactés par courriel. La méthodologie combinant questionnaire et entretiens semi-dirigés a été validée par le comité d'éthique. Nous utilisons la triangulation des méthodes (questionnaire structuré et entretiens semi-dirigés) pour réduire le biais et renforcer la validité. Les entretiens semi-dirigés individuels ont ensuite été réalisés pour approfondir les réponses au questionnaire et clarifier les pratiques observées, avec des options de réponse standardisées (oui, non, possible, non applicable). L'utilisation d'un langage uniforme lors des entretiens, guidés par le questionnaire, contribue à la fiabilité et à la cohérence des données. Cette approche permet de quantifier les perceptions et pratiques, facilite l'analyse statistique et la comparaison entre les profils tout en offrant une flexibilité pour expliciter et contextualiser certaines réponses.

3.2.3 Article 3

Basé sur les résultats de l'article 2 et sur une revue de la littérature universitaire et industrielle, l'article 3 propose un modèle de GPP adapté aux défis du secteur minier, validé par l'application au cas d'une mine souterraine a posteriori (SO3). Une approche opérationnelle est utilisée, s'appuyant sur les données collectées lors du stage in situ et complétée par des entretiens menés trois ans plus tard avec deux acteurs clés de la TN au sein de l'entreprise YXE. Ces entretiens permettent d'obtenir une rétrospective sur la gestion de leur portefeuille de projets, d'ajouter des informations contextuelles et de documenter l'évolution des initiatives du portefeuille initial. L'application du modèle au cas test requiert des informations quantitatives et qualitatives. Les données mobilisées pour la phase d'évaluation proviennent des études de faisabilité, des rapports techniques NI43-101 publiés par l'entreprise YXE, ainsi que de sources publiques telles que des cas d'étude et divers rapports industriels. Dans le cadre de cette recherche, une plateforme d'intelligence artificielle (IA) générative a également été utilisée comme source d'information complémentaire pour regrouper et synthétiser les données destinées à la phase de validation du modèle. Cela a permis d'identifier des références et des chiffres relatifs aux différents critères d'évaluation, facilitant la collecte d'informations dispersées dans les rapports industriels. Toutefois, afin de garantir la fiabilité et la rigueur scientifique, chaque source identifiée par l'outil a été lue, vérifiée et validée par la chercheuse, et seules les informations corroborées par des publications ou rapports fiables ont été intégrées. Cette approche assure que l'IA ne remplace pas l'analyse critique, mais sert d'assistant pour structurer les données et orienter la recherche. Ses limites principales résident dans la dépendance aux données disponibles en ligne, le risque d'omissions et la nécessité de validation humaine pour éviter l'intégration d'informations inexactes ou hors contexte. Ainsi, l'outil d'IA est utilisé de manière encadrée, comme complément au processus analytique, et non comme source principale, renforçant l'efficacité tout en maintenant la rigueur méthodologique.

Les contributions importantes de ces travaux ont donné lieu aux articles suivants qui forment le cœur de cette thèse:

- Article 1: Echternach-Jaubert, M., Pellerin, R., & Gamache, M. (2024). Opportunities for research to achieve the vision of the Smart Mine. *CIM Journal*, *15*(4), 201–234. https://doi.org/10.1080/19236026.2024.2377527;

- Article 2: Echternach-Jaubert, M., Pellerin, R., & Gamache, M. (2025). Implementation Approaches for Digital Transformation: Current State of the Mining Industry. *Mining, Metallurgy & Exploration Journal*. https://doi.org/10.1007/s42461-025-01347-5; et
- Article 3: Echternach-Jaubert, M., Pellerin, R., & Gamache, M. (2025). Digital transformation in mining: A practical portfolio management model, *CIM Journal* (soumis le 4 novembre 2025).

Les trois chapitres suivants présentent ces articles.

CHAPITRE 4 ARTICLE 1: OPPORTUNITIES FOR RESEARCH TO ACHIEVE THE VISION OF THE SMART MINE

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4.1 Résumé

L'industrie minière est façonnée par la TN en cours, qui aboutit à la mine intelligente. Cet article vise à clarifier ce concept pour les opérations d'extraction souterraine, tel qu'il est exprimé par les praticiens de l'exploitation minière, et à comparer cette vision avec les récents travaux universitaires. Sur la base d'une analyse documentaire axée sur l'industrie, cet article catégorise la vision de la mine intelligente en termes d'objectifs, de solutions et de processus de gestion d'entreprise. Le cadre est ensuite utilisé pour analyser des articles académiques sélectionnés à partir d'une revue systématique de la littérature. Les résultats montrent que les praticiens de l'exploitation minière et les universitaires s'accordent sur les objectifs financiers, opérationnels, commerciaux, sécuritaires et environnementaux de la mine intelligente souterraine. De multiples solutions pour réaliser une mine intelligente sont proposées et impliquent l'infrastructure, la technologie, les personnes, la culture, les systèmes de gestion, les processus et l'équipement. Les universitaires et les praticiens de l'exploitation minière se concentrent sur les initiatives en matière d'équipement et de technologie, alors que les personnes et la culture sont sous-estimées. Ces solutions impliquent divers processus de gestion d'entreprise, les praticiens mettant davantage l'accent sur la gestion environnementale, sociale et de gouvernance (ESG) et sur la gestion de l'information et des données. Cependant, la littérature académique sur les processus de gestion d'entreprise est relativement rare et se concentre principalement sur l'éducation et la formation, la gestion de l'automatisation et la gestion ESG. La gestion des actifs, la gestion du changement et la gestion des risques et de la sécurité devraient être développées.

Mots clés : cadre de travail, Industrie 4.0, mine intelligente, mine souterraine, transformation numérique

4.2 Abstract

The mining industry is being shaped by ongoing digital transformation, leading to the Smart Mine. This article aims to clarify this concept for underground extraction operations as expressed by mining practitioners and compare this vision with recent academic work. Based on an industry-focused literature review, this paper categorizes the vision of the Smart Mine in terms of objectives, solutions, and business management processes. The framework is then used to analyze academic papers selected from a systematic literature review. Results show that mining practitioners and academics are aligned in terms of the financial, operational, business, safety, and environmental

objectives of the underground Smart Mine. Multiple solutions to achieve a Smart Mine are proposed and involve infrastructure, technology, people, culture, management systems, processes, and equipment. Both academics and mining practitioners focus on equipment and technology initiatives, while people and culture are underestimated. These solutions involve various business management processes, with a greater emphasis from practitioners on environmental, social, and governance (ESG) and information and data management. However, the academic literature on business management processes is relatively sparse and mainly focuses on education and training, automation management, and ESG management. Asset management, change management, and risk and safety management should be further developed.

Keywords: Digital transformation, Framework, Industry 4.0, Smart Mine, Underground mine

4.3 Introduction

Mining is one of the last industrial sectors to digitalize operations (Young & Rogers, 2019). Mining companies face several unique challenges with integrating digital technologies, such as scattered digital transformation terminology, lack of agility, data abundance, health and safety concerns, pressure to increase productivity to meet global demands, and a high level of uncertainty (Ali & Frimpong, 2020). Mines also face an aging workforce and a lack of digitally literate employees and leaders (Dragičević & Bošnjak, 2019). Most challenges are related to executing technology integration, mainly because most mining companies do not have a clear vision of the objectives of digital transformation (Barnewold & Lottermoser, 2020). Moreover, the life of the mine, its residual value, and the return on investment are highly decisive in steering digital investments (Institut National des Mines, 2021) in a context wherein mining complexes are ephemeral organizations: The first day of the operation of a mining complex is also the first day of its closure plan. One of the major discrepancies in visions of the future mine is the path to achieve it (Gipps et al., 2011).

Although the mining industry is moving toward the Smart Mine, the definition of this concept has not yet been established (Sörensen & Clausen, 2021). The terms *Smart Mine, Intelligent Mine, Digital Mine,* and *Mine 4.0* are used interchangeably in the academic literature to describe mines of the future. A distinction can be made here between the digital mine, which is the extension of the digital project used in the mine (Ge & Zhang, 2011), and the Smart Mine. Mine 4.0 relates to Industry 4.0. In this paper, we use the term Smart Mine, which is related to the state of the future

mine. From a practitioner's perspective, a Smart Mine refers to "an autonomous, electric, carbon dioxide-free, connected, sustainable mine" (ABB, 2022; Canadian Mining Journal Staff, 2021; Hillal, 2022). Some researchers broadly interpret this concept and describe a Smart Mine as a "long-term vision of a digitally connected, autonomous mine in which the connected systems can reduce the ever-increasing complexity to such an extent that improved decision-making can be realized in real-time while reducing the environmental impact of operations and enhancing productivity and safety" (Sörensen & Clausen, 2021).

Recognizing the different interpretations of the Smart Mine concept, our objectives are to evaluate recent research on the digital transformation in mining to (1) clarify the vision of the Smart Mine as defined by mining practitioners for underground extraction operations and (2) encourage research opportunities to achieve the practitioners' expectations regarding the Smart Mine. More precisely, this paper attempts to answer the following research questions:

1. What are the objectives of the Smart Mine?
2. How can the objectives of the Smart Mine be accomplished?
3. Which business processes should be implemented to meet the targeted objectives?
4. What are the opportunities for academic research to help the mining industry achieve the Smart Mine?

The remainder of the paper is organized as follows. We first outline our research methodology for gathering industry-focused and academic literature and then review the concepts of the Smart Mine, focusing on the digital transformation of underground mines linked to the extraction phase. We follow with a comparison of the mining industry's vision to the academic literature. The industry-focused review is used to conceptualize the vision of the Smart Mine into a transformation initiative alignment framework to guide mining practitioners. Finally, we conclude by identifying gaps and opportunities for potential future research.

4.4 Methodology

We gathered industry-focused literature from Google, Onemine.org, The Australasian Institute of Mining and Metallurgy (AusIMM), the Society of Manufacturing Engineers (SME), The Southern African Institute of Mining and Metallurgy (SAIMM), The Canadian Institute of Mining, Metallurgy and Petroleum (CIM), presentations, webinars, and newsletters (Figure 4.1). Our queries included the keywords digital transformation, Smart Mine, digital mine, intelligent mine,

Mine 4.0, underground mine, unmanned mining, and automation. Most (70%) of the studies included in the review were industry reports and magazine articles. Only five studies were published before 2016, and the number of studies generally increased in subsequent years. Given the focus on underground mines, we excluded literature related to surface mines. Solution mines were excluded because no underground human intervention occurred. Papers related to coal and longwall mining were excluded from the search results based on the formal ontology that classifies mine types (Cheng, G. et al., 2011). Coal mines mainly use longwall mining methods, a continuous, fully automated process.

The systematic review of the academic literature was conducted based on the strategy proposed by Tranfield et al. (2003) presented in Figure 4.1. The paper selection process ensured that the literature review was replicable. We queried Scopus, Web of Science, AusIMM, SME, SAIMM, and CIM Journal databases according to the themes that emerged from the industry literature, regrouped in the Vision of the Smart Mine framework (Figure 4.2). Articles containing the keyword "Smart Mine" or its synonyms were collected that (1) addressed the underground Smart Mine concept linked to the extraction phase, (2) were written in French or English, and (3) were published in or after 2011 when the Industry 4.0 concept first appeared. Note that at the time of writing, few articles had been published in 2024. In total, 160 articles addressing the key concepts of the Smart Mine were retrieved, 41% of which were published in peer-reviewed journals. The 160 articles were classified according to three predominant research themes from the Vision of the Smart Mine framework (Figure 4.2). Some articles dealt with more than one theme. We then conducted a cross-analysis of the objectives and solutions according to the articles' keywords to determine the advancement of the research.

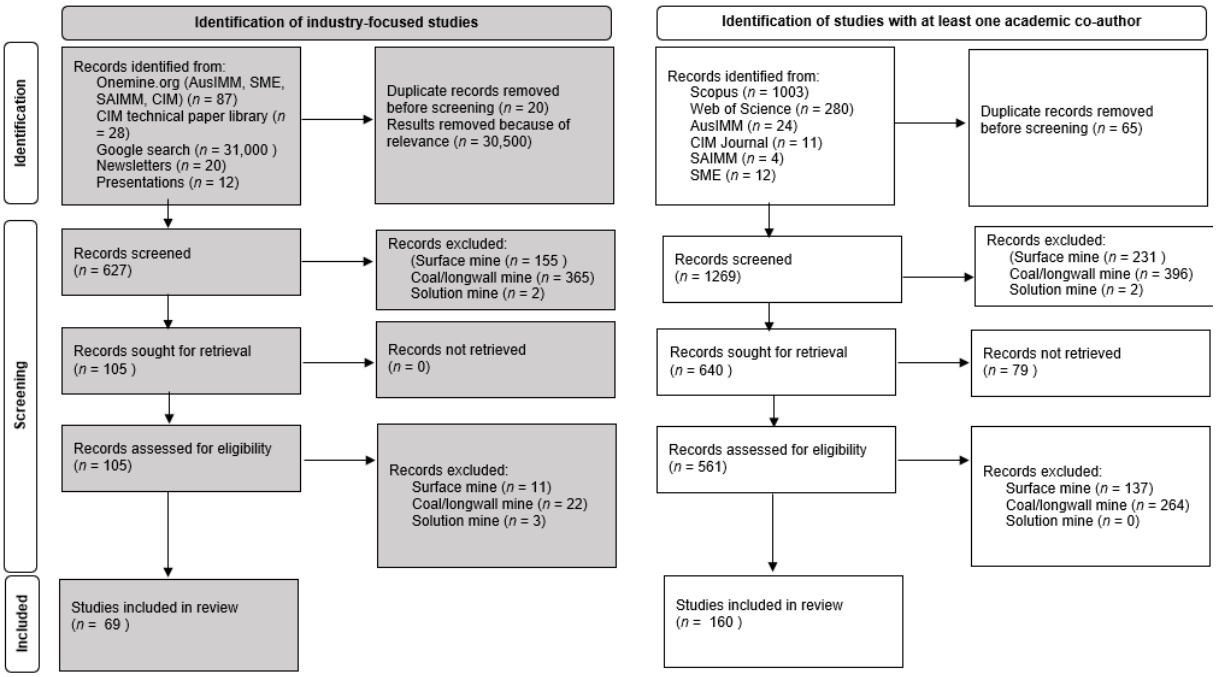

Figure 4.1 Research protocol

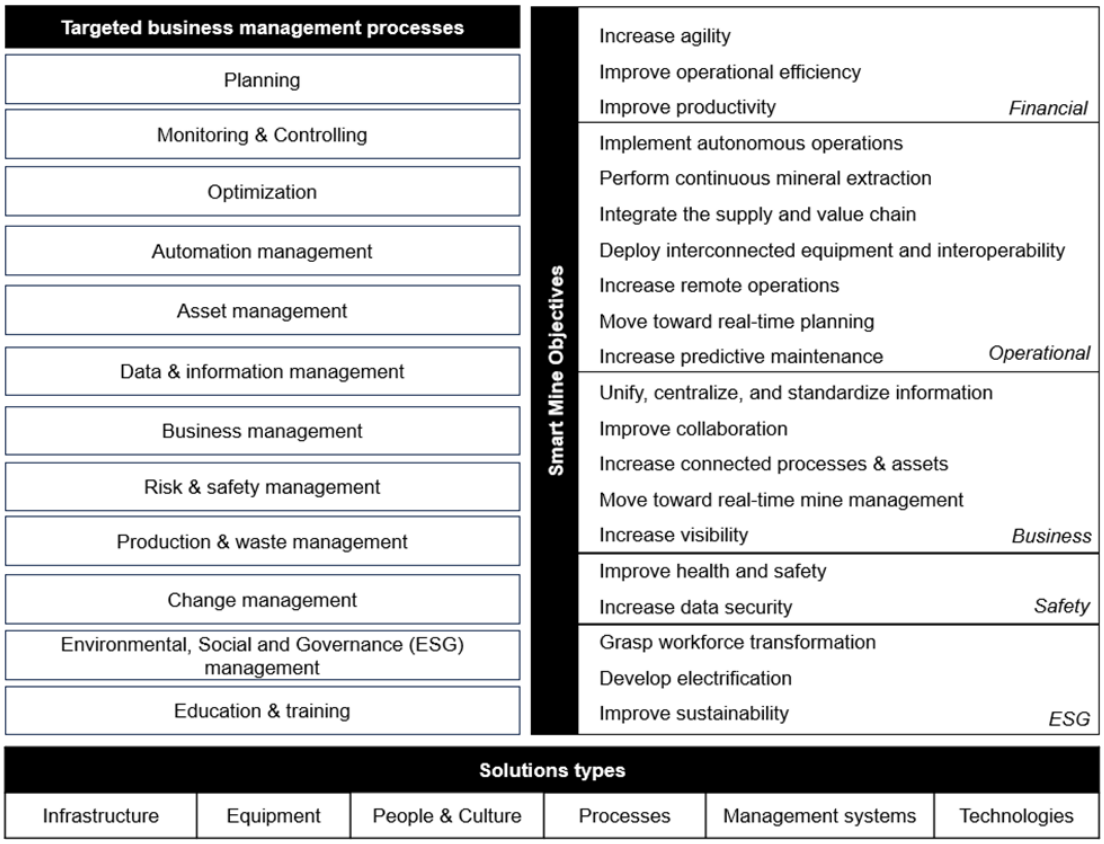

Figure 4.2 Vision of the Smart Mine framework as defined by mining practitioners for underground extraction operations

The academic literature review on the concept of Smart Mine presented here is thus distinct from the work of Faz-Mendoza et al. (2020), who linked the concept of Industry 4.0 with Mining 4.0. They reviewed the trends, challenges, and opportunities of intelligent process 4.0 technologies required by the mining sector to successfully digitize a mine. Qassimi et Abdelwahed (2022) reviewed smart manufacturing and disruptive technologies, such as the Internet of Things (IoT), cyber-physical systems, and digital twins, to assist the mining industry in moving toward data-driven smart manufacturing. Smith et Sepasgozar (2022) analyzed scientific studies on regulating Industry 4.0 and how to best meet the standards on which the mining industry will depend.

4.5 VISION OF THE SMART MINE FROM AN INDUSTRY-FOCUSED PERSPECTIVE

According to industrial studies, the Smart Mine is based on four pillars (Figure 4.3): the digitally connected mine (ABB, 2022), the autonomous mine (ABB, 2022), the sustainable mine (Schroedter, 2020), and the Miner 4.0 mine (Institut National des Mines, 2021). The Miner 4.0 mine emphasizes a human-centered workforce transformation. The pillars of the Smart Mine are described below according to the objectives, solutions, and targeted business management processes and are summarized in Figure 4.2.

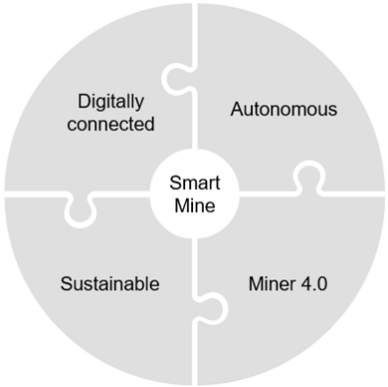

Figure 4.3 The four pillars of the Smart Mine

4.5.1 Smart Mine objectives

The objectives refer to the strategic goals of the Smart Mine. According to mining practitioners, the objectives are classified into five categories: financial, operational, business management, safety, and environmental (Figure 4.2).

4.5.1.1 Financial objectives

Increase agility

Agility refers to the ability to quickly adapt to events and respond to market changes with digitally enabled business solutions. Mines must perform agile adjustments to lifecycle plans based on real-time information, rather than guesses based on professional experience or historical data. Smart Mines will shift from a siloed to an agile value-driven business model (AVEVA, 2018b; GMG, 2022; Moore, 2019; Schroedter, 2020).

Improve operational efficiency

Operational efficiency refers to the effectiveness of the mining process, mining equipment, and the entire supply and value chains. The Smart Mine links every piece of equipment, person, and infrastructure to create a digital model that can be used to assess decisions in real time and drive efficient operations. New technologies, digital training, software, processes, and innovative equipment will help make business processes, decision-making, and operations more efficient (Braul, 2017; Gleeson, 2018, 2022a; GMG, 2022; Hedlin, 2011; Hejny, 2016; Luedtke, 2021; McHattie, 2014; Sörensen & Clausen, 2021).

Improve productivity

Productivity refers to mine performance. Mining companies develop roadmaps that consider different strategic programs to improve productivity. The Smart Mine leads to more-productive operations and personnel and improves planning and decision-making processes through processes, technologies, software, and equipment (Cann, Hall, Shemer, et al., 2021; Gleeson, 2018, 2022a; GMG, 2019b; Moore, 2019).

4.5.1.2 Operational objectives

Operational objectives relate to the operations side of the extraction stage, encompassing the mining method, equipment, and processes.

Implement autonomous operations

Autonomous operations, one of the four pillars of the Smart Mine (Figure 4.3), is facilitated by autonomous equipment, systems, and capacities. The focus is on autonomous operations that integrate data-critical variables from processes, assets, environment, and financials that can be

controlled and leveraged (AMCConsultant, 2022; Caterpillar, 2011; GMG, 2022; Hillal, 2022; Honeywell, 2022; Lopez-Pacheco, 2017; McHattie, 2014; Scales, 2019a; Schroedter, 2020; Sörensen & Clausen, 2021). Equipment, technologies, processes, infrastructure, and security are necessary to achieve autonomous production (Cann, Hall, Shemer, et al., 2021; Kral et al., 2016; Lopez-Pacheco, 2019).

Perform continuous mineral extraction

Continuous mechanical excavation of mineral deposits, especially hard rock, is essential to Smart Mine operations. New continuous cutting machines will replace the traditional drill, blast, and muck mining sequence {Chadwick, 2017; Hedlin, 2011; Hejny, 2016; Moore, 2022).

Integrate supply and value chains

Digitalizing the supply chain from pit to port is a trend that is expected to continue. The Smart Mine will share data across the entire value chain, and the supply chain will be more integrated by digitally connecting people, processes, and technology (AVEVA, 2018b; Gleeson, 2018; Hillal, 2022; Moore, 2019, 2022; Quash, 2019; Schroedter, 2020).

Deploy interconnected equipment and interoperability

Interoperability has become a vital driver for all miners. Smart mining using interconnected machines will become commonplace, so the need for interconnected and interoperable equipment is considerable. Miners seek not to be constrained by a single original equipment manufacturer (OEM) system to add technology to their operations (Cann, Hall, Meeson-Frizelle, et al., 2021; Cann, Hall, Shemer, et al., 2021; ERNQ, 2019; Gleeson, 2018; Institut National des Mines, 2021; Lopez-Pacheco, 2019; Sörensen & Clausen, 2021).

Increase remote operations

The industry is exploring how mining operations can be supported via remote operations centers to control underground equipment, ventilation, and dewatering systems as well as to monitor the mining process (AMCConsultant, 2022; AVEVA, 2018a; Cann, Hall, Meeson-Frizelle, et al., 2021; Hejny, 2016; Keating, 2019b).

Move toward real-time planning

The Smart Mine is turning toward predictive agile planning, where operations are planned in real-time and events lead directly to adjustments in planning and execution (GMG, 2019a; Hillal, 2022; McHattie, 2014; Schroedter, 2020).

Increase predictive maintenance

Predictive maintenance overcomes reactive maintenance and avoids downtime, thereby improving productivity. Based on the equipment's actual use and operating conditions, predictive maintenance leads to prescriptive maintenance involving analytic approaches such as big data analysis, artificial intelligence (AI), machine learning (ML), and deep learning. Obtaining real-time operational data is the most important factor to achieve predictive maintenance (AVEVA, 2018b; Chadwick, 2017; Gleeson, 2022a; Marek et al., 2012; Moore, 2019; Provencher 2020).

4.5.1.3 Business management objectives

Unify, centralize, and standardize information

Unifying and centralizing information from information silos and the operational side of projects promotes data exchange and leads to data-driven decision-making. Standardization of data exchange is one of the most important methods to connect data and operations to achieve the Smart Mine (Chadwick, 2017; ERNQ, 2019; Gleeson, 2018; GMG, 2022; Hejny, 2016; Luedtke, 2021; Moore, 2019).

Improve collaboration

Collaboration (and connected processes and assets below) objectives refer to breaking down silos and promoting communication between machines and people and among people. Interdisciplinary collaboration among all parties involved in mining projects, including OEMs, suppliers, customers, competitors, workers, technology companies, data scientists, academics, technical experts, and communities around mining sites is key to transforming the mining business (AVEVA, 2018a, 2018b; Chadwick, 2017; ERNQ, 2019; GMG, 2019a, 2022; Hillal, 2022; Luedtke, 2021, 2022; Moore, 2022; Schroedter, 2020).

Increase connected processes and assets

Operations— from the office to the underground face—are connected in the Smart Mine through connected machines, operations, and people (ABB, 2022; Chadwick, 2017; Gardner, 2021; GMG, 2022; Kral et al., 2016; Lopez-Pacheco, 2019).

Move toward real-time mine management

Mine management is about decision-making. The Smart Mine is more predictive than reactive; every activity in the mine is continuously digitally monitored, and the mine plan is automatically optimized for the short-, medium-, and long-term to better achieve the company's strategic goals. Operation staff will also be able to select from various suggested scenarios that consider safety, feasibility, and profitability (AVEVA, 2018b; Braul, 2017; ERNQ, 2019; Schroedter, 2020).

Increase visibility

Visibility refers to the ability of a company to know what is happening in real time and the overall status of the mine. Total real-time visibility connects upstream, midstream, and downstream operations and reduces operational silos (ABB, 2022; AVEVA, 2018a, 2018b; Honeywell, 2022; McHattie, 2014; Schroedter, 2020).

4.5.1.4 Safety objectives

Safety refers to the physical and psychological (i.e., equity, diversity, inclusion, and belonging) health and safety of workers and safeguards digital information throughout the entire value chain.

Improve health and safety

A high level of automation removes workers from the working face and dangerous situations. The development of new technologies should incorporate health and safety design criteria and guidelines such as those related to autonomous systems and automated equipment developed by the U.S. National Institute for Occupational Safety and Health in partnership with academia, government, labor, industry, and professional organizations (ABB, 2022; AVEVA, 2018a; Cann, Hall, Meeson-Frizelle, et al., 2021; Caterpillar, 2011; Chadwick, 2017; Gardner, 2021; GMG, 2019a; Haight et al., 2021; Hejny, 2016; Hillal, 2022; Kral et al., 2016; Lopez-Pacheco, 2019; Luedtke, 2021; Moore, 2022).

Increase data security

Data security is one of the intangible factors of the Smart Mine. The mining industry must increase vigilance and protect worker and company private information. All critical variables from the process, assets, environment, and financial data will be controlled in a cyber-secure way (ERNQ, 2019; Honeywell, 2022; Institut National des Mines, 2021).

4.5.1.5 Environmental, social, and governance (ESG) objectives

This section focuses on approaches to transform the workforce to retain talent, implement electrification to reduce greenhouse gas emissions, and enhance the sustainability of the mining environment.

Grasp workforce transformation

Digital transformation transforms all facets of the mining industry. The Smart Mine will break down silos by relying on multidisciplinary teams and versatile employees with a broad set of skills while enhancing ESG mandates. Miner 4.0 (Institut National des Mines, 2021) comprises eight worker attributes: powerful, augmented, virtual, health, intelligent, collaborative, social, and analytic (AVEVA, 2018a; Cann, Hall, Shemer, et al., 2021; Gardner, 2021; GMG, 2022; Keating, 2019b; Rolfe, 2022; Schroedter, 2020).

Develop electrification

Electrification reduces the carbon footprint of the Smart Mine. The journey toward all-electric mine sites has begun with battery-electric vehicles (BEVs). However, no “one-size-fits-all” solution exists: Site-specific factors such as the electrical supply, ventilation airflow requirements, charging strategies, and shift cycles must be considered (ABB, 2022; GMG, 2022; Hillal, 2022; Luedtke, 2021, 2022; Moore, 2022; Scales, 2019a).

Improve sustainability

Sustainability is the most important pillar of the Smart Mine (Figure 4.3). The development of innovative techniques, technologies, machines, and equipment is necessary for efficient exploitation of minerals, disposal of waste, and upholding the commitment to become carbon neutral (AVEVA, 2018b; Gardner, 2021; Gleeson, 2022b; Hedlin, 2011; Hejny, 2016; Hillal, 2022; Hitachi construction machinery, 2022; Institut National des Mines, 2021; Luedtke, 2021; Moore,

2022; Schroedter, 2020; Sörensen & Clausen, 2021). “Geomimic” refers to processes and technologies that mimic long-term geological processes and is a starting point for mine engineering to find environmentally benign extractive technologies (Javier, 20160. The relationship between technology and sustainability is made explicit in the concept of the “human-centered climate Smart Mine” (Clausen & Sörensen, 2022), whereby the mine goes beyond being digitally connected and autonomous toward being human centered and environmentally conscious, placing people and sustainability at the forefront of the digital transformation.

4.5.2 Smart Mine proposed solutions

4.5.2.1 Infrastructure

Communication, connectivity, and information technology infrastructure are essential for the Smart Mine to ensure communication and information transfer among different systems and types of equipment (GMG, 2022; Hitachi construction machinery, 2022; Hiyate, 2017; Institut National des Mines, 2021; Luedtke, 2021; Moore, 2022; Scales, 2019a; Schroedter, 2020; Sörensen & Clausen, 2021).

4.5.2.2 Equipment

Robots

Robots help with repetitive, rule-based processes and tasks and remove workers from the working face to improve worker safety. Research and development for autonomous underground technology focuses on refining robotic vehicles to self-learn (Hillal, 2022; Lopez-Pacheco, 2019; Schroedter, 2020; Sörensen & Clausen, 2021).

Drones and unmanned aerial vehicles

Drones are making their way into underground mines to facilitate mapping and real-time data capture, monitoring, and inspection of dangerous zones (Hrabar, 2021; Institut National des Mines, 2021; Sörensen & Clausen, 2021).

Trucks

Trucks are the most common autonomous equipment in underground mines. Battery electric trucks are being developed and used at some mine sites. The conversion to electric trucks reduces

emissions, diesel-particulate-matter levels, and ventilation requirements (Caterpillar, 2011; Li, G. et al., 2024; Scales, 2017b, 2018; Scales, 2019b; Schroedter, 2020).

Load-haul-dump vehicles (LHDs)

Remote LHD operations from a central control room have been developed and are in operation. The transition is now on converting diesel to electric LHDs (Acuña-Duhart et al., 2024; Lopez-Pacheco, 2017, 2019; Luedtke, 2021, 2022; Quash, 2019).

Bolters and drills

Intelligent cable bolter and battery electric drilling equipment is being developed (Scales, 2017a; Scales, 2019b).

Continuous machines

Continuous machines such as road headers are being developed to meet the specific requirements of hard-rock mining (Moore, 2022).

Other mining equipment

New underground mining equipment, such as autonomous transportation vehicles, is being developed and used. Transitioning from diesel-powered vehicles to BEVs is gaining popularity across the mining industry (GMG, 2019a; Luedtke, 2021; Moore, 2022; Scales, 2019a).

Wearable devices

Wearable technologies, such as connected personal protective equipment and tracking devices, will provide data and offer insights for mining operators and improve safety. Real-time decision-making and enhanced communications are additional benefits (AVEVA, 2018b; Institut National des Mines, 2021; Scales, 2019a; Schroedter, 2020).

4.5.2.3 People and culture

Digital transformation will change the way mines work. It is crucial to invest in cultural change in the organization, workforce, rights holders, and communities while implementing the Smart Mine (Chadwick, 2017; Gardner, 2021; GMG, 2019a; Keating, 2019b; Schroedter, 2020; Sörensen & Clausen, 2021). The mine of the future is not only about technical breakthroughs but also about culture and language (Zaffron et al., 2019). All workers will need to adapt to digital transformation,

and it is necessary to invest in people and the development of new competencies during the integration of technology (AVEVA, 2018b; GMG, 2019a; Institut National des Mines, 2021; Keating, 2019b; Sörensen & Clausen, 2021).

4.5.2.4 Processes

Mining operations, production, and business processes will be redefined with the digital transformation, ranging from the development of low-impact mining methods to process automation, from traditional blasting to continuous extraction processes, and from traditional business processes to real-time decision-making to make the entire mining process more efficient and sustainable (Hejny, 2016; Hillal, 2022; McHattie, 2014; Schroedter, 2020; Sörensen & Clausen, 2021).

4.5.2.5 Management systems

Management systems are necessary for remote and autonomous mining to fill the gap between operations technology and information technology. The principal systems are monitoring, controlling, fleet management, energy management, information management, and operations management (ABB, 2022; Cann, Hall, Meeson-Frizelle, et al., 2021; Cantin, 2011; Caterpillar, 2011; ERNQ, 2019; Keating, 2019b; Lopez-Pacheco, 2019; Luedtke, 2021; McHattie, 2014; Scales, 2019a; Sörensen & Clausen, 2021).

4.5.2.6 Technologies

Technologies are categorized into foundational and emerging technologies for the mining industry.

Cybersecurity

Cybersecurity is an intangible means of improving data security and running a successful Smart Mine (Honeywell, 2022). Mine operations will increasingly rely on digital systems, and their operations technology network will be particularly vulnerable due to lower security maturity. The number of cyberattacks is increasing, and mining companies must embed cybersecurity into their digital transformation strategy (Georgel, 2022).

Cloud

Cloud solutions allow collaboration between mine employees and beyond, from management to the floor (Institut National des Mines, 2021; Scales, 2019a; Schroedter, 2020; Sörensen & Clausen, 2021).

Software

Digital transformation in mining involves software and platforms that integrate all mining disciplines to manage the mine in real time. Modeling, simulation, analysis, and mine-planning software are a large part of the Smart Mine for collecting and analyzing data to connect design to production to supply chains via a collaborative approach (AVEVA, 2018b; Cann, Hall, Meeson-Frizelle, et al., 2021; Gleeson, 2018; Insight Editor, 2022b; Institut National des Mines, 2021; Kral et al., 2016; Lopez-Pacheco, 2019; Moore, 2019; Sörensen & Clausen, 2021).

Big data and analytics

Data are the heart of automation. Collecting, analyzing, and interpreting data from equipment and tools empowers users by obtaining real-time visibility and data-driven insights to simulate decision-making, mitigate risk, and achieve better outcomes. Algorithms to interpret the data are necessary to generate actionable insights and warnings for safety, maintenance, and production. The analysis of big data is simplified by data standardization (AVEVA, 2018b; ERNQ, 2019; Gleeson, 2018; Luedtke, 2021; McHattie, 2014; Scales, 2019a; Schroedter, 2020; Sörensen & Clausen, 2021).

Sensor and onboard systems

The increased use of intelligent sensors and onboard systems will synchronize operations between equipment and workers to improve productivity. Sensors are used more frequently underground to track machines and vehicles to predict and optimize transportation time. The development of collision avoidance systems is a priority for implementing autonomous equipment (Cantin, 2011; ERNQ, 2019; Hejny, 2016; Schroedter, 2020; Sörensen & Clausen, 2021).

Localization and positioning

These technologies can be used to create a model that represents the "as-operated" reality of the mine as well as improve safety by tracking materials, machines, and assets to provide automated surveillance (ABB, 2022; Chadwick, 2017; McHattie, 2014; Sörensen & Clausen, 2021).

Pattern recognition

Advances in material detection, mineral characterization, structural control, and geotechnical identification constitute a substantial step for autonomous equipment operation (Chadwick, 2017; Hedlin, 2011; Hejny, 2016; Sörensen & Clausen, 2021).

Remote sensing

Remote sensing has the potential to revolutionize underground mining operations. Laser and light detection and ranging (LiDAR) captures data underground for autonomous equipment operation and 3D mapping. In a GPS-denied environment, LiDAR and simultaneous localization and mapping allow autonomous systems to navigate, avoid collisions, and build maps in real time (Chadwick, 2017; Gleeson, 2018; Hrabar, 2021).

Emerging technologies are described in the next sections.

3D printing

Onsite 3D printing is emerging in the mining industry for applications such as creating spare parts for equipment, service infrastructure, personal protective equipment, and drones (Goodbody, 2021; Institut National des Mines, 2021; Sörensen & Clausen, 2021).

Blockchain

Digitalizing the entire document exchange through blockchain and portals eliminates non–value-added tasks, complies with ESG requirements, and enhances the transparency of the supply chain. Mass adoption of this technology has yet to be achieved. It will be primarily used for mineral tracking, mineral provenance, and parts tracking from mining OEMs (Caplin, 2022; Cosgrove, 2019; Ellis, 2021; Schroedter, 2020). The World Economic Forum's Mining and Metals Blockchain Initiative has released a proof of concept to trace greenhouse gas emissions, especially CO2, across the value chain with blockchain technology (Russo, 2022).

AI and ML

The Smart Mine will be AI-enabled for mining control, autonomous systems, data analysis for predictive planning, preventive maintenance, and safety monitoring. AI and ML technologies will be used to analyze drilling data to characterize geological models, better estimate drilling time, and optimize drilling and blasting patterns. Advances in preventive maintenance will lead to better equipment condition prognosis and directly influence productivity. A remaining challenge is to collect adequate data to provide the necessary algorithms (GMG, 2019a; Insight Editor, 2022a; Schroedter, 2020; Sörensen & Clausen, 2021).

Simulation and visualization

3D models, digital twins, augmented reality, and virtual reality are among the most important emerging technologies for the Smart Mine, from mine design and visibility of operations to maintenance, training, and simulation (Chadwick, 2017; ERNQ, 2019; Gleeson, 2018; GMG, 2022; Hillal, 2022; Honeywell, 2022; Insight Editor, 2022a; McHattie, 2014; Neethling, 2021; Schroedter, 2020; Sörensen & Clausen, 2021).

4.5.3 Targeted business management processes

Targeted business management processes refer to optimized business management processes to be implemented to produce products or services and coordinate activities to accomplish the vision of the Smart Mine (Figure 4.2).

4.5.3.1 Planning

Planning and scheduling are important and challenging business processes. For the Smart Mine, it is essential to move toward real-time planning that integrates day-to-day and business planning to plan the life of the mine, gain better insights, and improve profitability. One of the challenges regarding real-time planning is data and information management. Simulation tools, data analytics, AI, ML, and digital twins are technologies that make it possible to predict different scenarios to improve production plans based on real-time data. Furthermore, underground localization and communication infrastructure contribute to real-time fleet management (AVEVA, 2018a; Schroedter, 2020; Shewale, 2023).

4.5.3.2 Monitoring and control

Monitoring, which involves collecting and analyzing data, is moving toward real-time monitoring of assets, environmental conditions, inventory, and equipment. Real-time monitoring is mandatory for developing remote and autonomous operations and making data-driven decisions (Cann, Hall, Meeson-Frizelle, et al., 2021; ERNQ, 2019; Institut National des Mines, 2021; Kral et al., 2016; Schroedter, 2020). Control uses the analyzed data to make changes. The Smart Mine is moving toward short-interval control to close the loop between planned and real-life operations scenarios underground (ABB, 2022; AVEVA, 2018a, 2018b; Braul, 2017; Cann, Hall, Shemer, et al., 2021; Schroedter, 2020).

4.5.3.3 Optimization

Process optimization and continuous improvement are essential parts of the Smart Mine. Value chain optimization is required to enhance visibility and maximize profits (AVEVA, 2018a; Braul, 2017)b(Schroedter, 2020).

4.5.3.4 Automation management

Automation management is a new requirement for developing automation strategies because there is no one-size-fits-all solution. The most cost-effective solution with the highest return on investment will differ from mine to mine and include different levels of autonomous solutions. A successful automation implementation strategy involves the best human intelligence. For this reason, the workforce must be on board and aligned with implementing automation projects (Lopez-Pacheco, 2017; Sörensen & Clausen, 2021). The International Organization for Standardization of Mining created the TC 82 subcommittee for autonomous mining to establish international standards (Skinner, 2016).

4.5.3.5 Asset management

Asset performance management is seen by McHattie (2014) as optimizing processes for the day-to-day running of assets to minimize operational costs and improve productivity. The solutions to achieve this are predictive analytics and platforms to link performance events and root causes (AVEVA, 2018b).

4.5.3.6 Data and information management

Information management platforms are essential to achieve greater returns on infrastructure investment, span capital, and operating expenditures (AMCConsultant, 2022). As a key factor for implementing AI solutions, data management is a high-priority area that needs improvement to move toward a more integrative approach to asset management, transparency, and understanding of situations and options before replacing the equipment in the system (GMG, 2019a, 2022; Hejny, 2016; Institut National des Mines, 2021; McHattie, 2014; Moore, 2019). Unfortunately, companies are often left with a proof of concept that shows exciting potential but fails to launch (Gravel, 2022).

4.5.3.7 Business management

Business management relies on the near real-time visibility of business information. Mining companies will become more customer-centric. The European I2mine initiative developed new concepts for mine management to reduce operational expenditures (AVEVA, 2018a; Hejny, 2016; Schroedter, 2020).

4.5.3.8 Risk and safety management

Risk and safety management is required to centralize real-time information and provide safety advice when needed. The U.S. National Institute for Occupational Safety and Health developed guidelines for health and safety related to autonomous systems and automated equipment. Risk and safety management combined with change management as a safety culture is integral to technology effectiveness in reinforcing a zero-harm approach (GMG, 2022; Haight et al., 2021; Moore, 2022).

4.5.3.9 Production and waste management

Production and waste management are key targeted business management processes for achieving a sustainable Smart Mine. The concept of zero-impact mining involves selective mineral extraction, thereby reducing waste. The majority of the installation is underground, with only the final product coming to the surface (AVEVA, 2018a; Hejny, 2016; Hillal, 2022; Moore, 2019).

4.5.3.10 Change management

Technological change should be implemented along with change management to overcome the challenge of introducing and gaining acceptance for new technology (GMG, 2022; Keating, 2019a; Lopez-Pacheco, 2019).

4.5.3.11 ESG management

The Smart Mine supports ESG mandates and opportunities for workforce diversification and barrier removal. ESG-related factors are increasingly becoming a cornerstone of decision-making by the public and investors. Partnerships with Indigenous Peoples bridge the gap between industry and community to transform the future of mining. The Smart Mine focuses on operating sustainably and strives to achieve ESG goals without sacrificing performance. Energy management is also fundamental to sustainable Smart Mines (Cann, Hall, Shemer, et al., 2021; Hitachi construction machinery, 2022; Reimer, 2023; Schroedter, 2020).

4.5.3.12 Education and training

One priority in mining is to attract, train, and retain a skilled workforce. With rapid technological changes, the need to recertify personnel with new skills is crucial. The specific skills that need to be added to training programs are based on the vision of the Smart Mine. On the one hand, the industry needs cybersecurity experts, data analysts, information and operations technology/IoT experts, and employees with programming and digital skills. On the other hand, employees need to know how to use emerging technologies and equipment, such as digital tools, remote control, simulation software, 3D printing, blockchain, and drones. Personnel also require soft skills such as collaboration, data analysis, critical thinking, and environmental adaptation. Many educational resources, simulators, and other virtual solutions are available to achieve this goal. Mining companies should invest in digital training for their workforce (AVEVA, 2018b; Cann, Hall, Meeson-Frizelle, et al., 2021; Gardner, 2021; GMG, 2019a, 2022; Hejny, 2016; Institut National des Mines, 2021; Moore, 2022).

Figure 4.2 summarizes the vision of the Smart Mine as defined by mining practitioners for underground extraction operations.

4.6 ACADEMIC LITERATURE ANALYSIS

In this section, the main concepts identified in the industry-focused literature (Figure 4.2) are used to characterize recent academic research contributions to the Smart Mine.

4.6.1 Objectives

Among the 160 scientific articles, 51 articles address the objectives of the Smart Mine (Figure 4.1). Most focus on business management objectives (40%), the next largest groups focus on operations (31%), ESG (31%), and financial objectives (29%). Only 21% of articles address safety objectives.

4.6.1.1 Financial objectives

Increase agility

Mining companies will benefit from the agility of management to avoid the tendency to form silos (Warr, 2019), agile software development to increase efficiency (Young & Rogers, 2019), and agility in operational data to offer more-transparent management transfer (Paiva et al., 2017).

Improve operational efficiency

Effective communication (Moridi et al., 2020), unmanned mining (Hu, N. et al., 2011; Ren, Z. et al., 2019), intelligent monitoring (Li, J. G. & Zhan, 2018), robots, automated machines, remote operation, automatic railway transportation systems, and centralized control (Bi et al., 2022) are effective methods to solve mine safety problems and enhance efficiency, thus reducing mining costs. Applying digital technology alone is insufficient for optimizing management, improving efficiency, and reducing costs (Bi et al., 2022). High efficiency will likely be achieved through sophisticated extraction and processing technologies; a greater degree of automation; and small, highly trained workforces (Sidorenko et al., 2020). An integrated supply chain from mine to port will significantly improve overall operational efficiency (Bi et al., 2022). Efficient operations use energy (Pradip et al., 2019) and water efficiently (Cacciuttolo & Valenzuela, 2022).

Improve productivity

The Smart Mine is safe, efficient, and economically exploitable (Seng & Shu, 2013a). Mining companies need to improve productivity through innovative information and communication technologies. Research organizations are developing and delivering technology to enhance the productivity of the identified industry challenges (Batterham & Robinson, 2019). Digital mine

construction will improve mine design decision-making through the use of new high-tech equipment to increase productivity (Seng & Shu, 2013a, 2013b) as well as IoT solutions (Rob & Sharifuzzaman, 2021). Lumley (2016) emphasizes the importance of benchmarking for mining companies to compare themselves to others.

4.6.1.2 Operational objectives

Implement autonomous operations

Multiple visions for the Smart Mine around autonomous operations are suggested, from autonomous equipment (Kumar, 2016) to zero-entry mines or areas within mines. Knights et Yeates (2019) presented the business case for zero-entry mines, and Nikolakopoulos et al. (2015)presented a roadmap of identified activities and technologies that move closer to this vision. However, a zero-entry, fully autonomous mine will be achievable only when robots can be maintained by other robots (Cucuzza, 2021). Future mines will not be as equipment-intensive as current mines, and implementing fully autonomous systems will be a more straightforward endeavor (Cucuzza, 2021). Gao, Y. et al. (2020) proposed a new solution for end-to-end autonomous mining operations composed of platforms, management and control centers, and remote systems using big data analysis, deep learning, virtual mining, and fleet management. Digitally connected, electric mines will become a reality in the not-too-distant future (Clausen & Sörensen, 2022), but fully autonomous mines are a long way from being implemented (Cucuzza, 2021).

Perform continuous mineral extraction

Autonomous operations facilitate continuous mineral extraction. Intelligent continuous mining technology, especially unmanned blasting technology, will be a significant development to realize this objective (Chi, 2020). Ranjith et al. (2017) suggested that continuous mining should be adopted for deep mining. Clausen et Sörensen (2022) state that technologies change how mineral extraction is performed with connected systems, workers, and processes. Further, mining companies and researchers could benefit from an expanded notion of Mine 4.0 to make their efforts more explicit and make mineral extraction more efficient, safe, environmentally friendly, and socially acceptable.

Integrate supply and value chains

In terms of the levels of automation, from Level 0, manual, to Level 5, fully autonomous (GMG, 2018)), there is currently no mine that is fully autonomous from extraction to port in operation, nor is one likely in the foreseeable future (Cucuzza, 2021). An integrated value chain is predicted to be a reality after the year 2030, when automated machinery will work together with open-source platforms, allowing interoperability and processes capable of self-learning and decision-making without human input (Cucuzza, 2021). Both digital hardware and electricity generation from renewables, including the technological challenges associated with energy storage, require a host of new metals and materials for which new value chains must be established (Pradip et al., 2019). Significant productivity gains could be obtained by integrating information across the value chain. However, complete value-chain integration is not yet possible for most operations (Fraser, 2015) due to low-grade ore, increasing depths of deposits, global climate change, and ESG constraints—challenges that can be partly solved by optimizing the entire mining value chain using advanced information and communication technologies (Jang & Topal, 2020).

Deploy interconnected equipment and interoperability

A lack of interoperability among machines and of compatibility among different systems is hampering the implementation of digitalization and progress toward autonomous systems (Clausen & Sörensen, 2022). Interoperability interfaces and technology for machine-to-machine communication still need to be developed and brought to market (Clausen & Sörensen, 2022). Cucuzza (2021) contends that only agnostic technology allowing interoperability will help fast-track toward a fully autonomous mine, and mining companies are asking for open-standard, vendor-agnostic technology solutions developed collaboratively by technical suppliers and OEMs with flexibility, value for money, and return on investment. A unified, comprehensive information system platform should be developed to integrate mining data visualization, real-time information sharing, and interoperability (Seng & Shu, 2013b).

Increase remote operations

Remote operation centers are omnipresent in the mining industry (Jang & Topal, 2020)and are the most prominent technology affecting the operational process level (Clausen & Sörensen, 2022). They are becoming indispensable tools for synthesizing and managing large volumes of data (Young & Rogers, 2019). Remote operations require automation, underground communications,

automatic real-time positioning, and navigation technology (Seng & Shu, 2013b). The shift to remote operations and mine automation will inevitably lower labor needs and affect communities around mine sites, including Indigenous communities (Holcombe & Kemp, 2019). Mining automation is undergoing rapid development as older technologies, such as line-of-sight remote control and tele-remote operations, are being replaced with semi-autonomous technologies (Moreau et al., 2019).

Move toward real-time planning

The Smart Mine pivots toward real-time and predictive planning. New technologies offer the possibility for agile planning (Manyuchi & Sukdeo, 2021), for example, short-term production planning using optimization modeling (Li, N. et al., 2021).

Increase predictive maintenance

Predictive maintenance uses data collected by intelligent monitoring via equipment sensors and equipment simulations to create analytical algorithms to evaluate the health of mining equipment to predict and avoid future equipment failures (Willingham & Marchant, 2016). A predictive maintenance system in a mine requires a data-sharing architecture, including connected equipment and machines (Froberg et al., 2015).

4.6.1.3 Business management objectives

Unify, centralize, and standardize information

Due to the lack of standards and norms, academia and industry have differing levels of awareness of digital mines. The variety of buzzwords surrounding digital transformation indicates the need to standardize digital terminology (Young & Rogers, 2019). Cheng, G. et al. (2011) developed an ontology for the construction of digital mines that can be used as a framework to integrate heterogeneous mine data. Information technology solutions and architectures allow data centralization and better data exchange to produce standard information (Miell, 2011). The increasing use of onsite control rooms and remote operation centers drives the requirements for communication, data exchange, and general interoperability standards (Fraser, 2015). Partnerships among mining engineering technology service companies have emerged to facilitate data exchange and standardize communication protocols. Working parties have been established by the Global Mining Guidelines Group to address the lack of interoperability standards across the industry, as

noted by Knights et Yeates (2019). Centralized data storage and control of business processes through collaborative platforms will achieve data interoperability (Wang et al., 2019).

Improve collaboration

Automation adoption has been facilitated by cooperation between academia and industry (Cucuzza, 2021) and is playing a significant role in the realization of the mine of the future, facilitated by research organizations such as the Canada Mining Innovation Council. The definition of remote control centers was broadened to encompass collaborative decision environments for cross-geography collaboration between functional silos and across assets (Chaudhuri & Chandran, 2012). The Smart Mine relies on coordination and cooperation among all key systems and participants (Ge et al., 2018). A shift toward more collaborative research and development with OEMs, technology suppliers, and other mining companies will help to develop an innovation ecosystem for open-source collaboration between suppliers, universities, start-ups, and organizations (Clausen & Sörensen, 2022). Farrelly et al. (2012) introduced the concept of the network-centric mine, wherein people, processes, information, and technology are connected, resulting in a highly collaborative business model.

Increase connected processes and assets

All equipment and processes must communicate with each other and with the remote operating center, especially for the zero-entry mine (Clausen & Sörensen, 2022; Nikolakopoulos et al., 2015). Wireless connectivity among more devices is a critical element of the journey toward digital mines (Santos, W., 2019). The mining industry already has all the ingredients necessary to achieve a fully connected mine (Cucuzza, 2021).

Move toward real-time mine management

The operations of the mine in the future will be more predictive than reactive, with the ability to make decisions in real time using big data and analytics and digital twins (Clausen & Sörensen, 2022; Ghahramanieisalou & Sattarvand, 2023; Rob & Sharifuzzaman, 2021).

Increase visibility

Mining companies need instantaneous visibility of production, equipment, and operational variables to achieve efficient operations. Sishi et Telukdarie (2020) demonstrated that using

Industry 4.0 technologies to integrate business systems and processes results in real-time visibility of the overall mine status.

4.6.1.4 Safety objectives

Improve health and safety

Healthy mining is part of the strategic implementation of the Smart Mine (Seng & Shu, 2013b). Although digitalization of operations helps ensure the health and safety of mine workers (Hu, N. et al., 2011), there is a substantial need to adopt state-of-the- art automation technologies, particularly for information and communication systems (Kumar, 2016; Moridi et al., 2020; Paavola & Seppälä, 2016) and monitoring (Moridi et al., 2014). Innovative solutions, best practices, and additional safety standards must be implemented as mines progress to deeper levels (Ranjith et al., 2017). Another way to protect workers is to develop zero-entry areas (Knights & Yeates, 2019). Peltier-Huntley (2022) highlighted the importance of a psychologically safe workplace and recommended strategies to achieve this goal.

Increase data security

Mining companies and OEMs need to enhance resources to protect the integrity of autonomous systems to prevent malicious damage and hacking (Knights & Yeates, 2019). Autonomous operations should integrate all the critical variables from the process, assets, environment, and finances to be controlled and updated online in a cyber-secure way (Bi et al., 2022). Although the IoT is changing the mining industry with wireless connections, embedded systems, and cloud support, its use comes with security and privacy issues such as data loss, privacy breaches, and unauthorized access to personal and company data (Rob & Sharifuzzaman, 2021).

4.6.1.5 ESG objectives

Grasp workforce transformation

Digital transformation affects all facets of the mining industry, including its workforce profile. Future mines will rely on digitally enabled workforces (Kawalec, 2019) and a highly skilled skeleton labor force that can perform several tasks through automated and remote-controlled operations and monitoring (Oshokoya & Tetteh, 2018). Achieving this goal requires an innovative and collaborative workplace culture (Young & Rogers, 2019) that is human- centered instead of work-centered (Cawood, 2020). Johansson et Johansson (2017) proposed the design of a workplace

to attract young and talented people with key components of health, safety, cooperation, and acceptance of diversity. Among the best practices proposed by Lumley et Trott (2012) to retain high-quality professional people are quantifying the gap, doing something about it, branding operational best practices, and broadcasting the mine performance to the industry.

Develop electrification

Electrifying mines and reducing—or ideally, eliminating—greenhouse gas emissions requires a redesign of processes and must consider the mine energy supply (Clausen & Sörensen, 2022) powered by renewable energy sources, electrification is increasingly being adopted by major mining companies (Pradip et al., 2019). Battery-electric motors allow for travel throughout the mine; however, challenges with battery life, recharge times, and flammability hazards need to be overcome before optimal operation can be achieved. Overhead power cables are most effective in areas with frequent or repetitive travel, such as within ramps or on haulage levels. In contrast, battery- electric equipment is more practical for temporary drift or stope operations (Moreau et al., 2019). Automated and electric equipment can lower operating costs, increase productivity and safety, and reduce energy consumption due to lower ventilation demands (Moreau et al., 2019).

Improving sustainability

Javier (2016) differentiated between the future of mining and mining in the future, exposed views and perspectives to pace innovation in mining, and introduced the concept of geomimicry. The ultimate goal of the Smart Mine is not only to meet human demand for mineral resources but also to adapt to the earth's ecological carrying capacity (Seng & Shu, 2013b), ensuring safe, efficient, green, and sustainable mining (Ranjith et al., 2017). Sustainable development is related to safety, economics, communities, resource efficiency, and natural protection. It can be achieved by continuous monitoring and the development of environmentally friendly technologies (Jang & Topal, 2020).

There has been pressure in recent years to create mining methods that result in more-sustainable operations. Asa'd et Levesque (2024) reviewed the potential impact of digital technologies on sustainability and decarbonization. Automation, the Industrial IoT, remote operation centers, connected workers, robotics, drone technology, electrification, 3D printing, integrated software platforms, advanced analytics, simulation and visualization, cloud computing, big-data management, cybersecurity, and e-learning have an impact on sustainability (Clausen & Sörensen,

2022). Sidorenko et al. (2020) evaluated the concept of small-scale mining for sustainability. Batterham et Robinson (2019) proposed bringing only the valued mineral instead of the raw materials to the surface for a more environmentally secure mining process. According to Clausen et Sörensen (2022), the components of a sustainable, intelligent mining system for the future are autonomous vehicles in mixed traffic, rock stress monitoring, autonomous battery charging, robotized inspection, real-time monitoring, autonomous material handling, AI-powered fleet optimization, Miner 4.0, mine design for the future, education, connectivity, and positioning.

4.6.2 Proposed solutions

Of the 160 relevant scientific articles (Figure 4.1), 125 (78%) address the solutions of the Smart Mine and 79 (62%) focus on technologies. Equipment is the second most addressed (22%), followed by infrastructure (18%) and management systems (18%). Process solutions (8%) and people and culture solutions (6%) are understudied.

4.6.2.1 Infrastructure

The Smart Mine is based on wireless communication networks (Chen, C. & Long, 2021; Moridi et al., 2020; Paavola & Seppälä, 2016; Zhao, B. et al., 2022). Wireless connectivity is a crucial element of connected devices: OEMs and system integrators need to collaborate to ensure the proper operation of connected machines and automation systems (Santos, W., 2019), and wireless network provides an efficient data-supporting platform for remote operations (Li, J. G. & Zhan, 2018). LTE seems to have better latency and reliability requirements for remote mining operations than 4 G or 5 G (Santos, W., 2019). LTE, ultrawideband technology, and fiber-optic cables are increasingly installed as the backbone system of wireless networks (Jang & Topal, 2020). However, mining companies need scalable wireless communication systems (Young & Rogers, 2019). Establishing a stable and efficient communication network platform should be a priority to achieve mining optimization through digitalization (Jang & Topal, 2020) as well as establishing a unified industrial internet platform (Bi et al., 2022). Chi (2020) described a remote-control initiation blasting process based on wireless networks. The design of an IoT architecture needs to consider interoperability among various devices (Li, J. G. & Zhan, 2018).

One way to achieve agility is to use wireless local area network infrastructure to replace paper reports and integrate online access to onboard computer systems (Paiva et al., 2017). Rob et

Sharifuzzaman (2021) stated that wireless sensor network technologies for data transmission must be chosen based on roaming; applicability to small, medium, and large scales; locations; soil types; and climatic conditions, as none dominate the market yet. It is necessary to design and choose a reasonable communication mode and equipment to ensure the security and reliability of information transmission (Gao, Y. et al., 2020). Mine design and antenna placement have a direct effect on reliable wireless communication systems (Hussain et al., 2017).

IoT, automation, and remote operation centers are becoming indispensable tools for managing, centralizing, and analyzing data; reducing exposure to risk; and increasing productivity (Young & Rogers, 2019). However implementing a communication network and IoT infrastructure is still challenging for underground operations (Clausen & Sörensen, 2022). Using real-time video technology to analyze operator performance can improve the productivity and safety of workers (Westh et al., 2012). Collaborative decision environments, which are the evolution of the control room in the remote operation center, are ideal for collaboration between functional silos, allowing real-time operation coordination (Chaudhuri & Chandran, 2012).

The three current electrification methods in underground mining are battery-electric motors, overhead power lines, and umbilical trailing cables connected to the mine's electric infrastructure (Moreau et al., 2019). Solar power generators and solar thermal power plants are being developed and implemented on site (Pradip et al., 2019). Additionally, energy storage solutions, such as microgrids, are being developed (Fleet et al., 2015).

4.6.2.2 Equipment

Robots

Assisting robots can extend the capabilities and perceptions of humans and could even replace workers in maintaining equipment (Zhao, L. et al., 2019). Only rescue robots (Kumar, 2016) have been developed. Nevertheless, to fully take advantage of robots, research on kinematics, augmented reality, remote control systems, force feedback, and characteristic identification are needed (Nikolakopoulos et al., 2015). Su et al. (2021) designed an autonomous path-planning system for mining robots. Kshirsagar et al. (2018) developed a simultaneous localization and mapping system for multiple robots. Kim et Choi (2020) found that the use of LiDAR combined with an inertial measurement unit with an encoder yielded the highest location accuracy.

Drones and unmanned aerial vehicles

Drones facilitate data collection from hazardous areas in mines, improving safety Pradip et al. (2019). Joo et al. (2022) proposed a metal-detection technology for drones. Sennersten et al. (2015) developed unmanned aerial vehicles with 3D interactive virtual models of underground environments to survey inaccessible underground mine voids.

Trucks

Autonomous trucks and haulage equipment can increase productivity, but their deployment in operations while addressing the human element is challenging (Cucuzza, 2021). Driverless trucks are the leading equipment for autonomous operations (Pradip et al., 2019). In Australia, autonomous drilling and hauling systems have already been implemented and have increased the efficiency of operations (Jang & Topal, 2020). However, automated equipment does not always guarantee productivity improvements due to environmental factors contributing to sensor malfunctions (Jang & Topal, 2020).

LHDs

Kawalec (2019) considers autonomous vehicles and machines, such as LHDs in underground mines, as key technologies. In Australia, the recent development of high-speed communication systems using fiber-optic cables has allowed mines to use semiautomated LHDs, where one operator can operate multiple LHDs from a control room. Zhang, T., Fu, et al. (2022); Zhang, W., Li, et al. (2022)studied intelligent electric shovels and optimal excavation trajectory planning, which influence production efficiency. Paraszczak et al. (2014)and Acuña-Duhart et al. (2024)found that electric wireless LHDs were more advantageous in automated applications than their diesel and cable-powered LHD counterparts, despite limited operating time and range. To achieve the vision of zero-entry mining, it will be necessary to ameliorate LHD autonomous capacity, such as unsupervised loading (Knights & Yeates, 2019). For a comprehensive review of advancements in LHD technology, see Xiao et al. (2022).

Bolters and drills

Driverless drills are being deployed in Australia (Holcombe & Kemp, 2019; Pradip et al., 2019) and Feng et al. (2022) presented their work on controllable downhole drilling tools. Automated

drilling technology must be aligned with a general strategy and vision for end-user equipment, allowing operators to develop skills along a gradual learning curve (Välivaara, 2016).

Continuous machines

Chen, H., Yang, et al. (2021) presented a multisensor-data-fusion method for detecting the road header fuselage pose. Active research on rock cutting for hard-rock mining above 120 MPa has been conducted and still needs to be developed to cut rock economically (Gipps et al., 2011).

Other mining equipment

Driverless vehicles address the health and safety of workers underground (Dong et al., 2020). In Australia, driverless trains transport ore from the mine to the port (Holcombe & Kemp, 2019; Pradip et al., 2019). Most unmanned mining vehicles are powered by batteries to reduce carbon consumption. Xiong et al. (2022) proposed an algorithm to reduce power consumption. Research on BEVs has been carried out to overcome air pollution underground, and Jang et Topal (2020) reviewed the existing electric equipment. The use of field tests to estimate utility BEV energy consumption operating in underground mines is increasing (e.g., (Acuña-Duhart et al., 2024; Li, G. et al., 2024)).

Wearable devices

Mining companies are collaborating with service providers to provide wearable technologies to enhance the safety of underground workers. Wearables allow the gathering of near real-time data to help individuals respond and react to changing environmental conditions (Pradip et al., 2019). Olmos de Aguilera et al. (2023) studied camera-aided technology to automatically detect worn personal protective equipment.

4.6.2.3 People and culture

The three main reasons for unsuccessful digitalization initiatives are the lack of an overall transformation vision or roadmap before choosing the technologies to be implemented, a gap between strategy and execution, and failing to make the required adjustments in company culture and management systems (Clausen & Sörensen, 2022). It is crucial for the industry's future success that a young and diverse workforce is attracted to the mining sector. The future workforce will support technological and cultural transformation and reshape the face of the mining industry (Clausen & Sörensen, 2022). Rather than a technology-driven environment, Chaudhuri et

Chandran (2012) describe a collaborative decision environment that transforms an organization's operational philosophy. The human factor must be included in technology development (Clausen & Sörensen, 2022; Zaffron et al., 2019).

Mine automation changes the required skill, organization, and location of personnel. The Smart Mine will require fewer operators and instead rely on highly skilled personnel, who can perform several tasks through automated and remote-controlled operations and monitoring (Holcombe & Kemp, 2019; Knights & Yeates, 2019; Oshokoya & Tetteh, 2018). Analytics development requires digitally literate workers recruited from outside of the mining industry to maintain, analyze, and improve operations (Young & Rogers, 2019).

4.6.2.4 Processes

Digital transformation makes mining processes safer, more remote, more automated, and more transparent (Young & Rogers, 2019). Most digitalization projects start with digital resource management, process control automation, and visualization of production scheduling (Hu, N. et al., 2011). Wang et al. (2019) developed a mine-wide decision support instrument to improve the overall performance of the underground mining process. Unmanned working faces and unmanned mines based on fully automated and unmanned mining processes have become essential fields of study (Ranjith et al., 2017). The mining blasting process impacts the efficiency of production. Wu et al. (2012) proposed a Smart Mine blasting concept, from design to initiation, to improve the controllability and predictability of this operation. Chi (2020) developed an unmanned remote blasting process. Well-defined workflows should be mapped for key value processes in a collaborative decision environment (Chaudhuri & Chandran, 2012). University-industry collaboration has led to the development of new robotic technologies to make new processes feasible (Cucuzza, 2021). Jang et Topal (2020) explain two possible mining methods for future underground mining: one using near real-time mineral exploration based on an AI data analysis and the other using micromining with AI and advanced robotics. Lööw, J. et Johansson (2015) suggest implementing lean production in mining as a management model to rethink work organization.

4.6.2.5 Management systems

Academic researchers have developed existing mining systems to improve current practices and new systems to take full advantage of automation and remote operation (Gipps et al., 2011). The Smart Mine includes monitoring and control systems that obtain real-time information and realize the control function of automation systems. “A mine control system is the brain of the intelligent mine” (Chen, Y., Xu, et al., 2021). The control system of future mines is expected to ensure efficient mining (Oshokoya & Tetteh, 2018) and to maintain efficient production.

Hu, D. T. et al. (2013) discussed the importance of effectively controlling the mine ventilation system and working on a digital mine ventilation system for real-time monitoring. Zhu, H., Song, et al. (2011) studied mine ventilation control systems to improve health and safety underground. The IoT allows real-time ventilation or supervising system monitoring (Rob & Sharifuzzaman, 2021). In the example of mine gas monitoring, Liu, Q. et al. (2014) applied sensor web service technology to enable collaborative tracking.

Xingguo et Kun (2020) introduced tools to package data monitoring systems to prevent mine disasters. Qiu et Wang (2020)explored a data monitoring module for mine disaster monitoring, and Wang et Zhang (2015) used a geosensor network to obtain real-time data and enhance the capability of the monitoring system. Küsel (2019) studied a monitoring system for digitized conveyor belts to increase their safety and efficiency. A completely autonomous mining system would prevent health or safety concerns as the operation would run remotely (Kumar, 2016). Liu, C. et al. (2019) established a remote monitoring system for unmanned excavation faces.

Using a cyber-physical system is one of the best ways to transform a mine into a smart environment. Sishi et Telukdarie (2020) developed an integrated Enterprise Resources Planning system with fuel management systems, modular management systems, tire management systems, manufacturing execution systems, and geology mine planning with vertical and horizontal integration. Autonomous haulage systems are used to manage fleets of driverless trucks (Pradip et al., 2019). Overall, the Smart Mine needs an integrated management system that manages hardware and software in a high-speed communications environment with augmented 3D visualization (Jang & Topal, 2020). Ge et al. (2018) proposed a Smart Mine management system architecture based on knowledge engineering and the IoT. Zhan et al. (2017) studied the digital management system of assets. Ren, L. Z. et al. (2013) researched mine drainage control systems to monitor water levels.

Qun (2011) developed a digital mine information system based on photographic surveying to obtain timely dynamic information, and Chang et al. (2012) designed a mineral resource management information system. Liu, X. R. et al. (2013) studied database and data characteristics to establish a production information management system for a metal mine to visualize 3D information and create automatic maps. The emergency management system (Ge & Zhang, 2011) is one of the four main components of the Smart Mine.

4.6.2.6 Technologies

Paschke et al. (2021) addressed the current laws and standards lagging technological progress and the lack of information on solutions needed by the mining industry. Sishi et Telukdarie (2018) implemented Industry 4.0 technologies to introduce a Smart Mine with real-time visibility of the overall mining status. Chaudhuri et Chandran (2012) highlight the availability of the correct tools and applications to increase efficiency in work execution. Clausen et Sörensen (2022) identify 15 core technologies leading the current wave of digital transformation: automation, IoT, remote operation centers, connected workers, robotics, drones, advanced analytics, simulation and visualization, cloud, big data, cybersecurity, e-learning, electrification, 3D printing, and integrated software platforms. The essential elements for autonomous mines are asset monitoring, communication, localization, mapping, navigation, material characterization, environmental perception, robotized inspection, mine automation and control, mine design, and energy management (Clausen & Sörensen, 2022). Foundational technologies are discussed in the next section.

Cybersecurity

Cybersecurity tools are among the technologies that affect mineral extraction (Clausen & Sörensen, 2022; Knights & Yeates, 2019). They do not reduce costs but rather help avoid losses related to cybercrime (Kawalec, 2019). Young et Rogers (2019) pointed out cybersecurity risks due to data-transmission-volume increase and the lack of economic incentive for cloud-services merchants to address this issue. Chi (2020) studied network-security-encryption technology for the remote blasting process. IoT device safety, new encryption standards, and security techniques require additional research and should receive the attention of academics (Rob & Sharifuzzaman, 2021). Min et al. (2023) proposed an intelligent reflecting surface-assisted secure transmission system for IoT devices to enhance the security and reliability of wireless communication.

Cloud

The enterprise business is fully interconnected via cloud collaboration from production to finance, including environmental, management, planning, and decision-making (Bi et al., 2022). The cloud mode improves management, production, and operation efficiency; improves collaboration between workers in a safer environment; and increases attractiveness for the next generation (Bi et al., 2022). The authors developed a cloud-mining model that integrates the core business of the mine as a new development direction for the production and management of Smart Mines. Cloud-based IoT systems enable the storage of data collected via connected sensors (Rob & Sharifuzzaman, 2021).

Software

Information and operational technology platforms are needed to promote a collaborative approach across time, space, and discipline (Wang et al., 2019) and to avoid islands of automation. Integrating various platforms will allow companies to transform their operations into information systems to collect, store, process, and distribute data to the mine management system (Young & Rogers, 2019). The Smart Mine relies on software systems, including a collaborative and controlling management platform and a data exchange platform (Chen, Y., Xu, et al., 2021). Some larger information technology suppliers provide software that acts as an "interoperability layer," which allows data from disparate third party databases and software packages to be integrated.

Real-time production data will be displayed, allowing decision-making instruction to go from person to person instead of layer by layer. The digital mine information platform should regroup real-time data collection and storage; simulate production status, safety monitoring devices, equipment, and processes; and use 3D visualization for real-time monitoring (Yang et al., 2019).

Scheduling system software improves transport system efficiency (Seng & Shu, 2013b). A decision support instrument, such as a schedule optimizer for mobile mining equipment, has been proposed for miners to find rescheduling solutions and adapt to changes rapidly (Song et al., 2015). Liu, T. et al. (2011)designed a 3D digital platform based on GIS (geographic information systems) for mine safety monitoring.

Connected mining information technology platforms provide solutions for predictive maintenance (Pradip et al., 2019). Song et al. (2013) developed a service-oriented Smart Mine system based on

databases, the internet, and simulation and visualization technologies. Zhang, J. et Xiao (2011) built a geospatial information service platform for digital mining that enhances the capability and range of mine surveying and mapping. Widzyk-Capehart et al. (2011) highlight the importance of having proper user interfaces, considering human information processing and cognitive abilities.

Big data and analytics

The Smart Mine requires a big-data analysis system (Chen, Y., Xu, et al., 2021). Analytics removes the gap between raw data and business processes and supports strategic planning, decision-making, supply chains, safety, risk, and financial and environmental processes. Among the data analytics technologies used in mining, big data and predictive analytics can maximize operational efficiency (Schneider & Grigoleit, 2015; Young & Rogers, 2019). Yang et al. (2019) studied the digital mine construction of the IoT and big data as a core technology. Big data associated with virtual reality scientific visualization allows optimization of the block cave mining system (Tibbett et al., 2015). IoT platforms enable real-time data analytics to assist with issue resolution, adjust performance indicators, and optimize operations (Rob & Sharifuzzaman, 2021). Research should focus on the collection, cleaning, and storage of data from all mining equipment and systems in a central repository that is available at all times (Sishi & Telukdarie, 2018, 2020). Guo et al. (2022) developed an algorithm to update 3D geological body models automatically according to new ore-body exploration data. Li, J. et al. (2022) developed an algorithm to improve underground mine ventilation, and Zhang, T., Fu, et al. (2022) explored the processing of mine wind speed data to improve Smart Mine ventilation.

Sensor and onboard systems

Sensors are the “eyes” of the equipment needed to accurately perform a sequence of operations (Kumar, 2016). Cacciuttolo et al. (2023) and Rob et Sharifuzzaman (2021) advocate using low-cost sensors for sustainability monitoring and safety issues. The IoT allows connected processes via information exchange from machine to machine, person to person, or person to machine, as well as RFID (radio frequency identification), sensors, and hyperphysical systems (Ge et al., 2018). Remote and automatic systems and wireless sensor networks enhance worker safety and health (Moridi et al., 2020). Improved sensors for remote operations and analytics can enable predictive maintenance (Pradip et al., 2019).

Localization and positioning

Dong et al. (2020) worked on localizing autonomous equipment to form an interconnected vehicle-to-vehicle system. The transportation layer requires wireless communication, precise positioning, and an intelligent navigation system integrated into the positioning and navigation platform (Li, W. et al., 2018). Mao et Cheng (2014) proposed an algorithm to improve localization, Cao et al. (2021) and Cheng, X. (2019) improved navigation technology for driverless vehicles. Ren, Z. et al. (2019) developed an algorithm for a novel simultaneous localization and mapping optimization model. To achieve the vision of a zero-entry mine, knowledge of localization is important for machines and equipment, infrastructure, and reference points (Nikolakopoulos et al., 2015).

Pattern recognition

Pattern recognition to characterize rock-mass discontinuities is critical for simulating mining processes (Hodgkinson & Elmouttie, 2020). Ore tracking systems use RFID sensors to monitor the movement of a rock after blasting (Jang & Topal, 2020). Using sensors for ore sorting has a significant economic and environmental impact by lowering water and energy usage (Klein et al., 2011). Metal extraction technology should be based on clean power (Pradip et al., 2019) due to the rapid development of technology-enhanced continuous mining (Ranjith et al., 2017). Young et Rogers (2021) built a spatial model of a long-term stockpile using fleet management system data and geostatistical code to optimize the mining process and create a digital mine-to-mill model. See Luo et al. (2022) for a review of ore-sorting technologies and equipment development.

Remote sensing

Trickey et al. (2013) developed imaging technology to overcome the limitations of traditional LiDAR to provide a real-time machine vision solution that supports machine autonomy. Eyre et al. (2016) evaluated three fully mobile automated mapping machines using simultaneous localization and mapping and concluded that hand-held automated mapping solutions have the potential to provide quicker data collection and accuracy for surveying but still have some challenges in terms of achieving relatable technology. Jang et Topal (2020) reviewed various laser scanning technologies, and Zhang, C. S. (2011) addressed 3D reconstruction of mine laneways with range photogrammetry and traverse surveying. Laser scanners are becoming integral to mine automation (Singh et al., 2023). 3D-laser-scanning technology improves the safety and efficiency of

underground surveys and assists in building digital mine databases (Li, L. et al., 2011). Emerging technologies are discussed in the next section.

3D printing

3D printing has been identified as a core technology for digital transformation and for modifying mineral and metal extraction processes (Clausen & Sörensen, 2022). A possible field of application is to produce spare parts and custom-built components using images of drones or point clouds from laser scanners to create digital items. This would change (and shorten) the supply chain of mines (Barnewold & Lottermoser, 2020).

Blockchain

Jian et al. (2021) conducted a comprehensive analysis of blockchain and edge computing technology to support the Smart Mine. Blockchain technology can trace gemstones throughout the entire value chain and the supply chain, from the mine to the buyer (Pradip et al., 2019). Blockchain can identify assets and people, data integrity, supply chain optimization, and human resource management (Young & Rogers, 2019). A proof of concept on CO2 emissions traceability with blockchain technology is being developed (Pons, 2024).

AI and ML

Algorithms and AI can be used to analyze data, make predictions, and assist in decision-making (Clausen & Sörensen, 2022). Several authors have used AI and ML techniques to classify minerals and characterize and detect ore content (Bui et al., 2021; Fu et al., 2022; Ouanan & Abdelwahed, 2019). The main tools for reducing downtime through predictive maintenance are the IoT, big data, digital twins (Pradip et al., 2019), and ML (Willingham & Marchant, 2016). Corrective mine planning systems use AI to develop integrated and optimized plans based on mine planning data (Manyuchi & Sukdeo, 2021). Lopez et al. (2021) assessed ML approaches for mill energy consumption. Mining companies use AI and ML to find new mining areas and analyze all geographical data to find the finest mineral extraction location (Rob & Sharifuzzaman, 2021). ML models are used for metal-detector technology onboard drones (Joo et al., 2022). Yao et al. (2022) developed an online detection method to trace material blockage in real time based on deep learning and machine vision technology, and Zhang, M. et al. (2021) applied a convolutional neural network for damage detection of conveyor belts. More et Wolkersdorfer (2023) used an ML graphic user

interface to help improve water management. Zamalloa et Dagdelen (2023) used adaptive AI techniques for operational fleet management systems to minimize losses and improve productivity.

Simulation and visualization

Bassan et al. (2011) proposed that the mining industry is a perfect candidate for augmented reality technology to address operational challenges. 3D modeling, visualization platforms, and 4D geographic information systems are the future of mining (Chen, Y., Xu, et al., 2021). An augmented reality platform was developed by Fang, J. et al. (2022) to improve the health and safety of workers for the automated mining process in underground mines.

Virtual reality is one of the technologies available for remote operations. 3D visualization exploiting data by virtual reality technology should function as a real-time monitor data display for the real-time status of equipment (Ge et al., 2018). It enhances remote operations and the inspection of autonomous equipment (Young & Rogers, 2019). Virtual and augmented reality are used to create IoT-based parallel mining (a virtual version of underground operations) to improve the safety of personnel and equipment (Gao, Y. et al., 2020). Due to the virtual parallel mining and equipment model equipment that corresponds to the real system, the video around the equipment no longer needs to be retransmitted during remote operation. Nevertheless, only the main parameters, such as the position and attitude of the equipment, are sent to the remote takeover terminal (Gao, Y. et al., 2020). Pishhesari et al. (2023) used a multiplayer virtual reality game to train truck drivers for proximity awareness. Ruggedized sensors form the basis for not only any kind of automation but also for remote operation and digitalization technologies such as advanced analytics, simulation, and visualization, such as digital twins (Clausen & Sörensen, 2022). The applications of digital twins in mining include fleet management, mine-to-mill optimization, decision-making, monitoring and maintenance, operational efficiency, and management (Ghahramanieisalou & Sattarvand, 2023; Plavšić & Mišković, 2022; Ziegler, 2022). Zhu, T., Wang, et al. (2011) focused on 3D blasting animation to improve the blasting process. Jin et al. (2011) proposed a 3D visualization framework model, and Hou, Y. et Cai (2012) proposed a modeling method for 3D tunneling. Che et al. (2011) developed a new method of tunnel 3D modeling, and Hou, E. et al. (2013) promoted the development of a digital mine with a new data model for 3D tunnel modeling. Tremendous development has occurred in the past two decades in advanced simulations of rock behavior under in situ stress conditions, such as by Ren, F. et al.

(2018), who used numerical simulations for rock-mass caving. Huixin et al. (2012) worked on 3D entity modeling to represent 3D spatial entities in digital mines.

4.6.3 Targeted business management processes

Forty-eight articles address targeted business management processes for the Smart Mine considered by mining practitioners. Among those articles, educating and training are the most discussed (23%), followed by ESG management (17%), risk and safety (15%), and monitoring (15%). Approximately 10% of articles involve other business processes, with the lowest number of articles involving automation management (6%) and change management (4%). Academics are not focused on this area; rather, there is a lack of research compared to the proposed solutions to achieve the objectives of the Smart Mine.

4.6.3.1 Planning

Manyuchi et Sukdeo (2021) discussed developing more accurate and agile planning. Short-range planning and short-interval control are targets for improvement (Young & Rogers, 2019). Langefeld et Binder (2017) proposed the concept of blue mining, focusing on alternative energy sources during mining operations and the postmining stage, concerning the postmining utilization of a mine for energy storage. They suggested integrating modern energy into the task of mine planning. Laptev et Gurin (2023) developed a multifactor algorithm for automated underground mine production planning.

4.6.3.2 Monitoring and control

Real-time monitoring of Smart Mines is indispensable (Chen, Y., Xu, et al., 2021). As envisioned, the IoT makes underground mine monitoring more accessible and effective through accurate positioning, tracking technology, early warning, and detecting environmental hazards (Rob & Sharifuzzaman, 2021). Every activity in the mine is continuously digitally monitored and fed into an algorithm to automatically optimize the mine plan in the short-, medium- and long-term to better achieve the company's strategic goals (Clausen & Sörensen, 2022). Atif et al. (2021) proposed a framework for near-real-time monitoring and management of tailing storage facilities. Operational control is feasible remotely using state-of-the-art digital platforms called digital twins and drones, which were introduced in mining for different monitoring activities (Pradip et al., 2019).

Xin et al. (2021) proposed a predictive control strategy model for planning the path trajectory tracking of driverless mine vehicles during mining operations. Moridi et al. (2015) developed a wireless sensor network-assisted GIS system to monitor and control near real-time underground mining applications from the surface office.

4.6.3.3 Optimizing

Mining optimization can be improved by digitization and real-time interaction via digital twins (Hodgkinson & Elmouttie, 2020). 3D mine modeling based on real-time data realized with aerial survey technologies and LiDAR will optimize mine production and development plans. Real-time geological data will optimize mine production by decreasing the dilution rate, leading to the development of real-time optimization models and allowing a faster reaction to production hazards (Jang & Topal, 2020). Real-time data will optimize algorithms for the design process and stope boundaries (Erdogan et al., 2017). To improve profit and recover the investment of a mine, it is essential to optimize the mining process and maintain near-optimal conditions to achieve the overall mine plan. This is partially possible by optimizing the scheduling of mining equipment based on actual operating-time data analysis. Song et al. (2015) and Li, N. et al. (2021) developed an optimization model for short-term resource planning that guides mine production operation and increases the haulage equipment utilization rate, increasing the mine production revenue to answer the need for a short-term production plan.

4.6.3.4 Automation management

To ensure successful implementation, mining technologies should be thought of as pieces of a puzzle that must be assembled deliberately and purposefully, considering the unique conditions of the mine and driven by its specific goals and values (Clausen & Sörensen, 2022). Clausen et Sörensen (2022) provided a roadmap for moving from automated to autonomous systems to achieve the vision of autonomous, green mines in the future. Gomes et al. (2015) outlined the objectives of an automated and centralized underground distribution system designed to detect faults and facilitate the quick restoration of power services. Effective automation management necessitates significant cultural shifts within organizations and the redesign of processes and personnel roles to enable seamless technology integration (Paiva et al., 2017).

4.6.3.5 Asset management

Asset and performance management are performed in real time with continuous feedback from technicians and operators. To move toward a more integrated approach to asset management, the industry needs to prioritize data management (Paiva et al., 2017; Rob & Sharifuzzaman, 2021). Knights et Yeates (2019) reported that the management of engineering changes will become critical to ongoing safe operations. Configuration management assists with maintaining the technical integrity of systems, equipment, and facilities as part of an asset management system. One tool used for asset management is RFID (Hussain et al., 2017). Huo et al. (2022)suggested a smart fleet management approach to reduce greenhouse gas emissions.

4.6.3.6 Information and data management

Data management is required for successful digital transformation (Young & Rogers, 2019). Currently, digital mining is challenging to implement due to constraints in data management (Rob & Sharifuzzaman, 2021).Liu, Q. et al. (2014) provided directions for data storage for monitoring systems. Effective information management depends on technology and operational processes (Paiva et al., 2017). defined the four main contents of the Smart Mine. One of them is a mine information resource-sharing platform.

4.6.3.7 Business management

Implementing digital management promotes sustainable mining development (Liang & Seng, 2012). Mining companies are shifting their strategies and implementing new business processes to include new technologies (Manyuchi & Sukdeo, 2021). The zero-entry mining concept can potentially enhance revenue, reduce operating costs and CAPEX, and enhance mine life. One associated challenge is the system's integrity management, as autonomous systems will require frequent modifications as mining operations expand (Knights & Yeates, 2019). Cloud mining establishes a new management mode, embodying changes in corporate development, decision-making, organizational structure, operation management, technical capabilities, and external cooperation. Cloud mining builds a cross-border integrated mining ecosystem (Bi et al., 2022).

4.6.3.8 Risk and safety management

Yu et al. (2011) proposed a technical approach to safety management for tailings dams with online system monitoring. Fan et al. (2022) proposed a Smart Mine safety assessment method. Li, C. et

al. (2012) proposed a 3D mine environment platform as a safety management technology. Hu, N. et al. (2011) studied a real-time safety management system that included work site, worker, and equipment data. Fang, Y. et al. (2011) used a real-time emergency route algorithm for integration into a digital mine system. Gipps et al. (2011) identified safety and operational risks as a component of future mining with a control and evaluation system to ensure safe operations. Tubis et al. (2020) proposed a risk assessment procedure to reveal the current cybersecurity status of a mine, which can be used as a guide for mine automation.

4.6.3.9 Production and waste management

Yao et al. (2022) proposed IoT-assisted sustainable waste management. Intelligent mining can promote the efficient, safe, green, and sustainable development of mineral resources, effectively reduce the discharge of mine solid waste, and significantly improve the utilization rate of mineral resources (Li, W. et al., 2018). Batterham et Robinson (2019) and Jang et Topal (2020) indicate that one way to achieve a more sustainable mining process would be to remove waste much earlier in the circuit, with production and processing systems implemented underground, which will minimize the use of space on the surface.

4.6.3.10 Change management

Local employees and communities can feel threatened by new technologies. Trust and community acceptance are essential prerequisites for successful operations (Holcombe & Kemp, 2019). Mind matters in future mining; a mindset change will deliver solutions to ESG issues (Javier, 2019).

4.6.3.11 ESG management

Water is essential for most operational components; therefore, integrating water management is a critical precondition for sustainable operation. Mine water treatment solutions using new and innovative technologies for the sustainable development of mine sites should be applied whenever economically viable. The best practices in water management and intelligent mine water management systems, if implemented in practice, will promote the sustainable use of mine water and thereby maintain an acceptable standard of living and social welfare in mining communities now and in the future (Soni & Wolkersdorfer, 2016). Mining companies, especially in dry climates, must implement cost-effective water-management strategies considering environmental, technical, regulatory, and community requirements (Cacciuttolo & Valenzuela, 2022). Sustainable

development should be considered at all stages of mine development. Sustainable development can be achieved, not by the conventional passive measure of environmental destruction due to mining, but through systematic and continuous monitoring, future- oriented recovery plans, and the development of environmentally friendly technologies (Jang & Topal, 2020). Fleet et al. (2015) proposed integrating renewable energy systems at mine sites to reduce environmental impacts and improve safety. Unfortunately, the barriers to adopting these devices are numerous and include the variability of energy availability and the cost of installation. Fortunately, different solutions could be implemented to overcome these challenges. Digital technologies could be part of energy and carbon management initiatives (Asa'd et Levesque, 2024). Yang et al. (2015) developed an energy management strategy based on velocity optimization for a hybrid electric mining truck, and organizations can establish a sustainable value-added strategy by increasing asset utilization (Paiva et al., 2017).

Mining companies have committed to supporting the United Nations sustainable development goals in their sustainability strategies; among other goals, they promote "inclusive and sustainable economic growth and employment and decent work for all." This goal poses a challenge to the automation of jobs for Indigenous people (Holcombe & Kemp, 2019).

4.6.3.12 Education and training

Paschke et al. (2021) called attention to the role of education in developing digital technologies in the mining industry. Davrajh et al. (2023) warned of the necessity of adopting an appropriate skills-development strategy to ensure that the workforce capitalizes on technological investments. Oshokoya et Tetteh (2018) explored mining engineering programs to ensure that mining-engineer education is prepared for the vision of the mine in the future. New and more-effective training programs, emergency procedures, and mine safety practices are designed using innovative risk analysis and management systems (Kumar, 2016).

Education provides new digital skill sets to the existing and future workforce. There are clear indications that the future of work requires reevaluating skill sets, qualifications, and certifications. Universities must adapt their programs to the new skills needed (Cawood, 2020). Skills in geology, mathematics, and all sciences are required to develop new approaches to mine design and understanding of the laws of nature (Javier, 2018).

Developing educational systems for the future workforce will have specific implications for Indigenous People who rely on mining industry employment (Holcombe & Kemp, 2019). It is, therefore, necessary to understand, from the onset, the impact of digitalization and automation on workplace design, diversity, skill sets, working environments, and safety.

Based on the development status of Smart Mines, Chen, Y., Xu, et al. (2021) proposed a curriculum system construction plan to incorporate the principle of merging traditional courses, introducing new courses, strengthening knowledge integration, highlighting the practical ability to train, and setting selective course groups according to the development of Smart Mines. A new curriculum must be appended to identify 12 areas suitable for academic research or curriculum development (Young & Rogers, 2019). Soni et Wolkersdorfer (2016) suggest that academic training is the key to appropriate mine-water management. Tomorrow's mining engineers must be agile to respond to ever-changing challenges. Curriculums must develop problem-solving skills, soft skills, and an entrepreneurial mindset.

Partnerships between industry and universities are essential for applying academic research to current industry problems. In that way, multiple living laboratories have been developed at mine sites, offering testing and training environments (Clausen & Sörensen, 2022). **C**omparison between the mining industry's vision and the academic literature

Gaps between the vision of the academic and the industrial communities are not uncommon with Industry 4.0. They have also been noted in the construction industry (Perrier et al., 2024). Both mining practitioners and academic authors focus on improving the productivity and efficiency of operations, but the academic literature also focuses on improving health and safety and sustainability, developing autonomous operations, and increasing connected processes and assets. Nevertheless, mining practitioners and academics are fairly aligned in terms of Smart Mine objectives (Tables 4.1 and 4.2).

With respect to environmental objectives, mining practitioners mainly focus on the electrification of mine sites with BEVs, and the academic literature focuses on redesigning processes and supplying renewable energy sources. However, academics are mainly focused on processes and people to improve sustainability and grasp workforce transformation, which are more advanced than industry objectives.

Tables 4.1 and 4.2 also highlight understudied objectives, which could inform future research. Two operational objectives are addressed in academic research: (1) improving the integrated supply chain and value chain and (2) moving toward real-time planning. The objectives of unifying, centralizing, and standardizing information and increasing visibility are not yet linked to the vision of the Smart Mine. The digital transformation process and enhanced data security are crucial to achieving the Smart Mine, which is represented by the increased number of scientific articles on cybersecurity.

Mining practitioners regard connectivity, communication networks, autonomous equipment, management systems, 4.0 technologies, localization, pattern recognition, and remote sensing as the solutions to achieving the vision of the Smart Mine. They focus on communication networks, robots, mining equipment, processes, management systems, software, sensors, simulation, and localization to improve efficient operations and productivity and develop autonomous operations. Additionally, communication networks, processes, software, simulation, and localization are the focus for improving health and safety. While developing electrification and improving sustainability objectives, the mining industry mainly focuses on BEVs and equipment.

Academic researchers are responding to these needs by comparing and improving these technologies. Researchers have also proposed new management systems for digital mines and introduced 4.0 technologies at mine sites. While mining practitioners have focused on redefining operation processes, academics have focused on developing new mining methods and blasting processes.

Mining practitioners are aware of the importance of cultural changes and involving people in digital transformation, yet they pay little attention to people and cultural aspects. Academics are studying cultural changes and their effects on people.

Regarding targeted business management processes, mining practitioners focus on ESG management, information and data management, and monitoring. Academic researchers focus on ESG management but also on education and training, automation management, and business management. More attention to asset management, change management, and risk and safety management is needed in both industry and academia. Academics need to conduct research on multiple business processes to help mining practitioners support the Smart Mine. The digital

transformation process and enhancing data security are also crucial for realizing the concept of a Smart Mine.

Academic researchers are developing new tools and technologies for the mining sector but with little consideration of feasibility and company operational constraints. Fortunately, some of these technologies have reached a high level of maturity, which has led to their adoption in the mining industry. Additionally, the horizons of interest are not the same. Academic authors focus on new developments that may be used in the long-term, while practitioners have sought short- and medium-term solutions.

The Smart Mine case is also unique because it involves multiple Industry 4.0 technologies. Therefore, technology integration is a real concern for practitioners. A similar observation was made in the construction industry (Perrier et al., 2024). Fortunately, intermediary research organizations are trying to bridge the gap between these two worlds (Suvinen et al., 2010). As stated in the Smart Mine Objectives section, collaboration with all the mining-environment actors is key to achieving the Smart Mine. Mining companies are looking for guidance in selecting digital projects to implement, and they would benefit from academic support in planning their digital transformation and prioritizing projects (Institut National des Mines, 2021).

Table 4.1 Financial and operational research opportunities identified in the industry-focused research in relation to the academic literature.

	Solutions \ Objectives	Financial			Operational						
		Increase agility	Improve operational efficiency	Improve productivity	Implement autonomous operations	Perform continuous mineral extraction	Integrate the supply chain & value chain	Deploy interconnected equipment & interoperability	Increase remote operations	Move toward real-time planning	Increase predictive maintenance
Infrastructure	Surface component	1	3	3	3	1	1	1	3		2
	Underground component	1	1	2	1				2		1
	Communication network		4	5	9			3	4		1
Equipment	Robots		2	3	9	2		2	1		
	Drones & UAVs		2	1	2	1		1	1		
	Truck		2	2	3	1			1	1	
	LHD		2	2	5	1			1		
	Bolter	1	3	2	3	1					1
	Continuous machine		1		2	2		1	1		
	Other mining equipment		5	3	9	3	2				
	Wearable device		1	1	4						
	Culture	1	3	5	3	1	1		1		1
	People	1	5	5	7	1	1	2	2		2
	Processes	2	12	10	9	2	3	2	2	1	4
	Management systems		5	6	8	1	1	1	4		2
Technologies	Cybersecurity		1	1	2			2			1
	Cloud		3	1	2			1			
	Software	1	10	6	7	2	2	2	4		1
	Big data & analytics		5	5	5	2	1	2	1	1	
	3D printing			1	1			1			
	Blockchain		1								
	AI & ML		5	4	8	2			1		1
	Sensor & on-board system	1	2	4	10	1		1	2		2
	Simulation & Visualisation		10	11	7	2	2	3	3		1
	Localisation & positioning		8	2	7	1		1	1		
	Pattern recognition		1	1	3				1		
	Remote sensing		4	3	5	1		1	1		

LEGEND (Number of studies) Not addressed | Low | Moderate | Extensive

Table 4.2 Business management, safety, and ESG research opportunities identified in the industry-focused research in relation to the academic literature

	Solutions \ Objectives	Business management					Safety		Environmental, Social and Governance		
		Unify, centralize, and standardize information	Improve collaboration	Increase connected processes & assets	Move toward real-time mine management	Increase visibility	Improve health & safety	Increase data security	Grasp workforce transformation	Develop electrification	Improve sustainability
Infrastructure	Surface component		1	3	2		3	1	2	2	4
	Underground component			1			2	1	1		1
	Communication network		1	4			13	2	1	1	2
Equipment	Robots			1	1	1	4		2	1	1
	Drones & UAVs						4		1	2	2
	Truck		1				2			2	2
	LHD		1				2			3	
	Bolter						2			1	3
	Continuous machine						1				
	Other mining equipment		1	4	1		5			3	4
	Wearable device						2				
	Culture			3	1		3		2	1	4
	People	1	3	3	3		4		7	2	5
	Processes		5	12	3	2	9	2	3	1	6
	Management systems	2	1	1	1		7	1	1	1	1
Technology	Cybersecurity						2	7	1	1	1
	Cloud	1	1	2			3	1		1	1
	Software	1	3	6	4	2	9	1	1	2	5
	Big data & analytics		2	4	4	1	2			3	5
	3D printing						1			1	1
	Blockchain						1	2			1
	AI & ML	2		2	2		6		1		4
	Sensor & on-board system	1	1	3	1		5				3
	Simulation & Visualisation	1	2	4	4	1	14			3	3
	Localisation & positioning		1	2			8			2	1
	Pattern recognition			1			2				
	Remote sensing	1	1	2	1		7				2

LEGEND (Number of studies) Not addressed | Low | Moderate | Extensive

4.7 Discussion

The industry-focused literature clarifies the vision of the Smart Mine and aims to guide mining practitioners toward it. This review describes the objectives, suggests solutions and targeted business management processes, and highlights interactions between these concepts. Mining practitioners and academics agree on 20 objectives related to the Smart Mine regrouped into five categories: financial, operational, business, safety, and ESG (Figure 4.4). The solutions supporting the vision of the Smart Mine can be grouped into six categories: infrastructure, equipment, technology, process, management systems, and people and culture. Numerous solutions and business processes can be adopted and transformed to achieve the Smart Mine objectives.

However, knowing where to start is a challenge for practitioners (Barnewold & Lottermoser, 2020), and while the mining industry is developing roadmaps, academics are not focusing on technology integration. In most cases, mines are brownfield sites, and their current processes and performance levels must be assessed prior to making investment decisions. As such, digital transformation plans for these mines are less flexible than those developed for greenfield mines (Saeidi & Allen, 2022).

Knowing that each mine has its own constraints, we must consider its lifespan, location, scalability, and actual productivity level when developing a transformation plan (Institut National des Mines, 2021). In general, the mining industry is primarily solution-centric, relying on OEMs and supplier solutions. To achieve the Smart Mine, the mining industry needs to think differently by positioning itself with clear objectives, leading to the development of new ideas and solutions. Solutions might be developed collaboratively among OEMs, suppliers, and academia. Solutions are not one-size-fits- all: Each mine site has its own specificities, and each solution has an impact on several business processes to be considered.

On the basis of these findings, we propose the versatile framework in Figure 4.4 to guide the selection of transformation initiatives, which can be used to identify small mine-site continuous improvement projects, problem-based projects, and larger investment projects to ensure that all considered solutions bring the mine toward the Smart Mine objectives.

The mining industry is active and ready to invest in digital transformation projects. In the case of top-down investment projects, the framework suggests first defining the strategy in terms of the Smart Mine objectives. The proposed solutions should then be evaluated in terms of their ability to meet or move toward these objectives. Next, impact analysis must be conducted to determine

which and how business processes will be impacted (Butt, 2020). Further, current problems need to be addressed by conducting continuous improvement initiatives (AVEVA, 2018b). As such, companies must balance and align top-down or bottom-up initiatives to simultaneously solve current problems and move toward their strategic goals (Lemieux et al., 2013; Richard et al., 2021). In the case of bottom-up initiatives, operational problems usually trigger the quest for solutions. The framework suggests prioritizing business processes and associated solutions specifically targeted by the Smart Mine objectives to ensure that continuous improvement activities contribute to the organization's overall strategy, as proposed by Heberle et al. (2017).

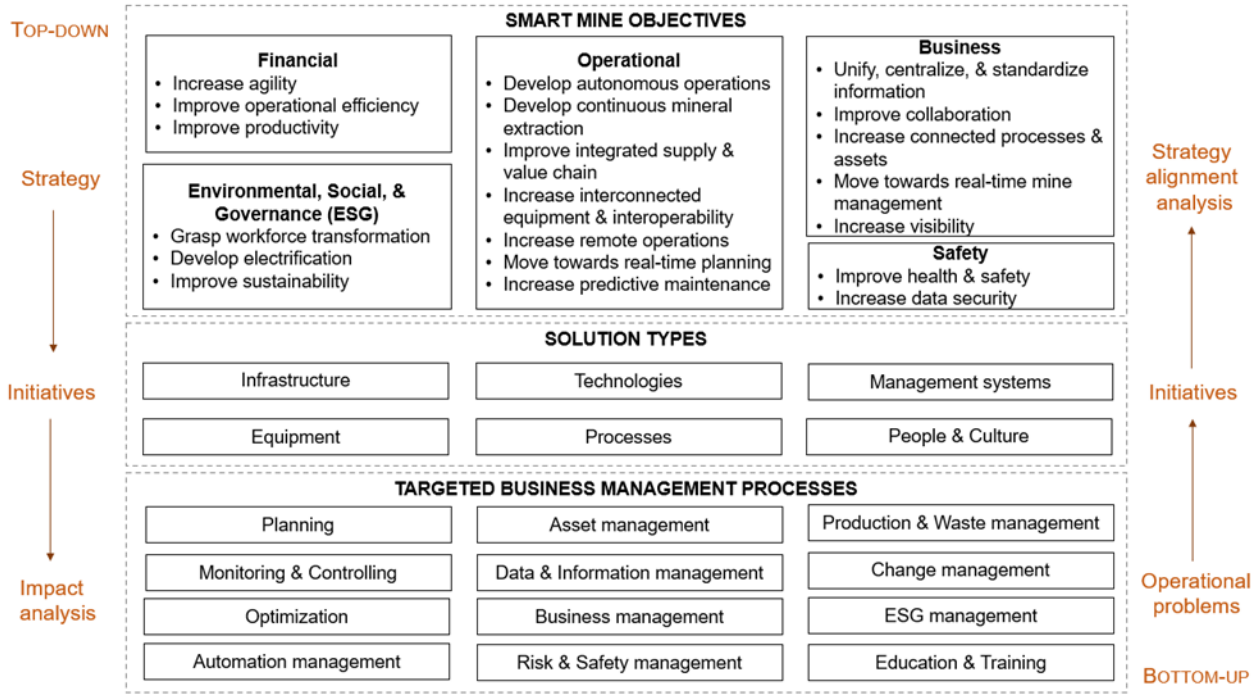

Figure 4.4 Transformation initiatives alignment framework

4.8 Conclusion

In this paper, we described the vision of the Smart Mine as defined by the mining industry and identified opportunities for academic research to help the mining industry achieve the Smart Mine. We first note that communities agree on the objectives of the Smart Mine. The most important objectives for industry are also the most studied by academics. However, some of the objectives are understudied.

Many solutions to achieve this vision are suggested. Academic research mostly focuses on developing new technologies and equipment and is beginning to focus on organizational culture and people. Nevertheless, academics have expressed the need to work on developing new and improving existing technologies that consider sustainability and data security issues.

Many specific targeted business management processes to support digital transformation are identified by the industry, among which academics primarily focus on education and training, automation management, ESG management, and business management. We also noted that technology integration and implementation are not addressed either in the industry or in the academic literature.

This study identified numerous Smart Mine objectives and a pool of suggested solutions and business processes. Although integrating those solutions poses several challenges and is beyond the scope of this article, we recognize that mining companies may struggle to keep up to date in a constantly evolving environment. Practitioners seek assistance from academic researchers in transitioning to the Smart Mine and guidance in choosing technologies to implement. Our proposed framework may serve as a first step toward guiding mining companies in their transformation process. However, it does not define how to precisely identify, select, and prioritize initiatives. Which initiatives to prioritize, in what sequence solutions should be implemented, and which business processes must be adapted remain real questions mining companies need to answer to successfully achieve their digital transformation.

Among potential developments, academics need to focus on specific targeted business management processes to support digital transformation. Additionally, a maturity scale could help identify problems in a more detailed manner when adopting a bottom-up approach or the development of capacity analysis tools allowing the evaluation of required budgets, resources, and competencies when studying potential investment projects adopting a top-down approach. Additional study is required to identify potential integration challenges and barriers associated with each investigated solution and the integration of sustainability factors into technologies, challenges of technology adoption and postadoption, and critical success factors. Most importantly, future research should focus on transforming the proposed framework into a more complete project portfolio management approach for the mining industry to guide them in their transformation process.

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4.10 Disclosure statement

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4.12 Review statement

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CHAPITRE 5 ARTICLE 2: IMPLEMENTATION APPROACHES FOR DIGITAL TRANSFORMATION : CURRENT STATE OF THE MINING INDUSTRY

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5.2 Résumé

La TN de l'industrie minière présente de nombreux défis, en particulier dans la transition stratégique vers le concept de Mine Intelligente, caractérisée par une connectivité numérique, la durabilité et des prises de décision en temps réel visant à améliorer la productivité et la sécurité, tout en mettant l'accent sur une transformation de la main-d'œuvre centrée sur l'humain. Cet article cherche à évaluer les méthodologies actuelles de TN mises en œuvre dans le secteur minier souterrain afin de soutenir ce processus de transformation. Pour ce faire, nous réalisons une revue approfondie de la littérature académique et industrielle portant sur les stratégies existantes guidant les initiatives de TN dans le domaine minier. Ensuite, nous extrayons les pratiques et méthodologies du secteur minier et de l'Industrie 4.0, en cherchant à évaluer les activités mises en œuvre et leur valeur correspondante à l'aide d'avis d'experts. Nos résultats révèlent un écart dans le respect de la séquence recommandée des phases de gestion de portefeuille, les phases de catégorisation et de balancement étant les moins utilisées. De plus, nous observons que la majorité des activités suggérées dans la littérature relative à l'Industrie 4.0 et au secteur minier sont appliquées par plus de 50 % des experts en gestion de portefeuille. Malgré ces variations d'application, la plupart des activités sont perçues comme ayant de la valeur ajoutée par les experts de l'industrie, ce qui souligne leur potentiel à contribuer à la TN du secteur minier.

5.3 Abstract

The mining industry's digital transformation (DT) presents a myriad of challenges, particularly in the strategic transition toward the concept of the Smart Mine, which is characterized by digital connectivity, sustainability, and real-time decision-making capabilities that enhance productivity and safety, focusing on human-centered workforce transformation. This paper seeks to evaluate the current DT methodologies employed within the underground mining sector to facilitate this transformative process. To accomplish this, we conduct a comprehensive review of academic and

industry literature on existing strategies that guide DT initiatives within the mining domain. Next, we extract successful practices and methodologies from both the mining sector and the broader Industry 4.0 landscape, seeking to evaluate the implemented activities and their corresponding value using expert insights. Our findings indicate a disparity in adherence to the recommended sequence for portfolio management phases, with notable challenges in the categorization and balancing phases, which are the least utilized. Moreover, we observe that the majority of activities suggested in the literature related to Industry 4.0 and the mining sector are employed by over 50% of portfolio management experts. Despite these variances in application, most activities are perceived as valuable by industry experts, underscoring their potential contribution to the mining sector's DT journey.

Keywords Digital transformation, Project Portfolio Management, Industry 4.0, Smart Mine, Underground mine

5.4 Introduction

The mining industry has undergone a digital transformation (DT) in recent years, bringing considerable changes across the sector. At the heart of this transformation is the development of the Smart Mine, utilizing a range of technologies to enhance mining infrastructure, equipment, culture, processes, and management systems (Echternach et al., 2024). This transformation parallels the shift seen in manufacturing organizations, referred to as Industry 4.0, which focuses on enhancing processes, products, and services (Richard et al., 2021).

It is essential to distinguish between digitization, digitalization, DT, and Artificial Intelligence (AI) transformation as these terms, though often used interchangeably, differ in scope. Digitization refers to the process of converting from analog to digital. Digitalization goes a step further by leveraging digital technologies to enhance existing processes. DT, meanwhile, is broader in scope: it encompasses the organization-wide implementation of digital technologies, requiring fundamental changes to business models, management practices, and workforce culture to create new ways of operating. At the operational level, automation refers to the application of these digital technologies, while AI transformation builds upon the DT transformation strategy in integrating AI tools (Bumann & Peter, 2019).

While the vision of the Smart Mine serves as a foundational element for guiding DT, mining companies encounter distinct challenges in their transformation efforts, particularly when

compared to manufacturing industries (Young & Rogers, 2019). These challenges encompass factors such as the finite operational lifespan of mines (Institut National des Mines, 2021), spatial limitations, prevalent dark and dusty conditions (Gao, S. et al., 2019), extreme weather variability (Sánchez & Hartlieb, 2020), the necessity for a digitally skilled workforce (Dragičević & Bošnjak, 2019; Lööw, Joel et al., 2019), stringent safety regulations (Gao, S. et al., 2019), issues related to connectivity (Rogers et al., 2019), scalability and dynamic adaptability interdependencies among multiple projects (Yendamuri et al., 2021), the imperative to maintain production performance (Visser, 2020), a high degree of uncertainty (Ali & Frimpong, 2020), and the need for coordination across various organizational silos (Sánchez & Hartlieb, 2020). Additionally, the complexity of digitalization is compounded by the difficulties in assessing the cost-benefit balance of investments due to challenges in accurately predicting the value generated by specific projects (Basulo-Ribeiro et al., 2023; Wael et al., 2022). This transformation extends beyond merely adopting new technologies; it necessitates organizational change and a focus on cultivating a human-centered workforce (Sánchez & Hartlieb, 2020).

In contrast to manufacturing firms with fixed production processes, underground mines are characterized by ongoing construction and expansion, creating a unique and complex environment with specific challenges. Due to the distinct characteristics of each mine, there is no universal solution for achieving the Smart Mine. Indeed, mining companies are undertaking DT projects employing various strategies to address industry priorities, minimize operating costs, and improve productivity and safety.

This diversity raises numerous questions regarding the most effective approaches to plan and execute these multiple DT initiatives. Still, the existing practices for DT adoption within the mining sector are not well-defined. This paper aims to enhance our understanding of the industry's current status by investigating the practices being implemented, their frequency of application, and the perceived value in facilitating DT within the sector.

The remainder of this paper is structured as follows. First, we provide a comprehensive review of both academic and non-academic literature. Next, we outline our methodology for identifying DT activities recommended within the mining industry and supporting Industry 4.0 initiatives. Subsequently, we present feedback from mining experts regarding these suggested activities,

evaluating their frequency of use and perceived value. Finally, we conclude by discussing potential opportunities for future research.

5.5 Literature review

Papers discussing specific DT approaches used in the mining sector remain fairly rare. Among them, Yaqot et Menezes (2022) demonstrate that the integration of digital technologies in the mining sector is typically performed on a case-by-case basis. This observation is reinforced by Wael et al. (2022), who suggest that mining operations often adopt diverse technologies—ranging from equipment automation and remote operation centers to software solutions—to address specific needs, often without incorporating these tools into a comprehensive DT strategy. Furthermore, mining enterprises face obstacles that impede DT's thorough and strategic implementation, with many depending on external suppliers for support. Although certain companies have developed clear DT frameworks featuring defined goals, training programs, risk assessments, and prioritized initiatives, considerations such as scalability and cybersecurity are frequently overlooked.

The literature also includes several case studies examining distinct DT aspects within the mining sector. Gao, S. et al. (2019) investigate the implementation of DT initiatives within mining companies through a qualitative case study centered on operational-level activities. Their findings indicate a prevalent resistance to change among firms and challenges in establishing goals and acquiring resources essential for executing transformations. Similarly, Nyström Eklund et Adelgren (2021) conduct a case study that explores the DT processes adopted by mining enterprises, identifying pivotal activities such as objective formulation, personnel training on new systems, the establishment of a centralized decision-making unit for project assessment and prioritization, encouragement of cross-departmental collaboration, and evaluation of digital readiness. Moreover, Benzane (2019) assesses DT within an African mining firm via qualitative research, revealing that respondents highlighted the significance of change management, a clear vision, and effective stakeholder engagement throughout the transformation journey. Additionally, Merma (2023) analyzes the DT strategies of various mining companies, noting that although each company pursues its own strategic trajectory, only multinational firms demonstrate full alignment with the Smart Mine concept.

Recognizing the critical role that consulting firms and suppliers play in supporting mining companies with their DT initiatives, we also undertook a review of non-academic literature, which yielded five additional pertinent documents. First, Rockwell Automation (2019) observes that a limited number of mining companies effectively align their digital strategies with broader business strategies. In many cases, firms establish their business objectives before identifying relevant digital technologies, while others turn to suppliers for their expertise. Although scalability is seldom considered in strategic planning, most companies assess the return on investment, present clear use cases, and prioritize project initiatives and their associated risks. Both Rockwell Automation (2021) and Jacobs et al. (2019) provide case studies demonstrating that suppliers often spearhead individual DT projects and sometimes collaborate with mining companies to plan their DT efforts. Furthermore, GMG (2021) highlights a multinational mining company's DT journey, emphasizing its inclusive approach, which encompasses employee training, fostering transparent communication with affected staff to enhance engagement, and implementing change management strategies aimed at career development pathways. Lastly, Harris, J. (2023) underscores that successful DT relies on collaboration among workers with diverse skill sets, strategic alignment, technical education, the appointment of on-site champions, scalability planning, an understanding of on-site transformation capabilities, and developing a long-term roadmap.

This literature review reveals a limited understanding of DT approaches employed within the mining industry. Although some articles discuss the implementation of DT activities, they fail to link these activities to project management practices explicitly. Furthermore, the majority of the reviewed articles concentrate on the execution of individual projects, neglecting the complexities involved in managing multiple interdependent projects concurrently. Despite the critical need for effective management of such portfolios of initiatives, none of the existing studies adopt a project portfolio management perspective. While best practice recommendations are provided, there is a notable lack of information regarding the overall adoption levels of these practices within the industry. This highlights a clear absence of empirical studies assessing the project management approaches and best practices employed in the mining sector to guide its DT.

5.6 Analytical Framework

To address the limited insights into the DT approaches utilized within the mining industry, we propose an analytical framework to evaluate the current state of DT practices. This framework is

designed to evaluate existing practices, identify areas for improvement, and facilitate a more comprehensive exploration of how DT initiatives are implemented in this sector. As the mining industry is rather broad, we focus on DT practices used in underground mining environments, excluding coal mining.

Two streams of research were analyzed to identify potential DT approaches and best practices along with their associated activities. First, numerous researchers have shown that DT, particularly when incorporating multiple Industry 4.0 technologies, necessitates the execution of various projects, highlighting the importance of project portfolio management approaches to encompass the entire transformation process (Brodeur et al., 2022; Richard et al., 2021). Accordingly, we integrated both academic and non-academic best practices from project and project portfolio management to develop our analytical framework. Second, we acknowledge that the mining industry's DT lags behind many other sectors (Young & Rogers, 2019) and academic research on DT approaches specifically for the mining industry is relatively recent and limited. Consequently, we broadened our research to encompass all industrial sectors to identify the best DT practices, with a significant portion sourced from the existing Industry 4.0 literature. Digital transformation models – centralized, federated, and hybrid – determine how organizations coordinate DT initiatives across corporate and operational domains. Top-down, corporate-led strategies characterize centralized models, whereas federated models emphasize local autonomy, enabling site-level customization of digital solutions (Bossert et al., 2023). Franco et al. (2024) highlight the advantages of hybrid models, which integrate centralized governance with decentralized implementation, particularly for firms facing complex organizational structures. In alignment with this perspective, the mining industry is increasingly adopting hybrid approaches (Accenture, 2012), embedding digital and data expertise within operational technical teams (McKinsey&Company, 2018).

The Project Management Institute (PMI) portfolio management standards will be used to structure our framework (Project Management Institute, 2008), as suggested by Richard et al. (2021) in their DT approach to guide manufacturing companies. This well-known standard suggests nine project portfolio management phases: identification, categorization, evaluation, selection, prioritization, risk, balancing, communication, and authorization. Those phases will be the foundation for classifying suggested academic and non-academic activities from the mining industry and Industry 4.0 literature. Accordingly, each identified best practice will be presented as a specific activity to

be conducted within a particular project portfolio management phase. The following sections will detail each phase in sequence.

5.6.1 Identification

The initial phase involves the identification of initiatives, focusing on recognizing needs, problems, and opportunities for DT. Among the literature, Echternach et al. (2024) developed a generic transformation initiatives alignment framework to assist mining companies in their DT efforts. In practice, either top-down or bottom-up methodologies can be employed to synchronize transformation initiatives with the company's strategy and its Smart Mine goals. Several studies recommend formulating a DT vision that includes key objectives (Allaoui et al., 2019; Wael et al., 2022), which should align with the company's business model (World Economic Forum, 2017). Various methods for defining these objectives are discussed in the literature. Nyström Eklund et Adelgren (2021) evaluate digital readiness, while Yaqot et Menezes (2022) advocate a leadership-supported strategy to pinpoint technologies tailored to the company's specific needs, capacities, and integrability. ABB (2024) endorses a collaborative approach, whereas Bechtold (2021) suggests implementing top-down governance to ensure cohesive vision coordination. Lemieux et al. (2013) recommend establishing quantifiable success metrics, while Epiroc (2024b), an Original Equipment Manufacturer, proposes a bottom-up agnostic strategy to track progress.

In terms of specific activities, the literature proposes various procedures for initiative identification. Basulo-Ribeiro et al. (2023) recommend mapping the "AS-IS" process to define and evaluate the current state (Mielli & Bulanda, 2019; Rockwell Automation, 2019). Barbosa et al. (2020) suggest assembling a multidisciplinary team from different departments to assess the current process, considering aspects such as production, quality, maintenance, and occupational health. Schumacher et al. (2019) employ a maturity assessment procedure for this purpose. Butt (2020) advocates for process reengineering to establish the "TO-BE" process based on an analysis of the "AS-IS" process, identifying potential initiatives.

Many researchers have proposed identifying actual problems to pinpoint potential initiatives. For instance, Richard et al. (2021) emphasize the importance of detecting problems and areas for improvement. Similarly, Bechtold (2021) and De Carolis et al. (2017) focus on identifying pain points, strengths, weaknesses, opportunities, and threats. Al-Banna et al. (2023) conducted a self-assessment to identify pain points and root causes. Brunelli (2020) recommends using top-down

governance to evaluate the current state and identify pain points, opportunities, and threats, highlighting the importance of enhancing existing processes—often without necessitating new technology. Moodley (2017) advocates combining top-down and bottom-up approaches to uncover gaps and opportunities. Additionally, Butt (2020) employs an integrated business process management (BPM) approach that encompasses process analysis.

In addition to these recommendations, Epiroc (2024a) promotes a bottom-up OEM-agnostic strategy to identify high-benefit automation areas through a lean DT approach. Richard et al. (2021) also highlight the need to recognize other ongoing initiatives and projects during the identification phase (Ernst & Young, 2018). Furthermore, Allaoui et al. (2019) recommended assessing organizational readiness to identify potential initiatives. Similarly, Nyström Eklund et Adelgren (2021) evaluated digital readiness, Jacobs et al. (2019) examined digital maturity, and Schumacher et al. (2019) proposed a maturity assessment procedure (Lemieux et al., 2013). De Carolis et al. (2017) and Rautenbach et al. (2019) have also developed a maturity-based model for assessing readiness, which encompasses six digital dimensions: strategy and leadership, people and organizational culture, technology, business model, product and service offerings, and customer experience. Finally, Ghobakhloo et al. (2022) evaluate supply chain readiness, and Bechtold (2021) incorporates digital capability development as a critical dimension for managing change during DT.

Interestingly, only a few authors emphasize the importance of change management, stakeholder management, risk management, and communication management as early as the identification phase. Bellantuono et al. (2021) reviewed DT models from the scientific literature through the lens of change management. They provided recommendations for change management, such as preparing teams for change during the identification phase. Industry perspectives support this activity, advocating for a human-centered change management approach (Epiroc, 2024b), fostering collaboration, training, workforce engagement (World Economic Forum, 2017), and emphasizing the necessity of continuous change management (Brunelli, 2020) alongside workforce management (Harris, F., 2019). Moreover, Allaoui et al. (2019), Lemieux et al. (2013), and Bellantuono et al. (2021) recommend establishing a dedicated team for transformation governance. Harris, F. (2019) suggests engaging champions to facilitate the change process. Both academic and industry experts concur on the significance of change management (Brunelli, 2020; Epiroc, 2024a; Project Management Institute, 2017), workforce management (Harris, F., 2019), and the establishment of

a comprehensive change management strategy (ABB, 2024; Butt, 2020; Visser, 2020). Additionally, Bellantuono et al. (2021) propose developing a resistance-management plan to address potential challenges.

Yendamuri et al. (2021) also emphasize the skills gap as a significant barrier to DT in the mining sector. Butt (2020) addresses this challenge by conducting a skills gap analysis, a step also endorsed by industry stakeholders (Ernst & Young, 2018; Jacobs et al., 2019).

In a different line of thought, the Project Management Institute (2021) underscores the importance of establishing effective Key Performance Indicators (KPIs) tailored to the chosen objectives for DT, a sentiment echoed by Visser (2020) and Santos, R. C., De Lima, et al. (2023). During the process analysis phase, Butt (2020) recommends defining not only KPIs (Al-Banna et al., 2023; Harris, F., 2019) but also Key Risk Indicators and Project Performance Indicators (Epiroc, 2024b), all of which are integral to the initiative identification process.

Regarding stakeholder engagement, both the (Project Management Institute, 2017, 2021)and Harris [45] advocate for developing a communication plan. Heberle et al. (2017) have created a standardized digitalization canvas employing a top-down and bottom-up approach, which includes concrete steps for defining DT projects, alongside the suggestion to interview stakeholders across the entire value chain. Barbosa et al. (2020) further recommend the collection of stakeholders' expectations and requirements. Gao, S. et al. (2019) and the World Economic Forum (2017) highlight the critical importance of collaboration, particularly external collaboration (Al-Banna et al., 2023; Bellantuono et al., 2021; Ghobakhloo et al., 2022). ABB (2024) exemplifies this collaborative approach by guiding mining companies through their DT journey.

At the portfolio management level, the PMI (Project Management Institute, 2017, 2019, 2024) advises on portfolio risk management to achieve balance among the programs and projects within the portfolio, aligning with the organization's objectives, capacities, and capabilities. The DT team is encouraged to develop a risk management strategy encompassing the categorization, management, identification, assessment, and response to risks. This requires ongoing monitoring for uncertainties and establishing risk thresholds at the portfolio, program, and project levels (both qualitative and quantitative). The portfolio risk threshold aims to balance overall risk, while the program risk threshold addresses the immediate impact of risk, and the project risk threshold focuses on cost, schedule, and scope. Mican et al. (2021) advocate for a digital risk management

strategy to identify, qualify, and quantify risk factors at each stage of project portfolio management. Furthermore, Butt (2020) suggests formulating a risk management strategy along with a contingency plan, while Harris, F. (2019) views risk management as an ongoing process that begins at the identification phase.

Table 5.1 summarizes the identification activities recommended in the literature, with non-academic references in bold italic.

Table 5.1 References per identification activities

Activities per phase		References
	Identification	
I1	Align strategic company vision with Smart Mine objectives	(Echternach et al., 2024)
I2	Define digital transformation vision with key objectives	(Allaoui et al., 2019; Nyström Eklund & Adelgren, 2021; Wael et al., 2022; Yaqot & Menezes, 2022) ***(ABB, 2024; Bechtold, 2021; World Economic Forum, 2017)***
I3	Develop a quantifiable measure for success	(Lemieux et al., 2013) (Epiroc, 2024b)
I4	Prepare teams to change	(Bellantuono et al., 2021) ***(Brunelli, 2020; Epiroc, 2024b; Harris, F., 2019; World Economic Forum, 2017)***
I5	Collect expectations and requirements of key stakeholders	(Barbosa et al., 2020)
I6	Diagnose AS-IS process of each improvement	(Al-Banna et al., 2023; Barbosa et al., 2020; Basulo-Ribeiro et al., 2023; Bellantuono et al., 2021; Butt, 2020; Mielli & Bulanda, 2019; Richard et al., 2021; Schumacher et al., 2018) ***(Brunelli, 2020; Epiroc, 2024b; Jacobs et al., 2019; Rockwell Automation, 2019)***
I7	Assess the current company's process digital capability readiness, change readiness, and as-is maturity of pre-defined dimensions	(Allaoui et al., 2019; De Carolis et al., 2017; Ghobakhloo et al., 2022; Lemieux et al., 2013; Nyström Eklund & Adelgren, 2021; Rautenbach et al., 2019; Schumacher et al., 2018) ***(Bechtold, 2021; Jacobs et al., 2019)***
I8	Identify initiatives based on opportunities, strengths, weaknesses, and threats	(De Carolis et al., 2017) ***(Bechtold, 2021; Moodley, 2017)***
I9	Define Key Performance Indicators	(Al-Banna et al., 2023; Butt, 2020; Santos, R. C., De Lima, et al., 2023; Visser, 2020) ***(Harris, F., 2019; Project Management Institute, 2021)***
I10	Define Key Risk Indicators	(Butt, 2020)
I11	Interview stakeholders of the entire value chain	(Heberle et al., 2017)
I12	Define "TO-BE" process	(Butt, 2020)
I13	Realize a skill gap analysis	(Bellantuono et al., 2021; Butt, 2020) ***(Ernst & Young, 2018; Jacobs et al., 2019; Yendamuri et al., 2021)***
I14	Identify possible collaboration	(Al-Banna et al., 2023; Gao, S. et al., 2019; Ghobakhloo et al., 2022) ***(ABB, 2024; Bellantuono et al., 2021; World Economic Forum, 2017)***
I15	Identify initiatives and on-going projects	(Richard et al., 2021) (Ernst & Young, 2018)
I16	Identify subteams and/or champion for implementation	(Allaoui et al., 2019; Bellantuono et al., 2021; Lemieux et al., 2013) (Harris, F., 2019)
I17	Design change management strategy	(Bellantuono et al., 2021; Butt, 2020; Visser, 2020) ***(ABB, 2024; Brunelli, 2020; Epiroc, 2024a; Harris, F., 2019; Project Management Institute, 2017)***
I18	Develop a communication plan	***(Harris, F., 2019; Project Management Institute, 2021)***
I19	Define Project Performance Indicators	(Butt, 2020) (Epiroc, 2024b)
I20	Establish a risk management strategy	(Butt, 2020; Mican et al., 2021) ***(Harris, F., 2019; Project Management Institute, 2017, 2019, 2024)***

5.6.2 Categorization

The second phase involves categorizing the identified initiatives according to their scope to organize them effectively. This phase is infrequently addressed in the literature.

Richard et al. (2021) propose establishing categories based on the strategic plan and evaluating initiatives against categorization criteria to assign each initiative to a specific category. Ghobakhloo et al. (2022) recommend classifying initiatives into the following categories: operational efficiency, operational reliability, financial performance, and marketing performance. Conversely, Hamzeh et al. (2018) categorize initiatives using the dimensions of operations, strategy, environment, and people. Additionally, the Project Management Institute (2017) suggests categorizing initiatives by risk categories and aligning them with relevant stakeholders.

Table 5.2 provides a summary of the categorization activities recommended in the literature, with non-academic references in bold italic.

Table 5.2 References per categorization activities

	Activities per phase	References
	Categorization	
C1	Identify categories based on the strategic plan	(Richard et al., 2021)
C2	Compare initiatives against the categorization criteria to assign a category	(Richard et al., 2021)
C3	Categorize initiatives into operational efficiency, operational reliability, financial performance, and marketing performance	(Ghobakhloo et al., 2022)
C4	Categorize project into operation, strategy, environment, and people	(Hamzeh et al., 2018)
C5	Categorize stakeholders	***(Project Management Institute, 2017)***
C6	Categorize by risk categories	***(Project Management Institute, 2017)***

5.6.3 Evaluation

The third phase involves the evaluation of initiatives, which serves as a decision-making tool by examining them from multiple perspectives.

Among recommendations, Al-Banna et al. (2023) and Sarvari et al. (2018) advocate for a comprehensive evaluation process. Similarly, Richard et al. (2021) propose evaluating initiatives by establishing criteria with assigned weights, which may include technological, managerial, strategic (Ebrahimi et al., 2018), risk, productivity improvement, technical, financial, and organizational factors (Isikli et al., 2018). Santos, R. C., De Lima, et al. (2023) also recommend defining both qualitative and quantitative criteria relevant to the mining industry, such as strategy, organizational, financial, time, risk, human resources, quality, productivity, sustainability, operational, flexibility, technological/technical, and product performance, and assigning appropriate weights to the selected criteria (Santos, R. C. et al., 2021). The Project Management Institute (2017) suggests considering realization factors (e.g., cost, time, results, resistance to change), organization-specific objective-oriented factors (e.g., ease, visibility, impact), and external factors (e.g., community perceptions) when evaluating portfolio components. Brunelli (2020) recommends assessing both the direct and indirect benefits of initiatives and their feasibility, while Lemieux et al. (2013) propose analyzing costs, resources, and time investments (Erol et al., 2016). Among practitioners, ABB (2024) emphasizes the importance of evaluating return on investment (Barbosa et al., 2020) and the potential impact on workers (Bellantuono et al., 2021).

During the evaluation process, Hamzeh et al. (2018) and Erol et al. (2016) include risk as a criterion for evaluation. At the same time, Butt (2020) suggests conducting a risk analysis of the initiatives alongside a cost-benefit analysis.

Table 5.3 presents a summary of the evaluation activities suggested in the literature, with non-academic references in bold italic.

Table 5.3 References per evaluation activities

	Activities per phase	References
	Evaluation	
E1	Define evaluation criteria	(Demircan Keskin, 2020; Ebrahimi et al., 2018; Isikli et al., 2018; Richard et al., 2021; Santos, R. C. et al., 2021) ***(Project Management Institute, 2017)***
E2	Define quantitative criteria	(Santos, R. C., De Lima, et al., 2023)
E3	Define qualitative criteria	(Santos, R. C., De Lima, et al., 2023)
E4	Define weight per criteria	(Richard et al., 2021; Santos, R. C. et al., 2021)
E5	Use technology criteria	(Ebrahimi et al., 2018)
E6	Evaluate the initiatives	(Al-Banna et al., 2023; Richard et al., 2021; Sarvari et al., 2018)
E7	Evaluate initiatives' direct and indirect benefits	***(Brunelli, 2020)***
E8	Evaluate the return on investment	(Barbosa et al., 2020) ***(ABB, 2024)***
E9	Evaluate the feasibility	(Barbosa et al., 2020)
E10	Evaluate the impact on workers	(Bellantuono et al., 2021)
E11	Evaluate the risk	(Erol et al., 2016; Hamzeh et al., 2018)
E12	Carry out a cost-benefit analysis	(Butt, 2020)
E13	Carry out cost, resources, and time investment analysis	(Erol et al., 2016; Lemieux et al., 2013)
E14	Undertake a risk analysis	(Butt, 2020)

5.6.4 Selection

The fourth phase focuses on selecting initiatives based on the evaluation results. The literature on best practices for this phase is also rather sparse.

Richard et al. (2021) prioritize initiatives by assigning ratings derived from the evaluation outcomes (Santos, R. C., De Lima, et al., 2023; Santos, R. C., Lima, et al., 2023). Ebrahimi et al. (2018) compare projects against selection criteria and rank them using decision-making tools. Wael et al. (2022) incorporate scalability criteria (Al-Banna et al., 2023; Epiroc, 2024a; Rockwell Automation, 2021) into their selection process. Additionally, Sarvari et al. (2018) employ the efficient frontier curve graph as a tool for initiative selection. Hamzeh et al. (2018) conduct a risk assessment and establish a risk threshold for the initiatives only after the selection of initiatives (Bellantuono et al., 2021; Project Management Institute, 2019, 2024).

Table 5.4 summarizes the selection activities recommended in the literature, with non-academic references in bold italic.

Table 5.4 References per selection activities

	Activities per phase	References
	Selection	
S1	Select using the scalability criteria	(Al-Banna et al., 2023; Wael et al., 2022) ***(Epiroc, 2024a; Rockwell Automation, 2019)***
S2	Use the efficient frontier curve graph to select initiatives	(Sarvari et al., 2018)
S3	Assign a rating to select and prioritize projects	(Richard et al., 2021; Santos, R. C., De Lima, et al., 2023)
S4	Compare projects with selection criteria and rank them based on criteria using decision-making tools	(Ebrahimi et al., 2018; Richard et al., 2021)
S5	Select projects based on the evaluation results	(Richard et al., 2021)
S6	Undertake a risk assessment of the initiatives and establish risk threshold	(Bellantuono et al., 2021; Hamzeh et al., 2018) ***(Project Management Institute, 2019, 2024)***

5.6.5 Prioritization

The fifth phase involves prioritizing the selected initiatives to determine which ones are most valuable for the organization.

Among recommendations, Isikli et al. (2018) prioritize initiatives by considering constraints and interdependencies (Richard et al., 2021; Yendamuri et al., 2021). To assist in the prioritization process, Wael et al. (2022) utilize a priority matrix, employ a grid value/risk approach (Rockwell Automation, 2019), or identify quick wins and return on investment (Barbosa et al., 2020)]. Additionally, Sarvari et al. (2018) incorporate expert input to prioritize initiatives based on revenue, savings, and risk.

Table 5.5 offers a summary of the prioritization activities recommended in the literature, with non-academic references in bold italic.

Table 5.5 References per prioritization activities

	Activities per phase	References
	Prioritization	
P1	Prioritize initiatives based on interdependency	(Isikli et al., 2018; Richard et al., 2021) ***(Yendamuri et al., 2021)***
P2	Map projects initiatives on a priority matrix or grid value/risk	(Mielli & Bulanda, 2019; Wael et al., 2022) ***(Rockwell Automation, 2019)***
P3	Prioritize based on revenue, saving, and risk	(Sarvari et al., 2018)

5.6.6 Risk

The sixth phase involves conducting a risk analysis of the prioritized initiatives to evaluate the associated risks. Such evaluation is essential (Project Management Institute, 2019). To do so, Butt (2020) recommends implementing a risk register and a mitigation plan, while Al-Banna et al. (2023) identify operational process risk, demand risk, and environmental risk. Santos, R. C., De

Lima, et al. (2023) also incorporate qualitative and quantitative risks, including technical, financial, time, managerial, and personnel risks.

Table 5.6 provides a summary of the risk activities suggested in the literature, with non-academic references in bold italic.

Table 5.6 References per risk activities

	Activities per phase	References
	Risk	
R1	Carry out a formal risk analysis	(Al-Banna et al., 2023; Butt, 2020; Santos, R. C., De Lima, et al., 2023) ***(Project Management Institute, 2019)***
R2	Develop a mitigation plan	(Butt, 2020)

5.6.7 Balancing

The seventh phase focuses on balancing the initiatives, which involves organizing the prioritized initiatives into a portfolio that optimally aligns with the organization's strategic goals. This phase is addressed in only one paper, as detailed in Table 5.7. Richard et al. (2021) evaluate the initial portfolio by considering resource constraints, optimizing it by allowing, terminating, or disabling specific initiatives, and allocating resources to the selected initiatives.

Table 5.7 References per balancing activities

	Activities per phase	References
	Balancing	
B1	Evaluate initial portfolio taking into account resource constraints	(Richard et al., 2021)
B2	Optimize portfolio	(Richard et al., 2021)
B3	Allow or terminate and disable initiatives in the portfolio	(Richard et al., 2021)

5.6.8 Communication

The eighth phase focuses on communication to ensure information is effectively distributed throughout the organization.

The Project Management Institute (2021) advises fostering open communication (Project Management Institute, 2017), informing stakeholders of portfolio decisions, and ensuring that the outcomes of program components are communicated to the appropriate stakeholders. Maintaining vertical and horizontal communication is also considered a good practice (Project Management Institute, 2024). Furthermore, the strategy, vision, and timing of the implementation should be communicated to all members involved in the transformation process (Allaoui et al., 2019;

Bellantuono et al., 2021). At this stage, it is essential to implement the change management strategy (Epiroc, 2024a; Harris, F., 2019).

Table 5.8 summarizes the communication activities recommended in the literature, with non-academic references in bold italic.

Table 5.8 References per communication activities

	Activities per phase	References
	Communication	
CO1	Foster open communication	***(Project Management Institute, 2017, 2021)***
CO2	Communicate portfolio decisions to stakeholders	(Project Management Institute, 2021)
CO3	Ensure outcomes of program's components are communicated to appropriate stakeholders	(Project Management Institute, 2021)
CO4	Ensure vertical and horizontal communication	(Project Management Institute, 2024)
CO5	Communicate change vision, strategy, and timing of implementation with all members involved	(Allaoui et al., 2019; Bellantuono et al., 2021)
CO6	Put in place the change management strategy	***(Epiroc, 2024a; Harris, F., 2019)***

5.6.9 Authorization

The final phase involves the authorization of initiatives to consolidate the portfolio.

The Project Management Institute (2017) recommends authorizing portfolio components at the conclusion of the process. However, Visser (2020) states that authorization may be required at different levels, depending on the scope and level of investment. During this phase, Richard et al. (2021) also mention the need to communicate portfolio decisions to stakeholders to secure authorization and allocate financial and human resources accordingly.

Table 5.9 summarizes the authorization activities recommended in the literature, with non-academic references in bold italic.

Table 5.9 References per authorization activities

	Activities per phase	References
	Authorization	
A1	Authorize portfolio components	***(Project Management Institute, 2017)***
A2	Communicate portfolio decisions to stakeholders for authorization and allocation of financial and human resources	(Richard et al., 2021)
A3	Authorize at different levels depending on the scope and investment level	(Visser, 2020)

5.7 Industry's current situation

This section provides a comprehensive understanding of current DT practices in the underground mining industry, based on the analysis framework outlined in Section 5.6. This framework guided

expert interviews to evaluate the sequence of portfolio phases, the level of use, and the value-added of each activity suggested in academic and non-academic literature. Their feedback also identified additional activities to support DT in mining. Ten experts representing various organizational levels (corporate leaders, portfolio and project managers, and a mine manager) from international and Canadian mining companies, consulting firms, and suppliers offered insights based on 5 to 25 years of experience across international and local mining operations in both soft and hard rock underground mines. Their input provides a comprehensive understanding of current DT practices in underground mining as exposed in the following sections.

5.7.1 Sequence of the portfolio phases used by mining practitioners

For each phase defined by the PMI, ten Canadian mining experts were asked in the questionnaire whether the phase was utilized in their DT process and its sequence. Figure 5.1 presents the results, illustrating the sequence of portfolio phases employed. Grey indicates phases used in the same order as recommended by the PMI, hatched grey signifies phases that are used but not in the prescribed sequence, and black denotes phases that are not used. The results highlight deviations from PMI guidelines in industry practices, with categorization and balancing being the least utilized phases. While most phases are generally followed in sequence, there is no consensus regarding the order of the risk phase.

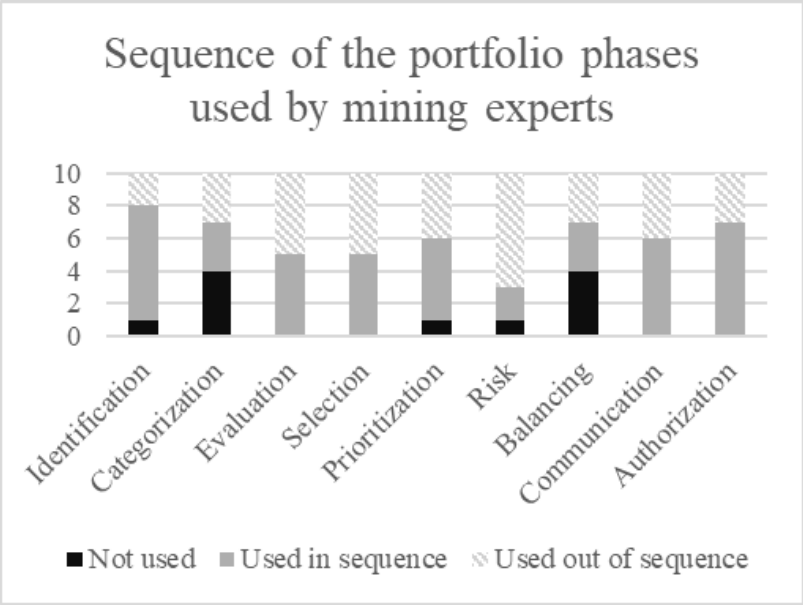

Figure 5.1 The sequence of the portfolio phases used by mining experts

5.7.2 Level of use and value-added of suggested activities

Based on feedback from mining experts, activities suggested by various approaches are generally utilized and considered valuable (Table 5.10). In the identification phase, most activities are not actively used but are still regarded as useful, whereas in the categorization phase, only a few activities are both used and deemed useful. However, more than 50% of experts recognize the categorization phase as beneficial. In the evaluation phase, experts consistently use and find the activities useful. In contrast, the selection phase shows that graphical tools are neither used nor considered useful, with selection decisions based on evaluation results as well as additional criteria. For the prioritization phase, while project interdependency is not considered to prioritize, it is still perceived as important and useful. As illustrated in Figure 5.1, the risk phase is not followed sequentially, with risk being assessed throughout the process—30% of experts evaluate risk at the beginning, 10% before selection, and 60% after selection. The balancing phase is used and considered useful by 60% of experts. Communication emerges as a critical phase, with consensus forming primarily towards the end of the process. Finally, the authorization phase typically occurs at the end, depending on project scope and investment level.

Industry recommendations suggest that risk management, communication, and stakeholder management, including change management, should be integrated throughout the entire process rather than treated as distinct phases (Epiroc, 2024b; World Economic Forum, 2017). By combining insights from the mining industry, Industry 4.0 approaches, best practices in project and portfolio management, and expert feedback, the proposed activities are tailored to the specific needs of the mining sector. Table 5.10 presents expert feedback on the phases' utilization and value-added as well as these activities' utilization and potential value-added for each phase. In the table, each square represents one expert, and grey indicates used and value-added activity, dotted grey represents occasional use or perceived value-added, black denotes activities that are neither used nor considered useful, while white signifies non-applicability. Some experts use the activity and validate the value-added, while others do not use the activity and only estimate the potential value-added.

Table 5.10 Use and potential value-added of project portfolio management activities

		Level of use	Level of value-added activities
	Identification		
I1	Align strategic company vision with Smart Mine objectives		
I2	Define digital transformation vision with key objectives		
I3	Develop a quantifiable measure for success		
I4	Prepare teams to change		
I5	Collect expectations and requirements of key stakeholders		
I6	Diagnose AS-IS process of each improvement		
I7	Assess the current company's process digital capability readiness, change readiness, and as-is maturity of pre-defined dimensions		
I8	Identify initiatives based on opportunities, strengths, weaknesses, and threats		
I9	Define Key Performance Indicators		
I10	Define Key Risk Indicators		
I11	Interview stakeholders of the entire value chain		
I12	Define "TO-BE" process		
I13	Realize a skill gap analysis		
I14	Identify possible collaboration		
I15	Identify initiatives and on-going projects		
I16	Identify subteams and/or champion for implementation		
I17	Design change management strategy		
I18	Develop a communication plan		
I19	Define Project Performance Indicators		
I20	Establish a risk management strategy		
	Categorization		
C1	Identify categories based on the strategic plan		
C2	Compare initiatives against the categorization criteria to assign a category		
C3	Categorize initiatives into operational efficiency, operational reliability, financial performance and marketing performance		
C4	Categorize project into operation, strategy, environment, and people		
C5	Categorize stakeholders		
C6	Categorize by risk categories		
	Evaluation		
E1	Define evaluation criteria		
E2	Define quantitative criteria		
E3	Define qualitative criteria		
E4	Define weight per criteria		
E5	Use technology criteria		
E6	Evaluate the initiatives		
E7	Evaluate initiatives' direct and indirect benefits		
E8	Evaluate the return on investment		
E9	Evaluate the feasibility		
E10	Evaluate the impact on workers		
E11	Evaluate the risk		
E12	Carry out a cost-benefit analysis		
E13	Carry out a cost, resources, time investment analysis		
E14	Undertake a risk analysis		

Not used / No value-added Used / value-added Occasional use / Perceived value-added N/A

Table 5.10. Use and potential value-added of project portfolio management activities (suite et fin)

		Level of use	Level of value-added activities
	Selection		
S1	Select using the scability criteria		
S2	Use the efficient frontier curve graph to select initiatives		
S3	Assign a rating to select and prioritize project		
S4	Compare projects with selection criteria and rank them based on criteria using decision-making tools		
S5	Select projets based on the evaluation results		
S6	Undertake a risk assesment of the initiatives and establish risk threshold		
	Prioritization		
P1	Prioritize initiatives based on interdependancy		
P2	Map projects initiatives on a priority matrix or grid value/risk		
P3	Prioritize based on revenue, saving, and risk		
	Risk		
R1	Carry out a formal risk analysis		
R2	Develop a mitigation plan		
	Balancing		
B1	Evaluate initial portfolio taking into account resource constraints		
B2	Optimize portfolio		
B3	Allow or terminate and disable initiatives in the portfolio		
B4	Allocate resources to selected initiatives		
	Communication		
CO1	Foster open communication		
CO2	Communicate portfolio decisions to stakeholders		
CO3	Ensure outcomes of program's components are communicated to appropriate stakeholders		
CO4	Ensure vertical and horizontal communication		
CO5	Communicate change vision, strategy, and timing of implementation with all members involved		
CO6	Put in place the change management strategy		
	Authorization		
A1	Authorize portfolio components		
A2	Communication portfolio decisions to stakeholders for authorization and allocation of financial and human resources		
A3	Authorize at different levels is required depending on the scope and investment level		

Not used / No value-added Used / value-added Occasional use / Perceived value-added N/A

5.7.3 Mining practitioners' suggestions

In addition to the proposed activities in Table 5.10, mining experts suggest additional activities to guide DT efforts (see Table 5.11).

Table 5.11 Activities suggested by mining practitioners

I	Collect expectations of each department
I	Identify initiatives per Smart Mine objectives
C	Categorize by the ease of the project, monetary resources, and timeframe
C	Categorize initiatives by proof of concept, prototype, case study, innovate
C	Categorize initiatives by Smart Mine objectives area
E	Evaluate CAPEX/OPEX
E	Evaluate scalability
E	Evaluate safety
E	Evaluate ESG
E	Identify possible collaboration
S	Select initiatives based on evaluation results and other criteria
P	Prioritize based on safety
P	Prioritize based on investment cost
R	Carry out a status quo risk assessment
R	Carry out a "To-be" risk assessment
CO	Inform impacted stakeholders when resources are needed
CO	Put in place the change management strategy
CO	Organize a kick-off to inform stakeholders

During the identification phase, some experts gather expectations at the departmental level rather than across the entire value chain. Others propose identifying initiatives based on Smart Mine objectives or categorizing them by objective areas. An alternative classification method considers project complexity, financial resources, and timeframe, while suppliers categorize initiatives by technological maturity (e.g., proof of concept, prototype, case study, and innovation).

Experts assess CAPEX/OPEX, scalability, safety, and ESG criteria in the evaluation phase. Collaboration opportunities are identified at different stages, with some experts addressing them during identification and others during evaluation. Most initiatives are selected based on evaluation criteria, supplemented by additional factors such as ease of implementation, resource availability, alignment with ongoing projects, safety, and risk considerations. Criteria not assessed in the evaluation phase, such as safety and investment cost, are incorporated during prioritization.

Some experts suggest conducting a status quo risk assessment to evaluate risks associated with not selecting a given initiative. In the communication phase, some experts engage with affected stakeholders only when resources are required for implementation. During the authorization phase, experts allocate resources, implement change management strategies, and organize kick-off meetings to inform stakeholders. Additionally, some experts conduct a "to-be" risk assessment, analyzing risks associated with the selected initiatives.

5.8 Conclusion

This study examined and analyzed activities recommended by the mining industry, Industry 4.0 methodologies, and best project and project portfolio management practices. The findings indicate that most canadian mining companies and suppliers integrate these practices and acknowledge their benefits by assessing the level of use and perceived value of these DT activities. A consensus emerged regarding the adoption of a combination of these practices within the underground mining sector.

However, as this evaluation is based on insights from ten experts specializing in Canadian underground mining, further research is required to determine the applicability of these activities to open-pit mining. Moreover, the value-added activities suggested by mining practitioners have yet to be systematically assessed to establish their relevance for DT.

Despite these limitations, our preliminary findings provide corporations, project portfolio managers, and project managers with valuable insights into DT practices within the canadian mining industry and offer a structured approach for planning and implementing DT initiatives. Future research should explore best practices for DT from both supplier and mining company perspectives. Additionally, this study could be expanded to develop a project portfolio management framework tailored to the mining sector's unique challenges, building upon this assessment's findings.

5.9 Statements and Declarations

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Marine Echternach-Jaubert. The first draft of the manuscript was written by Marine Echternach-Jaubert and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing Interests The authors report there are no competing interests to declare.

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6.1 Résumé

La transition de l'industrie minière vers la Mine Intelligente est freinée par la complexité de l'environnement minier et par le manque de lignes directrices pour la gestion de la TN. Les entreprises minières s'appuient souvent sur leurs fournisseurs pour orienter leurs efforts de TN, révélant une absence d'approches structurées permettant d'aligner stratégiquement leurs initiatives. En conséquence, les initiatives de TN sont fréquemment mises en œuvre de manière isolée, sans intégration dans une approche plus large de GPP. Cet article comble cette lacune en proposant une approche pratique de GPP adaptée au contexte minier pour la gestion des portefeuilles de TN. Le modèle proposé a été développé à partir d'une synthèse des méthodologies de GPP, des meilleures pratiques de l'Industrie 4.0 et des connaissances d'experts du secteur minier. Il combine des approches descendantes et ascendantes, met l'accent sur la cartographie visuelle des interdépendances et intègre des fonctions de gestion transversales (gestion des risques, du changement, des parties prenantes et de la communication) comme processus continus. Des outils et techniques sont intégrés pour soutenir chaque activité. Le modèle a été validé par son application à un cas réel de mine souterraine. Il a permis d'améliorer l'identification, la sélection, la priorisation et la séquence des initiatives, tout en explicitant leurs interdépendances. Le portefeuille de TN obtenu a favorisé l'alignement entre la stratégie d'entreprise et les objectifs à long terme de la Mine Intelligente, tout en tenant compte des défis et contraintes opérationnelles propres au contexte souterrain.

6.2 Abstract

The mining industry's transition toward the Smart Mine is hindered by the complexity of the mining environment and limited guidance on managing digital transformation (DT). Mining companies often rely on suppliers to steer their DT efforts, revealing a lack of structured approaches to strategically align their initiatives. Consequently, DT initiatives are often implemented in isolation, without integration into a broader project portfolio management (PPM) approach. This paper addresses this gap by providing a practical, mining-adapted PPM approach for DT portfolio management. The proposed model was developed by synthesizing PPM methodologies, Industry 4.0 best practices, and mining expert insights. It combines top-down and bottom-up approaches, emphasizes visual mapping of interdependencies, and embeds enabling management

functions (risk, change, stakeholder, and communication management) as continuous processes. Tools and techniques are incorporated to support each activity. The model was validated through its application in a real underground mining test case. The model enhanced the identification, selection, prioritization, and sequencing of initiatives, explicitly delineating their interdependencies. The obtained DT portfolios aligned corporate strategy and long-term Smart Mine objectives, while considering underground challenges and operational constraints.

6.3 Introduction

The mining sector is undergoing a profound DT, advancing toward the Smart Mine paradigm, also known as Mining 4.0, rooted in Industry 4.0 principles (Merma, 2023). This transformation reshapes operational practices by integrating advanced technologies, infrastructure, equipment, processes, and management systems to optimize performance, safety, sustainability, and workforce capabilities (Asa'd & Levesque, 2024; Echternach et al., 2024). Similar to manufacturing Industry 4.0 shift, the Smart Mine extends beyond technology to encompass organizational change, process innovation, and human-centric development, influencing both the people workforce and public perception of the mining industry (Beneteau et al., 2025).

However, managing DT in mining presents unique challenges, including the finite lifespan of mines, finite-horizon return on investment (Institut National des Mines, 2021), spatial and environmental constraints, as well as safety regulations (Gao, S. et al., 2019; Sánchez & Hartlieb, 2020), and limited connectivity (Rogers et al., 2019). Underground mines add layers of complexity due to their continuous expansion and difficulty in deploying scalable systems (Yendamuri et al., 2021). These conditions necessitate strategic coordination across organizational levels to manage multiple simultaneous DT projects, each with high uncertainty and interdependent outcomes (Ali & Frimpong, 2020; Sánchez & Hartlieb, 2020; Yendamuri et al., 2021). Chen et al. (2025) identify PPM, governance, and leadership as critical factors for successful DT initiatives and Ellström et al. (2021) based on dynamic capacities theories, demonstrate that DT relies on sensing (detect technological opportunity), seizing (exploit them strategically), and transforming (reconfigure resources and organizational structures) with governance and PPM as key mechanisms to strategically align DT with company's strategy. However, unlike manufacturing, which benefits from relatively stable environments and mature PPM systems to guide their DT initiatives (Richard et al., 2021), similar approaches are largely absent in mining (Echternach et al., 2025).

Existing literature reveals a fragmented understanding of how DT is approached in the sector. Research by Yaqot et Menezes (2022), Plavšić et Mišković (2022), and Wael et al. (2022) shows that technology adoption is often reactive and project-specific, rather than being driven by a coherent DT strategy. Case studies by Gao, S. et al. (2019), Nyström Eklund et Adelgren (2021), Benzane (2019), and Merma (2023) identify common barriers such as resistance to change, unclear goals, poor resource allocation, and limited cross-departmental collaboration. These studies focus primarily on single-project implementation, overlooking the need to coordinate multiple DT initiatives simultaneously. Moreover, Le et al. (2023) and non-academic sources (Jacobs et al. (2019); Rockwell Automation (2019, 2021), GMG (2021), and Harris, J. (2023)) reinforce the observation that DT is often supplier-led, with mining firms relying on external expertise to guide digital implementation. While these sources emphasize the importance of change management, strategic alignment, and employee engagement, they also highlight that scalability and long-term planning are often underestimated.

Although numerous frameworks and best practices for DT exist, there is a lack of empirical research examining how mining companies prioritize, structure, and manage portfolios of DT initiatives (Echternach et al., 2025). Notably, the absence of a mining-specific PPM framework leaves organizations without a structured approach to manage the concurrent, interrelated DT initiatives effectively. This study addresses this gap by exploring the following research question: How can mining companies effectively structure a portfolio of DT initiatives to support the transition toward the Smart Mine, while accounting for underground mining specificities?

To address this question, the paper proposes a mining-specific PPM model, based on the work of Echternach et al. (2025), developed from a synthesis of academic and industry literature, expert feedback, and validated with a real underground mining test case. The model aims to provide a structured, practical approach for mining organizations to strategically manage their DT portfolio.

The remainder of this paper is structured as follows. Section 6.4 reviews PPM approaches for Industry 4.0 initiatives. Section 6.5 outlines the research methodology. Section 6.6 presents the proposed model; Section 6.7 illustrates its application to an underground mining case. Section 6.8 discusses findings; and Section 6.9 concludes with key contributions, limitations, and future research directions.

6.4 Literature Review

The Project Management Institute (PMI) provides comprehensive standards and guidelines for portfolio management, advocating proactive communication, stakeholder engagement, continuous uncertainty monitoring (PMI, 2017), and provides guidance on portfolio risk management, recommending that organizations define clear risk thresholds (PMI, 2019). These guidelines, however, remain generic and non-specific to DT initiatives.

A comprehensive review of academic and industry literature on Industry 4.0 PPM approaches identified eleven sector-specific publications, addressing interdependencies, governance, uncertainty, risk, human resources, change, communication, and stakeholder management. Several studies have adapted established PPM standards to specific industry requirements. For instance, Richard et al. (2021) draw on the Project Management Institute (2008) standard to develop a nine phases (identification, categorization, evaluation, selection, risk assessment, prioritization, balancing, communication, and authorization) practical PPM approach for manufacturing small and medium-sized enterprises, acknowledging project interdependencies. Still in the manufacturing industry, Echternach et al. (2025) identified activities from Industry 4.0 and mining best practices deemed necessary by mining experts to create a portfolio of DT initiatives. Their findings indicate that a combination of these practices is commonly applied in the field; however, an integrated practical model that consolidates these approaches is still lacking.

Several researchers have explored complementary dimensions of PPM. First, Killen et Kjaer (2012) emphasize managing interdependencies when balancing projects within a portfolio, and using visual tools to enhance decision-making, supported by both top-down and bottom-up interactions, promoting alignment between strategic objectives and operational execution. They argue that PPM methods and tools should be adapted to the specific organizational context to ensure effective outcomes, and underscore the impact of organizational culture and communication across teams on PPM practices. Similarly, Pajares, J. et López (2013) reinforce this dual approach for multi-project management, integrating identification, evaluation, selection, prioritization, balancing, and resource allocation. They emphasize ongoing portfolio monitoring to accommodate the integration of new projects, supported by a feedback loop that adjusts resource allocation accordingly. Visser (2020) proposes an improvement-oriented portfolio management system to support selection and control based on project scope and value uncertainty. This approach identifies the appropriate

organizational level responsible for each project with a limited set of activities. Extending these ideas, Dreyer et al. (2022) propose a mathematical model accounting for project interdependencies to support project selection in the context of smart factory environments.

The growing complexity of I4.0 initiatives has introduced new dimensions of risk. Mican et al. (2021) recommend continuous portfolio risk assessment, and Petit (2012) calls for ongoing assessment of change and uncertainty as an integral part of the PPM process. Additionally, effective human resource management, considering factors such as resource availability, reliance on external expertise, and the alignment of competencies, should be addressed when balancing the project portfolio.

While the literature offers valuable insights into PPM practices across various sectors, most research overlooks mining's specific constraints. Authors such as Dreyer et al. (2022); Killen et Kjaer (2012); Pajares, Javier et López (2014) emphasize interdependencies, uncertainty, organizational adaptation, and multi-project coordination, but lack applicability to underground environments characterized by spatial, environmental, and connectivity constraints, as well as challenges related to the deployment of DT initiatives, such as scalability, limited project lifespans, high safety standards, and real-time operational constraints inherent to underground mining. On the other hand, the PMI standards, while strong on governance, risk, and change management, lack sector-specific applicability in high-risk, time-sensitive contexts such as mining environments, where project outcomes are deeply interdependent. Even when addressing human resource management during the balancing phase (Petit, 2012) or DT impact on risk (Mican et al., 2021), these researches lack to consider mining-specific constraints and guidance on cross-sector applicability. Manufacturing-focused models by Richard et al. (2021) offer a prescriptive PPM approach for stable, connected environments, designed to guide non-experts through DT planning, but does not address the physical constraints or scalability of mining operations. Moreover, their models include risk, communication, and change as discrete phases, whereas Echternach et al. (2025) argue that they should function as enabling management activities integrated throughout all PPM phases. Moreover, while Richard et al. (2021) focus on problem-based initiative identification and explore predefined Industry 4.0 technology groups as potential solutions, mining requires a more diverse diagnostic-driven approach involving multiple activities, such as digital capability readiness, change readiness, and AS-IS maturity level assessment, SWOT analysis, and AS-IS/TO-BE process mapping (Echternach et al., 2025). DT initiatives in mining extend beyond

technological solutions to encompass infrastructure, management systems, processes, workforce, organization culture, and equipment (Echternach et al., 2024). Unlike the model of Richard et al. (2021), mining sector experts advocate for a more flexible approach, incorporating optional activities to support the planning of DT initiatives to fit diverse contexts.

While Visser (2020) introduces a decision-support framework aimed at enhancing project governance within the portfolio project management (PPM) paradigm, its conceptual nature limits its practical applicability in the context of mining operations. Overall, while current literature offers valuable insights into DT and PPM across industrial sectors, it lacks a formalized, practical model that addresses the unique challenges of underground mining environments.

6.5 Research Methodology

This study employs a qualitative, exploratory research methodology to develop an operational PPM model tailored to DT in underground mining. The research design combines best practices from the academic and industry literature on Industry 4.0 PPM approaches and draws on the work of Echternach et al. (2025), which synthesizes existing frameworks, best practices, and challenges in managing DT portfolios in both mining and Industry 4.0 contexts.

To complement and validate the literature findings, qualitative data were collected through semi-structured interviews with ten Canadian DT experts in underground mining, representing various organizational levels (corporate leaders, portfolio and project managers, and a mine manager) from international and Canadian mining companies, consulting firms, and suppliers. Participants, with 5 to 25 years of experience in soft and hard rock operations, provided insights on PPM phases, DT-specific activities within each phase, operational challenges, and gaps in current management practices. Their inputs were analyzed to assess the value-added of activities identified in the literature, while revealing additional field practices. This combined approach facilitated the extraction of foundational elements required to develop a mining-adapted PPM model.

The identified value-added activities were consolidated into a structured PPM model adapted to the specificities of underground mining, integrating enabling management functions such as risk, stakeholder, communication, and change management to support the execution and governance of the portfolio. The resulting model was first validated using an input/output interrelation diagram to ensure logical consistency and coherence between its components. Then, it was tested through a real-world test case, utilizing data collected during a six-month in-situ period and follow-up

interviews conducted two years later with employees involved in the transformation, which confirmed its practical applicability and relevance in mining operations. The proposed model is presented in the following section.

6.6 Digital Transformation Project Portfolio Management Model

6.6.1 Model development

To adapt PPM principles to the mining industry, the previously identified approaches from the literature review were analyzed through a PPM lens aligned with PMI standards and enriched with industry experts' insights to identify existing limitations. Table 6.1 summarizes this comparative analysis by PPM phases, mining-specific constraints, methodological approach, domain, and enabling management functions.

Since no single approach fully addresses all mining constraints and enabling management functions, a deeper analysis was conducted to combine the strengths of various approaches and develop a more suitable model for mining companies seeking to establish DT initiative portfolios. Drawing on the work of Echternach et al. (2025), who had already consolidated key elements from PPM approaches, assessed by mining experts on the activity usage and value-added. As the model is intended for mining companies, particular attention was given to the perspectives of project and portfolio managers, while supplier feedback, often more technology-driven and narrower in scope, was considered less critical. Activities unanimously deemed value-added were designated as mandatory, whereas others are considered optional.

The final structure follows the PPM phases defined by Richard et al. (2021), with one adjustment: risk and communication management are embedded as continuous, cross-cutting processes throughout the portfolio lifecycle (Echternach et al., 2025).

Table 6.1 Classification of existing approaches identified in the literature review

Authors	PPM phases	Mining constraints	Approach	Structured model	Domain	Enabling management functions
Dreyer et al. (2022)	S	Interdependancies	multi-criteria decision model	No	Manufacturing	X
Echternach et al. (2025)	I,C,E,S,P,B, R,CO,A	Interdependancies, ROI, Scalability Lifespan, Safety regulation Spatial and environmental	PPM	No	Mining	Risk, change, communication
Killen and Kjaer (2012)	B	Interdependancies Uncertainty	PPM - visual representation	No	Manufacturing	Communication
Mican et al. (2021)	X	X	PPM - risk	No	General	Risk
Pajares and López (2014)	I, E, S, P, B	Multi-project ROI	PPM	No	General	X
Petit (2012)	I,C,E,S,P,B, R,CO,A	Uncertainty Safety regulation	PPM	No	Service	Change
Project Management Institute (2019)	I,C,E,S,P,B, R,CO,A	Risk	PPM	No	General	Risk
Project Management Institute (2017)	I,C,E,S,P,B, R,CO,A	X	PPM	No	General	Communication, Stakeholder
Richard et al. (2021)	I,C,E,S,P,B, R,CO,A	X	PPM	Yes	Manufacturing	X
Visser (2020)	S	Interdependancies	PPM	No	Mining	X

I= identification, C=categorization, E=evaluation, S=selection, P=prioritisation,B=balancing, R=risk, CO=communication, A=authorization
X= not included

6.6.2 Mining industry PPM model

The approaches described in the previous section were integrated to develop a PPM model tailored to the mining industry through four steps:

1. Extracting value-added activities and expert-suggested activities from Echternach et al. (2025);
2. Comparing them with those from the literature to verify overlaps and add missing steps, validated by mining experts, thereby completing the model;
3. Regrouping activities and combining them within PPM phases; and
4. Linking each activity to relevant tools and techniques from the literature and Echternach et al. (2025).

As shown in Figure 6.1, the proposed model includes seven main phases: identification, categorization, evaluation, selection, prioritization, balancing, and authorization (depicted within a large rectangle), and three enabling management functions: risk, change, and communication and stakeholder management (represented within smaller rectangles). Activities are labeled according to their corresponding phase and enumerated chronologically, with underlined ones considered optional, while enabling management functions remain unlabeled due to their continuous nature. Activities also are color-coded by sources: blue corresponds to the activities suggested by the mining experts extracted from Echternach et al. (2025), gray to Butt (2020), orange to PMI standards, salmon to Richard et al. (2021), and purple to Bellantuono et al. (2021). Green indicates activities drawn from various models, including Echternach et al. (2024), Wael et al. (2022), Brunelli (2020); De Carolis et al. (2017) ; Mican et al. (2021), Gao, S. et al. (2019), Harris, F. (2019), Heberle et al. (2017); Lemieux et al. (2013) ; Pajares, Javier et López (2014) ; Schumacher et al. (2019), and Killen et Kjaer (2012).

Several activities are considered specific to the mining sector, being extracted either from the literature or mining expert interviews; yet, they may also be applicable in other sectors. Sector-specific examples include aligning strategic company vision with Smart Mine objectives, identifying possible collaborations, prioritizing initiatives based on interdependencies and other relevant criteria, and authorizing portfolio components at different levels depending on scope and investment cost. Mining-specific challenges are reflected in the evaluation criteria (timeframe,

capital expenditure (CAPEX)/Operational expenditure (OPEX)/Return on investment (ROI)), in the other selection criteria (scalability, safety regulation), and prioritization (interdependency).

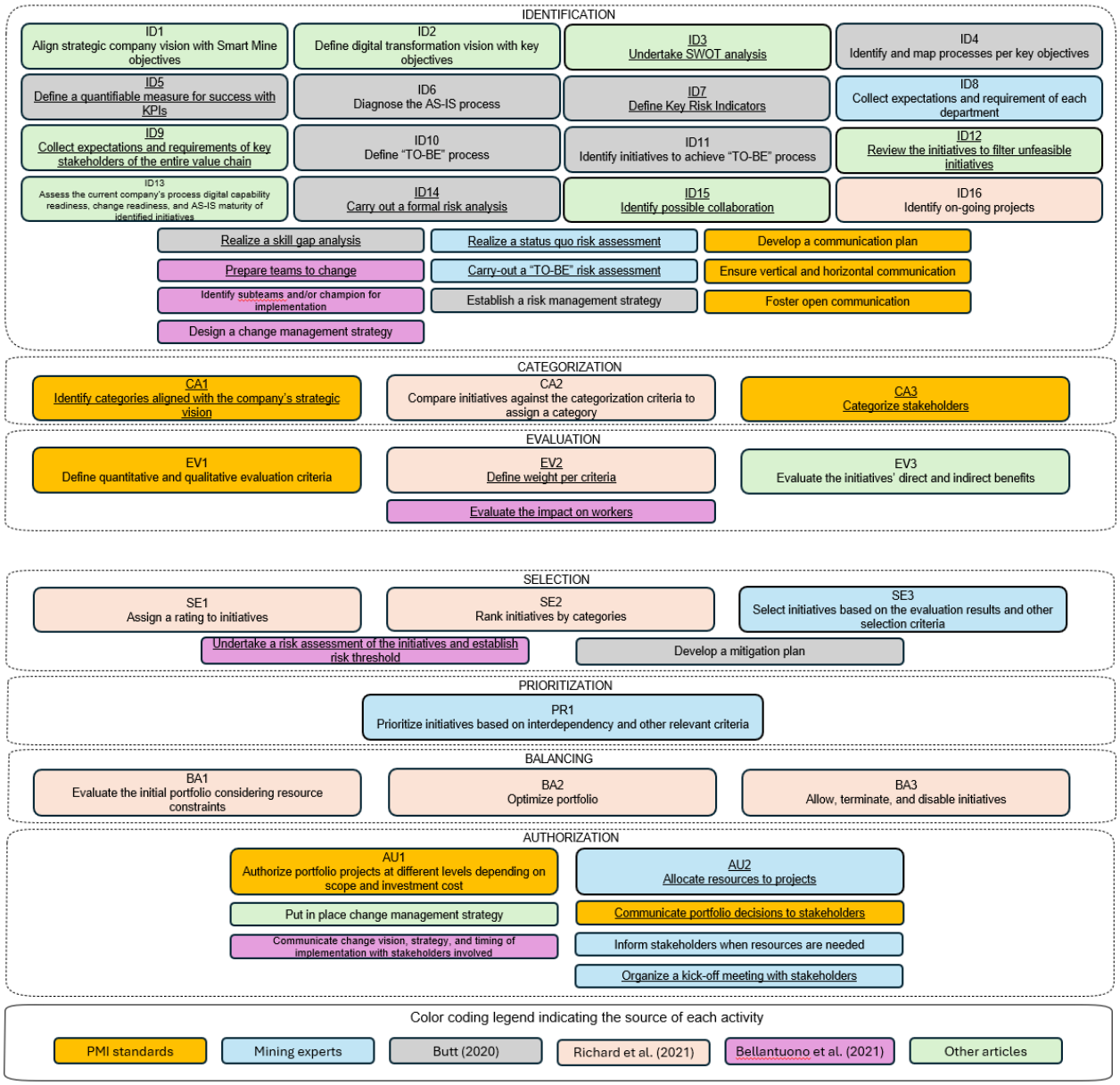
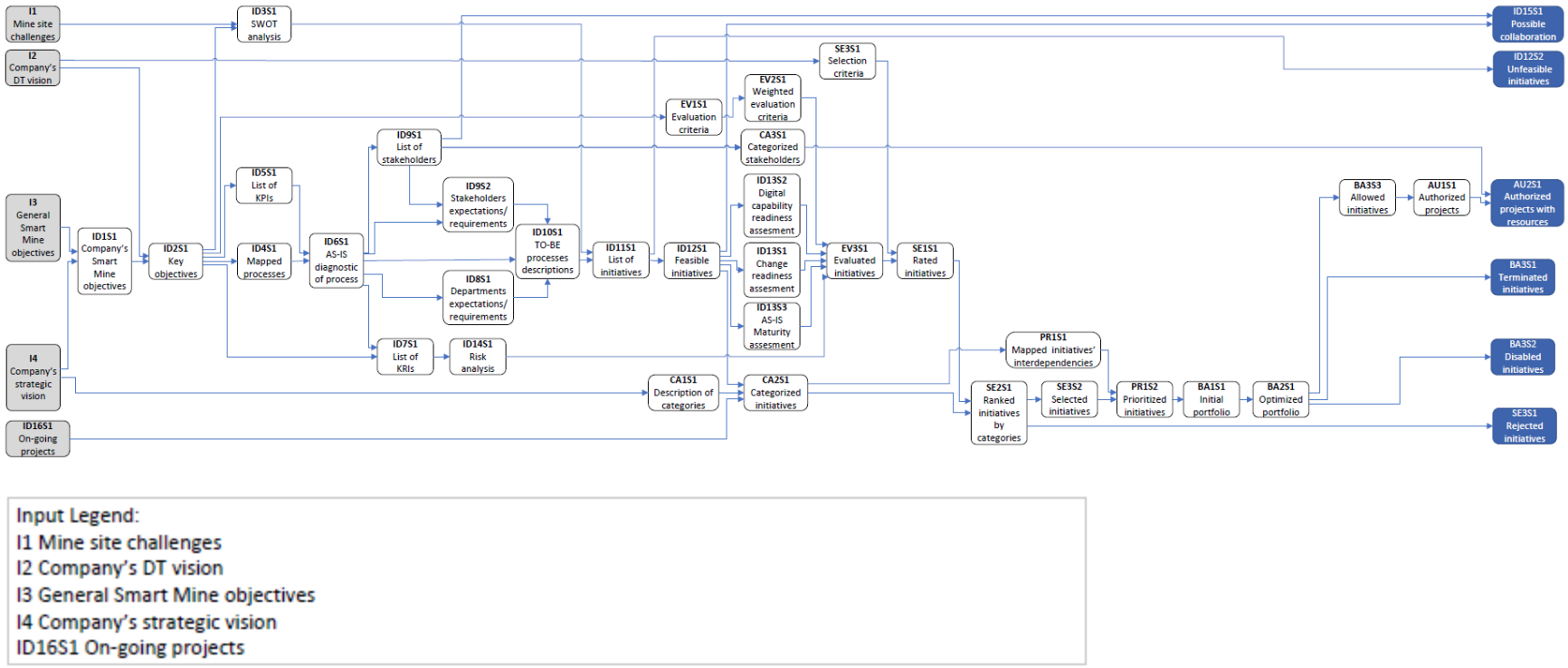


Figure 6.1 PPM model with activities extracted from the literature review and Echternach et al. (2025)

As part of the validation process, an interrelationship diagram (Figure 6.2) maps the model's inputs and outputs to ensure each output is relevant to the model's execution and contributes to subsequent activities. Inputs are shown in gray, intermediate outputs in white, and final outputs in blue. Each output is labeled according to its corresponding activity and appears as a deliverable in Table 6.2. For each activity, suitable techniques and tools were identified in the literature (Table 6.2), with several options provided to allow companies to select those best suited to their specific context.



Input Legend:
I1 Mine site challenges
I2 Company's DT vision
I3 General Smart Mine objectives
I4 Company's strategic vision
ID16S1 On-going projects

Figure 6.2. Inputs/Outputs interrelation diagram

Table 6.2 Tools and techniques per PPM activities

PPM activities	References	Tools & Techniques	Deliverables
IDENTIFICATION			
ID1 Align strategic company vision with Smart Mine objectives	Echternach et al. (2024)	Smart Mine objectives defined by Echternach et al. (2024)	Company's Smart Mine Objectives
ID2 Define digital transformation vision with key objectives	Wael et al. (2022)	Top-down & bottom-up approach (Pajares and Lopez , 2014)	Key objectives
ID3 Undertake strengths, weaknesses, opportunities, and threats (SWOT) analysis	De Carolis et al. (2017)	Information-gathering, tree diagram, expert judgement (Richard et al., 2021)	SWOT analysis
ID4 Identify and map processes per objective	Butt (2020)	Stakaholder map, SWOT analysis, organizational chart, context diagram, business use-case diagram, process flow chart, value-stream map (Butt, 2020)	Mapped processes
ID5 Define a quantifiable measure for success with Key Performance Indicators (KPIs)	Visser (2022); Butt (2020)	-	List of KPIs
ID6 Diagnose the AS-IS processes	Butt (2020)	BPM, process analysis, KPI (Butt, 2020)	AS-IS diagnostic of process
ID7 Define Key Risk Indicators (KRIs)	Butt (2020)	-	List of KRIs
ID8 Collect expectations and requirements of each department	Mining experts extracted from Echternach et al. (2025)	Top-down & bottom-up approach (Pajares and Lopez , 2014)	Departments expectations/ requirements
ID9 Collect expectations and requirements of key stakeholders of the entire value chain	Heberle et al. (2017)	Top-down & bottom-up approach (Pajares and Lopez , 2014)	Stakeholders expectations/ requirements
ID10 Define "TO-BE" process	Butt (2020)	process reengineering, cause and effect diagram, FMEA, Simulation tools (Butt, 2020)	TO-BE processes descriptions
ID11 Identify initiatives to achieve “TO-BE” process	Butt (2020)	Team workshop (Butt, 2020); Top-down & bottom-up approach (Pajares and Lopez , 2014); Expert judgment (Richard et al., 2021)	List of initiatives
ID12 Review the initiatives to filter unfeasible initiatives	Heberle et al. (2017); De Carolis et al. (2017)	Top-down & bottom-up approach (Heberle et al., 2017) ; Expert judgment (Richard et al., 2021)	Feasible initiatives Unfeasible initiatives
ID13 Assess the current company’s process digital capability readiness, change readiness, and as-is maturity of identified initiatives	Lemieux et al. (2013); De Carolis et al. (2017); Schumacher et al. (2019); Brunelli (2020)	Change readiness questionnaire, cartography of change and actors (Le Grand et al., 2019); Radar graphic and questionnaire (Lemieux et al., 2013); Digital capability readiness evaluation tools (De Carolis et al., 2017 ; Nystrom, 2021; Rautenbach et al., 2019)	Digital capability readiness assessment Change readiness assessment Maturity assessment
ID14 Carry out a formal risk analysis	Butt (2020)	Brainstorming, risk register (Butt, 2020)	Risk analysis
ID15 Identify possible collaboration	Mining experts extracted from Echternach et al. (2025)	-	Possible collaboration
ID16 Identify on-going projects	Richard et al. (2021)	-	-
Prepare teams to change	Bellantuono et al. (2021); Butt (2020)	Cross-functional teams; Obeya room (Bellantuono et al., 2021)	-
Carry-out a “TO-BE” risk assessment	Mining experts extracted from Echternach et al. (2025)	-	"TO-BE" risk assessment
Realize a status quo risk assessment	Mining experts extracted from Echternach et al. (2025)	-	Status quo risk assessment
Realize a skill gap analysis	Butt (2020)	-	Skill gap analysis
Identify subteams and/or champion for implementation	Bellantuono et al. (2021)	-	List of champion / subteams
Design change management strategy	Bellantuono et al. (2021); Butt (2020)	ADKAR model, Lewin's change management model, Kotter's change management model (Butt, 2020)	Change management strategy
Develop a communication plan	PMI (2017)	-	Communication plan
Establish a risk management strategy	Butt (2020); PMI (2019)	Brainstorming, risk register (Butt, 2020); Risk assessment, risk threshold, risk classification (PMI, 2019)	Risk management strategy
Ensure vertical and horizontal communication	PMI (2017)	-	-
Foster open communication	PMI (2017)	-	-

Table 6.2 Tools and techniques per PPM activities (suite et fin)

PPM activities	References	Tools & Techniques	Deliverables
CATEGORIZATION			
CA1 Identify categories aligned with the company's DT vision (objective, performance dimension, risk profile, strategic domain, effort-cost-time)	PMI (2017) ; Richard et al. (2021)	Strategic categorization of components (Richard et al., 2021)	Description of categories
CA2 Compare initiatives against the categorization criteria to assign a category	Richard et al. (2021)	Expert judgment (Richard et al., 2021)	Categorized initiatives
CA3 Categorize stakeholders		Use a taxonomy (PMI, 2017)	Categorized stakeholders
EVALUATION	PMI (2017)		
EV1 Define quantitative and qualitative evaluation criteria	PMI (2017); Richard et al. (2021)	Evaluation methodologies: check-lists, multi-criteria scoring, mathematical models (Pajares and López, 2014)	Evaluation criteria
EV2 Define weight per criteria	Richard et al. (2021)	Evaluation grid with weighted multi-criteria (Richard et al., 2021)	Weighted evaluation criteria
EV3 Evaluate the initiatives' direct and indirect benefits	Brunelli (2020); Mining experts extracted from Echternach et al. (2025)	Information gathering (Richard et al., 2021)	Evaluated initiatives
Evaluate the impact on workers	Bellantuono et al. (2021)	-	Impact evaluation
SELECTION			
SE1 Assign a rating to initiatives	Richard et al. (2021)	Evaluation grid with weighted multi-criteria (Richard et al., 2021); AHP (Pajares and López, 2014)	Rated initiatives
SE2 Rank initiatives by categories	Richard et al. (2021)	-	Ranked initiatives by categories
SE3 Select initiatives based on the evaluation results and other selection criteria	Richard et al. (2021); Mining experts extracted from Echternach et al. (2025)	Pugh matrix (Butt, 2020); Multi-criteria decision model (Dreyer et al., 2022); GRACIAS tool to filter out ineffective technologies (Al-Banna et al., 2023)	Selected initiatives Rejected initiatives
Undertake a risk assessment of the initiatives and establish risk threshold	Bellantuono et al. (2021)	PPRA (Mican et al., 2021)	Risk threshold Initiatives risk assessed
Develop a mitigation plan	Butt (2020)	-	Mitigation plan
PRIORITIZATION			
PR1 Prioritize initiatives based on interdependency and other relevant criteria	Mining experts extracted from Echternach et al. (2025); Richard et al. (2021)	Dependency matrix, strategic bucket approach (Richard et al., 2021); Prioritization matrix (Wael et al., 2022); Visual project mapping (Killen and Kjaer, 2012)	Prioritized initiatives
BALANCING			
BA1 Evaluate the initial portfolio considering resource constraints	Richard et al. (2021); Pajares and Lopez (2014)	Time, type of projects (Pajares and López, 2014)	Initial portfolio
BA2 Optimize portfolio	Richard et al. (2021); Petit (2012)	Graphical analysis method, cost and benefit analysis, scheduling, expert judgment (Richard et al., 2021)	Optimized portfolio
BA3 Allow, terminate, and disable initiatives	Richard et al. (2021)	portfolio authorization process (Richard et al., 2021)	Allowed initiatives Terminated initiatives Disabled initiatives
AUTHORIZATION			
AU1 Authorize portfolio components at different levels depending on scope and investment cost	PMI (2017); Visser (2022); Mining experts extracted from Echternach et al. (2025)	Value of change vs uncertainty about scope and value graph (Visser, 2022)	Authorized projects
AU2 Allocate resources to projects	Mining experts extracted from Echternach et al. (2025)	Expert judgment, portfolio management roles and responsibilities (Richard et al., 2021)	Authorized projects with resources
Communication portfolio decisions to stakeholders	Richard et al. (2021); PMI (2017)	Analysis of communication needs (Richard et al., 2021)	-
Inform stakeholders when resources are needed	Mining experts extracted from Echternach et al. (2025)	-	-
Communication change vision, strategy, and timing of implementation with stakeholders involved	Bellantuono et al. (2021)	-	-
Put in place the change management strategy	Harris (2019)	-	-
Organize a kick-off meeting with stakeholders	Mining experts extracted from Echternach et al. (2025)	-	-

6.7 Test case

The test case validates the model's feasibility through its application to a real-world scenario. It involves Company YXE, a Canadian-owned international mining firm with fewer than 250 employees and under 10 underground mines, currently embarking on its digital transformation journey.

6.7.1 Description of the Case

At the time of the initial field analysis, the selected underground hard-rock mine located in northern Canada had a planned 10-year mine life and was at the development stage with minimal Industry 4.0 technology integration. Company YXE had recently embarked on its DT journey, which required the identification, selection, prioritization, and implementation of multiple DT projects. Company YXE followed a top-down approach driven by corporate leadership, with on-site involvement from the mine captain.

The site faces multiple challenges: hard-rock geomechanical conditions, poor ground stability, harsh weather, lack of an on-site mill, limited energy supply, dust and low visibility, budget constraints, unreliable connectivity, stringent environmental permitting, and workforce resistance to change. The mine operates through a portal access and relies on traditional drill-and-blast methods, with the use of explosives to break the rocks. Company YXE's DT vision targets carbon neutrality through electrification, enabling 100% remote and autonomous operations, and enhanced health and safety, with operational goals of higher productivity, cost reduction, and continuous extraction process (i.e., a mechanized process where a machine continuously cuts and removes materials from the mine face, without the need for drill and blast).

Project identification was driven by vendor influence and aligned with broader Smart Mine objectives, focusing on operational and safety improvements associated with explosives, but no formal project categorization was used. Evaluation combined quantitative (machine performance, cost, noise levels, and risk) and qualitative (environmental, implementation feasibility) criteria; weights were informally considered and not documented. Indirect impacts on costs and operations were acknowledged but not systematically integrated into the decision-making processes. Risk assessment relied on a qualitative risk matrix with mitigation strategies based on internal expertise and third-party input. Selection and prioritization were conducted at the corporate level, primarily

guided by safety, environmental, social, and governance (ESG), and community considerations. However, non-formal portfolio balancing mechanisms were employed. Communication strategies involved designating on-site champions and stakeholder engagement.

At the end of the process, the portfolio included several key initiatives: remote blasting technology, acquisition and deployment of a continuous cutting machine, establishment of a communication and connectivity network, the deployment of an underground crushing and sorting system, as well as a conveyor system. Company YXE made a corporate-level decision to purchase a continuous cutting machine for gallery development, to reach the future zones of the production area, continue with the existing project of scaling network infrastructure, and integrate remote blasting technology. Later down the road, deploy a conveyor system, an underground crushing and sorting system, as well as an underground garage.

The process was supported by a general DT vision loosely defined with a feasibility study, and the implementation heavily relied on the machine supplier. Project success was ambiguously defined as achieving operational stability, with few predefined KPIs and minimal further questioning. Project execution involved machine acquisition, delivery, site-specific adaptation, analysis of existing operational processes, adjustments to accommodate the new equipment, underground deployment, operator training, and on-site troubleshooting. A preliminary process mapping ("as-is" analysis) was performed to compare existing operations against the new technology's requirements. Notably, significant project interdependencies emerged post-deployment, particularly in terms of the need for supporting infrastructure such as power supply and connectivity to enable effective machine operation underground.

Activities suggested by the proposed model and carried out by company YXE are summarized in Table 6.3 with their outcomes.

Table 6.3 YXE's outcomes following the activities suggested in the proposed PPM model

PPM activities	YXE's outcomes
IDENTIFICATION	
ID1 Align strategic company vision with Smart Mine objectives	Improve operational efficiency; Improve productivity; Implement autonomous operations; Perform continuous mineral extraction; Increase remote operations; Improve health and safety; Develop electrification; Improve sustainability
ID2 Define digital transformation vision with key objectives	Minimize waste; Improve operations; Reduce downtime; Increase the mineral quantity extracted; Implement autonomous machine; Develop a continuous extraction process; Integrate teleoperates machines; Remove workers from working face; Remove explosives for gallery development; Implement electric machine; Increase local community engagement; Control wastewater
ID4 Identify and map processes per objective	Ore waste process; Maintenance processes; Extraction process; Operation processes; Blasting process; Community relation process; Water management process
ID5 Define a quantifiable measure for success with Key Performance Indicators (KPIs)	Not all KPIs are available; Waste-to-ore ratio; OEE; Ore tonnes to surface per shift; tonnes/hr throughput
ID6 Diagnose the AS-IS processes	Carried out after the authorization of the portfolio
ID10 Define "TO-BE" process	Ore crushed underground, waste used for backfill or disposal, gr;ade hoisted to surface, crushers/sorters automated and remotely operated, conveyors or trucks move ore/waste, real-time monitoring and maintenance system, emergency/maintenance access ensured, waste plan in place; Equipment serviced underground, spare parts stored underground; Optimized automated dispatch with RFID tracking; Machines fully autonomous, zero operator exposure; Continuous cutting machine feeds conveyors to surface; transfer stations in place, conveyor maintenance integrated; 3D-model-based blast design; smart detonators; clearance verified by personnel tracking; remote blasting from surface; post-blast sensors monitor results; electric equipment fleet; community relations office on site; optimize water use and savings
ID11 Identify initiatives to achieve "TO-BE" process	Deploy an underground sorting and crushing system; Construct an underground mechanic shop; Redefine maintenance processes; Deploy a conveyor system; Deploy fully autonomous machine; Implement a continuous cutting machine; Integrate teleoperated machines; Implement remote blasting technology; Integrate BEVs; Implement a community relations office and program; Review water management system
ID14 Carry out a formal risk analysis	Risk assessment using qualitative risk matrix supplemented by third-party input
ID15 Identify possible collaboration	Confidential information for supplier; Geology department; Mechanic department; universities; community groups; engineering department; consulting firms
ID16 Identify on-going projects	Scale network infrastructure; Implement remote blasting technology
Realize a skill gap analysis	Training operators for continuous cutting machine
Identify subteams and/or champion for implementation	Operator champion for continuous cutting machine
Develop a communication plan	Communication plan for stakeholders, community, employees
Foster open communication	Communication mostly vertical
CATEGORIZATION	No categorization
EVALUATION	
EV1 Define quantitative and qualitative evaluation criteria	Risk, cost, KPIs, technology criteria, noise levels, environmental, implementation feasibility
EV3 Evaluate the initiatives' direct and indirect benefits	Indirect impact on operation
SELECTION	
SE1 Assign a rating to initiatives	Information not available
SE3 Select initiatives based on the evaluation results and other selection criteria	Other selection criteria: safety; ESG; community Selected initiatives: Deploy an underground sorting and crushing system; Construct an underground mechanic shop; Deploy a conveyor system; Implement a continuous cutting machine; Integrate teleoperated machines; Implement remote blasting technology; Integrate BEVs; Implement a community relations office and program; Review water management system; Scale network infrastructure Rejected initiatives: Redefine maintenance processes; Deploy fully autonomous machine
Develop a mitigation plan	Information not available, but developed during the evaluation phase
PRIORITIZATION	Informal realized at the corporate level
BALANCING	
BA1 Evaluate the initial portfolio considering resource constraints	Resource constraints + interdependencies
BA2 Optimize portfolio	Deploy an underground sorting and crushing system; Construct an underground mechanic shop; Deploy a conveyor system; Implement a continuous cutting machine; Integrate teleoperated machines; Implement remote blasting technology; Integrate BEVs; Review water management system; Scale network infrastructure
BA3 Allow, terminate, and disable initiatives	Allow: Implement a continuous cutting machine; Implement remote blasting technology; Scale network infrastructure Terminate: Review water management system; Disable:Deploy an underground sorting and crushing system; Construct an underground mechanic shop; Deploy a conveyor system; Integrate BEVs; Integrate teleoperated machines
AUTHORIZATION	
AU1 Authorize portfolio components at different levels depending on scope and investment cost	Portfolio authorized at the corporate level
AU2 Allocate resources to projects	Information not available
Communication portfolio decisions to stakeholders	Information not available
Organize a kick-off meeting with stakeholders	Information not available

6.7.2 Analysis and model application

This section outlines the phases of the proposed model as applied a posteriori to company YXE. Since the company had already begun its DT using its own portfolio at the time of this study, only the model's process could be validated, not the resulting portfolio.

6.7.2.1 Identification Phase

Appendix A and Appendix B summarize the intermediate outputs of the PPM model identification activities, detailing the steps required to identify DT initiatives. Eight Smart Mine objectives aligned with YXE's strategic and DT vision were translated into nineteen key objectives. A SWOT analysis was conducted, with only an overview provided for clarity. Similarly, process mapping is presented in the process-name level, and only the most relevant KPIs are reported. An AS-IS diagnostic of the identified processes and a list of KIRs were established. Stakeholders linked to these processes were identified, and through a bottom-up approach, their expectations and requirements, as well as departmental expectations, were incorporated into the TO-BE processes. These steps generated an initial list of forty initiatives, of which thirty-four were deemed feasible based on their Technology Readiness Levels (TRL) and the current stage of mine development. For feasible initiatives, change readiness was assessed on a 0–20 scale using the questionnaire from Le Grand et Deneckere (2019), while digital capability readiness and "AS-IS" process maturity were assessed on a 0–5 scale following respectively Rautenbach et al. (2019) and De Carolis et al. (2017). Finally, a brief risk analysis of the initiatives was conducted, along with the identification of possible collaboration and ongoing projects.

6.6.2.2 Categorization phase

The categories were defined based on YXE's DT vision, which encompasses operations, support systems, technology, safety, equipment, and sustainability, with feasible initiatives deemed feasible classified accordingly. Similarly, stakeholders identified per activity, listed in Appendix A, are grouped into four categories: external, corporate, departmental, and workforce.

6.7.2.3 Evaluation Phase

Both qualitative and quantitative criteria were selected to reflect underground mining challenges and YXE's DT vision, with weights set by YXE's strategic priorities and perceived importance (Ease of implementation, CAPEX, OPEX, ROI, and timeframe of implementation: 0.1; Sustainability, energy consumption reduction, and GHG reduction: 0.04; Health: 0.08; Risk reduction and productivity gain: 0.15). Values between 0.04 and 0.15 were chosen to avoid excessive dispersion, limit the effect of a dominant criterion, and reflect differences in priority. Criteria related to economic and operational feasibility (ease of implementation, CAPEX, OPEX, ROI, implementation horizon) were set at 0.10, indicating a high but balanced importance, consistent with their central and cross-cutting roles in evaluating digital transformation initiatives. Criteria associated with risk reduction and productivity gains received the highest weighting (0.15), reflecting the significant challenges facing the mining sector. Health-related criteria were weighted at 0.08, reflecting a significant but distinct importance from criteria directly related to operational performance. Finally, sustainability criteria, including reducing energy consumption and GHG emissions, were weighted at 0.04 to reflect their complementary role in YXE's current context, where operational and safety priorities remain paramount. Initiatives were evaluated in terms of their direct and indirect benefits, using approximate values derived from industry case studies and publicly available data sources. Values have been normalized. The ease of implementation criteria incorporates the score of the change readiness, digital capability readiness, and maturity assessment from the identification phase, as well as TRL considerations.

6.7.2.4 Selection Phase

Each feasible initiative was rated and ranked within its category. Three initiatives were excluded based on additional selection criteria: explosive loader robots were rejected due to a limited ROI, renewable energy sources were rejected due to high CAPEX, an extended implementation timeframe, harsh climatic conditions, and limited scalability at the mine site. Similarly, autonomous dewatering systems were not pursued due to insufficient ROI, a long timeframe, and low site readiness.

6.7.2.5 Prioritization Phase

Initiatives were prioritized based on their interdependencies. Initiatives evaluation scores were re-evaluated considering the number of required predecessors for each initiative (treated as a negative factor) and the number of initiatives that depend on it (same factors value but treated as positive). The interdependencies are illustrated visually in Figure 6.3, where circles represent initiatives (larger circles indicate more dependents) and arrows indicate dependency direction (initiatives at the arrowhead depend on those at the tail). For clarity, only the nine initiatives rated the highest in the evaluation phase are mapped; achieving these initiatives requires completing some lower-rated initiatives, which are represented by a non-continuous line. These lower-rated initiatives are consequently considered mandatory and included in the initial portfolio.

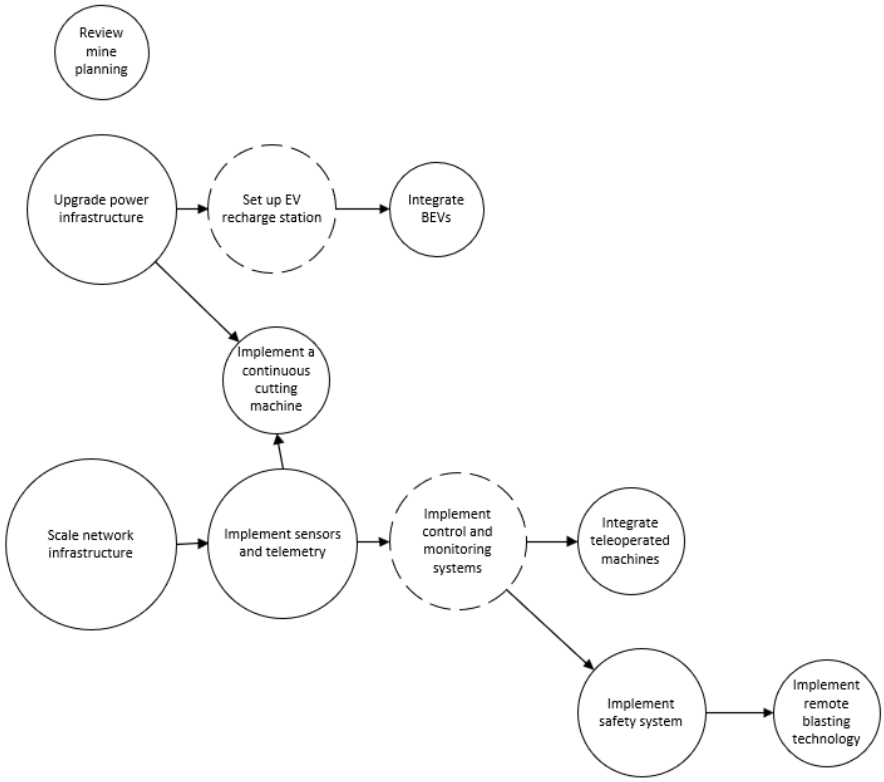


Figure 6.3 Initiatives interdependencies

6.6.2.6 Balancing phase

First, the initial portfolio was evaluated against resource constraints, considering competencies and external expertise (Petit, 2012). A few initiatives were removed due to insufficient skills, financial

or material resources, inadequate infrastructure or IT capacity, and limited time availability. Subsequently, the portfolio was optimized considering a budget of CAD 30 million (as reported in YXE's feasibility study). Table 6.4 summarizes the PPM model phases carried out to develop the final portfolio. Initiatives are grouped by category, brackets show evaluation scores, bold values reflect the final score after prioritization, strikethrough indicates excluded initiatives during the selection phase, gray indicates those removed due to resource constraints in the balancing phase, lighter gray indicates initiatives disabled for later implementation, and white for those allowed in the final portfolio.

Table 6.4 Selected, disabled, and terminated initiatives per category

Operation	Support system	Technology	Safety	Equipment	Sustainability
0,47 Deploy conveyor system [0,57]	**0,54** Review mine planning system [0,50]	**0,72** Scale network infrastructure [0,46]	**0,50** Implement cybersecurity [0,32]	**0,50** Implement continuous cutting machine [0,56]	**0,59** Integrate BEVs [0,63]
0,38 Implement predictive maintenance [0,40]	**0,51** Upgrade power infrastructure [0,45]	**0,64** Implement sensors and telemetry [0,40]	**0,38** Ensure compliance for automation & manual operations [0,34]	**0,41** Integrate teleoperated machines [0,45]	**0,30** Develop carbon offset strategy [0,28]
0,28 Develop remote-control operations centre [0,48]	**0,51** Implement safety system [0,39]	**0,38** Implement ventilation on demand [0,42]	**0,30** Develop training, mental health and well-being, EDI, and personal development programs [0,27]	**0,33** Set up EV recharge stations [0,33]	**0,21** Implement community relations office and program [0,21]
~~Develop autonomous dewatering systems~~ ~~[0,43]~~	**0,44** Improve data analytics and visualization [0,36]	**0,37** Implement remote blasting technology [0,47]	**0,24** Deploy e-learning platforms [0,26]	**0,31** Implement connected wearables devices [0,37]	~~Utilize renewable energy sources~~ ~~[0,48]~~
	0,42 Redefine maintenance processes [0,36]	**0,33** Deploy cloud infrastructure [0,35]		**0,29** Implement inspection robots and drones [0,43]	
	0,39 Develop water management system [0,41]	**0,31** Deploy VR simulation [0,33]		~~Implement explosives loader robot~~ ~~[0,49]~~	
	0,34 Implement control and monitoring systems [0,40]	**0,28** Deploy video technology and video management system [0,28]			
	0,29 Redefine inventory processes and inventory tracking system [0,25]				
	0,27 Implement fleet management [0,35]				

Dark grey= terminated activity; Light grey= disabled activity; White= allowed activity; Strikethrough= activity excluded
[n]= evaluation score; **n**= score considering interdependencies

6.7.2.7 Authorization phase

The authorization phase was not examined in this study, as it requires corporate-level decision-making based on the balanced portfolio, and relevant information was unavailable. This phase typically encompasses formal approval processes, strategic alignment, and executive endorsement to allocate resources and proceed with implementation. While essential for practical deployment, it falls outside the scope of the current analysis.

Finally, it is essential to note that only the activities needed to validate the model were conducted. In practice, enabling management functions remains essential for successfully implementing DT initiatives.

Considering interdependencies, resource availability, and the budget constraints, the final portfolio was established. Figure 6.4 presents a Gantt diagram showing the implementation schedule illustrating the sequencing of initiatives, their estimated timing, and dependencies. This visualization enables a clear understanding of how prioritized initiatives are phased over time. The final portfolio created applying this model is shown in gray, while YXE's initial portfolio is shown in black.

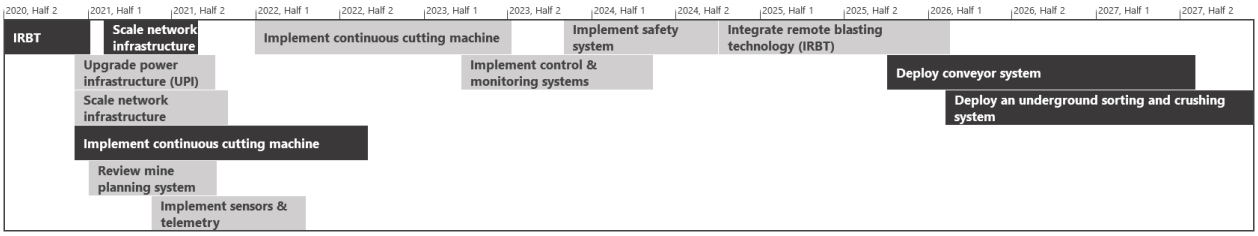


Figure 6.4 Gantt diagram of portfolio initiatives

6.8 Discussion

While YXE employed an unstructured portfolio approach, only 10 out of 16 identification activities were completed, relying primarily on a top-down, problem-based approach. Risk analysis was limited, as no KRIs were defined, and it was not followed by a comprehensive risk management strategy. Discrepancies between YXE's portfolio and the one built by applying the model emerged at the second step. Fewer key objectives were identified, and the SWOT analysis was not carried out, leading to fewer processes linked to each objective. Since the on-site "AS-IS" process diagnostic was conducted after portfolio authorization, and stakeholder and departmental

expectations and requirements were not gathered, the “TO-BE” processes differ. The initiatives were not filtered to remove unfeasible ones, although, in this case, this omission did not affect the outcomes. The company did not assess its digital capability readiness, change readiness, or as-is maturity of the identified initiatives, directly influencing the evaluation phase, as these criteria were not considered in the evaluation. Additionally, only a few enabling activities related to risk, change, communication, and stakeholder management were undertaken, indicating a lack of DT support. Overall, the identification phase proved crucial for portfolio creation. However, YXE’s approach lacked a formal structure and bottom-up participation, resulting in the identification of only eleven initiatives and the absence of critical ones.

No categorization was conducted. Categorizing initiatives would have enabled YXE to select and prioritize initiatives from each category, ensuring balanced coverage of all aspects of the DT vision. Consequently, the resulting portfolio does not include initiatives from support systems, safety, or sustainability, an omission that is also reflected in the final portfolio produced through the model regarding safety and sustainability.

The evaluation relied on unweighted quantitative and qualitative evaluation criteria, with initiative selection based on their scores, and included additional criteria such as safety, ESG, community, and technological factors, which had not been previously considered. Two initiatives were rejected following evaluation results. A mitigation plan was also developed at this stage. Prioritization occurred at the corporate level, guided by evaluation scores, available resources, and technology criteria. The balancing phase accounted for resource constraints and evident interdependencies. Three initiatives were allowed, one was terminated, and five were disabled. Based on YXE’s available budget information, it appears that not all allocated funds for DT initiatives were utilized. Finally, the portfolio was authorized according to the project scope and investment cost. While stakeholder and communication management were addressed during this phase, change management remained largely overlooked.

Applying the proposed PPM model to company YXE generated a revised sequencing of DT initiatives, indicating that the priorities are upgrading the power infrastructure, scaling the network infrastructure, and reviewing the mine planning system. These foundational elements are followed by the implementation of sensors and telemetry, after which the continuous cutting machine can be introduced. Subsequently, control and monitoring systems should be deployed, followed by the

installation of the safety system, and finally, the integration of remote blasting technology. While YXE's ongoing projects were well selected and retained in this portfolio, this sequencing reflects the interdependencies among initiatives and underscores the necessity of establishing a robust digital infrastructure backbone before advancing toward automation and safety systems. YXE had initiated several relevant initiatives, including the partial deployment of remote blasting technology for surface detonation, the implementation of a continuous cutting machine, and the scaling of network infrastructure. However, some of these initiatives were undertaken without fully addressing prerequisites, such as upgrading power infrastructure. In the future, the company plans to deploy a conveyor system and an underground sorting and crushing system. This misalignment highlights the importance of explicitly mapping interdependencies to prevent troubleshooting later. It is, however, necessary to note that due to the ongoing expansion of the underground mine, projects related to mine growth, such as scaling network infrastructure, must be treated as continuous initiatives (as shown in Figure 6.4).

We also note that conducting an "AS-IS" diagnostic during the identification phase with a bottom-up approach that gathers stakeholders and departmental expectations and requirements would have made the identification process more effective, highlighting the value of multiple identification activities rather than relying solely on a problem-based approach. Categorizing initiatives could have provided an overview of the different operational areas, while assigning weights to evaluation criteria would have highlighted their relative importance, enabling better-informed selection decisions. Outcomes would have varied according to the weights applied, allowing different scenarios to be explored. Although a risk assessment was conducted early in the process and a mitigation plan was subsequently developed, no risk threshold was defined, and no risk assessment was performed for the selected initiatives. This reveals gaps in risk management throughout the process and during portfolio execution. Furthermore, visualizing interdependencies could have clarified the initiative's relationship by drawing on stakeholders' and departments' feedback, which is critical for on-site project execution.

As a result, YXE's top-down approach, combined with limited focus on change management and workforce engagement, led to resistance from underground operators despite the presence of an on-site champion. The implementation of the continuous machine was largely supplier-led, reflecting both YXE's reliance on external expertise and a lack of operator involvement, which

contributed to skill gaps and resistance to process changes. The enabling management functions highlighted in the model allow for better portfolio development and preparation for execution.

To mitigate these problems, we operationalize the proposed PPM approach by applying the tools and techniques outlined in Table 6.2. To identify initiatives, information was gathered through a combined bottom-up and top-down approach using expert judgment. However, stakeholders' and department expectations and requirements were collected through on-site observation and discussions, as well as follow-up interviews with a limited set of stakeholders a posteriori. Conducting a SWOT analysis requires a multidisciplinary team to capture on-site and corporate feedback. Mapping the AS-IS process is challenging due to the complexity of operations. The chosen tool should capture all necessary information, which was partially achieved for this test case based on available data. The initiatives should be identified to achieve the "TO-BE" process through expert judgment and team workshops, ensuring multidisciplinary input for a comprehensive perspective, which was validated based on the observations made. Assessing the current company's process digital capability readiness, change readiness, and as-is maturity of identified initiatives is challenging because existing models, developed for the manufacturing industry, may require internal or external expertise.

Also, the initiative's evaluation employed a weighted multi-criteria approach. Criteria weights were based on the importance of the company's DT vision and strategic vision, which directly influence the outcomes of the portfolio. Assessing the initiatives' direct and indirect benefits is challenging and requires careful information gathering and expert judgment. Visual project mapping helped highlight interdependencies, though the large number of initiatives complicates clarity. Balancing was mainly based on resource constraints from the follow-up interview, but would benefit from a more structured process and tools, which were not available for this test case.

The proposed model structure and operationalize the continuous integration of enabling management functions as a transversal mechanism that inform decision-making at each stage of the portfolio creation. While it is important to emphasize that only the activities necessary to test the proposed model were carried out during this research, the framework itself is designed to support ongoing managerial integration, corporate decision-making processes and expert judgment must ultimately guide the formal authorization and implementation of projects. This continuous integration is a key added value of the model, as it responds directly to the realities of underground

mining environments, where elevated operational risks, persistent resistance to change, and the need for workforce acceptance significantly influence the viability and impact of transformation efforts. By embedding enabling management functions throughout the lifecycle, the model enhances coherence, adaptability, and decision quality, increasing the likelihood that DT initiatives deliver sustainable value beyond their initial implementation.

6.9 Conclusion

This study addressed a critical gap in the DT literature by proposing a practical PPM model tailored to the mining sector, developed with expert input and validated through an underground mining test case. Grounded in Industry 4.0 approaches and based on the critiques from the literature review, the model adopts a diagnostic-driven perspective, combining a top-down strategic alignment with bottom-up operational feedback, as suggested by Pajares, Javier et López (2014) and Lemieux et al. (2015).

The model also incorporates specific challenges of underground mining within the PPM phases, where organizational change and workforce reluctance remain key barriers to DT implementation. Change management is a core enhancement of our model, reinforcing workforce engagement throughout the process to improve acceptance and increase the likelihood of success. Rather than focusing solely on existing problems, the model employs a wide range of identification activities and embeds enabling management functions (risk, change, communication, and stakeholder management) throughout the portfolio lifecycle.

Unlike existing PPM approaches, the proposed model suggests multiple identification activities and explicitly considers interdependencies to prioritize initiatives. Visual mapping of these interdependencies, as suggested by Killen et Kjaer (2012), emerges as a crucial tool, enabling rapid identification of critical paths, prerequisites, and potential bottlenecks. While other models emphasize primarily financial metrics, this model integrates qualitative and quantitative criteria to assess social, environmental, and operational dimensions, critical in the mining context. The model suggests multiple tools and techniques, as well as facultative activities, from which companies can select those most appropriate to their context to operationalize the model.

Although some aspects of the model, such as assigning weights or assessing interdependencies, rely on assessor expertise and may affect the consistency of outcomes, the model represents a step toward more systematic and evidence-driven DT portfolio development. By aligning initiatives

with both the company's DT vision and Smart Mine objectives, it supports the creation of a portfolio financially sound and strategically coherent over the long term.

However, the model has been tested on a single underground mine and primarily focuses on extraction-related initiatives, although it may also apply to surface mining contexts. Indeed, the core logic of the model, grounded in project portfolio management principles, continuous integration of enabling management functions, is independent of site-specific operational parameters. The model can accommodate the mine site operational differences through adaptable inputs and top-down bottom-up approach and provide a flexible decision-support framework that can be tailored to other underground operations, and with appropriate adaptation to surface mines. The evaluation phase relied primarily on estimated data from case studies and industry reports, which directly shaped the portfolio outcomes and may explain the discrepancies between YXE's initial portfolio and the one obtained by applying the model.

Moreover, this model does not yet fully incorporate all portfolio lifecycle phases suggested by Project Management Institute (2017), such as optimizing, transitioning, controlling, and terminating portfolio components, nor does it integrate continuous monitoring mechanisms to integrate new projects over time. Future research should aim to extend the model to include these dynamic aspects and organizational levels for project authorization, execution, and governance. The model would benefit from further validation across various mining operations, including surface mining, and could be extended to encompass the full-mining lifecycle to strengthen its adaptability to different operational contexts. In addition, longitudinal studies could track portfolio creation and evolution over time to assess the model's impact on decision-making and performance. Finally, future research could explore the model's applicability beyond the mining sector, particularly in other industries with limited lifecycles such as forestry, the naval industry, and construction.

Appendix A: Identification phase outcomes

ID1S1 Company's Smart Mine objectives	ID2S1 Key objectives	ID3S1 SWOT analysis	ID4S1 Mapped processes	ID5S1 List of KPIs	ID6S1 AS-IS diagnostic of process	ID7S1 List of KRIs	ID8S1 Departments expectations / requirements	ID9S1 List of stakeholders	ID9S2 Stakeholders expectations/ requirements	ID10S1 TO-BE processes descriptions	ID11S1 List of initiatives	ID12S2 Unfeasible initiatives
Improve operational efficiency	Minimize waste	S: Corporate involvement, reduce cycle waste, on-site champions W: Lack of KPIs, no formalized PPM, workforce skills gap, budget limits O: deploy new technologies, training programs, electrification, IT backbone T: underground environment, harsh climate, remoteness, workforce resistance	Ore waste process	Waste-to-ore ratio	Blasted ore mucked, hauled to surface, crushed and sorted at plant	deviation from planned dilution limit	Optimize ore recovery, reduce dilution, improve material tracking, efficient blasting & haulage.	Regulators, shareholders, local communities, plant manager, mine operation manager, geology department, software provider	Regulatory adherence, minimized tailings, sustainable reputation.	Ore crushed underground; waste used for backfill or disposal; grade hoisted to surface; crushers/sorters automated and remotely operated; conveyors or trucks move ore/waste; real-time monitoring and maintenance system; new SOPs; ventilation upgrade; emergency/maintenance access ensured; waste plan in place	Deploy an underground sorting and crushing system	Deploy an underground sorting and crushing system
	Improve operations		Scheduling	Schedule adherence	Hand-made schedules machine availability based on mechanics/operators feedback	frequence of missed critical milestones	Streamlined workflows, real-time monitoring, predictive planning.	Mine workers, management, engineering department, IT department	Safer, more reliable, and cost-effective operations.	Align with DT vision and corporate strategy; stakeholder collaboration;cross-department integraiton;cloud-based with real-time data	Review mine planning Implement fleet management	
	Reduce downtime		Inventory processes	Time wait for a piece	Manual stock tracking; no reorder indicators; basic spare parts inventory	Mean Time between spare pieces received	Spare part availability, printing on-site, tracking system	Mechanics, warehouse manager,	Higher utilization, contractual uptime guarantees.	Real-time tracking of parts/stock via RFID; automated reorder points; 3D printed parts;tablets for staff; optimized warehouse layout; predictive maintenance linked to inventory; digital parts library; dashboard for stock levels	Integrate 3D printing technology Redefine inventory processes Implement an inventory tracking system	Integrate 3D printing technology
			Maintenance processes	OEE	Planned repairs at surface shop; daily breakdowns repaired underground; limited spare parts on vehicles, surface mechanic shop with FEMCO phone + radio; indirect communications via truck drivers	MTBF trend deviation	Predictive maintenance systems, remote troubleshooting, spare part availability	Mechanics, mine workers, IT department, engineering department	Safe, skilled, future-ready workforce.	Equipment serviced underground; predicitve maintenance triggers part orders; spare parts stored underground; inventory digitally linked to maintenance system	Construct an underground mechanic shop Deploy video technology and video management system Implement predictive maintenance strategy Integrate AI tools for predictive maintenance Redefine maintenance processes	Construct an underground mechanic shop Integrate AI tools for predictive maintenance
	Develop education & training		Onboarding process / Training process	Training completion	2-day on-boarding process for site familiarization; equipment sign-off	Skill gap ratio	Upskilling workforce, VR/AR training, competency frameworks.	Employees, HR department, IT department	Safe, skilled, future-ready workforce.	on-site practical workshops + e-learning modules	Develop training Deploy e-learning platforms Deploy VR simulation	
Improve productivity	Increase the mineral quantity extracted	S: Acquisition of cutting machine Clear corporate producitivty goal W: lack of on-site mill, reliance on vendor, no data O: Deploy conveyor system and underground crushing sorting facility, blast-free operations T: hard-rock condition for cutting machine, high CAPEX risk, energy constraints	Extraction process	Ore tonnes to surface per shift	Dispatching via face-to-face communication during shift meeting; equipment tracked on whiteboards from operator report; manual shift reports in excel; downtime undocumented; fixed intervals for maintenance	AI integration	Precision drilling, efficient haulage, optimized stope design.	Communities, mine operation management, superintendant, mine manager, engineering department, operators, geology department	Maximized recovery, minimized impact.	Optimized automated dispatch with RFID tracking; tablets for operator input; live data collection; production monitored in real-time; AI tools for predicitve maintenance	Deploy a conveyor system	
Implement autonomous operations	Implement autonomous systems	S: Strong corporate ambition, safety motivation, remote equipment towards autonomy W: low digital maturity, lack of roadmap, no training O: Teleoperation, sensors and telemetry, workfroce training T: unreliable connectivity, workforce resistance, OEMs non-agnostic system	Dewatering process / Ventilation process / Control process / Monitoring process	Pump availability / VoD efficiency / process control / % systems monitored in real-time	90" fan sit hstaged vent tubes and booster fans; negative ducting; surface manual switch; programme heater in winter	water ingress rate exceeding system capacity / air quality exceedance incidents / frequency of control system overrides / data transmission failure rate	Reliable connectivity, integration with existing fleet, cybersecurity.	operators, management, engineering department, IT department, supervisors,	Safer, more productive, lower-cost operations.	VoD with sensors and regulators; remote monitoring; smart alerts for pump and fans	Develop autonomous ventilation Deploy VoD Develop autonomous dewatering system	Develop autonomous ventilation
	Implement autonomous machine		Operation processes	% autonomous machine	Human-operated machines underground; line of sight teleoperated machine	System override	Autonomous haul trucks, loaders, drills; training for operators.	management, engineering department, IT department, operators, supervisors	Reduced human exposure, higher productivity.	Machines fully autonomous; monitored from control room; real-time scheduling and assignments;predicitive maintenance trigerred automatically, zero operator exposure	Deploy fully autonomous machine Implement control and monitoring system	Deploy fully autonomous machine
Perform continuous mineral extraction	Develop a continuous extraction process	S: Investment into cutting machine, reduction of explosives W: lacked structure roadmap and KPIs, succes criteria ambiguous, reliance on vendor for troubleshooting O: continuous cutting, integrate conveyor, reduce cycle waste, improve ground stability T: machine performance unproven in hard-rock, high maintenance, budget limits, workforce resistance	Extraction process	Tonnes/hr throughput	drill-blast-excavate cycle with LHDs, trucks, bolters, shotcrete, humbo drills, manual explosives set up	unplanned stoppage frequency	Mechanical cutting, conveyor systems, real-time ore flow monitoring.	Management, operators, shareholders, investors, mine manager, engineering department, IT department	Break reliance on batch cycles	Continuous cutting machine feeds conveyors to surface; transfer stations in place; conveyor maintenance integrated	Implement a continuous cutting machine	

Appendix A: Identification phase outcomes (continued and end)

ID1S1 Company's Smart Mine objectives	ID2S1 Key objectives	ID3S1 SWOT analysis	ID4S1 Mapped processes	ID5S1 List of KPIs	ID6S1 AS-IS diagnostic of process	ID7S1 List of KRIs	ID8S1 Departments expectations / requirements	ID9S1 List of stakeholders	ID9S2 Stakeholders expectations/ requirements	ID10S1 TO-BE processes descriptions	ID11S1 List of initiatives	ID12S2 Unfeasible initiatives
Improve operational efficiency	Minimize waste	S: Corporate involvement, reduce cycle waste, on-site champions W: Lack of KPIs, no formalized PPM, workforce skills gap, budget limits O: deploy new technologies, training programs, electrification, IT backbone T: underground environment, harsh climate, remoteness, workforce resistance	Ore waste process	Waste-to-ore ration	Blasted ore mucked, hauled to surface, crushed and sorted at plant	deviation from planned dilution limit	Optimize ore recovery, reduce dilution, improve material tracking, efficient blasting & haulage.	Regulators, shareholders, local communities, plant manager, mine operation manager, geology department, software provider	Regulatory adherence, minimized tailings, sustainable reputation.	Ore crushed underground; waste used for backfill or disposal; grade hoisted to surface; crushers/sorters automated and remotely operated; conveyors or trucks move ore/waste; real-time monitoring and maintenance system; new SOPs; ventilation upgrade; emergency/maintenance access ensured; waste plan in place	Deploy an underground sorting and crushing system	Deploy an underground sorting and crushing system
	Improve operations		Scheduling	Schedule adherence	Hand-made schedules machine availability based on mechanics/operators feedback	frequence of missed critical milestones	Streamlined workflows, real-time monitoring, predictive planning.	Mine workers, management, engineering department, IT department	Safer, more reliable, and cost-effective operations.	Align with DT vision and corporate strategy; stakeholder collaboration;cross-department integraiton;cloud-based with real-time data	Review mine planning Implement fleet management	
	Reduce downtime		Inventory processes	Time wait for a piece	Manual stock tracking; no reorder indicators; basic spare parts inventory	Mean Time between spare pieces received	Spare part availability, printing on-site, tracking system	Mechanics, warehouse manager,	Higher utilization, contractual uptime guarantees.	Real-time tracking of parts/stock via RFID; automated reorder points; 3D printed parts;tablets for staff; optimized warehouse layout; predictive maintenance linked to inventory; digital parts library; dashboard for stock levels	Integrate 3D printing technology Redefine inventory processes Implement an inventory tracking system	Integrate 3D printing technology
			Maintenance processes	OEE	Planned repairs at surface shop; daily breakdowns repaired underground; limited spare parts on vehicles, surface mechanic shop with FEMCO phone + radio; indirect communications via truck drivers	MTBF trend deviation	Predictive maintenance systems, remote troubleshooting, spare part availability	Mechanics, mine workers, IT department, engineering department	Safe, skilled, future-ready workforce.	Equipment serviced underground; predicitve maintenance triggers part orders; spare parts stored underground; inventory digitally linked to maintenance system	Construct an underground mechanic shop Deploy video technology and video management system Implement predictive maintenance strategy Integrate AI tools for predictive maintenance Redefine maintenance processes	Construct an underground mechanic shop Integrate AI tools for predictive maintenance
	Develop education & training		Onboarding process / Training process	Training completion	2-day on-boarding process for site familiarization; equipment sign-off	Skill gap ratio	Upskilling workforce, VR/AR training, competency frameworks.	Employees, HR department, IT department	Safe, skilled, future-ready workforce.	on-site practical workshops + e-learning modules	Develop training Deploy e-learning platforms Deploy VR simulation	
Improve productivity	Increase the mineral quantity extracted	S: Acquisition of cutting machine Clear corporate producitivty goal W: lack of on-site mill, reliance on vendor, no data O: Deploy conveyor system and underground crushing sorting facility, blast-free operations T: hard-rock condition for cutting machine, high CAPEX risk, energy constraints	Extraction process	Ore tonnes to surface per shift	Dispatching via face-to-face communication during shift meeting; equipment tracked on whiteboards from operator report; manual shift reports in excel; downtime undocumented; fixed intervals for maintenance	AI integration	Precision drilling, efficient haulage, optimized stope design.	Communities, mine operation management, superintendant, mine manager, engineering department, operators, geology department	Maximized recovery, minimized impact.	Optimized automated dispatch with RFID tracking; tablets for operator input; live data collection; production monitored in real-time; AI tools for predicitve maintenance	Deploy a conveyor system	
Implement autonomous operations	Implement autonomous systems	S: Strong corporate ambition, safety motivation, remote equipment towards autonomy W: low digital maturity, lack of roadmap, no training O: Teleoperation, sensors and telemetry, workfroce training T: unreliable connectivity, workforce resistance, OEMs non-agnostic system	Dewatering process / Ventilation process / Control process / Monitoring process	Pump availability / VoD efficiency / process control / % systems monitored in real-time	90" fan sit hstaged vent tubes and booster fans; negative ducting; surface manual switch; programme heater in winter	water ingress rate exceeding system capacity / air quality exceedance incidents / frequency of control system overrides / data transmission failure rate	Reliable connectivity, integration with existing fleet, cybersecurity.	operators, management, engineering department, IT department, supervisors,	Safer, more productive, lower-cost operations.	VoD with sensors and regulators; remote monitoring; smart alerts for pump and fans	Develop autonomous ventilation Deploy VoD Develop autonomous dewatering system	Develop autonomous ventilation
	Implement autonomous machine		Operation processes	% autonomous machine	Human-operated machines underground; line of sight teleoperated machine	System override	Autonomous haul trucks, loaders, drills; training for operators.	management, engineering department, IT department, operators, supervisors	Reduced human exposure, higher productivity.	Machines fully autonomous; monitored from control room; real-time scheduling and assignments;predicitive maintenance trigerred automatically, zero operator exposure	Deploy fully autonomous machine Implement control and monitoring system	Deploy fully autonomous machine
Perform continuous mineral extraction	Develop a continuous extraction process	S: Investment into cutting machine, reduction of explosives W: lacked structure roadmap and KPIs, succes criteria ambiguous, reliance on vendor for troubleshooting O: continuous cutting, integrate conveyor, reduce cycle waste, improve ground stability T: machine performance unproven in hard-rock, high maintenance, budget limits, workforce resistance	Extraction process	Tonnes/hr throughput	drill-blast-excavate cycle with LHDs, trucks, bolters, shotcrete, humbo drills, manual explosives set up	unplanned stoppage frequency	Mechanical cutting, conveyor systems, real-time ore flow monitoring.	Management, operators, shareholders, investors, mine manager, engineering department, IT department	Break reliance on batch cycles	Continuous cutting machine feeds conveyors to surface; transfer stations in place; conveyor maintenance integrated	Implement a continuous cutting machine	

Appendix B: Identification phase outcomes from feasible activities

ID12S1 Feasible initiatives	ID13S1 Change readiness assessment (0 to 20)	ID13S2 Digital capability readiness assessment (0 to 5)	IS13S3 Maturity assessment (0 to 5)	ID14S1 Risk analysis	ID15S1 Possible collaboration	ID16S1 On-going projects
Review mine planning	5	3	3	Misalignment between DT vision and operational constraints; requires departments input	Geology + engineering consultants, mine planning software vendors, universities optimization	
Implement fleet management	7	2	2	Poor connectivity; workforce resistance to monitoring	OEMs, FMS providers, IT integration firms	
Redefine inventory processes & implement an inventory tracking system	5	1	1	Upfront cost; reliance on digital literacy; skill gap	ERP vendors, RFID/IoT suppliers, logistics experts, universities on supply chain	
Deploy video technology and video management system	8	1	2	Connectivity limitations underground; privacy concerns; data protection	Security tech vendors, network providers, safety regulators	
Implement predictive maintenance strategy	8	2	1	Reliable data and sensors; need IT backbone	OEMs, AI startups, universities, CIM,GMG	
Redefine maintenance processes	7	2	3	Disrupt routines, workforce adaptation challenges	consulting firms, workforce	
Develop training, mental health and well-being, EDI, and personal development programs	9	1	1	Low participation; integrate into culture; requires update	HR specialist, community groups, NGOs, universities	
Deploy e-learning platforms	8	1	1	Connectivity limitations; platform develop, content development	E-learning vendors, training consultants	
Deploy VR simulation	8	1	2	High cost, underuse	VR developers, universities, OEMs	
Deploy a conveyor system	8	1	2	High CAPEX, complex engineering in unstable ground, bottlenecks	Engineering and EPCM firms, conveyor manufacturers, OEMs	
Deploy VoD	7	1	2	Extensive sensor coverage, important maintenance; safety	Ventilation consultants, sensor providers, univerisities	
Develop autonomous dewatering system	7	1	2	Dependance on sensors and controls; safety	Pump OEMs, automation providers	
Implement control and monitoring system	7	2	2	Connectivity issues, reliability, integration challenges	SCADA vendors, system integrators, cybersecurity firms	
Implement a continuous cutting machine	8	3	3	Reliance on vendor, ground instability, no proof on hard-rock, maintenance	OEMs, R&D partnerships with universities for rock mechanics	
Develop a ROCC	6	3	2	High cost, workforce acceptance, connectivity	OEMS, telecom providers, EPCM fims	
Integrate teleoperated machines	6	3	2	Connectivity; training	OEMs, network provider, simulation training centers	
Deploy sensors and telemetry	6	2	2	Harsh conditions, robust maintenance	IoT startups, OEMs, network providers, universities	
Scale network infrastructure	6	2	2	Harsh conditions, scalability	Telecom providers, government grants, networking firms	Scale network infrastructure
Implement cybersecurity	6	2	2	Cyberthreats, skill gaps	Cybersecurity firms, universities, government agencies	
Deploy cloud infrastructure	5	2	2	Data sovereignty/ regulatory concerns	Cloud providers, IT consultants	
Implement safety system	6	1	2	Safety gaps; compliance	Safety equipment OEMs, regulators, wearable providers	
Improve data analytics and visualization	6	2	2	Poor data quality; training	univerisities, software providers, startups, external consultants	
Implement explosives loader robotos	7	2	1	Safety; regulatory compliance, TRL	OEMs, robotics startups, universities	
Ensure regulatory compliance regarding automation & manual operations	5	2	3	Permitting; delays; restrictions; regulations	Government agencies, CIM, GMG, legal firms	
Implement connected wearables devices	8	1	2	Resistance, reliability	PPE OEMs, IoT startups, safety regulators	
Implement remote blasting technology	7	3	3	Connectivity; regulatory compliance	Explosive OEMs, universities	Implement remote blasting technology
Implement inspection robots and drones	8	2	2	Hharsh ground, maintenance, TRL	Robotics startups, drone companies	
Set up EV recharge station	6	1	1	Power capacity; high infrastructure costs	Power utilities, BEV OEMs, EPCM firms, government grants	
Upgrade power infrastructure	5	3	3	Expensive, scalability, permits, remote	Power utilities, BEV OEMs, EPCM firms, government grants	
Integrate BEVs	7	1	1	Weather conditions, electricity dependency	BEV OEMs	
Implement a community relations office and program	11	2	2	On-going cost, community distrust	Local communities, indigeneous groups, NGOs	
Utilize renewable energy sources	5	1	1	Integration costs, climate	Renewable energy firms, utilities, government funding agencies	
Develop a carbon offset strategy	5	1	2	Greenwashing, reputational exposure	Environmental NGOs, carbon credit agencies, external consultant	
Review water management system	5	3	3	Regulatory, weather	Hydrology consultants, environmental regulators	

CHAPITRE 7 DISCUSSION GÉNÉRALE

Ce chapitre présente une discussion des contributions de cette recherche à l'égard des objectifs spécifiques, propose des perspectives de recherche et met en évidence les limites de l'approche.

7.1 Résultats obtenus

7.1.1 Sommaire des contributions

L'article 1 apporte une contribution majeure en clarifiant le concept de la Mine Intelligente pour les opérations minières souterraines, jusque-là abordé de façon fragmentée dans la littérature, autant scientifique qu'industrielle. Aucun article ne propose une définition consolidée, les éléments d'une Mine Intelligente étant éparpillés. Pour pallier ce manque, une analyse documentaire de soixante-neuf articles industriels a permis de regrouper les éléments en trois grands thèmes : les objectifs poursuivis, les solutions proposées et les processus d'affaires qui les soutiennent. L'article aboutit à la création d'un cadre conceptuel de la Mine Intelligente appliqué aux mines souterraines, offrant une vision structurée qui sert de référence pour accompagner les entreprises minières dans leur transition vers la Mine Intelligente. Afin de mettre cette vision en perspective, une revue de littérature systématique de cent soixante articles scientifiques a été menée pour comparer les récents travaux universitaires avec la vision de l'industrie. Les résultats soulignent une forte convergence globale, mais également des divergences, phénomène déjà observé dans l'Industrie 4.0 (Perrier et al., 2024). Les priorités des industriels correspondent globalement aux thématiques les plus étudiées par les universitaires ; cependant, les industriels et les universitaires ne concentrent pas leur recherche sur les mêmes aspects, que ce soit au niveau des objectifs, des solutions ou des processus d'affaires. L'article met en lumière des thèmes peu étudiés, qui constituent des opportunités de recherche pour le milieu universitaire et des pistes d'évolution pour les industriels, les incitant à élargir leur champ des priorités. Enfin, l'article propose un cadre d'alignement des initiatives de TN reposant sur une approche ascendante et descendante, destiné à orienter la sélection des initiatives de TN.

L'article 2 propose une adaptation des pratiques de TN et GPP reflétant les réalités et défis de l'industrie minière souterraine. Ce travail contribue à une meilleure compréhension des pratiques de TN dans le secteur minier souterrain canadien en recensant et en évaluant les approches de TN actuellement employées. Les activités de GPP recensées dans la littérature sur l'Industrie 4.0 ont

été structurées selon les phases définies par le PMI, afin d'évaluer leur séquence, leur niveau d'utilisation et leur valeur ajoutée. L'évaluation menée auprès d'experts en gestion de projets miniers indique que les phases de GPP sont généralement appliquées de manière séquentielle, mais que certaines dimensions, notamment le risque, apparaissent de manière transversale à plusieurs étapes, sans consensus entre les experts. Par ailleurs, plusieurs activités de l'Industrie 4.0, bien que rarement mises en œuvre dans la pratique, sont unanimement reconnues par les experts comme étant à forte valeur ajoutée. Les pratiques sont utilisées de manière adaptative, en fonction du niveau de maturité organisationnelle et des contraintes opérationnelles du site minier. Les phases d'identification et de catégorisation reflètent cela. Bien que plusieurs activités y soient peu utilisées, elles sont reconnues comme potentiellement utiles par les experts, ce qui suggère un potentiel d'amélioration. À l'inverse, les phases d'évaluation, de sélection et de balancement concentrent les pratiques les plus utilisées et perçues comme créatrice de valeur. Certaines pratiques sont peu mobilisées, comme la priorisation selon les interdépendances, révélant un écart entre valeur perçue et applicabilité opérationnelle. Enfin, la diversité des réponses, certains experts utilisent les pratiques tandis que d'autres en évaluent uniquement la valeur potentielle, reflète l'hétérogénéité des niveaux de maturité en GPP au sein du secteur minier. Les pratiques peuvent être synthétisées autour de trois axes : les pratiques utilisées et créatrices de valeur, les pratiques reconnues comme utiles, mais peu déployées et les pratiques jugées peu pertinentes dans le contexte actuel. Cette structuration permet de mieux comprendre l'état actuel des pratiques de TN du secteur minier canadien. L'apport principal de l'article réside dans la mise en évidence de la nécessité d'intégrer la gestion du risque, de la communication, des parties prenantes et du changement tout au long du processus de GPP. Ces fonctions se veulent ainsi transversales et ne doivent pas être exécutées comme des phases distinctes.

L'article 3 répond à notre objectif de recherche en élaborant un modèle opérationnel et contextualisé destiné à guider les entreprises minières dans le développement de leur portefeuille de projets de TN. Ce modèle intègre à la fois les défis particuliers de l'industrie et les impératifs stratégiques liés à la transition vers la Mine Intelligente. Construit à partir de retour d'experts, ce qui permet d'ancrer le modèle dans la réalité terrain et des meilleures pratiques issues de l'Industrie 4.0, le modèle suit une approche ascendante et descendante. Il s'appuie sur les phases proposées par le PMI, tout en distinguant explicitement les processus de gestion de soutien tels que

la gestion du risque, du changement, de la communication et des parties prenantes. Il intègre des activités propres au contexte minier, notamment un grand nombre lors de la phase d'identification.

Le modèle combine et adapte des activités issues de différentes approches de l'Industrie 4.0 et propose un éventail de techniques et d'outils, laissant aux entreprises la flexibilité de sélectionner ceux qui correspondent le mieux à leur contexte. Son application permet de visualiser les interdépendances entre les initiatives et de faire émerger les critères d'évaluation importants pour l'entreprise. Ces critères tiennent compte des spécificités du secteur minier, telles que la durée de vie limitée, le retour sur investissement contraint et le développement continu de la mine. L'ensemble aboutit à la construction d'un portefeuille de projets de TN aligné à la fois sur la vision de la Mine Intelligente et la vision stratégique de l'entreprise.

7.1.2 Contributions

Les résultats de cette recherche apportent des contributions scientifiques et pratiques pour l'industrie minière souterraine, avec un potentiel d'application plus large à d'autres types de mines et à divers secteurs industriels caractérisés par des cycles de vie limités comme la construction, la foresterie, les chantiers navals ou aéronautiques.

Sur le plan scientifique, l'étude clarifie le concept de Mine Intelligente, jusque-là traité de manière fragmentée, en distinguant ce qui se fait réellement en pratique et ce que la littérature scientifique propose. Le concept crée une base théorique pour analyser l'intégration de TN dans le secteur minier. Pour concrétiser la vision de la Mine Intelligente, la collaboration entre le milieu universitaire et industriel est nécessaire. Cette recherche unifie la compréhension du concept, met de l'avant les axes de collaboration, oriente les travaux universitaires vers les besoins concrets du terrain et encourage les entreprises à s'appuyer sur la recherche pour adapter, améliorer et développer de nouvelles technologies, méthodes et procédés répondant aux problématiques rencontrées dans le secteur.

L'intégration et la mise en œuvre technologique demeurent des angles peu abordés dans la littérature, tant du côté des praticiens que des chercheurs, qui pourtant sont au cœur des opérations d'automatisation. Ce constat oriente les besoins futurs de recherche vers des dimensions telles que la gouvernance stratégique des projets, la gouvernance des données et compétences, et la gouvernance inter organisationnelle et écosystémique, nécessaire pour soutenir la Mine Intelligente. Ces dimensions font écho aux travaux sur les capacités dynamiques, soulignant

l'importance des capacités de coordination et de reconfiguration des ressources pour soutenir des TN évolutives. Du côté de la gouvernance écosystémique, la complexité de la Mine Intelligente met en évidence le rôle essentiel des associations intermédiaires, qui jouent un rôle de catalyseur et de médiateur entre les acteurs du secteur. Par elles, les pôles d'excellence et clusters miniers, tel que le groupe MISA et le CEMI, qui centralisent et diffusent les connaissances, facilitent l'intégration des technologies et des innovations, et servent d'interface entre chercheurs et entreprises minières. Les centres de recherche appliquée adaptent et développent les technologies aux contraintes opérationnelles. Les organisations de standardisation et de promotion de l'innovation, telles que le PDAC, définissent des lignes directrices et mettent en relation les acteurs industriels et technologiques. Enfin, les plateformes collaboratives et les consortiums, incluant le GMG, réunissent les minières, les équipementiers et les fournisseurs pour tester conjointement des solutions, ainsi que pour partager et accélérer l'adoption de technologie et de standards. Ces structures jouent un rôle clé pour transformer la vision de la mine intelligente en solutions concrètes.

Notre recherche souligne l'importance pour les entreprises minières de développer leur propre approche d'intégration, plutôt que de se fier uniquement à des fournisseurs et équipementiers. Cette posture s'inscrit dans les travaux sur la gouvernance de projets et des portefeuilles, qui montrent que la création de valeur repose sur la capacité des organisations à conserver un contrôle stratégique sur leurs choix technologiques, tout en orchestrant des acteurs externes. Une approche agnostique permet à l'entreprise de conserver le contrôle de sa stratégie technologique et sa capacité décisionnelle qinsi que d'adapter les solutions aux contraintes spécifiques de son exploitation, sans être bloquée sur une technologie. La constitution d'un portefeuille de projets et l'évaluation de leur faisabilité constituent un levier central de cette gouvernance stratégique. La collaboration avec des experts internes et externes, tels que les fournisseurs, est cependant un élément essentiel pour guider les décisions, en tant qu'acteurs techniques. Cela implique de renforcer les compétences internes, en développant des expertises liées à la TN, en recrutant des talents issus d'autres secteurs industriels, afin de bénéficier des savoir-faire. Le modèle proposé offre une trajectoire de gouvernance cible permettant de répondre aux limites observées dans les approches existantes, constituant un changement organisationnel et stratégique. Ce positionnement rejoint les travaux sur l'innovation digitale, soulignant que la réussite de TN repose moins sur l'adaptation isolée de technologies que sur la capacité organisationnelle à les intégrer et les coordonner. Le renforcement

graduel des compétences internes, combiné à une collaboration ciblée avec des experts internes et externes, y compris les fournisseurs, permet une montée en maturité progressive. Les fournisseurs sont repositionnés comme partenaires techniques plutôt qu'architectes de la stratégie de TN. L'inertie organisationnelle et la structure industrielle minière constituent des freins importants, mais les minières réalisent l'importance de supporter la montée en compétence des travailleurs et le besoin de compétences jusqu'ici peu représenté dans le domaine minier. Par ailleurs, notre approche comprend une forte concentration d'activités lors de la phase d'identification. Cette concentration est plus marquée que dans d'autres secteurs de l'Industrie 4.0, en raison de la complexité d'identifier la bonne solution qui n'est pas seulement liée à résoudre un problème existant, mais également à répondre à des défis présents et aux objectifs de la Mine Intelligente, à l'amélioration des processus et à la réalité du terrain provenant des opérateurs. Cette approche illustre une gouvernance hybride, combinant une logique descendante (vision stratégique) et ascendante (réalité opérationnelle), contribuant ainsi aux travaux sur la gouvernance adaptative des projets et des portefeuilles. Notre modèle, adapté aux défis du secteur minier souterrain, combinant les meilleures pratiques issues de l'Industrie 4.0 et l'avis d'experts, enrichit la littérature interdisciplinaire en matière de gestion de projets, d'ingénierie et de TN, en proposant une approche de gouvernance intégrée, contextualisée et orientée vers le développement de capacités organisationnelles durables.

En s'intéressant aux activités suggérées dans le modèle qui ont été validées par les experts du domaine minier, nous remarquons des divergences marquées entre experts selon leur rôle organisationnel, révélant à la fois des enjeux de gouvernance et des différences de maturité numérique au sein des organisations minières. Ces écarts apparaissent dès la phase d'identification, où plusieurs activités structurantes, telles que la définition des objectifs de la Mine Intelligente, la mesure du succès, l'analyse SWOT, le diagnostic des processus existants (AS-IS) ou la définition des processus cibles (TO-BE), sont rarement mises en œuvre dans les petites entreprises minières et peu portées par les fonctions corporatives. À l'inverse, certains rôles intermédiaires, notamment les gestionnaires de portefeuille et de projets, sont davantage impliqués dans la préparation des équipes au changement, l'identification des écarts de compétences ou la mise en place de collaborations, ce qui souligne une délégation implicite de responsabilités stratégiques vers des niveaux opérationnels.

La phase de catégorisation illustre également ces divergences, puisque ni les fonctions corporatives ni les gestionnaires de portefeuille ne procèdent systématiquement à la catégorisation des projets ou des parties prenantes, traduisant une gouvernance encore peu formalisée du portefeuille. Lors de la phase d'évaluation, plusieurs activités clés, telles que la définition des pondérations, l'évaluation des bénéfices directs et indirects ou l'impact sur les travailleurs, sont peu prises en charge au niveau corporatif, suggérant une focalisation prioritaire sur des critères financiers ou techniques, au détriment des dimensions humaines et organisationnelles. De plus, le risque n'est généralement pas intégré comme critère d'évaluation au niveau corporatif.

Ces écarts se poursuivent dans les phases de sélection et de priorisation, où les décisions ne reposent jamais uniquement sur les résultats d'évaluation formalisés, mais intègrent des critères additionnels implicites. La prise en compte des interdépendances entre projets pour la priorisation demeure marginale et principalement observée chez certains acteurs corporatifs. De même, la gestion des risques apparaît fragmentée : les plans de mitigation sont rarement formalisés en collaboration avec les gestionnaires de mine.

Enfin, les phases de balancement, de communication et d'autorisation révèlent des différences significatives selon la taille et la maturité des entreprises. L'allocation des ressources n'est pas systématiquement pilotée par les gestionnaires de portefeuille, tandis que les pratiques de communication verticale et horizontale, ainsi que la diffusion de la vision, de la stratégie et du calendrier de transformation, sont principalement observées dans les grandes entreprises. Ces activités sont alors portées par les gestionnaires de projets et de mines, plutôt que par les fonctions corporatives.

Dans l'ensemble, ces divergences soulignent une gouvernance hétérogène de la transformation numérique, où les responsabilités sont fragmentées entre niveaux organisationnels et fortement dépendantes de la maturité numérique de l'entreprise. Elles mettent en lumière la nécessité de renforcer les mécanismes de gouvernance du portefeuille afin de mieux aligner les rôles corporatifs, tactiques et opérationnels, et de soutenir une transformation numérique cohérente et systémique dans le secteur minier souterrain.

Sur le plan pratique, le modèle constitue un outil d'aide à la décision pour les entreprises minières permettant de créer leur portefeuille de projets de TN aligné sur leur stratégie et sur la vision de la Mine Intelligente. Il facilite la visualisation des interdépendances entre les initiatives et

l'intégration continue des processus de gestion du risque, du changement, des parties prenantes et de la communication tout au long de la création du portefeuille de projets. Toutefois, l'implantation effective du modèle repose sur une culture favorable au changement et à l'apprentissage ainsi qu'un leadership capable de porter la vision de la TN au-delà des projets technologiques, ainsi qu'une direction présente supportant la transformation. En ce sens, le modèle mobilise implicitement les capacités dynamiques et les systèmes sociotechniques, en soulignant que le succès de la transformation dépend de l'alignement technologique, culture organisationnelle, compétence et gouvernance. Le modèle prend en compte la durée de vie limitée des mines, ce qui implique la nécessité de réévaluer le portefeuille en cas d'extension ou de changement de contexte. Cette dynamique requiert des capacités organisationnelles agiles permettant d'adapter les priorités, de réallouer les ressources et de maintenir l'alignement stratégique. Cette approche permet de prioriser les initiatives à intégrer immédiatement et de mettre de côté celles dont l'adoption est différée en fonction des contraintes d'investissement, du CAPEX, de l'OPEX et des ressources, nécessitant un degré de maturité des pratiques de gouvernance et de gestion de portefeuille. Enfin, le modèle incite les compagnies minières à examiner non seulement les initiatives technologiques, mais aussi les processus et méthodes de travail comme leviers de création de valeur. Sa mise en œuvre nécessite un engagement organisationnel soutenu, un alignement clair des rôles et responsabilités entre les niveaux corporatifs et opérationnels, ainsi qu'une capacité à accompagner les équipes dans le changement, afin d'adapter les initiatives aux besoins réels de la mine et de maximiser leur impact opérationnel.

Cette recherche incite également les industriels à accorder davantage d'attention à des thématiques souvent négligées, telles que la durabilité, la transformation du travail et l'intégration humaine des technologies. Le concept de Mine Intelligente est centré sur l'humain. Même dans un futur de plus en plus automatisé, les résultats soulignent que l'humain demeure indispensable tant que les systèmes autonomes ne peuvent pas remplacer la maintenance et la supervision sur le terrain. Dans les entreprises minières, la technologie et l'optimisation des processus sont souvent prioritaires, alors que les enjeux environnementaux, pourtant régulés et de grande importance, sont souvent relégués. Ceci illustre une hiérarchisation des priorités qui peut laisser certains aspects critiques en suspens. Les initiatives qui ne sont pas liées directement à la production, mais à la santé, la sécurité et l'environnement, qui sont des critères qualitatifs, apparaissent plus bas dans l'échelle des priorités. Enfin, la gestion de portefeuille de projets de TN restant un processus dynamique, la

tension entre la vision de la maison-mère et la réalité opérationnelle sur le site peut générer de la résistance au changement, ainsi que des craintes liées aux nouvelles technologies, susceptibles de modifier les pratiques établies et de remplacer certaines tâches, d'où l'importance d'intégrer une approche ascendante.

De manière plus large, contrairement à d'autres secteurs manufacturiers, où la notion d'usine intelligente est certes largement mobilisée, mais demeure fortement hétérogène en raison de la diversité des produits, des procédés et des contextes industriels, la Mine Intelligente bénéficie désormais d'une vision clarifiée et contextualisée. Les concepts d'usine intelligente, d'agroalimentaire 4.0 et de construction 4.0 partagent l'objectif commun d'intégrer les technologies de l'Industrie 4.0, leurs finalités, leurs contraintes et leurs chemins de transformation différents. Alors que la littérature sur l'industrie 4.0 reste abondante, mais fragmentée (Francisco da Silva et al., 2022), la Vision de la Mine Intelligente réduit cette ambiguïté dans le contexte minier. Dans le cas des mines souterraines, l'enjeu principal ne réside plus dans le « quoi », mais dans le « comment ». À cet égard, le modèle proposé structure le cheminement permettant de passer de la vision à la mise en œuvre, ouvrant la voie aux autres secteurs confrontés à des enjeux similaires.

Enfin, la méthodologie proposée pourrait être transposée à d'autres contextes industriels présentant des cycles de production temporaires ou évolutifs, comme la construction, les grands projets d'ingénierie, l'aéronautique ou la construction navale, où les décisions d'investissement ou de construction doivent concilier les contraintes de temps, d'environnement et de rentabilité. Les nouvelles activités identifiées et développées pour le secteur minier pourraient apporter une valeur ajoutée à ces autres secteurs, qui, bien que soumis à des contraintes différentes, partagent des environnements opérationnels comparables. Par exemple, dans la foresterie ou dans les grands travaux, tels que les barrages hydroélectriques, la question se pose de savoir si l'investissement dans certaines technologies est pertinent au regard des délais et des priorités opérationnelles.

D'un autre côté, les mines à ciel ouvert présentent des contraintes opérationnelles moins strictes que les mines souterraines, ce qui suggère que la méthodologie développée pour les exploitations souterraines pourrait être adaptée aux mines de surface. Certains éléments spécifiques, tels que la planification de l'expansion et la gestion des délais, devront toutefois être ajustés, car les horizons temporels et les contraintes varient. Néanmoins, de nombreuses caractéristiques fondamentales (la

gestion des interrelations entre les projets, la priorisation des initiatives, l'intégration des technologies, la gestion du changement) restent similaires et permettent de transposer les principes de la méthodologie aux particularités propres aux mines à ciel ouvert.

7.2 Limites

Notre recherche se concentre spécifiquement sur les opérations d'extraction des mines souterraines, en excluant les mines de charbon, les exploitations minières en longue taille, les mines d'exploitation in situ utilisant la dissolution et les mines à ciel ouvert. Ce choix méthodologique s'explique d'une part par l'abondance de la littérature dédiée aux mines de charbon, qui aurait considérablement élargi le champ d'analyse, et d'autre part par la spécificité de ces exploitations. En effet, les mines de charbon, généralement exploitées en longue taille, présentent déjà un haut degré d'automatisation en raison de la nature continue de leur procédé, tandis que les mines d'exploitation in situ utilisant la dissolution ne nécessitent pas de présence humaine souterraine et présentent d'autres défis opérationnels. Pour les mines à ciel ouvert, les défis opérationnels et technologiques sont moins complexes, d'où notre décision de ne pas les inclure dans notre recherche.

Le concept de la Mine Intelligente présenté dans cette thèse a été clarifié seulement pour les opérations d'extraction souterraines et ne s'étend pas à l'ensemble de la chaîne de valeur minière, notamment les activités de surface et les usines de traitement du minerai. Le modèle de GPP a été élaboré à partir des retours d'expérience de dix experts du secteur minier canadien, ce qui constitue une limite quant à la diversité des perspectives recueillies. De plus, la recherche a été confrontée à plusieurs enjeux liés à la collecte de données par questionnaire et entretiens, en raison du contexte industriel et du profil des participants. En raison de contraintes de disponibilité, des experts ayant répondu aux questionnaires n'ont pas pu participer à l'entretien. Cette situation a limité la possibilité d'inclure les réponses dans notre analyse. La longueur et la complexité du questionnaire constituent également une limite. La nécessité de couvrir un large éventail de pratiques de GPP et de dimensions liées à la TN a pu influencer le taux de complétion et le niveau de détail des réponses fournies. L'autre facteur est la confidentialité sur un sujet critique comme la TN des mines dans un secteur très compétitif, ce qui a aussi limité la participation de certaines minières. Enfin, la collecte de données a été réalisée sur une période limitée, avec un accès restreint aux experts, reflétant les contraintes habituelles de la recherche en milieu industriel. Ces obstacles soulignent l'importance

pour de futures recherches de prévoir des questionnaires plus courts, avec des phases de collecte étalées dans le temps et des mécanismes incitatifs favorisant la participation.

Par ailleurs, son application s'est concentrée sur un seul cas, une mine de roche dure exploitée par un procédé par lots, et les initiatives identifiées concernent les opérations d'extraction, excluant les dimensions plus larges de la chaîne de valeur. Seules les activités liées à la création du portefeuille de projets ont été validées, laissant les activités liées à la gestion du changement, du risque, des parties prenantes et de la communication uniquement validées par les retours d'experts.

7.3 Perspectives de recherche

Pour approfondir cette recherche, l'intégration des travaux portant sur les mines de charbon permettrait d'enrichir et de nuancer le cadre conceptuel de la Mine Intelligente. De même, l'analyse pourrait être élargie aux mines à ciel ouvert, afin de comparer les dynamiques d'intégration technologique selon les contextes d'exploitation. Le cadre conceptuel de la Mine Intelligente pourrait être élargi pour englober l'ensemble des opérations de la chaîne de valeur minière.

Le modèle proposé gagnerait à être testé dans d'autres contextes miniers, notamment dans des mines souterraines de roche molle, telles que les mines de potasse, où les procédés d'extraction en continu présentent d'autres défis. Le modèle pourrait être consolidé en mobilisant davantage d'experts, en validant les activités de fonctions supports et en intégrant un éventail plus large d'initiatives. Enfin, le modèle pourrait être validé sur un horizon temporel plus long, permettant d'évaluer son applicabilité dès les premières phases de création d'un portefeuille de projets et de suivre sa mise en œuvre incluant les activités de gestion du risque, du changement, des parties prenantes et de la communication.

CHAPITRE 8 CONCLUSION

Cette thèse visait à **améliorer la gestion de GPP pour guider la TN des mines souterraines,** en comblant les lacunes identifiées dans la revue de la littérature et en s'appuyant sur la réalité opérationnelle du terrain. Cette thèse répond aux sous-objectifs en proposant un cadre conceptuel clarifiant le concept de Mine Intelligente appliqué aux opérations d'extraction souterraines, en faisant état des pratiques actuelles de TN dans le secteur minier souterrain canadien, ainsi qu'en développant un modèle de GPP de TN répondant aux défis de l'industrie minière. L'objectif général de cette thèse est atteint dans la mesure où le modèle fournit une approche structurée de GPP pour guider la TN des mines souterraines.

Sur le plan scientifique, ce travail apporte une contribution significative en clarifiant le concept de la Mine Intelligente, dont la définition demeurait jusqu'à présent fragmentée et ambiguë. La recherche met en évidence les divergences et convergences entre la vision des praticiens et les recherches universitaires, offrant une base pour orienter les recherches universitaires et les praticiens vers la Mine Intelligente. Cette recherche met en lumière les spécificités techniques, humaines et organisationnelles propres au secteur minier. En mobilisant les apports théoriques de l'Industrie 4.0, tout en les adaptant au contexte spécifique des opérations minières souterraines, cette thèse propose un ensemble d'activités de GPP regroupant les meilleures pratiques, incluant la gestion du risque, du changement, des parties prenantes et de la communication tout au long du processus. Le modèle inclut également une visualisation des interdépendances entre les initiatives.

Sur le plan pratique, le modèle développé constitue un outil d'aide à la décision permettant de concevoir un portefeuille de projets de TN, cohérent et aligné sur la stratégie d'entreprise et la vision de la Mine Intelligente. Il intègre les dimensions clés de la gestion contemporaine de projets, notamment la gestion du risque, du changement, des parties prenantes et de la communication, offrant une vision globale et dynamique du processus de transformation. Le modèle met de l'avant une approche ascendante et descendante, favorisant la participation de l'ensemble des parties prenantes et une meilleure identification des initiatives. L'implantation effective du modèle repose sur une culture favorable au changement et à l'apprentissage, un leadership capable de porter la vision de la TN au-delà des projets technologiques, et une direction présente qui soutient la transformation. Sa mise en œuvre nécessite également un engagement organisationnel soutenu, un

alignement clair des rôles et responsabilités entre les niveaux corporatifs et opérationnels, ainsi qu'une capacité à accompagner les équipes dans le changement.

Les résultats montrent que la transition vers la Mine Intelligente dépasse la seule dimension technologique, en s'inscrivant dans une logique de transformation organisationnelle où l'humain occupe une place centrale. Cette dimension, souvent sous-estimée, constitue un levier fondamental de réussite pour toute stratégie de TN dans le secteur minier.

Sur le plan méthodologique, le modèle a été appliqué et validé dans le cadre d'un cas portant sur une mine souterraine de roche dure, démontrant sa pertinence et sa faisabilité opérationnelle. Toutefois, son application à d'autres contextes miniers permettrait d'en évaluer la transférabilité. Par ailleurs, cette approche pourrait être adaptée à d'autres secteurs industriels caractérisés par des cycles de production complexes ou temporaires, tels que les grands travaux d'ingénierie.

Pour conclure, cette recherche contribue à améliorer la TN du secteur minier en proposant un cadre conceptuel de la Mine Intelligente et un modèle de GPP adapté au secteur minier. Elle ouvre des perspectives de recherche, notamment l'élargissement du cadre conceptuel de la Mine Intelligente à l'ensemble de la chaîne de valeur et l'applicabilité à d'autres contextes miniers, voire aux secteurs industriels.

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