UNIVERSITÉ DU QUÉBEC

THÈSE PRÉSENTÉE À
L'UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES
COMME EXIGENCE PARTIELLE
DU DOCTORAT EN INGÉNIERIE
OFFERT EN EXTENSION
EN VERTU D'UN PROTOCOLE D'ENTENTE
AVEC L'UNIVERSITÉ DU QUÉBEC À CHICOUTIMI

PAR
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PRISE DE DÉCISION EN GESTION DES ACTIFS INDUSTRIELS EN TENANT COMPTE DES RISQUES

JUIN 2018

UNIVERSITÉ DU QUÉBEC

Doctorat en INGÉNIERIE (Ph.D.)

Programme offert par l'Université du Québec à Chicoutimi (UAQC)

en extension avec

l'Université du Québec à Trois-Rivières

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DÉDICACE

À ma famille.

REMERCIEMENTS

La décision de poursuivre des études dans le cadre d'un deuxième doctorat, dans un autre domaine, n'était pas ordinaire. Il a fallu avoir du courage, de la détermination, mais surtout de l'amour pour la science pour se lancer dans ce projet. Toutefois, je l'ai fait sans hésitation. Le sujet était trop d'actualité et intéressant pour ne pas l'aborder.

Bien que le résultat de ce projet est le fruit d'un travail individuel, il a impliqué de nombreuses personnes et a demandé des sacrifices tout au long des années de recherche.

Je ne peux trouver de mots suffisamment justes pour remercier mon épouse Nermina qui a cru en moi pour une autre fois, un autre doctorat. Elle a fait preuve d'une compréhension et d'une patience exceptionnelles et m'a encouragé tout au long de ce cheminement. Ô combien de fois nous nous sommes privés de sorties ou d'activités pour que je puisse travailler sur ma recherche.

Je remercie aussi mes enfants, Jasna et Zlatko, qui avaient confiance que leur papa réussirait une autre fois. Ils m'ont aussi donné la force nécessaire pour persévérer.

Je tiens également à remercier très profondément mon directeur de recherche, le professeur Georges Abdul-Nour, pour son soutien inconditionnel et ses conseils judicieux tout au long de ce travail de recherche. Il a cru en moi et était prêt à se lancer dans cette entreprise dès le moment où je lui ai proposé ce projet.

Les coauteurs des articles, soient le professeur Nemanja Popovic, avec lequel j'ai commencé ma carrière scientifique il y a plus que 35 ans à l'Université Tuzla en génie des mines, Jean-François Boudreau, Mohamed Gaha et Christian Langheit, chercheurs à l'IREQ, et Michel Bourgeois, ingénieur à Hydro-Québec Distribution, méritent toute ma reconnaissance pour leur participation aux travaux communs. Leurs connaissances et leur expertise ont contribué à réaliser un travail de haute qualité.

À la fin, un gros merci à tous mes amis et collègues qui m'ont encouragé tout au long de ce travail (malgré quelques blagues à mon égard concernant ce projet). Sans leur soutien sincère, ce travail aurait été beaucoup plus difficile.

RÉSUMÉ

Les entreprises modernes sont des organisations complexes par leur structure organisationnelle, opérationnelle et le type de gestion. Elles évoluent dans un environnement opérationnel et d'affaires complexe confronté à des incertitudes significatives liées à des facteurs naturels, techniques, technologiques, commerciaux, organisationnels, économiques, financiers, politiques, etc. affectant leur gestion et leurs opérations. L'environnement opérationnel et d'affaires complexe génère également de nouveaux types de risques relativement inconnus il y a quelques décennies (par exemple, la cyber sécurité). Un tel environnement crée aussi des conditions favorables à l'émergence d'événements extrêmes et rares susceptibles de perturber sérieusement la performance des entreprises à court et à long terme. Les pratiques et analyses actuelles négligent généralement de prendre en compte ces types de risques. Les intrants des experts techniques, des planificateurs stratégiques ou des gestionnaires pourraient s'avérer insuffisants ou trop circonscrits pour tenir compte adéquatement de la complexité dans un environnement complexe en constante évolution et à peine prévisible. Cette situation est généralement causée par un manque de connaissances concernant le type et l'envergure des incertitudes, la nature des interconnexions entre les facteurs d'influence, le niveau de complexité, ainsi que notre faible capacité à prédire les événements futurs.

La mondialisation et la forte concurrence font partie de l'environnement opérationnel et d'affaires contemporain typique. La capacité des entreprises à créer et à mettre en œuvre des concepts innovants est déterminante pour répondre aux exigences en matière de compétitivité et pour assurer leur fonctionnement durable et leur développement futur. Au cours des deux dernières décennies, la gestion des actifs (GDA) est devenue une approche répandue parmi les organisations à succès

en tant que concept efficace permettant de générer de la valeur à partir des actifs et d'assurer la durabilité de l'entreprise et de ses opérations.

La prise de décision est essentielle dans la GDA. Elle est influencée par différents facteurs (stratégiques, techniques/technologiques, économiques, organisationnels, réglementaires/juridiques, sécurité, marchés, concurrence, etc.). La prise de décision adéquate doit tenir compte de la complexité et des facteurs d'influence pertinents pour équilibrer les risques, les opportunités, la performance, les coûts et les bénéfices.

Malgré les progrès récents afin de mieux comprendre les défis et développer de nouvelles approches de modélisation, les programmes de gestion d'actifs n'ont pas toujours réussi à éviter des pertes coûteuses ou même des faillites d'organisations causées par divers facteurs économiques ou non techniques discutés ci-dessus qui n'ont pas été compris ou pris en compte adéquatement dans le processus de prise de décision. La pratique montre également qu'une définition inadéquate des rôles et des responsabilités et le manque de communication contribuent également à l'inefficacité de la GDA et de son processus de prise de décision.

Le but du présent travail de recherche est de développer une méthodologie de prise de décision en gestion des actifs en tenant compte de la complexité de l'environnement d'affaires et opérationnel.

Dans la présente recherche, une méthodologie intégrale de prise de décision en GDA en tenant compte des risques (*Risk-Informed Decision-Making – RIDM*) en trois étapes a été développée. La GDA est considérée comme un système de systèmes complexes adaptatifs. La recherche a également développé la méthode de caractérisation et d'intégration des risques d'événements extrêmes et rares dans le

processus décisionnel par l'application de la science de la complexité et de la théorie des valeurs extrêmes.

La méthodologie est appliquée et validée avec succès dans le cas de trois industries : minière, nucléaire et une utilité électrique. Elle démontre le potentiel d'une application répandue dans diverses industries lors d'un développement futur.

Mots clés : gestion des actifs, système de systèmes complexes adaptatifs, incertitudes, prise de décision en tenant compte des risques, événements extrêmes et rares, risques.

ABSTRACT

Modern companies are complex organizations as per their organizational, management and operational structure. They also operate in a complex business and operational environment facing significant uncertainties related to natural, technical, technological, market, organizational, economic, financial, political, etc. influential factors affecting their business, management and operations. The complex business and operational environment also generates new types of risks that were relatively unknown just a few decades ago (e.g. cyber security) and creates favorable conditions for the emerging of extreme and rare events that may seriously disrupt the short and long-term performance of enterprises. Current practices and analyses generally neglect taking into account those risks. Advice and input from technical experts, strategic planners or knowledgeable managers may be insufficient or too narrowly focused to adequately manage the complexity of the systems and structures in a constantly changing and barely predictable environment. It is generally due to a lack of knowledge regarding the type and range of uncertainties, the nature of interconnections, the level of complexity, as well as our low ability to predict future events.

Globalization and strong competition are part of a typical contemporary operational and business environment. The ability of enterprises to create and implement innovative concepts is decisive to meet the demands regarding competitiveness, and to ensure their sustainable operations and further development. During the last two decades, Asset Management (AsM) has become prevalent approach among successful organizations as an effective concept allowing delivering value from assets and ensuring the sustainability of the business and its operations.

The decision-making is essential in AsM. It is influenced by various factors (strategic, technical/technological, economic, organizational, regulatory/legal, safety, markets, competition, etc.). A sound decision-making ought to take into account relevant factors for balancing risks, opportunities, performance, costs, and benefits.

Despite recent progress in better understanding challenges and developing new modeling approaches, asset management programs have not always been successful in avoiding costly losses or even bankruptcies of organizations caused by various economic or non-technical factors discussed above that have not been either understood or adequately considered and addressed in the decision-making process. Practice also shows that inadequate definition of roles and responsibilities and lack of communication also contribute to the inefficiency of the AsM and its decision-making process.

The goal of this thesis is to develop an integral asset management decision-making methodology taking into account the complexity of the business and operational environment.

A holistic three-step Risk-Informed Decision-Making (RIDM) methodology tailored for AsM considering it as a Complex Adaptive System of Systems (CASoS) has been developed in this research work. The research has also developed the method regarding the integration of risks of extreme and rare events into the RIDM through the application of the complexity science and the extreme value theory.

The methodology is successfully applied and validated in the case of three industries: mining, nuclear and electrical utilities. It demonstrates its potential of a large application across various industries through a further development.

Keywords: asset management, complex adaptive system of systems, uncertainties, risk-informed decision-making, extreme and rare events, risks.

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ADP	Analytic Deliberative Decision Making Process
AHP	Analytic hierarchy process
AIChE	American Institute of Chemical Engineers (AIChE)
AIEA	Agence internationale de l'énergie atomique
AIG	American International Group Inc.
ALARA	As low as reasonably achievable
ALARP	As low as reasonably practial
ASAI	Average Service Availability Index
AsM	Asset Management
ASME	American Society of Mechanical Engineers
ATR	Allowable time-at-risk
BCM	Business Continuity Management
BOP	Balance of Plant
BP	Bruce Power
BSI	British Standards Institution
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CANDU	Canada Deuterium Uranium
CAS	Complex Adaptive System
CASoS	Complex Adaptive System of Systems
CBA	Cost-Benefit Analysis
CCSN	Commission canadienne de sûreté nucléaire
CHI	Client heures interrompues (Client Hours of Interruption)
CIGRÉ	Conseil international des grands réseaux électriques
CNSC	Canadian Nuclear Safety Commission
COG	Candu Owners Group
CSG	Complex System Governance

DBA	Design Basis Accident
E&RE	Extreme and rare events
ECC	Emergency Core Cooling
ECCS	Emergency Core Cooling System
EDF	Électricité de France
EFPH	Equivalent Full Power Hours
EPRI	Electrical Power Research Institute
ERM	Enterprise Risk Management
ETA	Event Tree Analysis
FAA	Federal Aviation Administration
FMECA	Failure Mode Effects and Criticality Analysis
FTA	Fault Tree Analysis
GDA	Gestion des actifs
HAZOP	Hazard and Operabilty Study
HQ	Hydro-Québec
HQD	Hydro-Québec Distribution
HSE	Health and Safety Executive (UK)
IAEA	International Atomic Energy Agency
INPO	Institute of Nuclear Power Operations
IREQ	Institut de recherche d'Hydro-Québec
ISO	International Standard Organization
KPI	Key Performance Indicator
LCM	Life Cycle Management
LLOCA	Large Loss of Cooling Accident
LOPA	Layers of Protection Analysis
LRF	Large Release Frequency
LTCM	Long Term Capital Management (hedge fund)
MADM	Multi-attribute decision-making
MAUT	Multi-attribute utility theory

MBCO	Minimum business continuity objective
MCDM	Multi-criterion decision-making
MCHI	Millions de client heures interrompues (Millions of Client Hours of Interruption)
MIT	Massachusetts Institute of Technology
MTPD	Maximum tolerable period of disruption
NAM	Nuclear Asset Management
NASA	National Aeronautics and Space Administration
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NPV	Net Present Value
NRC	U.S. Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
O&M	Operation and maintenance
ODÉMA	Outil décisionnel économique pour la maintenance
OPG	Ontario Power Generation
OPP	Operating Policies and Principles
OS&H	Occupational safety and health
PAS	Publicly Available Specification
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
RAM	Reliability, Availability, Maintainability
RD	Regulatory Document
RIAM	Risk-Informed Asset Management
RIDM	Risk-Informed Decision-Making
SAIDI	System Average Interruption Duration Index
SCDF	Severe Core Damage Frequency
SERI	Smarter Energy Research Institute
SME	Subject Matter Expert

SSC	Systems, structures and components
SST	Santé et sécurité au travail
STAMP	Systems-theoretic accident model and processes
UK	United Kingdom
USA	United States of America

AVANT-PROPOS

Le présent travail de recherche représente la formalisation de mes nombreuses années de travail de recherche mais aussi d'ingénierie dans le domaine de la fiabilité, de l'optimisation de maintenance, de la gestion des actifs et d'analyse des risques dans diverses industries : minière, nucléaire, production, transport et distribution d'électricité. La combinaison des éléments théoriques et pratiques dans ce travail offre un résultat qui pourrait intéresser des chercheurs, gestionnaires d'entreprise et ingénieurs.

Nous avons privilégié le format de thèse par articles de revues intégrés dans le corps du document. Les liens entre les articles (publiés ou soumis), présentés sous forme de chapitres, ont été clarifiés de manière à démontrer la continuité des travaux et garantir une fluidité dans la lecture.

Les pages préliminaires, l'introduction, les trois premiers chapitres, la conclusion générale et les recommandations sont rédigés en français. Les chapitres consacrés aux résultats sont constitués d'articles de revues scientifiques publiés en anglais. Nous sommes conscients de la problématique de l'utilisation de deux langues dans un même document. De plus, une thèse composée de plusieurs articles entraîne aussi une dispersion des informations. Nous considérons malgré tout que la diffusion des résultats par le biais d'articles de revues est une excellente opportunité de partager ces résultats et d'en discuter avec une grande partie de la communauté scientifique.

Ainsi, les résultats de cette recherche ont fait l'objet de plusieurs publications. Leur diffusion a principalement été réalisée par trois articles de revues avec comité de lecture. Le travail de recherche a également été complété par des conférences arbitrées nationales et internationales. De plus, plusieurs autres articles de revues et des conférences indirectement liés au sujet de recherche ont aussi été publiés pendant la durée des études. Ils sont mentionnés dans le chapitre sur la méthodologie.

CHAPITRE 1 – INTRODUCTION

1.1 Mise en contexte

Les entreprises contemporaines font face à la concurrence accrue à l'échelle nationale et internationale. Elles possèdent généralement des systèmes, structures, équipements et composants (dorénavant, actifs) intégrés dans des installations technologiques complexes. De plus, les entreprises opèrent dans un environnement commercial, naturel, légal, technologique, technique, organisationnel, financier et de marché complexe[1] (dorénavant, l'environnement d'affaires et opérationnel) caractérisé par des incertitudes aléatoires et épistémiques significatives[2].

La capacité des organisations à réaliser des concepts novateurs sera décisive pour répondre aux exigences accrues en matière de compétitivité. Dans ce contexte, elles ont besoin de méthodologies, d'outils et de processus appropriés pour rationaliser et optimiser leurs pratiques décisionnelles afin d'améliorer leur compétitivité et même leur survie sur le marché. La plupart des entreprises font face à ce fardeau en utilisant divers modèles et concepts qui aident à réduire les spéculations et incertitudes. Une des disciplines récentes qui a été développée pour y faire face est connue sous le nom de gestion des actifs (GDA).

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1 Ici, le terme « complexe » fait référence aux « systèmes complexes », qui se définissent comme « un ensemble constitué d'un grand nombre d'entités en interaction qui empêchent l'observateur de prévoir ou modéliser avec précision sa rétroaction, son comportement ou son évolution. Le comportement d'un système complexe ne peut être facilement déduit à partir des caractéristiques et comportement des différentes parties ou variables qui le composent créant ainsi un comportement émergent (OECD, 2011).

2 Le terme « aléatoire » est associé à la variabilité naturelle et aléatoire d'un phénomène en étude. Les incertitudes aléatoires demeurent même lorsque la probabilité d'un événement est connue avec certitude. Le terme « épistémique » est lié à un manque de données ou nature incomplète des connaissances ou l'imprécision d'une information. Les incertitudes épistémiques font référence à une connaissance de base imparfaite (Kumamoto, 2007; Paté-Cornell and Cox, 2014; US NRC, 2013).

La GDA est définie comme un ensemble d'actions et de pratiques systématiques et coordonnées permettant à une organisation de gérer ses actifs et ses systèmes d'actifs de manière optimale et durable, incluant leur performance, risques et coûts associés tout au long de leur cycle de vie (BSi, 2008).

La nouvelle norme internationale ISO 55000 (ISO, 2014a,b,c) définit la GDA comme une activité coordonnée d'une organisation pour réaliser de la valeur à partir d'actifs. La valeur (matérielle ou immatérielle, financière ou non financière) doit refléter les attentes des parties prenantes en fonction des objectifs stratégiques de l'organisation. Il existe plusieurs autres définitions de la gestion des actifs qui sont plus ou moins basées sur l'idée similaire.

Ces deux définitions sont plutôt génériques et peuvent s'appliquer à tout type et toute taille d'organisation. Selon la compréhension commune, la GDA ne doit pas se concentrer sur « faire des choses pour les actifs » mais plutôt à les utiliser de façon optimale pour réaliser le meilleur rapport qualité-coût et atteindre ses objectifs stratégiques (The Institute of Asset Management, 2015a,b; Hastings, 2010).

Dans la pratique, la GDA est parfois vue comme étant essentiellement liée à la maintenance et à la fiabilité des actifs (The Institute of Asset Management, 2015a; ISO, 2017). Cependant, elle couvre beaucoup plus que ces deux domaines. Le comité technique ISO pour les systèmes de gestion des actifs, ISO/TC251, clarifie la différence entre les concepts de *gestion des actifs* et de *gérer des actifs* (*Asset Management* vs *Managing Assets*) (ISO, 2017). Il souligne qu'au fil des années, des personnes, des organisations et des entreprises ont développé des disciplines entières pour aider à définir les meilleures façons de prendre soin des actifs tout au long de leur vie utile. À ce titre, elles *gèrent des actifs* depuis très longtemps. Avec l'introduction du concept formel de la *gestion des actifs* il y a environ 20 ans, des approches structurées ont été développées pour garantir que ces activités de soin des actifs valorisent l'organisation et ne se contentent pas de juste promouvoir le meilleur entretien de ceux-ci.

Dans ce contexte, il est primordial d'assurer une aptitude au service et une pérennité optimale des actifs pour pouvoir réaliser des plans stratégiques des entreprises. Cette tâche implique une multitude d'activités et problématiques interdépendantes dont les interrelations sont difficiles à modéliser et à maîtriser dans le fin détail et à optimiser sur le plan opérationnel[3]. En effet, les actifs incluent de plus en plus d'éléments technologiques modernes et complexes (EPRI, 2004e; Zio, 2016). Leurs caractéristiques deviennent de plus en plus difficiles à intégrer dans le cadre de la planification et de l'optimisation de leur durée de vie. Il devient donc essentiel de distinguer la durée de vie et la durée d'utilisation des actifs. Cette frontière est de plus en plus mince, surtout dans le cas des actifs de télécommunication et des technologies de l'information. Le risque d'incompatibilité logicielle ou matérielle entre les générations d'équipements est élevé en raison de l'accélération de l'évolution technologique sur le marché. Une saine gestion de ces actifs constitue un avantage concurrentiel stratégique pour une entreprise. Ce sujet inclut aussi la collecte et le traitement des données nécessaires ainsi que la mise en place de programmes d'inspection et de maintenance optimaux qui sont essentiels pour assurer l'aptitude au service des actifs. L'optimisation de la durée de vie des actifs demande ainsi plus que jamais des équipes multidisciplinaires et des modèles d'optimisation novateurs, intégrateurs et efficaces. Ces modèles doivent être dynamiques, flexibles et capables de modéliser et d'optimiser des systèmes complexes et interconnectés qui tiennent compte des risques et incertitudes significatifs (Komljenovic, Gaha, Abdul-Nour, Langheit et Bourgeois, 2016; Reinert, Rollenhagen, Pietikäinen et Heikkilä, 2015; Zio, 2016).

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3 Cette tâche comprend la sélection, l'acquisition, la gestion, l'opération, la fiabilité, la maintenance, la maîtrise du vieillissement et de la désuétude ainsi que le remplacement des actifs.

Pour réussir, la gestion des actifs doit être intégrale, systématique, systémique, tenir compte des risques et mise en œuvre avec un engagement ferme de la direction et soutenue par des employés compétents. La GDA doit être intégrale dans la mesure où tous les éléments de son cadre référentiel doivent être couverts. L'excellence dans un domaine ne compense pas les écarts dans d'autres domaines. La gestion des actifs doit permettre de balancer les coûts, bénéfices, risques, opportunités et la performance. Outre les actifs physiques, sa conception devrait prendre en compte un contexte plus large avec d'autres types d'actifs, notamment les actifs humains, d'information, intangibles et financiers (The Institute of Asset Management, 2015a; Jardine et Tsang, 2013).

La gestion des actifs est une discipline relativement jeune et elle est toujours en cours de développement (The Institute of Asset Management, 2015a). Bien que de nombreux travaux de recherche aient été réalisés ou sont en cours de réalisation dans ce domaine, d'autres améliorations sont encore nécessaires pour inclure des sujets qui ne sont pas systématiquement pris en compte ou des méthodes scientifiques qui ne sont pas entièrement au point. Cette problématique concerne également l'impact d'événements extrêmes et rares, généralement disruptifs (naturels, financiers, commerciaux, humains, etc.) sur la GDA. Ils ont la capacité de complétement bouleverser la planification stratégique d'une organisation incluant la gestion des actifs. Les travaux actuels dans ce domaine semblent négliger cet aspect. Toutefois, les expériences récentes montrent qu'il est important de prendre en compte de tels événements pour que la GDA soit efficace.

1.2 Problématique de la recherche

Les enjeux et les défis des organisations modernes sont complexes et multiples. Leur caractère est souvent imprévisible dans un environnement d'affaires et opérationnel complexe. Les solutions devraient intégrer les connaissances de plusieurs disciplines en ingénierie et au-delà, tout en gérant des risques et des incertitudes significatifs (Allen, Azarm et Simpson, 2011; Reinert *et al.*, 2015).

Les récents travaux dans le domaine de la gestion des actifs ont apporté plusieurs contributions importantes. Les industries à forte intensité de capital et les industries à risque (nucléaire, pétrochimie, aviation, transports, minière, production, transport et distribution d'électricité, etc.) ont élaboré des approches spécifiques à cet égard.

Dans le domaine de l'ingénierie, il y a des avancements significatifs de connaissances aidant une bonne compréhension et la modélisation des phénomènes physiques liés à la gestion des actifs (défaillance d'équipements, physique de dégradation, fiabilité des systèmes techniques, problèmes du vieillissement et d'obsolescence, optimisation de la maintenance, diagnostic et pronostic, etc.). Les enjeux de la collecte de données, de leur traitement et de leur utilisation adéquate en GDA sont fréquemment présents mais les nouvelles technologies (TI) et l'analytique aident à les maîtriser.

Malgré ces progrès, des programmes de gestion des actifs n'ont pas toujours réussi à faire éviter des pertes coûteuses ou même des faillites d'organisations causées par divers facteurs économiques ou non techniques discutés ci-dessus qui n'ont pas été soit compris ou considérés de façon adéquate dans le processus décisionnel. La pratique montre également qu'une définition inadéquate des rôles et des responsabilités ainsi qu'un manque de communication contribuent aussi à l'inefficience de la GDA et de son processus décisionnel. De telles situations apportent confusion, désalignement, gaspillage de ressources et pertes potentiellement coûteuses, réduisant la performance globale de l'entreprise et menaçant parfois même sa survie.

L'un des principaux problèmes est lié à un manque de compréhension de la complexité de l'environnement d'affaires opérationnel : les entreprises modernes fonctionnent dans un contexte hautement complexe causé par des facteurs externes et internes dont il a été question précédemment. En outre, elles réalisent leurs activités dans un monde étroitement interconnecté à de nombreux niveaux et de différentes manières. Les entreprises contemporaines sont aussi complexes par leur structure et la gestion interne ainsi que la technologie déployée.

Généralement, cette complexité et cette interconnectivité ne seraient pas adéquatement modélisées et prises en compte. Au lieu de cela, les approches traditionnelles (classiques) dans la planification et la gestion sont utilisées (Reinert *et al.*, 2015; Stacey and Mowles, 2016). Elles ne sont pas entièrement appropriées dans un contexte d'affaires et opérationnel en constante évolution, complexe, dynamique et peu prévisible. Par conséquent, ces méthodes traditionnelles pourraient parfois fournir des résultats erronés.

Ainsi, les approches de la prise de décisions en GDA existantes peuvent être améliorées et complémentées afin d'assurer une intégration adéquate de tous les facteurs pertinents dans un processus décisionnel cohérent d'une organisation. Comme un système de gestion des actifs est principalement conçu pour soutenir la réalisation d'un plan stratégique organisationnel, d'autres facteurs doivent également être pris en compte. Ils incluent, mais ne sont pas limités à :

- la prise en compte et la modélisation adéquates de la complexité de l'environnement d'affaires et opérationnel en gestion des actifs et son processus décisionnel. Cette question inclut également le traitement approprié des incertitudes aléatoires et épistémiques. La planification et gestion des actifs d'une entreprise éprouvent parfois des difficultés en raison de la négligence, de l'incompréhension ou du traitement inadéquat de la complexité et des incertitudes;

- la considération des risques des événements extrêmes et rares (événements de faible probabilité/impact élevé qui peuvent être naturels, technologiques ou d'origine humaine)[4] : l'expérience montre que les humains ont tendance à être « aveugles » à de tels événements et de les négliger. Il est pratiquement impossible de calculer avec précision une très faible probabilité d'occurrence de tels événements en raison du manque de données fiables et pertinentes (statistiquement, ils sont souvent considérés comme des valeurs aberrantes et rejetés). Cependant, de tels événements se produisent. Ils ne doivent donc pas être négligés dans le monde moderne étroitement interconnecté. Cette problématique inclut également la contagion et les effets de cascade des événements qui sont souvent sous-estimés. Ces événements se produisent principalement dans des systèmes et environnements complexes. Ils peuvent entraîner des conséquences graves, systémiques et indésirables pour une organisation ou même compromettre sa survie. Toutefois, ils peuvent aussi créer des opportunités pour l'entreprise;
- la prise en compte des critères de décision intangibles ou non quantifiables tels orientations stratégiques, changements organisationnels et de priorités, implications socio-économiques, contraintes sécurité et de cybersécurité,

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[4] Les événements extrêmes et rares comprennent, sans s'y limiter: les catastrophes naturelles, krach financiers et de marché, pandémies, défaillances majeures d'actifs critiques, accidents industriels majeurs, conflits de travail d'envergure, pénurie prolongée d'électricité et d'énergie, changements politiques majeurs, instabilité politique, attentats terroristes, changements radicaux d'un cadre réglementaire, traitement extrêmement négatif dans les médias créant un environnement d'affaires défavorable, poursuites judiciaires importantes, nouvelles technologies compétitives, défaut de paiement ou perte de clients importants, etc. Les combinaisons et coïncidences de plusieurs de ces événements pourraient aussi être appropriées pour les analyses.

Les plans de contingence pour gérer certains de ces événements et leurs combinaisons dans la GDA doivent être alignés sur le programme global de gestion des risques d'une organisation et sur les mesures d'urgence. En attendant, il convient de souligner que plusieurs de ces événements peuvent également créer des opportunités d'affaires pour une organisation et devraient être considérés et analysés en tant que tels.

changement technologique, contraintes opérationnelles ou liées à la santé et sécurité au travail (SST), aspects culturels, changements réglementaires, juridiques et politiques significatifs, contraintes associées à la protection de l'environnement, exigences du développement durable, etc. peuvent parfois avoir un rôle décisif dans la prise de décision en GDA par rapport aux facteurs économiques ou d'ingénierie. Ils ne sont pas toujours correctement considérés;

- l'intégration globale de la GDA aux processus de l'entreprise : liens horizontaux et verticaux plus efficaces entre les processus existants et la GDA en tenant compte des contraintes et particularités discutées ci-dessous sont nécessaires. Des nouveaux concepts et méthodes sont requis pour répondre à ces défis et enjeux. Cela ne signifie pas que l'on doit abandonner des méthodes traditionnelles. Il s'agit surtout de combiner harmonieusement celles-ci avec des nouvelles approches pour mieux décrire et modéliser la réalité moderne.

Il est donc nécessaire de développer une méthodologie efficace de prise de décisions en GDA dans le contexte de la complexité interne et externe de l'entreprise pour assurer sa robustesse, sa résilience et sa flexibilité afin de garantir l'opération et le fonctionnement efficaces à long terme. Ces caractéristiques sont aussi essentielles à leur performance économique ou à leur survie en ce qui concerne les perturbations majeures internes et externes susceptibles d'affecter leur environnement d'affaires et opérationnel au cours du cycle de vie d'un actif.

Considérant les éléments discutés ci-dessus, on se rend compte de l'importance de développer une méthodologie améliorée de prise de décision intégrée en GDA qui aidera à s'attaquer à ces problèmes et à surmonter les faiblesses existantes.

1.3 Questions, but et objectifs de la recherche

La problématique et les enjeux discutés dans les sections précédentes aident à définir les questions, but et objectifs de cette thèse. Dans le but de mieux orienter les travaux à la suite de la problématique identifiée, les questions de recherche suivantes ont été définies :

1. Comment tenir compte de la complexité croissante de l'environnement opérationnel et d'affaires en gestion des actifs?
2. Comment inclure les risques des événements extrêmes, rares et disruptifs dans la prise de décision en gestion des actifs et comment les quantifier?
3. Quelle est l'approche optimale pour supporter la prise de décisions en GDA dans le contexte de complexité?

Le but du présent travail de recherche est de développer une méthodologie intégrale de prise de décision en gestion des actifs en tenant compte de la complexité de l'environnement d'affaires et opérationnel.

Les objectifs de la recherche sont les suivants :

- intégrer de manière structurée, dans la méthodologie, tous les facteurs d'influence pertinents : quantitatifs, qualitatifs, organisationnels et intangibles, incluant les risques et incertitudes;
- développer l'approche pour identifier, caractériser et intégrer l'impact d'événements extrêmes, rares et disruptifs sur la performance globale de la gestion des actifs;
- élaborer la méthodologie pour qu'elle soit générique, adaptable et applicable à toutes les tailles et à tous les types d'entreprises;
- valider la méthodologie par des études de cas réels.

CHAPITRE 2 – REVUE DE LITTÉRATURE

La recherche proposée intègre plusieurs domaines d'expertise pertinents tels que les systèmes complexes et la théorie (science) de la complexité, la prise de décision en tenant compte des risques (*Risk-Informed Decision-Making – RIDM*), la gestion des actifs, le traitement des incertitudes en ingénierie et la prédiction d'événements extrêmes. La revue de la littérature ci-dessous résume les contributions importantes dans ces domaines liées au sujet de la recherche.

2.1 Systèmes complexes et la théorie (science) de la complexité

Un nouveau domaine interdisciplinaire appelé la science (ou la théorie) de la complexité a vu le jour et s'est développé au cours des dernières décennies. Elle cherche à comprendre, prédire et influencer les comportements de systèmes complexes. Dans ce mouvement, l'Institut Santa Fe a été créé au début des années 1980 dans le but de découvrir, comprendre et communiquer des principes fondamentaux communs dans des systèmes physiques, informationnels, biologiques et sociaux complexes (Santa Fe Institute for Complexity Science, 2018). Cette discipline traite des problèmes que la science traditionnelle a déjà eu du mal à résoudre tels que la non-linéarité et les discontinuités, l'auto-organisation, l'émergence, les modèles macroscopiques agrégés plutôt que les événements microscopiques causaux, résultats et prévisions probabilistes plutôt que déterministes, changements dynamiques au lieu de l'équilibre, etc. (OCDE, 2009, 2011).

La complexité peut sembler dommageable lorsqu'elle augmente la vulnérabilité des systèmes en raison d'interactions inattendues et de défaillances en cascade. Ces comportements sont le résultat d'une combinaison de connectivité forte et de couplage étroit entre les composants du système. En raison de leurs caractéristiques intrinsèques, les systèmes complexes ne peuvent pratiquement jamais atteindre un état d'équilibre complet.

L'expérience a montré que les solutions élaborées pour des systèmes et des problèmes simples ont souvent échoué lorsqu'elles ont été appliquées à des systèmes ou à des problèmes complexes. Dans de telles situations, les conceptions, les experts techniques, les plans stratégiques et les gestionnaires compétents peuvent s'avérer insuffisants pour gérer adéquatement des systèmes complexes dans un environnement en constante évolution et à peine prévisible (Glouberman et Zimmerman, 2002). Ces systèmes complexes composés d'unités interdépendantes en forme de réseaux s'adaptent continuellement aux environnements dynamiques. Ainsi, il arrive que les évaluations ou l'expertise des experts soient trop étroitement ciblées et des conséquences imprévues peuvent survenir lorsque de telles évaluations sont utilisées. Les méthodes et les outils de la science de la complexité sont nécessaires dans ces cas pour comprendre leur comportement et concevoir des politiques de gestion appropriées (Helbing, 2013; Pyne, Keating et Katina, 2016; OCDE, 2009, 2011). Cette question est également discutée par Smith, Binns et Tushman (2010) et Sornette (2009).

Homer-Dixon apporte un point de vue intéressant considérant que les systèmes complexes construits par l'homme dépendent d'une énergie de haute qualité. À mesure que l'on développe des institutions et des technologies plus complexes, l'exigence d'une énergie de haute qualité pour les construire et maintenir augmente (Homer-Dixon, 2011).

En fait, la science de la complexité aide à recadrer nos points de vue des systèmes complexes qui ne sont que partiellement compris par les analyses scientifiques traditionnelles. Ainsi, elle offre une vision alternative et complémentaire du monde réel. De nouvelles applications et utilisations de ce concept apparaissent continuellement. Cependant, il n'y a presque pas de travaux de recherche liés à l'application de systèmes complexes et à la science de la complexité pour une meilleure compréhension de la gestion des actifs.

Pour effectuer des analyses dans le domaine de la complexité, plusieurs méthodes et outils ont été développés et utilisés tels que les modèles multi-agents et les analyses dynamiques du réseau. Des techniques supplémentaires liées à la complexité sont également utilisées, bien que leur utilisation ne soit pas unique à la science de la complexité : forage de données, modélisation de scénarios, analyse de sensibilité, modélisation et simulation de systèmes dynamiques, intelligence artificielle, théorie des jeux, théorie de panarchie, etc. (Blouin, 2013; Efatmaneshin, Bradley et Ryan, 2016; Farmer, 2012; Helbing, 2013; Holling, 2001; Homer-Dixon, 2011; OCDE, 2009, 2011).

2.2 Prise de décisions en tenant compte des risques (RIDM)

La prise de décision en tenant compte des risques (*Risk-Informed Decision-Making – RIDM*)[5] est un concept qui a d'abord été élaboré au sein de l'industrie nucléaire. Le concept RIDM est apparu de la nécessité d'utiliser les résultats des études probabilistes de sûreté pour la prise de décision dans une approche intégrée tenant compte des risques. Dans cette approche, les résultats et les conclusions des évaluations déterministes et probabilistes sont combinés pour prendre des décisions sur les questions de sûreté (IAEA, 2011). L'utilisation croissante de l'outil d'évaluation probabiliste de sûreté a grandement contribué au développement du RIDM.

5 L'abréviation RIDM sera utilisée dorénavant pour signifier ce concept.

En 1999, le personnel de l'US NRC a présenté le livre blanc sur la réglementation tenant compte des risques et de la performance dans le secteur nucléaire aux États-Unis. La NRC a défini les conditions et décrit ses attentes en matière de réglementation fondée sur ce concept (Travers, 1999). Les organismes de réglementation de certains pays, l'Agence internationale de l'énergie atomique (AIEA) et l'Institut des opérations nucléaires (INPO) au niveau international, ont commencé à fournir des cadres réglementaires ou des guides méthodologiques (US NRC, 2011a,b, 2012; IAEA, 2010, 2011; Bujor, Gheorghe, Lavrisa et Ishack, 2010; HSE, 2001; Hidaka, 2008, Ishack, 2007; INPO, 2012).

Les applications de RIDM en industrie nucléaire sont très répandues et touchent virtuellement toutes les activités (Apostolakis, 2004; Schinzel, 2008; COG, 2005; Petti, Spencer et Graves, 2008; Kumamoto, 2007; Ashar, Imbro et Terao, 2003; Saliba, Komljenovic, Chouinard, Vaillancourt, Chrétien et Gocevski, 2010; EPRI, 2004c,d, 2007c, 2008b; Komljenovic, Hotte et Beaudet, 2009; Cepin, 2011; Borgonovo et Apostolakis, 2001; Reinert et Apostolakis, 2006; Vaurio, 2011; Volkanovski et Cepin, 2011; Hill, 2009; Elliott et Apostolakis, 2009; Elliott, 2010; Modarres, 2009; Saji, 2003a,b; Mishra et Pandey, 2007).

L'application du RIDM peut également impliquer une utilisation structurée du jugement d'expert. Ce sujet est analysé dans quelques travaux de recherche (Forrester, 2005; Tregoning, Abramson, Scott et Chokshi, 2007; Simola, Mengolini et Bolado-Lavin, 2005; US NRC, 2008; EPRI, 2008b).

Après l'industrie nucléaire, d'autres industries à risque commencent à adapter ce concept à leurs besoins spécifiques. Elles comprennent l'industrie pétrochimique, l'industrie spatiale, le transport en général, l'énergie d'hydrogène, les problèmes de sécurité, la production et distribution d'énergie, la protection de l'environnement, la sécurité des barrages hydroélectriques, etc. (Aven, 2014; Aven and Vinnem, 2007;

ASME, 2009; AIChE, 2013; FERC, 2018; Gharabagh, Asilian, Mortasavi, Mogaddam, Hajizadeh et Khavanin, 2009; Anderson et Mostue, 2012; Papazoglou, Nivolianitou, Anezaris, Christou et Bonanos, 1999; Rahmawati, Whitskon, Foss et Kuntadi, 2012; Suedel, Kin, Clarke et Linkov, 2008; U.S. Bureau of Reclamation, 2013; Paté-Cornell et Dillon, 2001; Catrinu et Nordgard, 2011; Nordgard, 2012; NASA, 2010, 2011; FAA, 2009; Podofillini, Zio et Vatn, 2006; Kazantzi, Kazantzis et Gerogiannis, 2011; Psarros, Skjong et Vanem, 2011; Ballis et Dimitriou, 2010; LaChance, 2009; LaChance, Tchouvelev et Ohi, 2009; McGill, 2008; Willis, 2007; Garrick, Hall, Kilger, McDonald, O'Toole, Probst, Parker, Rosenthal, Trivelpiece, Van Arsdale et Zebroski, 2004; Patterson et Apostolakis, 2007).

Il y a aussi plusieurs autres publications décrivant un concept général de RIDM en dehors de l'industrie nucléaire avec des discussions sur l'acceptabilité des risques (Aven, 2009; Aven et Kristensen, 2005; Hopkins, 2013; EPRI, 2012b; FERC, 2018; Pasman, 2000; Ersdal et Aven, 2008; HSE, 2001; Vanem, 2012; Aven and Steen, 2010; Van Bossuyt, 2012; Leveson, 2011; The National Academies, 2008; Mohaghegh-Ahmadabadi, 2007; Kavoliunas, Klim et Komljenovic, 2009; Klim, Balazinski et Komljenovic, 2011; Pasman, Knegtering et Rogers, 2013; Aven et Hiriart, 2013).

Ainsi, l'état actuel du développement des RIDM montre que ce concept mûrit et se développe relativement rapidement dans diverses industries. Il poursuivrait vraisemblablement son développement et expansion en raison de sa capacité de supporter l'optimisation des ressources et de permettre une approche intégrale dans la résolution des problèmes.

2.3 Gestion des actifs et processus décisionnel en GDA

Le concept de gestion des actifs est en train de devenir un concept privilégié des organisations performantes (The Institute of Asset Management, 2015a,b). Il a suscité de l'intérêt dans diverses industries et continue d'acquérir de la maturité. Des contributions principales dans ce domaine seront présentées ci-dessous.

Un développement important a été réalisé par le British Standards Institute en publiant sa norme PAS 55 sur la gestion des actifs (BSI, 2008). Ce PAS a été développé en consultation avec un grand nombre d'organisations internationales et des experts provenant d'un large éventail d'industries. Il est en principe neutre sur le plan technologique et applicable à toute taille d'entreprise. Cette norme définit plusieurs types d'actifs : physiques, qui sont dans son champ d'application, humains, financiers, informationnels et intangibles (réputation, image, moral, impact social, etc.).

Cette norme constate qu'une gestion des actifs n'est pas une transformation rapide ou un succès instantané dans une organisation. Il s'agit plutôt d'une approche, d'un mode de pensée, d'une évolution organisationnelle et d'une élimination des « silos » départementaux (organisationnels) existants. Le document présente les caractéristiques de haut niveau d'une bonne gestion des actifs : multidisciplinaire, systématique, orienté système, tient compte du risque, optimal, durable et intégré.

L'élément essentiel d'un bon système de gestion des actifs est la connectivité claire entre le plan stratégique de l'organisation (communément appelé plan d'affaires) et les activités quotidiennes des différents services (planification, ingénierie, approvisionnement, exploitation, maintenance, performance, gestion, etc.). La figure 2.1 présente schématiquement les éléments principaux du système de GDA et leurs liens (BSI, 2008, 2009).

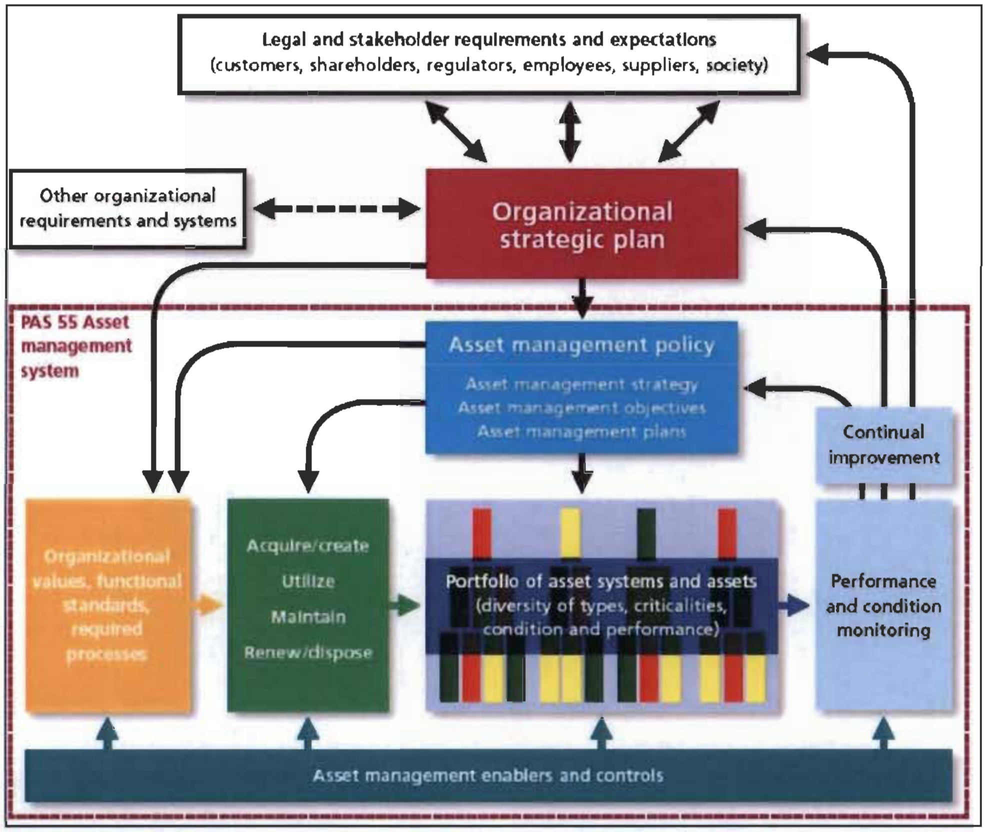


Figure 2.1. Éléments principaux du système de la gestion des actifs selon PAS55 (BSI, 2008, 2009)

L'Organisation internationale de normalisation (ISO) a publié, en janvier 2014, la norme internationale sur la gestion des actifs ISO55000 qui est principalement basée sur PAS 55 (ISO, 2014a,b,c). La norme est composée d'une série de trois documents : ISO55000 (gestion des actifs – aperçu, principes et terminologie); ISO55001 (gestion des actifs – systèmes de gestion – exigences); ISO55002 (gestion des actifs – systèmes de management – lignes directrices pour l'application de l'ISO 55001) (ISO, 2014a,b,c). La figure 2.2 présente la relation entre les éléments principaux d'un système de gestion des actifs selon cette norme.

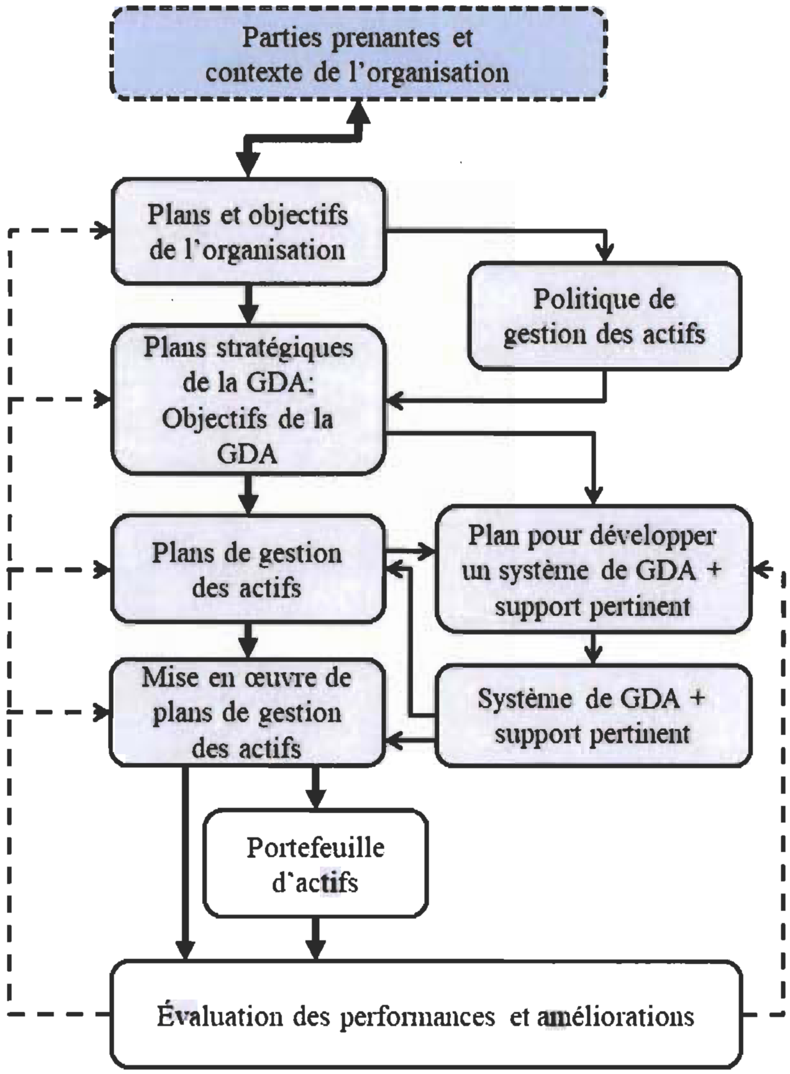


Figure 2.2. Relation entre les éléments principaux d'un système de gestion des actifs selon ISO 55000

The Institute of Asset Management a publié, en décembre 2015, un guide d'application des principes en gestion des actifs (The Asset Management Anatomy) en tenant compte de la norme ISO 55000 (The Institute of Asset Management, 2015a,b) et le retour d'expérience de ses applications dans diverses industries. Il décrit six groupes de connaissances regroupés dans 39 domaines. La figure 2.3

présente le modèle global de la gestion des actifs. Ce guide discute la complexité de la GDA sans aborder les méthodes pour la modéliser.

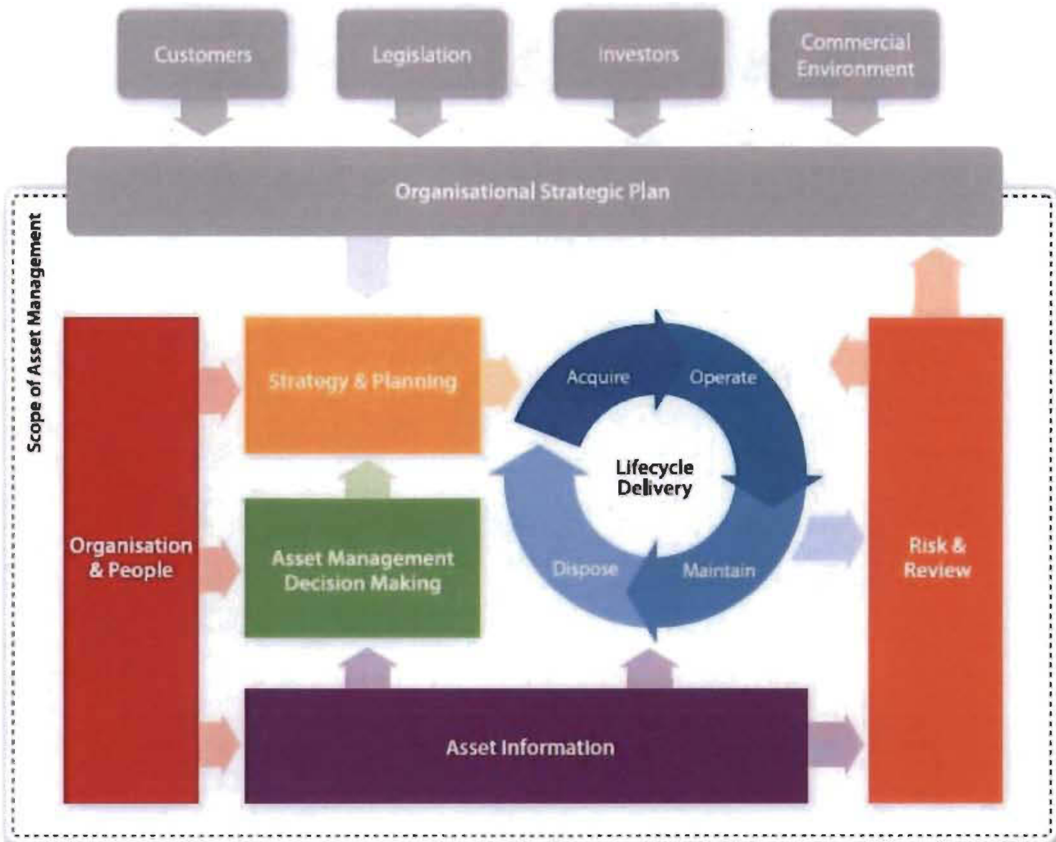
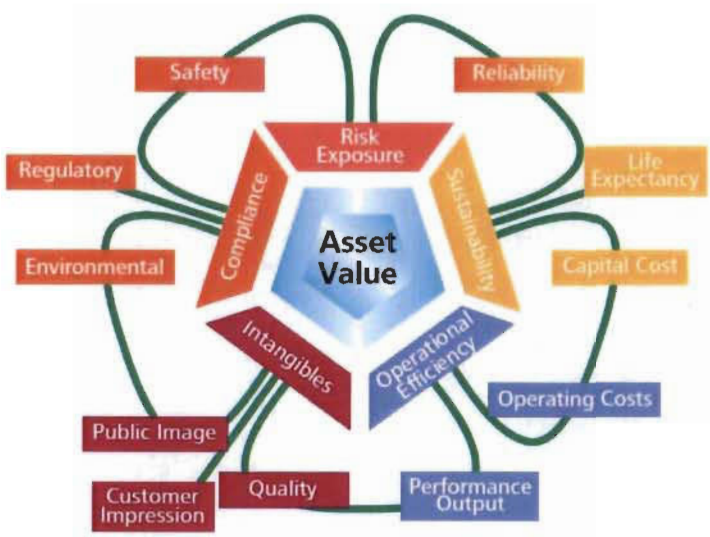


Figure 2.3. Modèle conceptuel de la gestion des actifs selon The Institute of Asset Management

Le même institut a publié un guide spécifique de la prise de décision en GDA (The Institute of Asset Management, 2015b). La figure 2.4 présente l'approche suggérée. Toutefois, la référence n'offre pas de détails des méthodes scientifiques ou techniques à utiliser dans le processus.



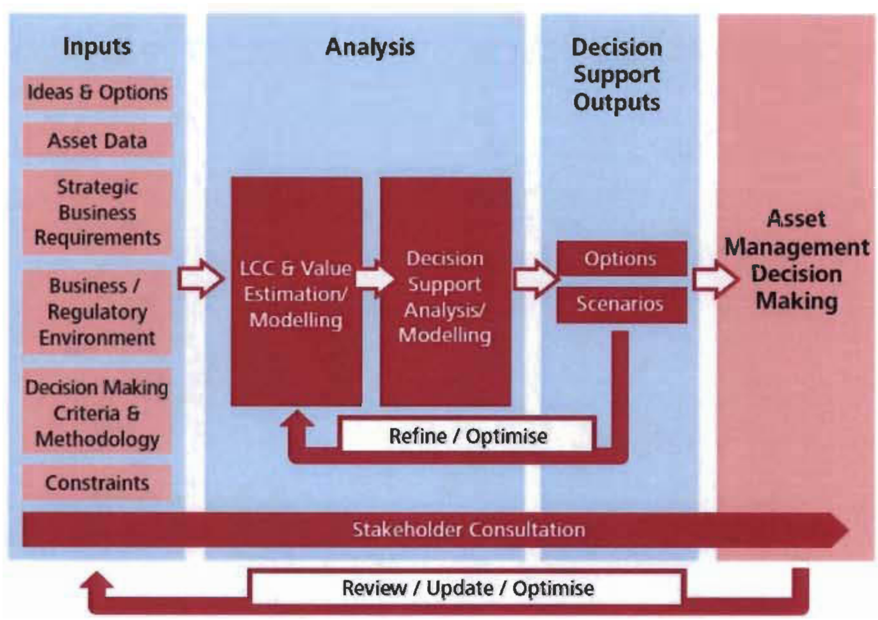


Figure 2.4. Approche décisionnelle en GDA selon The Institute of Asset Management

L'industrie nucléaire a investi des efforts importants dans l'élaboration d'approches et de méthodes de gestion des actifs adaptées à ses besoins et à ses particularités. Les travaux ont principalement été effectués par l'EPRI, l'INPO, l'Institut de l'énergie nucléaire, l'Agence internationale de l'énergie atomique (AIEA), les organismes de réglementation, de nombreuses universités et diverses institutions de recherche.

Cette industrie a essentiellement développé le processus de gestion des actifs nucléaires (NAM) à tous les niveaux d'une entreprise de production nucléaire afin de maximiser la valeur des centrales nucléaires pour les parties prenantes, tout en assurant la sûreté du public et du personnel de la centrale (EPRI, 2007a). Pour aider l'industrie nucléaire à atteindre ces objectifs, le NEI a publié l'AP-940, Description du processus de gestion des actifs nucléaires et lignes directrices (Huffman, 2007).

Le NAM définit un objectif d'affaires pour un retour sur investissement maximal tout au long du cycle de vie des actifs. Il vise à fournir plus de détails pour soutenir des activités NAM efficaces et efficientes. Ce processus est structuré de manière à traiter la nature multidimensionnelle de la prise de décision dans la gestion d'actifs : a) impact sur la sûreté, b) impact économique, c) risques d'affaires, d) risques technologiques.

Le secteur de l'énergie nucléaire a également élaboré la gestion des actifs en tenant compte des risques (*Risk-Informed Asset Management – RIAM*), qui est une méthode financière/d'ingénierie complémentaire à NAM qui utilise la technologie de gestion des risques pour soutenir la planification à long terme et les décisions d'investissement au niveau de systèmes ou d'équipements. RIAM optimise les valeurs économiques et minimise les risques, tout en maintenant des niveaux acceptables de sûreté nucléaire et d'autres valeurs d'intérêt pour les parties prenantes (EPRI, 2002, 2005b). La figure 2.5 présente le modèle conceptuel de RIAM (EPRI, 2002).

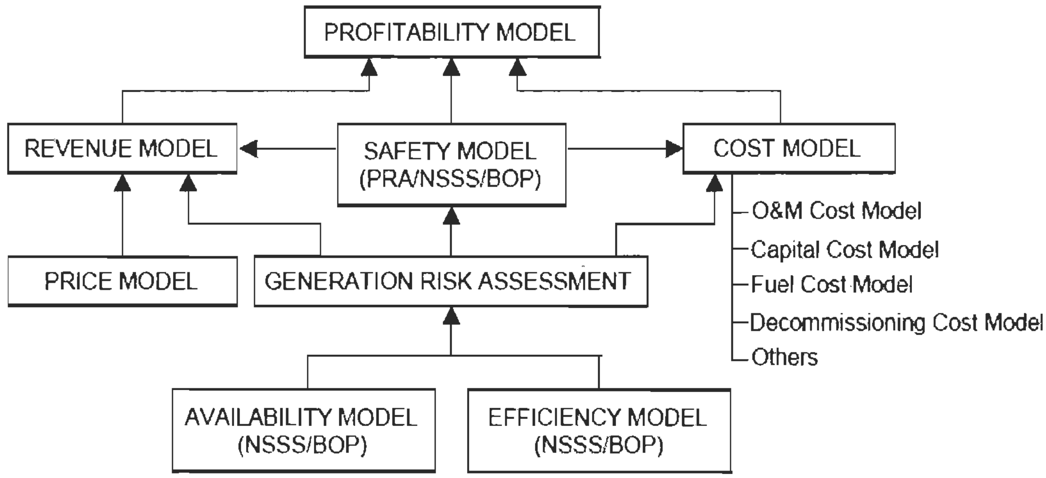


Figure 2.5. Modèle conceptuel de RIAM selon EPRI

L'EPRI a également développé d'autres outils, y compris des indicateurs financiers pour soutenir le NAM et RIAM qui sont utilisés par les services publics de l'énergie nucléaire (EPRI, 2001a,b, 2003a, 2004a,f,g, 2007d, 2008, 2010; Lee, Moh, Min et Yang, 2006). Les problèmes de vieillissement des systèmes, structures et composants (SSC) sont au centre des travaux de recherche dans le secteur de l'énergie nucléaire depuis plusieurs années. L'EPRI et Électricité de France (EDF) ont eu une collaboration fructueuse dans ce domaine pendant de nombreuses années (EPRI, 2006b). L'AIEA a produit un document de base à cet égard (IAEA, 2009). Par exemple, l'organisme de réglementation nucléaire canadien, la Commission canadienne de sûreté nucléaire (CNSC) a introduit le problème du vieillissement dans la réglementation et exige que les services publics canadiens élaborent et mettent en œuvre des programmes de gestion du vieillissement conformes au document réglementaire RD-334 (CNSC, 2011). D'un autre côté, l'EPRI a également élaboré plusieurs processus de gestion des actifs hors industrie nucléaire (EPRI, 2003b, 2005a, 2007b, 2012c). Ils ont souvent été inspirés par les expériences et les approches développées par l'industrie nucléaire.

D'autres initiatives et travaux de recherche sont également en cours. Par exemple, IBM et certains services de production d'électricité ont lancé le Smarter Energy Research Institute (SERI), conçu pour accélérer l'innovation dans le secteur de l'énergie et des services publics, notamment dans le domaine de la gestion d'actifs (IBM, 2018). De nombreux autres travaux de recherche analysent divers aspects liés aux approches GDA génériques (Schneider, Gaul, Neumann, Hografer, Wellssbow, Schwan et Schnettler, 2006; Woodhouse, 2005; Rojo, 2011; Rahim, Refsdal et Kenett, 2010; Hassan et Khan, 2012; EPRI, 2007b).

Certains processus spécifiques à un type d'industrie ont également été élaborés. Pour les systèmes de production et de distribution d'électricité, plusieurs publications analysent ce sujet (Dashti et Yousefi, 2013; Adoghe, Awosope et Ekeh, 2013; Catrinu et Nordgard, 2011; Nordgard, 2012; Lacroix et Stevenin, 2016; Khuntia, Rueda, Bouwman et van der Meijden, 2016). Le Conseil international des grands réseaux électriques (CIGRÉ) a publié le processus décisionnel conceptuel suggéré pour les utilités électriques (CIGRÉ, 2013, 2014). La figure 2.6 présente le concept du modèle proposé.

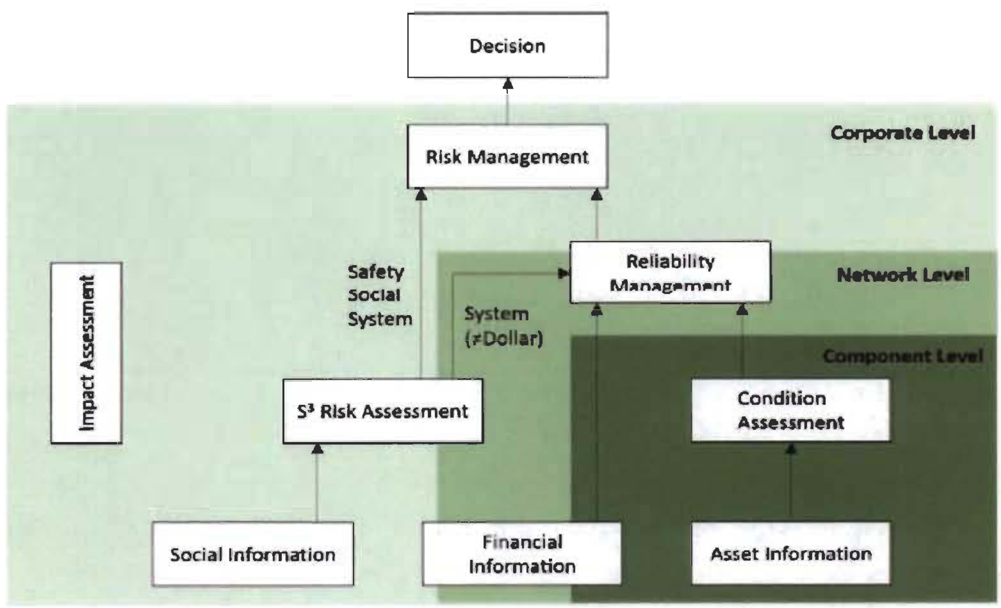


Figure 2.6. Processus décisionnel en utilités électriques suggéré par CIGRÉ

L'industrie du transport a également réalisé quelques travaux dans ce domaine (Ballis et Dimitriou, 2010; Dornan, 2002; NAS, 2018). L'industrie minière commence à élaborer certaines méthodes liées à la gestion des actifs (Koro, 2013; Komljenovic, 2007, 2014). La gestion de connaissances en GDA commence à susciter un certain intérêt, comme le montrent les études récentes (Schiuma, Carlucci et Sole, 2012).

Très peu d'études existent sur la gestion des actifs où elles prennent en compte l'impact d'événements rares et extrêmes dans la prise de décision. Mendonça, Pina e Cunha, Ruff et Kaivo-oja (2009) utilisent le terme *wildcards* pour de tels événements et apportent une discussion à ce sujet.

Malgré les avancements en gestion des actifs au cours des 10-15 dernières années dans diverses industries, comme décrit ci-dessus, il s'agit toujours d'une discipline en pleine croissance et ainsi d'autres développements sont nécessaires. Cela est particulièrement vrai concernant une modélisation plus précise et réaliste et des processus GDA plus efficaces qui prennent en compte de manière adéquate la complexité de l'environnement opérationnel et d'affaires ainsi que des facteurs d'influence les plus dominants, y compris ceux qui sont en dehors d'un environnement d'entreprise.

2.4 Incertitudes en ingénierie et leur impact

La physique et l'ingénierie ont relativement bien réussi à prédire les résultats futurs à partir des modèles qu'elles ont développés. En identifiant des modèles et relations précis, ces disciplines peuvent les extrapoler ou les interpoler pour obtenir des prévisions satisfaisantes. Les comportements des phénomènes étudiés peuvent être exprimés avec des modèles mathématiques exacts ou presque exacts. Cela peut s'expliquer par le fait que les lois naturelles régissant ces domaines ne changent pas ou que les changements sont si lents qu'on peut les négliger pour des raisons pratiques. On a seulement besoin de les découvrir et de les comprendre pour une éventuelle application (Komljenovic, Abdul-Nour et Popovic, 2015).

Les incertitudes sont relativement bien comprises et décrites dans les activités d'ingénierie. Ces incertitudes sont étudiées en détail dans l'industrie nucléaire, notamment dans les applications RIDM et des études probabilistes de sûreté (EPS) (EPRI, 2004b, 2006a, 2008a, 2012a; US NRC, 2008, 2011a, 2013; Reinert, 2003; Reinert et Apostolakis, 2006; Elliott, 2010; Université of Waterloo, 2018).

En général, il y a deux familles d'incertitudes dans l'ingénierie : aléatoire et épistémique comme discuté dans la section d'introduction. Il existe trois types d'incertitude épistémique (Kumamoto, 2007; US NRC, 2013).

– Incertitudes de paramètres/données

  Le modèle pour exprimer de l'incertitude aléatoire est adéquat mais comporte un ou plusieurs paramètres inconnus à estimer. Par exemple, la durée de vie de composants est distribuée avec une distribution exponentielle. Cette distribution a un seul paramètre appelé taux de défaillance. L'erreur dans l'estimation du taux de défaillance du composant génère une incertitude de paramètre.

  L'incertitude des paramètres est causée par des facteurs tels que l'incertitude statistique due aux données sur composants ou l'incertitude d'évaluation des données due aux interprétations subjectives des données de défaillance.

– Incertitudes de modélisation

  Les modèles peuvent ne pas être réalistes en raison de diverses approximations et hypothèses qui sont faites, par exemple, pour la performance humaine et les défaillances de cause commune ou pour les processus physiques complexes.

Ce type d'incertitude inclut aussi les limites des techniques (méthodes) de modélisation utilisées.

- Incertitude de complétude (intégralité)

  Le paramètre calculé (p. ex., le niveau de risque) présente une déviation de sa valeur réelle lorsqu'il existe des contributeurs qui ne sont pas pris en compte dans l'analyse (non analysés par hypothèse ou inconnus au moment de l'analyse). Des modes de fonctionnement exceptionnels peuvent également ne pas être analysés. En ce qui concerne les actions humaines, on ne peut analyser toutes les erreurs de commission ou omission car il existe, en théorie, un nombre incalculable d'erreurs. L'incomplétude est une limitation de la portée et génère des écarts par rapport à la réalité. Ainsi, l'incertitude de complétude concerne les contributeurs qui ne sont pas comptabilisés dans le modèle. Ce type d'incertitude peut en outre être catégorisé comme étant connu, mais non inclus dans le modèle, ou inconnu. Les types d'incertitude connus et inconnus sont importants pour la validité des résultats. Par exemple, les propagations des incertitudes des paramètres produisent des distributions de l'estimation du risque, c'est-à-dire des distributions de probabilité et de conséquence. D'autres incertitudes épistémiques sont traitées par des études de sensibilité plutôt que par des propagations d'incertitudes (Kumamoto, 2007).

  D'autres travaux de recherche contribuent également à mieux comprendre les risques et incertitudes dans le domaine de l'ingénierie (Aven, 2013a,b, 2016a,b; Hu, 2012; Zio et Aven, 2013; Aven et Reniers, 2013; Helsel, 2005; Heinonen, Karjalainen, Ruotsalainen et Steinmüller, 2017; Catrinu et Nordgard, 2011; Efatmaneshin *et al.*, 2016; Li et Ellingwood, 2006; NAS, 2012).

En général, les études mentionnées ci-dessus fournissent un cadre de référence pour une approche de prise de décision en tenant compte des risques (RIDM) qui considère intrinsèquement les incertitudes pertinentes. Cette approche peut offrir une assurance raisonnable que les décisions prises en fonction des risques sont robustes (EPRI, 2012a).

2.5 Prévisions et risques des événements extrêmes et rares

Comme indiqué précédemment, la planification stratégique et la gestion des actifs sont des activités et des engagements continus à long terme d'une organisation. Ainsi, la prévision de tous les facteurs d'influence pertinents, de leur environnement commercial et opérationnel est essentielle pour pratiquement toutes les décisions économiques et d'affaires. Elle représente donc un élément clé d'une prise de décision judicieuse. Cela inclut également la prise en compte de l'impact des événements extrêmes et rares.

La revue de la littérature a montré qu'il y a très peu de travaux de recherche qui abordent le sujet des risques des événements extrêmes et rares en GDA. Toutefois, la revue ci-dessous présente une contribution pertinente dans ce domaine en dehors de la GDA. Elle pourrait être donc utile pour analyser leur impact sur la GDA.

D'un autre côté, plusieurs articles traitent des limites des méthodes de prévision actuellement utilisées. Il existe plusieurs cas montrant qu'une prévision précise dans le monde économique et d'affaires n'est généralement pas possible (Makridakis, Hogarth et Gaba, 2009)[6].

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[6] Par exemple, dans le domaine de l'économie, on n'a pas été en mesure de prédire la crise des subprimes et des crédits, la bulle Internet, la contagion asiatique, les crises immobilières et d'épargne et de crédit, la crise du crédit en Amérique latine, la chute des prix du pétrole et autres catastrophes majeures. Dans les affaires, qui « prédisait » l'effondrement de Lehman Brothers, Bear Stearns, AIG, Enron ou WorldCom (aux États-Unis) et Northern Rock, Royal Bank of Scotland, Parmalat ou Royal Ahold (en Europe) ou l'effondrement pratique de toute l'économie islandaise? Dans la finance, qui a prédit la disparition de LTCM et Amaranth, ou les centaines de fonds mutuels et de *hedge funds* qui ferment chaque année après avoir subi d'énormes pertes? (Makridakis et Taleb, 2009a).

D'une part, accepter les limites de la précision des prévisions implique l'impossibilité d'évaluer avec l'exactitude des décisions et l'incertitude associées. D'un autre côté, croire en la possibilité de prévisions précises signifie de succomber à l'illusion du contrôle et éprouver des surprises, souvent avec des conséquences négatives (Stacey et Mowles, 2016; Pyne, Keating et Katina, 2016). De nombreux auteurs sont d'avis qu'il est pertinent d'élaborer de nouvelles approches concernant les prévisions dans le monde complexe (Goodwin et Wright, 2010; Wright et Goodwin, 2009; Wright, Heijden van Der, Burt, Bradfield et Cairns, 2008; Juslin *et al.*, 2011; Juslin, Winman et Nilsson, 2003; Makridakis *et al.*, 2009; Goldstein et Gigerenzer, 2009; Makridakis et Taleb, 2009b; Rickards, 2009; Heinonen *et al.*, 2017). Plusieurs travaux de recherche traitent de la prévisibilité limitée de l'environnement économique et d'affaires. Ils offrent également un cadre de référence qui permet aux décideurs et d'y faire face à l'avenir – malgré les limites inhérentes aux prévisions et l'incertitude, parfois importantes, entourant la plupart des décisions orientées vers l'avenir.

L'estimation des coûts des produits ou des projets et les décisions fondées sur ces prévisions sont exposées à de nombreuses incertitudes liées à des facteurs tels que des développements futurs inconnus. Cela a été abordé à plusieurs reprises dans des études de recherche axées sur différents aspects de l'incertitude. Malheureusement, cet intérêt n'a pas encore été pleinement adopté dans la pratique (Kreye, Goh, Newnes et Goodwin, 2012). La capacité de prévision dans pratiquement tous les systèmes complexes affectant nos vies est faible tandis que l'incertitude entourant ces prédictions ne peut être évaluée avec exactitude. La seule exception concerne les systèmes techniques en physique et en ingénierie (Orrell et McSharry, 2009; Makridakis et Taleb, 2009a; Shiller, 2013).

Makridakis et Taleb (2009a) analysent la prévisibilité limitée et le haut niveau d'incertitude dans pratiquement tous les domaines importants de notre vie et ses implications. Le travail de recherche compile une grande quantité de preuves empiriques accumulées au cours des dernières décennies qui démontrent les conséquences négatives de prévisions inexactes dans des domaines allant de l'économie et des affaires aux inondations et aux médicaments. Les auteurs soulignent que le problème important est que la grande majorité des gens et décideurs croient toujours que des prévisions précises soient possibles et que l'incertitude peut être précisément évaluée. Cependant, la réalité montre le contraire et l'article discute de ce problème.

De nombreux autres travaux de recherche (Makridakis *et al.*, 2009; Taleb, 2010; Orrell and McSharry, 2009; Hammond, 2010; Taleb and Tapiero, 2010; Triana, 2009; Singh, Allen et Powell, 2012; Rickards, 2009; Farmer, 2012; Heinonen, Karjalainen, Ruotsalainen et Steinmüller, 2017) fournissent des preuves empiriques qu'une prévision précise dans le monde économique et d'affaires (en tant que systèmes complexes) n'est généralement pas possible, en raison de l'énorme incertitude, car pratiquement toutes les activités économiques et commerciales sont soumises à des événements imprévisibles. La société continuera à faire face à des événements rares et uniques qui sont complètement inattendus, et même en dehors du domaine de notre imagination, ce que Taleb (2010) appelle *black swans*[7].

7 Définition d'un *black swan* : d'abord, c'est un événement d'une valeur aberrante car il se situe en dehors du domaine des attentes régulières, parce que rien dans le passé ne peut pointer de manière convaincante sur sa possibilité. Deuxièmement, il a un impact extrême. Troisièmement, en dépit de son statut de valeur aberrante, la nature humaine nous oblige à élaborer des explications sur son occurrence après coup, la rendant explicable et prévisible (Taleb, 2010). Aven a également ajouté: « Pour résumer, je conclus qu'un *black swan* doit être vu comme un événement extrême surprenant par rapport aux connaissances/croyances actuelles. Par conséquent, le concept doit toujours être considéré en relation avec les connaissances/croyances dont nous parlons » (Aven, 2013b, p. 48). (Makridakis *et al.*, 2009) expliquent qu'une fois que nous acceptons qu'il y ait des connus-connus, des inconnus-connus et des inconnus-inconnus, nous pouvons commencer à penser de façon plus systématique à l'incertitude sous-jacente, parce que nous savons exactement ce qui va arriver. Dans le cas d'inconnues-connues, nous pourrions être en mesure de quantifier et de modéliser l'incertitude pour certains événements, mais pas tous. Nous pouvons modéliser l'incertitude d'un tirage au sort mais il est impossible de quantifier ou de modéliser l'incertitude concernant les krachs futurs sur les marchés financiers, même si nous pouvons clairement nous attendre à ce qu'ils se produisent. Dans ce contexte, Sornette (2009) a développé le concept de « rois-dragons » (*dragon kings*) correspondant

D'autres auteurs ont également analysé ce phénomène (Aven, 2014; Chichilnisky, 2010; Hammond, 2010; Schiller, 2013; Taleb et Tapiero, 2010; Triana, 2009; Muller, 2010; Singh *et al.*, 2012; Alexerov et Egorova, 2012). Nobilis a publié en 2010 un numéro spécial « Sigma » compilant des contributions sur des événements rares (Muller, 2010). Les contributeurs à cette édition analysent les événements rares naturels et anthropologiques qui ont eu des conséquences majeures dans un passé récent (les volcans, les crises financières, les attentats du 11 septembre, les pandémies, les accidents industriels majeurs, etc.). En introduction de cette édition spéciale, le rédacteur en chef, H. Gilbert Muller, déclare :

> Nous avons rapidement découvert que, bien que nous pensions avoir compris le concept d'« événement rare », nous n'avions pas de définition satisfaisante et il n'est pas trivial d'en arriver à une. Nous étions aux prises avec cette tâche, lorsque trois événements se sont succédés : le volcan islandais Eyjafjallajökull, la catastrophe de Deepwater Horizon dans le golfe du Mexique et le Dow Jones Industrial Average qui a perdu 1 000 points, surnommé *Flash Crash*[8]. (Muller, 2010, p. 1)

Il ajoute :

> Les décideurs des secteurs public et privé, ainsi que les analystes, les ingénieurs et les scientifiques, doivent comprendre qu'il n'est plus acceptable de considérer les événements rares comme extérieurs à leur conception, à leur analyse et à leurs plans d'exploitation. Dans ce numéro, nous parlons de la façon dont la perception de tels événements change à mesure que les connaissances à leur sujet augmentent et offrent un mécanisme pour comprendre cette évolution… Notre cadre d'évolution n'est pas destiné à classer un événement comme rare ou non; c'est simplement un rappel que des connaissances variées sont nécessaires pour réaliser des analyses et des conceptions sur mesure. (Muller, 2010, p. 1).

à des valeurs aberrantes significatives, qui coexistent avec les lois de puissance dans les distributions de tailles d'événements dans une large gamme de conditions dans une grande variété de systèmes.

8 La chute historique de l'indice Dow Jones au début de février 2018 confirme une fois de plus l'impossibilité de prévisions précises dans les systèmes complexes.

L'incapacité à anticiper ces événements découle en grande partie de la confiance accordée à des analyses qui ne tiennent pas suffisamment compte de ceux-ci.

Duffey (2013) présente une nouvelle méthode pour prédire la probabilité future (postérieure) d'événements rares basés sur le cas extrême d'un apprentissage insuffisant des événements complexes qui ne se sont produits que très rarement. L'auteur utilise des mesures d'expérience à la fois pour l'opportunité d'apprentissage et l'exposition au risque. Il compare les prévisions avec les résultats obtenus en utilisant loi de puissance pour les événements rares et établit les incertitudes et les risques potentiels en tant que fonction explicite de l'exposition future au risque. L'article souligne que pour les événements rares et les probabilités très faibles dans les systèmes complexes, il n'y a pas de signal d'alarme, d'indicateur ou de signal d'avertissement intégré, facile ou évident, pouvant être déduit en ajustant les filtres ou les techniques de lissage des données.

L'Organisation de coopération et de développement économiques (OCDE) a entrepris une étude afin de mieux comprendre l'impact des futurs chocs mondiaux (OCDE, 2011). Le but de ce rapport de l'OCDE est d'aider à mieux comprendre comment améliorer la capacité globale à faire face à des menaces soudaines et hautement perturbatrices, compte tenu des variables inconnues, des incertitudes, des liens de causalité et des seuils de résistance des systèmes sur lesquels elles impactent. Le concept de « chocs globaux » prend en compte un profil de risque différent : les risques en cascade qui deviennent des menaces actives lorsqu'ils se propagent à travers les systèmes mondiaux, qu'ils surviennent dans les systèmes climatiques, sociaux ou financiers.

Certains autres auteurs utilisent le terme *wildcard* pour des événements rares et perturbateurs (Mendonça *et al.*, 2009; Markmann, Darkow et Von der Graht, 2013; Ecken, Gnatzy et Von der Gracht, 2011; Wardekker, de Jong, Knoop et van der

Sluijs, 2010; Linz, 2012; Heinonen *et al.*, 2017). Dans leur recherche, ils utilisent la méthode Delphi pour prévoir et intégrer des événements rares et disruptifs, qui peuvent être internes et externes à l'entreprise, y compris les moyens d'accroître la résilience[9] face à ces événements. Ces auteurs concluent également que les *wildcards* ne peuvent pas être prévus avec précision mais que des dispositions peuvent être conçues pour eux. La discussion sur ce sujet est fondamentalement la même que celle mentionnée ci-dessus sur la question de *black swan*, c'est-à-dire qu'il existe des incertitudes épistémiques liées aux inconnues-connues et aux inconnues-inconnues.

La résilience est habituellement mesurée par la perte du niveau de performance et par le temps de recouvrir la perte (figure 2.7).

[9] Il n'y a pas de définition unique de la résilience et de la robustesse. Certaines normes internationales ainsi que des articles scientifiques fournissent quelques définitions qui seraient acceptables :

résilience : capacité d'adaptation d'un organisme dans un environnement complexe et changeant (ISO, 2009b).

robustesse : capacité d'un organisme ou installation « approximations vagues et/ou zones d'ignorance » afin de prévenir des impacts indésirables, notamment la dégradation des propriétés qui doivent être maintenues (Aven, 2016b; Zio, 2016).

vulnérabilité : propriétés intrinsèques de quelque chose entrainant une sensibilité à une source de risque pouvant induire un événement avec une conséquence (ISO, 2009b).

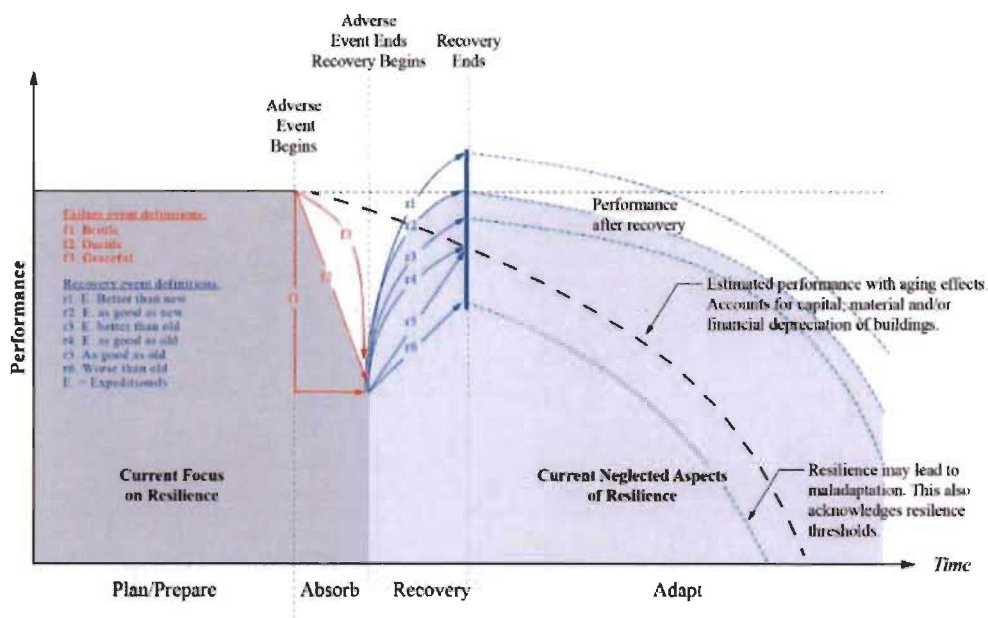

Figure 2.7. Courbe de résilience (Kurth *et al.*, 2018)

Paté-Cornell considère que les statistiques sont souvent insuffisantes pour soutenir la gestion des risques d'événements rares étant donné que les échantillons peuvent être trop petits et que le système peut avoir changé (Paté-Cornell, 2012). Elle déclare que les événements *black swan* représentent l'incertitude épistémique ultime ou le manque de connaissances fondamentales. L'auteure affirme que les événements rares présentent des défis majeurs en matière de gestion des risques en génie, en médecine, en géophysique, en finance et dans de nombreux autres domaines.

En ce qui concerne la performance humaine, plusieurs auteurs soutiennent que nous ne pouvons pas supposer que la prise de décision est toujours rationnelle (Kahneman, 2012; Mosey, 2014; Rickards, 2009; Shiller, 2013; Taleb, 2010). Dans de telles situations, des biais cognitifs et motivationnels sont susceptibles de se produire dans le processus de prise de décision. Ces biais pourraient avoir une incidence négative sur les résultats obtenus (Kahneman, 2012; Montibeller et Winterfeldt, 2015). Cela ajoute à la complexité globale de l'environnement opérationnel et d'affaires et peut finalement créer des conditions favorables à l'occurrence des événements extrêmes dans un système.

Ainsi, l'incapacité de prédire avec précision les événements futurs dans une majorité de situations de la vie réelle crée un doute quant à la « meilleure » prévision. Il y a au moins trois raisons à une telle situation :

- premièrement, dans la plupart des cas, les erreurs ne sont pas indépendantes les unes des autres; leur variance n'est pas constante, alors que l'on ne peut pas confirmer que leur distribution suit une courbe normale, ce qui signifie que la variance elle-même sera soit intraitable, soit un mauvais indicateur d'erreurs potentielles, ce qu'on appelle *wild randomness* ou *mandelbrot randomness* (Taleb, 2010; Rickards, 2009);
- deuxièmement, il y a toujours la possibilité que des événements hautement improbables ou totalement inattendus se matérialisent (Makridakis *et al.*, 2009; Makridakis et Taleb, 2009a; Taleb, 2010; Triana, 2009; Juslin, Nilsson, Winman et Lindskog, 2011; Goodwin et Wright, 2010; Evans, 2012; Homer-Dixon, 2006; Hammond, 2010; Hand, 2014);
- troisièmement, il existe un problème important en dehors des configurations artificielles : la probabilité n'est pas observable et il est problématique de savoir quel modèle probabiliste il faut utiliser. On doit donc se rendre compte que certaines erreurs de prévision peuvent causer des préjudices ou des opportunités manquées tandis que d'autres peuvent être bénignes (Makridakis *et al.*, 2009; Makridakis et Taleb, 2009a; Taleb, 2010; Kahneman, 2012).

Ainsi, toute analyse de prévision doit prendre en compte la dimension pratique : à la fois les conséquences des erreurs de prévision et la fragilité et la fiabilité des prévisions. Dans le cas d'une faible prévisibilité, on doit donc savoir comment agir en fonction des pertes potentielles et des opportunités.

L'expérience a montré que les humains sont généralement trop confiants aux attentes positives, tout en ignorant ou en déclassant les informations négatives (Makridakis *et al.*, 2009; Taleb, 2010). Cela pose un problème car les méthodes statistiques ne peuvent pas non plus prévoir les récessions et les crises financières majeures, créant un vide entraînant des surprises et des difficultés financières pour un grand nombre de personnes/entreprises. Personne ne leur a fourni des informations leur permettant de prendre en compte toute l'incertitude associée à leurs investissements ou à d'autres décisions et actions.

La plupart des modèles des séries chronologiques correspondent bien aux données passées mais ne sont pas bons pour les prévisions (Makridakis *et al.*, 2009; Makridakis et Taleb, 2009a; Taleb, 2010; Triana, 2009; Juslin *et al.*, 2011; Goodwin et Wright, 2010; Evans, 2012; Homer-Dixon, 2006; Hammond, 2010; Heinonen *et al.*, 2017). Par conséquent, Orrell et McSharry (2009) proposent d'améliorer les modèles de prévision en intégrant des informations provenant de sources disparates afin de réaliser de telles améliorations. De nombreux auteurs discutent des moyens de mitiger et de réduire à la fois les erreurs de prévision et leurs conséquences (Anda, Golub et Strukova, 2009; Makridakis et Taleb, 2009b; Goldstein et Gigerenzer, 2009; Chichilnisky, 2000, 2010; Taleb, 2009, 2010, 2012a,b; Armstrong, 2006; Bones, Barrella et Amekudzi, 2013; Bowman, MacKay, Masrani et McKiernan, 2013; Paté-Cornell, 2012; Cox, 2012; Bradfield, Wright, Burt, Cairns et Heijden van der, 2005; Kerr, Farrukh, Phaal et Probert, 2013; Kwakkel, Auping et Pruyt, 2013; Whrigt et Goodwin, 2009). Dans un tel contexte, on peut prendre des décisions en fonction des conséquences potentielles des erreurs de prévision. On peut également concevoir les systèmes pour qu'ils soient résilients et robustes à de telles erreurs. Ainsi, on peut faire des changements dans les processus de décision affectés par les prédictions futures (Wright et Goodwin, 2009; Taleb, 2010; Taleb, 2012a,b).

CHAPITRE 3 – MÉTHODOLOGIE DE RECHERCHE

3.1 Introduction à la méthodologie

Ce chapitre présente la méthodologie de recherche et définit la structure des prochains chapitres de la thèse. Son développement se base sur les questions, but et objectifs de recherche.

Elle vise à développer de manière originale les éléments constitutifs de la méthodologie et du modèle global de prise de décision en GDA en passant par les étapes principales suivantes :

- élaborer un modèle intégral de la gestion des actifs en tenant compte de la complexité de l'environnement opérationnel et d'affaires et des risques;
- effectuer des analyses approfondies pour identifier les parties constitutives et leurs relations au sein du modèle intégral; déterminer les niveaux de complexité et les types d'incertitude des éléments constitutifs du modèle;
- identifier et caractériser événements extrêmes et rares pouvant affecter la performance du processus de la GDA;
- définir des principes pour atteindre la robustesse, la résilience et la flexibilité de l'organisation en GDA;
- élaborer un modèle intégral de prise de décision en gestion des actifs.

La recherche fournira un cadre de référence amélioré pour des stratégies de la GDA optimales. Le processus global de prise de décision en tenant compte des risques en GDA doit également intégrer les intrants de l'orientation stratégique d'une organisation, les incertitudes associées (aléatoires et épistémiques) et les contraintes liées à la gestion globale du risque. En outre, le modèle devrait intégrer intrinsèquement un processus d'amélioration continue basé sur divers retours d'expérience interne et externe pertinents au cours du cycle de vie de l'organisation et des actifs (par exemple, audits internes et externes et/ou expérience d'exploitation).

La recherche actuelle n'a pas l'intention de développer tous les sous-modèles en GDA étant donné que certains d'entre eux sont déjà partiellement ou entièrement disponibles ou peuvent être développés et améliorés dans de futurs travaux de recherche.

Le travail portera principalement sur la gestion des actifs physiques. Dans le même temps, il considérera également d'autres types d'actifs (financiers, humains, information, autres) lorsqu'ils ont un impact sur la gestion optimisée des actifs physiques et pour assurer une cohérence globale de la GDA.

La thèse est constituée sept chapitres. Les trois chapitres suivants présentent les articles de revues avec comité de lecture qui sont directement liés au sujet de cette recherche. En effet, quatre catégories d'articles ont été produites durant les travaux de recherche. Elles sont présentées à la figure 3.1.

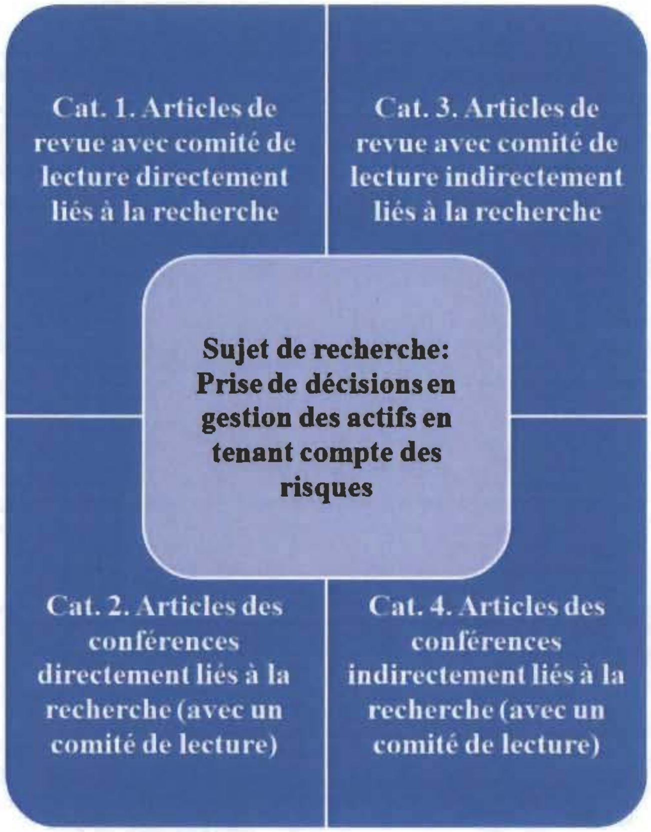

Figure 3.1. Catégories des articles publiés

Les articles de la catégorie 1 (articles directement liés au sujet de la recherche et publiés dans des revues avec comité de lecture) représentent le résultat principal du développement de la méthodologie et de son application.

Les articles de la catégorie 2 (articles directement liés au sujet de la recherche et publiés dans des conférences internationales avec un comité de lecture) ont précédé les articles correspondants de la catégorie 1 et montrent une phase essentielle du développement de la méthodologie de recherche. Les études de cas des articles des catégories 1 et 2 sont réalisées en industrie minière, nucléaire ainsi qu'une utilité électrique d'envergure (Hydro-Québec). Ce fait démontre l'universalité de la méthodologie développée et son potentiel de l'application dans diverses industries (figure 3.2).

Les articles de la catégorie 3 et 4 représentent du développement et des applications spécifiques d'un des éléments constitutifs du modèle intégral de la gestion des actifs : a) la méthodologie améliorée de la prise de décision dans le contexte particulier des énergies renouvelables, b) l'impact de la complexité sur la gestion des actifs en industrie minière (travail exploratoire) et c) l'analyse des risques systémiques et organisationnels en santé et sécurité au travail (SST) en industrie minière en tenant compte de la complexité (figure 3.2). Ce développement est parfois réalisé dans le cadre d'un autre projet de recherche mais en lien avec les recherches dans la présente thèse.

L'indication des articles des catégories 2, 3 et 4 sert à illustrer l'envergure des travaux de recherche réalisés. Les résultats de ces travaux ont permis de démontrer le potentiel d'application de la méthodologie intégrale en GDA dans différentes disciplines ou industries.

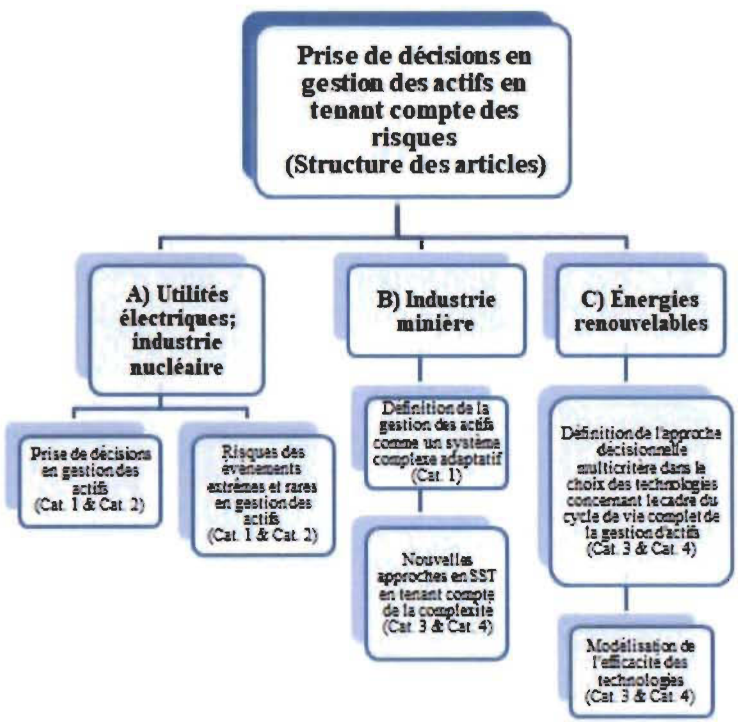

Figure 3.2. Domaines de l'application des articles

Le tableau 3.1 présente la liste des articles de la catégorie 1 produits durant les travaux de recherche. La description de la méthodologie ci-dessous se base sur ces articles. Les articles des autres catégories démontrent l'applicabilité de la méthodologie développée dans divers domaines et activités industrielles. Un total de 18 articles a été préparé et/ou publié depuis le début de la recherche en 2013 dont neuf dans deux premières catégories. Tous les articles sont énumérés dans l'annexe 1.

Tableau 3.1. Articles produits durant la recherche

Catégorie 1. Articles de revues avec comité de lecture directement liés à la recherche
Komljenovic, D., Abdul-Nour, G., & Boudreau, J.F. (2018). Risk-informed decision-making in asset management as a complex adaptive system of systems. *International Journal of Strategic Engineering Asset Management (IJSEAM)*, (soumis pour la revue des pairs en janvier 2018.
Komljenovic, D., Gaha, M., Abdul-Nour, G., Langheit, C., & Bourgeois, M. (2016). Risks of extreme and rare events in asset management. *Safety Science, 88*, 129-145.
Komljenovic, D., Abdul-Nour, G., & Popovic, N. (2015). Approach for strategic planning and asset management in mining industry in the context of business and operational complexity. *International Journal of Mining and Mineral Engineering (IJMME), 6*(4), 338-360.

3.2 Structure et contribution scientifique des articles

Les trois prochains chapitres détaillent les résultats de la recherche présentés dans les trois articles de la catégorie 1 (tableau 3.1). Cette structure de la présentation des articles est réalisée dans le but de clarifier le lien et la continuité de ces travaux. La revue des articles expose les résultats de la recherche incluant la démarche méthodologique y étant utilisée.

En général, la thèse propose un changement majeur de la manière d'analyser et de modéliser le processus de la gestion des actifs. Cette recherche contribue à l'état des connaissances par l'introduction de la théorie de la complexité en GDA et son processus décisionnel. Elle fait aussi la démonstration de l'importance d'y inclure les risques des événements extrêmes, disruptifs et rares à cause de l'environnement opérationnel et d'affaires complexe qui est susceptible de créer de tels événements. Ce fait implique que les méthodes traditionnelles d'analyse et de modélisation ont atteint leurs limites d'efficacité et de capacité de représenter adéquatement le processus de la gestion des actifs. Il devient clair que celui-ci ne peut être strictement contrôlé et des approches améliorées doivent être conçues pour assurer son efficience dans le contexte de la complexité. Naturellement, le travail de recherche ne vise pas à remplacer entièrement les méthodes traditionnelles. Il propose d'utiliser des méthodes et concepts novateurs basés sur la théorie de complexité pour complémenter ceux traditionnels. Par conséquent, ils aideront à améliorer la compréhension des éléments constitutifs de la GDA, leurs caractéristiques et leur comportement et finalement, l'élaboration des modèles plus réalistes. La description ci-dessous présente l'évolution du développement de la méthodologie à travers trois articles de la catégorie 1 (tableau 3.1) et les contributions scientifiques de la recherche. La figure 3.3 présente le processus du développement de la méthodologie à travers trois articles principaux.

Article 1. Processus de la gestion des actifs comme un système complexe adaptatif et la création du modèle intégral initial de la GDA

Komljenovic, D., Abdul-Nour, G., & Popovic, N. (2015). Approach for strategic planning and asset management in mining industry in the context of business and operational complexity. *International Journal of Mining and Mineral Engineering, 6*(4), 338-360.

Cet article identifie la planification stratégique et le système de gestion des actifs en industrie minière comme un système complexe adaptatif. Il démontre que l'environnement opérationnel et d'affaires est aussi un système complexe en statuant que l'utilisation singulière des méthodes traditionnelles de modélisation et d'analyse n'est plus entièrement appropriée pour capturer et modéliser adéquatement cette complexité. Par conséquent, l'article propose la structure principale initiale des éléments constitutifs d'un modèle intégral de la gestion des actifs dans le contexte de la complexité. Il introduit la théorie de complexité pour complémenter les méthodes traditionnelles d'analyse et démontre la pertinence de cette approche. L'article montre aussi que les principes développés pour l'industrie minière sont facilement adaptables et applicables dans d'autres types d'industrie. Il discute aussi les bénéfices potentiels de la nouvelle approche ainsi que les défis rencontrés pour y arriver et énumère les recherches futures. Cette manière d'aborder et analyser la GDA représente une nouveauté scientifique.

Article 2. Amélioration du modèle intégral de la GDA et l'introduction des risques des événements extrêmes et rares en GDA

Komljenovic, D., Gaha, M., Abdul-Nour, G., Langheit, C., & Bourgeois, M. (2016). Risks of extreme and rare events in asset management. *Safety Science*, *88*, 129-145.

Le travail de recherche améliore le modèle initial. Il identifie et caractérise les facteurs d'influence critiques en GDA. L'article démontre à nouveau que la GDA est un système complexe adaptatif. Il développe spécifiquement pour la GDA le concept de la prise de décision en tenant compte des risques (RIDM). Le modèle amélioré intègre sept sous-modèles spécifiques et identifie les types d'incertitudes dominants dans chacun (aléatoire ou épistémique). Il identifie aussi les types de connections et liens entre les sous-modèles ainsi que leurs caractéristiques et leur niveau de complexité. L'approche pour caractériser les risques des événements extrêmes et rares en GDA est aussi élaborée. La recherche a démontré qu'il n'est pas approprié de calculer les probabilités extrêmement faibles des événements rares à cause des incertitudes et la possibilité de se tromper de plusieurs ordres de grandeur. Dans ce contexte, il est important d'appliquer le concept de robustesse et de résilience pour se protéger contre ce type de risques et assurer la continuité des opérations de l'entreprise sans détruire sa viabilité économique. Deux études de cas (l'utilité électrique et l'industrie nucléaire) démontrent l'applicabilité et la validation de la méthodologie développée. L'article définit aussi les recherches futures d'intérêt pour approfondir le sujet. L'ensemble des éléments élaborés dans l'article représentent une contribution scientifique.

Article 3. Prise de décision en gestion des actifs en tenant compte des risques et de la complexité – modèle intégral

Komljenovic, D., Abdul-Nour, G., & Boudreau, J.F. (2018). Risk-informed decision-making in asset management as a complex adaptive system of systems. *International Journal of Strategic Engineering Asset Management* (soumis pour la revue des pairs en janvier 2018).

L'article présente l'étape finale du développement du modèle intégral en gestion des actifs en élaborant une approche novatrice de la prise de décision en tenant compte des risques et de la complexité. La méthodologie développée se base sur les deux articles précédents et introduit la définition et séparation des rôles des analystes, experts et décideurs. La considération du niveau de connaissances des intervenants et son impact sur le résultat final est introduit à la méthodologie comme un facteur important. La délibération dans le processus décisionnel est introduite dans la méthodologie et son importance est démontrée. Le modèle décisionnel intègre aussi les risques d'événements extrêmes et rares dans l'évaluation globale des risques dans la prise de décision en GDA. La méthodologie propose l'introduction du concept de gouvernance de système complexe comme moyen de faire face à la complexité en GDA. L'approche développée montre aussi les limites des modèles quantitatifs et du danger de leur utilisation singulière comme base de la prise de décision en GDA. Les recherches futures sont identifiées pour continuer à améliorer le modèle proposé. Le concept développé représente une contribution scientifique dans le domaine.

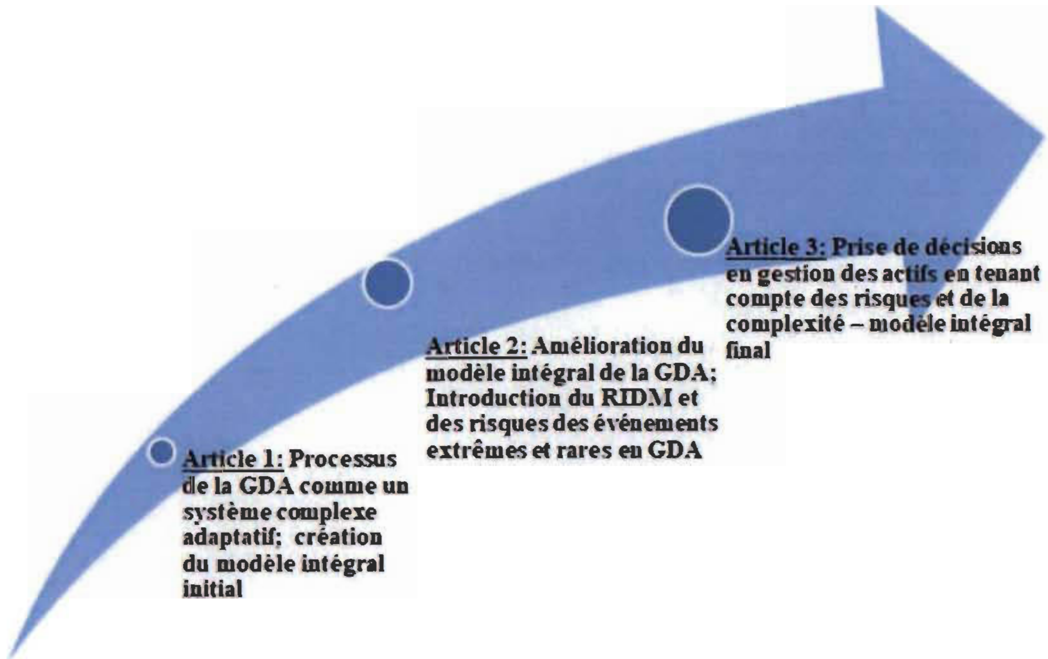

Figure 3.3. Processus du développement de la méthodologie

CHAPITRE 4 – ARTICLE 1
AN APPROACH FOR STRATEGIC PLANNING AND ASSET MANAGEMENT IN THE MINING INDUSTRY IN THE CONTEXT OF BUSINESS AND OPERATIONAL COMPLEXITY

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International Journal of Mining and Mineral Engineering, 2015, *6*(4), 338-360.

Abstract

Modern mining companies are complex organizations as per their organizational, management and operational structure. They also operate in a complex business and operational environment facing significant uncertainties related to natural, technical, technological, market, organizational, economic, financial, political, etc. influential factors affecting their business, management and operations. This environment also includes the impact of extreme, rare often disruptive events (natural or human made) triggering sometimes devastating consequences.

Traditional approaches and tools in strategic planning, asset management and decision-making in the mining industry have frequently been unable to adequately capture, characterize and address those uncertainties and complexity.

This paper proposes a new complementary approach in the strategic planning and asset management for mining enterprises by analyzing them as complex adaptive systems (CAS). The methods and tools drawn from the complexity science and theory usually used in modelling CAS may help to better comprehend the complex environment of mining organizations providing more realistic understandings upon it. Thus, we consider that they may be useful in designing an enhanced strategic asset management decision-making framework.

The benefits, challenges, as well as recommended future research works and applications of this concept in mining are also discussed.

Key words: strategic planning, asset management, mining operations, complexity science, complex adaptive systems, uncertainties, simulation, multi-agent modelling.

4.1 Introduction

Globalization and increased competition are keywords used to describe the market development worldwide. This context also applies quite well to the mining industry. The ability of mining enterprises to develop and implement innovative concepts in both strategic planning and asset management will be decisive to meet the progressive demands on competitiveness, and to ensure their sustainable operation and development. The organizational strategic planning is described as an overall long-term plan for an organization that is derived from, and embodies, its vision, mission, values, business policies, stakeholders' requirements, objectives and risk management (BSi, 2008).

Asset management is defined as an ensemble of systematic and coordinated actions and practices through which an organization optimally and sustainably manages its assets and asset systems, as well as their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan (BSi, 2008; BSi, 2009). This definition is rather generic and applies to any type and any size of organization, including mining companies.

The same Standard provides the definition of an asset as plant, machinery, property, buildings, vehicles and other items that have a distinct value to the organization. In this context, orebodies exploited by mining companies should also be considered as their assets.

The newly published International Standard on AsM ISO55000 defines asset management as "a coordinated activity of an organization to realize value from assets" (ISO, 2014).

The essential element of a good asset management system is the clear connectivity between the organization's strategic plan and the daily activities of each department (planning, engineering, procurement, operations, maintenance, performance management, etc.) (The Institute of Asset Management, 2012; BSi, 2008; ISO, 2014).

Usual industry-wide asset management systems focus on traditional facilities such as factories, assembly lines, etc. that has a more or less controlled and stable operational environment. Mines are different. The experience in the mining industry has often shown that what works at one mining site does not always work well at another one due to local conditions, culture and available resources which can substantially vary from site to site (Carter, 2015). Moreover, most of the main mining equipment is mobile. Such a context adds to further complexity in mining operations.

Mining enterprises also operate in a business, natural, technical, technological, organizational, regulatory, legal, political, financial, and market environment (hereafter called business and operational environment), which is complex and characterized by significant intrinsic uncertainties (Komljenovic, 2007).

Additionally, modern mining companies conduct their operations and business in the contemporary world which is tightly connected at numerous levels and in different ways (e.g. communications and IT, markets, finances, transportation, etc.). These are quite favourable to normal business, but may reveal damaging effects in cases of major perturbations. In fact, the mining industry is rather sensitive to various extreme and rare events (natural and human-made)[1]. Meanwhile, there is not much research in this field that helps understanding their impact on the strategic planning and asset management in the mining sector.

Furthermore, mining companies are themselves complex by their organizational, management and operational structure (particularly the larger ones), which also adds to the overall complexity and uncertainties. Hence, the modern world is complex, and mining companies operate in a complex business and operational environment which is predominantly dynamic, and rarely entirely foreseeable. Those web-like

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[1] Those events may include but are not limited to natural disasters, financial and market crashes, major failures of critical assets, major industrial accidents, prolonged shortage of power/energy supply, political unrests and instability, armed conflicts or terrorist attacks, radical changes in regulatory framework, extremely negative treatment in mass-media creating an unfavourable business environment, major legal pursuits, payment defaults or loss of major customers, etc.

complex structures and organizations of interdependent constituent elements continually adapt to their constantly changing environment.

Thus, issues and challenges in the mining industry are complex and multidimensional. They have emergent and often unpredictable behaviour. Anticipating and assessing the latter requires extensive knowledge from multiple disciplines in engineering and beyond while managing a wide range of risks and uncertainties.

Handling the issues discussed above has recently shown to be inefficient while using traditional approaches (Makridakis and Taleb, 2009a,b). Advices and input from technical experts, strategic planners or knowledgeable managers may be insufficient or too narrowly focussed to adequately manage the complexity of systems and structures in a constantly changing and barely predictable environment (Glouberman and Zimmerman, 2002). It is generally due to a lack of knowledge regarding the type and the range of uncertainties, the nature and the intensity of interconnections between the constituent parts of the systems, the level of their complexity, as well as human's low ability to predict future events and their characteristics. It should be highlighted that these concerns are similar in other industries (Allen *et al.*, 2011).

Most mining organizations deal with these issues by using various models and tools that help decrease uncertainties and risks in their decision-making process in order to increase their overall effectiveness. They are often based on traditional methods that have limits in adequately treating the above mentioned complexities and uncertainties. As a result, mining companies sometimes suffer from low efficiency, and are vulnerable to occasional major perturbations. It appears that the complexity of business and operational environment in the mining industry sometimes overwhelms the ability of mining companies to efficiently analyse and manage such increasingly difficult issues.

Consequently, there is a need for some alternative and enhanced methods and tools in order to comprehensively understand and model the complex business and operational environment in mining. The former may help define more efficient means of organizing and managing mining enterprises. This way, mining enterprises can improve their overall effectiveness, enabling a sound management and sustainable development.

We consider that in such a context, mining enterprises should be considered as complex adaptive systems (CAS). The methods and tools of complexity science (theory) are recommended in those circumstances in order to better understand their behaviour and to design appropriate management policies (OECD, 2009, 2011; Farmer 2012). This is also discussed and recognized by Smith *et al.* (2010). The definition and characteristics of both the CAS and complexity science will be addressed below.

This paper aims at proposing an enhanced and complementary approach for a strategic planning and asset management decision-making framework for mining companies by considering them as CAS.

Section 2 introduces the concept of complexity science (theory). It also includes a high level description of complex (adaptive) systems and their characteristics. Section 3 presents a literature review upon the analysed topic, and section 4 proposes a global model of strategic planning and asset management in mining in the context of business and operational complexity. Section 5 discusses the benefits, and impending challenges of applying this concept in the mining industry. It also highlights some future research works in this field.

4.2 Overview of the Complexity Science and Complex Adaptive Systems

A new interdisciplinary field called *complexity science* has emerged and evolved over last few decades. It seeks to understand, predict, and influence behaviours of complex systems (Chan, 2001; Farmer, 2012; Blouin, 2012; OECD, 2009; Rickards, 2009). In this movement, the Santa Fe Institute was created in the early 1980s aiming at discovering, comprehending, and communicating common fundamental principles in complex physical, computational, biological, and social systems (Santa Fe Institute for Complexity Science, 2015). This discipline deals with issues that traditional science has previously had difficulty addressing, such as non-linearity and discontinuities, self-organization, emergence, as well as aggregated macroscopic patterns rather than causal microscopic events, probabilistic rather than deterministic outcomes and predictions and changes instead of equilibrium (OECD, 2009).

There is no commonly agreed definition of complexity science. For example, the University of Southampton and its Centre of Complexity Science Focus suggested a definition which may be reasonably acceptable:

> Complexity science is the scientific study of complex systems, systems with many parts that interact to produce global behaviour that cannot easily be explained in terms of interactions between the individual constituent elements (Complexity Science Focus, 2015).

Ramalingam and Jones (2008) explain that complexity science is not a single theory – it encompasses more than one theoretical frameworks and is highly interdisciplinary, seeking the answers to some fundamental questions about living, adaptable, and changeable systems.

Another document produced by the European Commission states that complexity science is merely the science at its limits (European Commission, 2007).

The complex adaptive systems (CAS) are dynamic systems able to adapt in and evolve with a changing environment. They exhibit coherence under change, via conditional action and anticipation, and they do so without a strong central direction. CAS are self-organizing, evolving, dynamic, rarely predictable, and not proportional nor additive. It is important to recognize that there is no exact separation between a complex system and its environment (Chan, 2001; NISAC, 2015; Current, 2000). In fact, the complexity may only arise in the context of a system.

Some basic characteristics of complex (adaptive) systems are listed below (Alderson and Doyle, 2009; Blouin, 2012; Carrillo, 2011; Farmer, 2012; Goldstein, 2008; Homer-Dixon, 2011; NISAC, 2015; Ramalingam and Jones, 2008; OECD, 2009, 2011; Current, 2000). Some theoretical background has been defined in the late 1980s (Bak *et al.*, 1987) where the authors numerically demonstrate that dynamical systems with extended spatial degrees of freedom naturally evolve into self-organized critical structures characterized by barely stable states. Other characteristics of CAS include:

- *Adaptability and feedbacks (feedback loops)*: allow systems to evolve i.e. to promote and/or inhibit changes within the systems. In this context, the boundaries of a complex system are rather irrelevant given numerous interconnections between both its environment and internal components. Example: A large company is a highly complex system, with individuals and organizations interacting on social, political, economic and physical levels, constantly changing and adjusting to one another.

- *Emergence*: where unexpected system characteristics and behaviors may emerge from simple rules of interactions (system-level patterns are not easily identified by examining the system's individual constituents).
- *Attractors:* some complex systems spontaneously and consistently mutate to recognizable dynamic states known as attractors. While they might, theoretically, be capable to exhibit a vast variety of states, they mostly exhibit the constrained attractor states. An attractor is a recognizable dynamic state of a system that may continuously reappear. Example: The rules, norms and culture of an organization are attractors which define its functioning and possible states. Complex systems have an extreme sensitivity to their initial conditions. Even minor differences in initial conditions may lead to a completely different evolution of events when those systems are involved.
- *Self-organized criticality and self-organization*: a complex system may possess a self-organizing attractor state that has an inherent potential for abrupt transitions of a wide range of intensities. At a system level, it means the autonomous adaptation to changing conditions as a result of the adaptability of the individual components. Experience has shown that complex systems can be influenced, but cannot be directly controlled. Example: financial markets, commodity prices, etc.
- *Chaos or edge of chaos*: one of the first known features of complex systems was chaotic dynamics, characterized by extreme sensitivity to initial conditions. Chaotic systems are not entirely predictable. They show order due to an underlying attractor. A system can be predictable and stable on one time scale, and complex/chaotic on another.
- *Nonlinearity*: complex systems usually exhibit nonlinear dependence of external and internal influential factors. This characteristic basically means that changes in one property or component may have a disproportionately large or small effect on another property or component. Prediction in such a system requires sophisticated probabilistic algorithms.

- *Phase transitions*: the behavior of complex systems changes suddenly and dramatically (and, often, irreversibly) when a "tipping point", or phase transition point, is reached.
- *Power laws*: complex systems are often characterized by probability distributions that are best described by a particular type of slowly decreasing mathematical function known as a power law (i.e. fat tail distributions).

EPRI (2004) defines eight characteristics of technical and organizational CAS that go well along with the features presented above:

- The system includes several functional, operational, and management layers.
- The technologies employed are multistage, multicomponent, heterogeneous, and distributed.
- The system comprises a combination of dynamic, interactive, and nonlinear entities.
- The behavior is influenced by uncertain cause-and-effect relationships and unscheduled discontinuities (for example, failures).
- The system is vulnerable to attacks and local disturbances with the risk of potentially rapidly propagating (almost instantaneous) cascading effects, leading to widespread system failures.
- Many independent points of interaction exist.
- The number of interactions increases much faster than the number of participants.
- The system behavior is too complex to enable centralized real-time control.

CAS may function at various time scales (from seconds to years or decades), and at multiple spatial scales (from less than one millimeter to several kilometers or more).

Orrell and McSharry (2009) state that complex systems cannot be reduced to simple mathematical laws to be modelled properly. This position is also shared at some extend by Farmer (2012).

Complexity science (or complexity theory) has known an application growth in recent years in almost all domains of human activities. Those applications also include the strategic management of complex organizations (Alderson and Doyle, 2009; Blouin, 2012; Carrillo, 2011; DeRosa *et al.*, 2008; Abbott, 2007; EPRI, 2004; Current, 2000; Farmer, 2012; Santa Fe Institute for Complexity Science, 2015; Gaha, 2012; Goldstein, 2008; Glouberman and Zimmerman, 2002; European Commission, 2007; Gershenson, 2013; Grobbelaar and Ulieru, 2007; Maldonado and Gómez Cruz, 2012; Lewin *et al.*, 1998; Homer-Dixon, 2011; Hu *et al.*, 2008; Smaldino, and Schank, 2012; Kemper, 2012; Kremers, 2012; NISAC, 2015; Meyer, 1998; OECD, 2009, 2011; Samet, 2011; Ulieru and Doursat, 2011).

The complexity science helps reframing our views of complex (adaptive) systems which are only partially understood by traditional modelling techniques. Thus, it offers an alternative and complementary view of the real world.

In order to perform analyses in this field, several methods and tools drawn from the complexity science have been developed and used such as Agent-based or Multi-agent Based Models, and Network Analyses. Additional complexity-related techniques are also employed, although their use is not unique to complexity science: Data Mining, Scenario Modelling, Sensitivity Analysis, Dynamical Systems Modelling, Artificial Intelligence, and Analytic Deliberative Decision Making Process (OECD, 2009, 2011; EPRI, 2004; Farmer, 2012; Gaha, 2012; Kremers, 2012; NISAC, 2015; Elliott, 2010).

Considering the characteristics discussed above, and taking into account the complexity of both modern mining organizations and their business and operational environment, we can reasonably consider them as CAS. Consequently, we strongly believe that the strategic planning and asset management in the mining industry may be enhanced through methods and tools rooting in complexity science.

4.3 Literature review

Research works in the fields of strategic planning, impact of uncertainties, optimization and asset management in mining using innovative approaches have been performed by several authors. Some key contributions are discussed below.

McGill University's research centre COSMO is devoted to develop new frameworks for orebody modelling and strategic mine planning based on stochastic models and optimization. This research program focuses on exploring a key element of sustainable mineral resource development, namely a new risk-based framework for holistic mine planning, design and production scheduling founded upon stochastic optimization and modelling (COSMO, 2015).

Dehghani *et al.* (2014) analyze simultaneously the uncertainty of both metal price and operating costs as the most important parameters in mine economic uncertainty. For this purpose, they use a pyramid technique method based on the multidimensional binomial tree method. The authors state that this technique enables evaluating the mining projects under the situation of multi-uncertainties. A case study is carried out and achieved results are compared with other methods such as binomial tree. The authors conclude that when uncertainties are studied with the pyramid method, the evaluation of the mine suggests a more reliable net present value.

Salama *et al.* (2013) performed research works using a combination of discrete event simulation and mixed integer programming (MIP) as a tool to improve decision-making in the process of generating and optimizing mine plans.

Dehghani and Ataee-pour (2013) analyze the effects of economic uncertainties on mining project evaluation using the Real Option Valuation (ROV). They used the Discounted Cash Flow and ROV methods to compute the Net Present Value of a copper mine under uncertainties regarding operating costs and metal price.

The same authors (Dehghani and Ataee-pour, 2012) consider mining projects as complex businesses that demand a constant risk assessment. This is due to various uncertainties that influence the value of a mining project. The authors classify those uncertainties as exploration, economic and engineering uncertainties. They state that the evaluation of a mining project under these uncertainties is difficult and may sometimes lead to make a wrong decision by managers and stockholders.

This research uses the binomial tree technique to compute the net present value of a copper mine under three scenarios. The authors conclude that the mine evaluation suggests greater net present value when uncertainty is considered for both price and operating costs.

Topal and Ramazan (2012) present a network linear programming (LP) model to efficiently optimize strategic planning and production scheduling by maximizing the net present value (NPV). The model is applied to optimize the strategic schedule over a 50-year life span for a large mining district in Western Australia, a region of the world that operates many mines and plants on its territory.

Evatt *et al.* (2012) present a methodology that enables to consider a modifying factor of price uncertainty to be included within such a reserve estimate. The paper proposes an efficient and general methodology which can quantify the effect of price uncertainty within reserve estimates, providing both the expected reserve size and the associated distribution.

Abdel-Sabour and Poulin (2010) investigate on how to deal with uncertainty when analyzing mine expansion decisions. The decision to go forward with a mine expansion proposal can represent a challenge to decision-makers who have to fully take into account uncertainties and risks. The authors show how ignoring uncertainties in the conventional financial analysis can affect the expansion decision.

Azapagic and Perdan (2010) propose an integrated approach to managing corporate sustainability along whole supply chains. The application of the approach is illustrated by a real case study of a company in the mining and minerals sector. The paper aims to contribute towards a more systematic and structured incorporation of sustainability thinking into corporate practice, as well as providing some practical guidance to companies in their efforts to become more sustainable.

Ben-Awuah *et al.* (2010) develop a discrete-event simulation model to link long-term predictive mine plans with short-term production schedules in the presence of uncertainty. They present a discrete-event simulation model for open pit production scheduling using the SLAM simulation language.

Komljenovic (2007) proposes a holistic risk-informed, performance-based asset management in mining. This approach is intended to maximize both net present value (NPV) of the mine, and long-term profitability through a continuous support of the decision-making process.

Considering that the strategic planning and asset management are continuous and long-term activities and the commitments of a mining company, forecasting both the trends and the behaviour of all relevant influential factors of their business and operational environment is vital. The literature review below highlights limitations of prediction approaches that should be taken into account. It also discusses how those limitations could affect both the strategic planning and asset management, as well as the overall performance of the enterprises.

There is growing empirical evidence which shows that accurate forecasting in the economic and business world is quite challenging. Practically all economic and business activities in the mining sector and other industries are exposed to events that are basically unpredictable. Some examples can illustrate our inability to foresee major crises or changes: recent substantial variations in commodity prices (e.g. coal, iron ore, oil, copper, gold), the subprime and credit crunch crises, major market crashes (1987, 2008/2009), the collapse of Lehman Brothers, Enron, WorldCom, LTCM and Amaranth, etc. (Makridakis *et al.*, 2009; Taleb, 2010; Triana, 2009; Hand, 2014; Orrell and McSharry, 2009; Kreye *et al.*, 2012). All those events had or may have a significant impact on the overall performance of the mining sector and other organizations since they usually produce cascading effects in the whole market.

Robert Shiller, the 2013 Nobel Prize Laureate in Economic Sciences considers that the models used in economic science are more vulnerable than those applied in physics or engineering given that their validity cannot be entirely determined due to various approximations and assumptions (Shiller, 2013). Furthermore, these models should also characterize and model human behaviours. The accurate modelling of the latter is quite challenging, and almost impossible due to its complexity. Additionally, numerous authors are of opinion that it is wrong to consider that human decision-making is always rational (Kahneman, 2012; Rickards, 2009;

Shiller, 2013; Taleb, 2010; Triana, 2009). This situation may lead to various cognitive and motivational biases in the decision-making process that could negatively affect the desired outcome (Montibeller and Winterfeldt, 2015).

The experience has shown that most of the time prediction models fit past data well, but are not so good to foresee future events and their trends. It is particularly true in the case of complex (adaptive) systems (Makridakis *et al.*, 2009; Makridakis and Taleb, 2009a; Taleb, 2010; Goodwin and Wright, 2010). Orrell and McSharry (2009) suggest that we could improve forecasting models by integrating information from disparate sources.

In addition, the society and the business sector continue to face extreme, rare and often disruptive events (natural and human-made) that are completely unexpected, and sometimes even outside the realm of our imagination (Hand, 2014; Taleb, 2010; OECD, 2011; Aven, 2013). These events are labelled as "Black Swans"[2] by Taleb (2010). Their occurrences often yield undesirable cascading effects that are very challenging to deal with. Several authors consider that they should be seriously taken into consideration in engineering and business analyses (Aven, 2014, 2013; Muller, 2010; OECD, 2011). H.G. Muller states: *"Decision makers in both the public and private sectors, as well as analysts, engineers, and scientists must understand that it is no longer acceptable to consider rare events as external to their design, analysis, and operating plans"* (Muller, 2010). Some researchers use the term "Wildcard" for those events in asset management and business planning (Markmann *et al.*, 2013; Mendonca *et al.*, 2009).

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[2] Definition of a "Black Swan" event such as provided by (Taleb, 2010): first, it is an outlier, as it usually lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature tries to elaborate explanations for its occurrence after the fact, making it explainable and predictable.

Several authors strongly recommend the complexity science (theory) and its various modelling techniques as one of the potential and promising means for coping with the complexity of systems and uncertainties (Farmer, 2012; Hazy *et al.*, 2007; OECD, 2009, 2011; Blouin, 2012; Homer-Dixon, 2011; Ramalingam and Jones, 2008; Samet, 2011; Ulieru and Doursat, 2011).

4.4 Global Model of Strategic Planning and Asset Management in Mining in the Context of Complexity

Strategic planning and asset management in mining are made up of a set of interacting and interdependent activities and constituent elements in a multilevel structure. Despite valuable research works in this area, there are still opportunities to further expand them. We believe that new concepts and approaches should take into account more systematically the overall complexity of the mining business and operating environment. One of the means consists in considering mining organizations as a complex adaptive system (CAS).

In addition, mining companies are part of larger systems and entities, each with their own people, processes, organizational structure and rules, technologies, markets, resources, legal constraints, and ways of carrying out business. There are elements that mining enterprises may efficiently predict and control (mostly technical and technological systems within them). Other factors may be rather efficiently influenced and directed, but not necessarily tightly controlled by a mining company (enterprise-wide structure and organization, way of performing business activities). The prediction of those factors is more challenging due to associated uncertainties. Finally, there are all other elements representing the environment of mining enterprises that they cannot accurately predict, control or strongly influence (e.g. natural, business, regulatory, political, and market conditions). However, those factors usually exercise both a strong influence and a major impact on their operations and overall performance. Figure 4.1 depicts the hierarchy of this overall operational and business context.

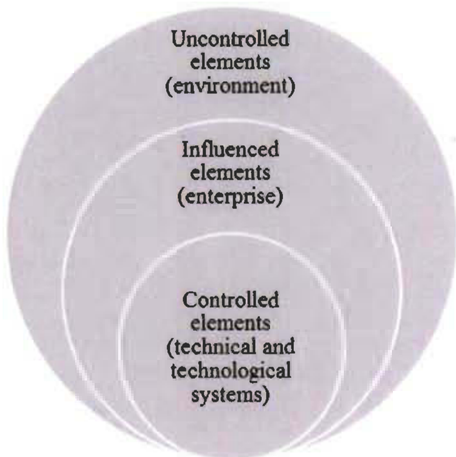

Figure 4.1. Operational environment of a mining enterprise

Thus, it is necessary to develop a theoretical, conceptual model of the strategic planning and asset management for mining companies that identifies and captures key constituent elements and influential factors, as well as their relationship, interdependencies and complexity. It is depicted below.

4.4.1 Global Model

This paper proposes a global model for strategic planning and asset management in mining, which integrates all relevant engineering, natural, operational, organizational, economic, financial, as well as other quantitative, qualitative and intangible influential factors in a structured and systematic manner. The impact of uncertainties and complexity of the business and operational environment is systematically taken into consideration. Such integrated model has not been considered in existing studies led in this field.

The approach can also take into account the impact of extreme and rare events in the overall strategic asset management decision-making process. This aspect has usually been neglected in both existing research works and practice despite the fact that those events could have severe consequences on the performance of mining organizations.

The proposed approach is intended to be generic, applicable and adaptable to any size and any type of mining companies. However, it should be stressed that it is not suggested for day-to-day decision-making, but rather to the strategic asset management decision-making affecting both mid and long term performance and sustainability of a mining enterprise.

Figure 4.2 presents a proposed high-level global model which consists of six sub-models:

1. market and revenue sub-model (predominantly external to a mining organization, but has a major impact on its global performance; this constituent element may not be efficiently controlled or influenced by an enterprise);
2. sub-model of reliability, availability and maintenance (RAM) factors (mainly internal to a mining enterprise; in principle, it may be well controlled and influenced);
3. sub-model of operations and operational constraints (mainly internal to an enterprise; it may be controlled and strongly influenced);
4. cost sub-model (both internal and external to a mining enterprise; it may be partly controlled and influenced);
5. organisational sub-model (mainly internal to a mining enterprise; it may be partly controlled and efficiently influenced), and

6. sub-model of impact regarding other influence factors (mainly external to a mining organization, but has a major impact on its global performance; normally, this factor cannot be efficiently controlled or influenced).

These sub-models and their constituent parts interact in a complex manner that leads to the behaviour of the global model (system) that is not obvious from the individual behaviour of its elements. The latter are complex themselves as far as their structure and functioning are concerned. Consequently, the strategic planning and asset management activities of a mining company may be considered to be an emergent phenomenon integrating several functional, operational, and management layers.

They involve numerous feedback loops reacting to the influences of their environment as well as the behaviour of the other constituent parts usually generating a non-linear and adaptive behaviour for the whole system. If any of the interacting processes or elements is changed or experiences more or less significant variations, the functioning and the performance of other elements and the entire system may be seriously altered.

With those characteristics, we clearly demonstrate that the mining enterprises show the main features of CAS, and should be analysed as such.

Therefore, the proposed global model of mining organizations as CAS would enable to continuously take into consideration and to integrate the overall feedback from its sub-models and their constituent parts. It also includes the impact of the mining organization's strategic orientation, asset management strategy, stakeholders' requirements and expectations, sustainable development goals, as well as risk management constraints (Figure 4.2).

Additionally, Figure 4.2 provides more details upon other factors which are constituent parts of those sub-models.

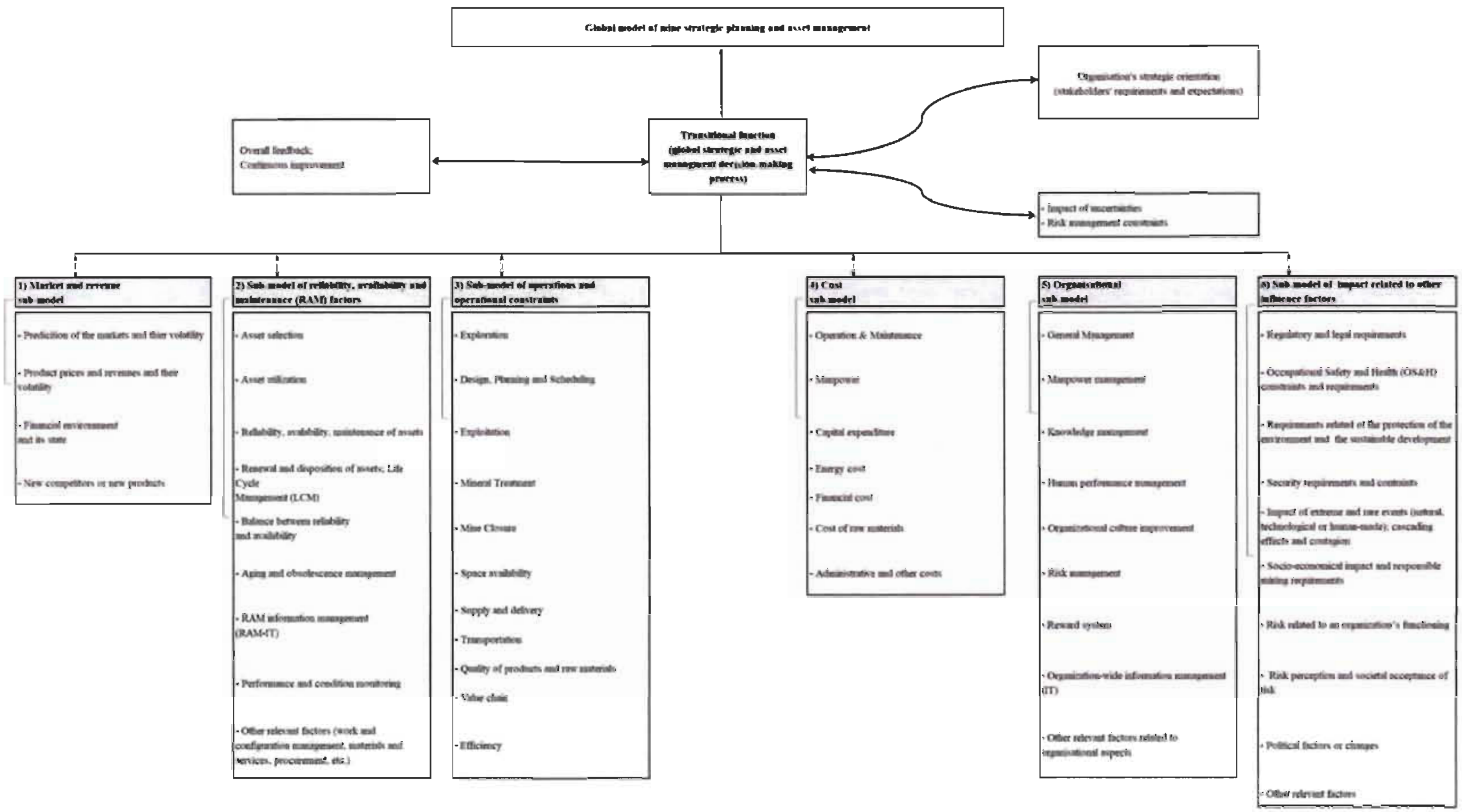

Figure 4.2. Global model of strategic planning and asset management in the mining industry

The model also enables to define and characterize the following elements:

a) identification and mapping the type and strength of connections between both the sub-models and their constituent parts, as well as the degree of their complexity;

b) mapping potential uncertainties related to sub-models and parts of the model susceptible to be affected by those uncertainties. In principle, the uncertainties affect all the sub-models;

c) approach to characterize and cope with uncertainties in the overall decision-making process (transitional function depicted in Figure 4.2);

d) approach to identify and characterize extreme and rare, but plausible events (natural and human-made) which may affect a mining organization's performance or even endanger its existence. It also involves the identification of business opportunities for the organization that could result from those events;

e) principles and approaches to achieve mining organization's robustness, resilience and flexibility facing various internal and external events both predicted and initially unforeseen in the context of business and operational complexity while remaining economically viable;

f) approach to define a more appropriate reward system for managers at different levels of a mining organization in order to ensure the development, implementation and sustainability of an efficient strategic planning and asset management framework;

The mapping process (points a) and b) above) basically includes the following components (adapted from OECD, 2011):

- Physical maps: delineate the spatial relationship between the constitutive parts of a mining enterprise and its operational and business environment. They may be as diverse as national boundaries or the locations of orebodies, mining sites, stores, customers, suppliers, energy sources, etc.

- Conceptual maps: are useful to provide insights regarding the structure and the evolution of mining companies as complex adaptive systems. They may or may not have tangible, physical components. These maps are mainly helpful in depicting "human" networks or other large, complex systems that do not necessarily have important physical components. In the strategic planning and asset management field, it basically involves all the sub-models presented in Figure 4.2.
- Process and/or organizational maps: describe a sequential and sometimes time-dependent process. In practice, these maps could be presented in the form of decision-trees, propagation trajectories, an order of operation or an organizational structure and hierarchy. Process maps provide information upon the order or structure of a system (example: to what extent is it linear?), the options available at each decision-point, external and internal factors which may affect the process, and a definition regarding possible outcomes or end-results.

Mapping tools enable us to better understand the structure and general features of a particular complex adaptive system. The proposed global model (Figure 4.2) is a first step in the mapping process that should be further refined. Once maps are developed adequately describing a CAS' scope, components and various relationships, an effort should be made to model the system. At the end of the mapping and modelling processes, it is necessary to perform a final, coherent integration of both the sub-models and their constituent parts into a definitive, holistic transition function representing a final decision-making model (Figure 4.2).

It should be stressed that the methods, steps and tolls mentioned above represent early ideas based on the experience and practices in the areas where the complexity science has already been applied. They do not preclude other new methods that could emerge by taking into account the specific needs and features of the mining industry.

The above presented sub-models and their constituent parts are partly developed and may already be used in various forms in the mining industry. However, they have been mostly established by using traditional, deterministic techniques with some improvements through probabilistic approaches. Thus, additional research works are recommended in order to apply the concepts of CAS and complexity science in this field.

4.4.2 Modelling Methods

Given that the overall proposed global model is fairly complex, the methods and tools of complexity science such as Multi-agent Models, Network Analyses, and Dynamical Systems Modelling are recommended for its development. Furthermore, the development of the global model should harmoniously integrate traditional approaches while describing the behaviour of mining organizations in their complex business and operating environment as CAS.

Some other techniques are also envisaged to support the above presented modelling methods. In this regard, Multi-attribute Decision-making methods (MADM), and Analytic Deliberative Decision Making Process (ADP)[1] are suggested. Further, Scenario Planning (Amer *et al.*, 2013; Bradfield *et al.*, 2005) may provide valuable

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1 Analytic Deliberative Decision Making Process (ADP) is a methodology that has been under development at MIT for a number of years, and has been used to study a number of decision problems (Elliott, 2010). It is applied for making decisions when there is adequate time for analysis and collective discussion, and is not appropriate for a real-time decision-making (Elliott, 2010). This methodology is also used by the U.S. Nuclear Regulatory Commission and NASA (US NRC, 2012; NASA, 2010).

inputs for a more global development of the model. They should be mainly used in handling uncertainties, and developing an integrated, holistic decision-making model (transitional function in Figure 4.2).

Meanwhile, we should be aware that building the proposed model is challenging at several levels: (i) data acquisition is difficult; (ii) each sub-model and its constituent parts are in principle independently complex; (iii) the operational and business environment is constantly changing and evolving; and (iv) governing regulations are continuously changing, and consequently difficult to capture.

4.5 Discussion

The consideration of mining companies and their strategic planning and asset management as complex adaptive systems (CAS) may potentially change some paradigms but also bring certain benefits. However, the development and implantation of this new approach also involve a number of challenges. Given that the proposed methodology is at initial stages, it is necessary to outline the future research agenda in this field. These elements are discussed below.

4.5.1 New insights through complexity science

The fact that the business and operational environment in the mining industry is complex is not always adequately recognized in analyses, management or decision-making processes. Mining companies often use traditional methods and reductionist models that are not necessarily able to capture their overall complexity. Complex systems or problems cannot be usefully deconstructed into their casual components. When this is done, more unknowns and uncertainties are introduced.

Obviously, traditional approaches in analyses, management or decision-making process cannot be abandoned. We are of opinion that both approaches are necessary and they should be considered as complementary. In fact, many problems or challenges may still be successfully resolved using traditional approaches. This paper proposes a concept where the complexity science may be introduced in the strategic decision-making process and asset management in the mining industry, but does not preclude the use of traditional or other approaches where appropriate. In fact, we should answer the following questions: what may the complexity science concept offer to mining companies, and how its insights differ from existing ones?

Some elements are discussed below based on the relevant experience in areas and activities where it has already been applied at various levels (Blouin, 2012; Brodu, 2009; Goldstein, 2008; Homer-Dixon, 2011; Farmer, 2012; NISAC, 2015; Current, 2000; Ramalingam and Jones, 2008; Miller *et al.*, 2004; OECD, 2009, 2011; Samet, 2011; Ulieru and Doursat, 2011; Alderson and Doyle, 2009; Carrillo, 2011; Smith *et al.*, 2010; Hu *et al.*, 2008; Wang, 2012; DeRosa *et al.*, 2008).

Since there is no tangible experience in the mining industry with complexity science and the CAS some thoughts are presented below. They are based on the experience of its application in other human activities, and may be relevant to the mining sector.

- Complexity science enables users to bridge natural, technical, socioeconomic, and management sciences by serving either as explanations of encountered phenomena or a guide for better understanding and actions.
- Through a better understanding of the patterns by which unpredictable, unknown and emergent changes happen, complexity science enables new ways to interpret mining companies as complex adaptive systems, as well as the problems emerging within them. The aim of complexity science is to

generate insights that help comprehending complex problems in a more realistic and holistic manner, thereby supporting more useful actions.

- These better insights may allow us to embrace what we have previously seen as "messy realities." In fact the concept of complexity science may be used in a flexible manner and in combination with traditional approaches. This might enable comparisons between scenarios, cases and systems that appeared previously not related, supporting relevant insights and helping to point toward possible effective actions.
- Experience has shown that we should be cautious while applying "good practices" or "best practices." They may work in one setting but play out in very different ways in other settings. It is especially true in the mining industry. Complexity science methods may help in investigating possible scenarios and developments in this regard and in recommending the best course of action.
- Therefore, the complexity science suggests new ways to think about known or anticipated problems and new questions that should be asked and answered. It focuses on identifying and analysing trends, patterns of behaviour, as well as associated probabilities and uncertainties, rather than seeking to predict specific events.

4.5.2 Anticipated benefits

The proposed model may bring some tangible benefits to mining companies. These include, but are not limited to:

- Elaboration of a robust and integrated strategic asset management decision-making model with a rigorous scientific and technical basis. Complexity science can offer new insights for better understanding and business model and operational environment, and thus help in designing more successful strategic asset management decision-making framework.

- Increased robustness, resilience and flexibility of mining organizations facing numerous uncertain future scenarios, including plausible extreme, rare and potentially disruptive events.
- Optimized return on investment and growth.
- Long-term planning and performance sustainability through more realistic models. One of the most important strengths of the models is their ability to assess a number of different scenarios in order to determine what conditions might lead to an event with undesirable (or desirable) consequences. Thus, adequate strategies may be designed to promote favorable scenarios.
- The ability to demonstrate best value-for-money within a constrained funding regime.
- Compliance with regard to the required standards and legislation.
- Improved health, safety and environmental performance.
- Improved corporate reputation and benefits which may include enhanced shareholder value, better staff satisfaction, and more efficient and effective procurement from the supply chain; the ability to demonstrate that sustainable development is actively considered within the strategic planning and management of the assets over their life cycles.

4.5.3 Challenges

It is also necessary to highlight the many challenges that the proposed approach may encounter. These include, but are not limited to:

- Gaps in our scientific understanding of complexity, and in our ability to apply it in real life situations in the mining industry.

- Adequate identification and mapping of constituent parts and sub-systems where complex issues may emerge or be encountered; satisfactorily describing the nature and extent of their connections (i.e. right understanding of the whole complex system).
- Availability of relevant data to perform required analyses. It should be investigated which input data are really needed, and whether they are available. Collecting and preparing data may involve considerable efforts.
- Availability and adequacy of decision-making support models and tools: they have to be developed and tailored to the needs in the mining industry. Real-world complexity adds challenges to the modeling of the strategic planning and asset management in mining. Moreover, CAS do not always act as expected, since each individual component, while easily described in isolation, may behave differently when functioning in combination with different system components. The difficulty also lies in the large number of parameters, which must be included to model the system accurately. Modeling in this situation becomes much more difficult and requires more sophisticated tools (OECD, 2011). To be useful for the purposes outlined above, the model shall be built on solid foundations and its limitations need to be understood. This work also requires an adaptation of existing traditional tools to better fit with novel methods and approaches.
- Consequently, the costs related to bringing a complexity framework into the mining industry may not be trivial (new research, data collection, development of methods and tools, implementation, training, maintenance, etc.). However, mid and long-term benefits are without doubt assured, as it has been shown in activities and industries which have already embraced it.
- Acceptability of the novel approach by the mining industry: An introduction of new ways of performing analyses or decision-making may face some resistance and unwillingness regarding their adoption.

Therefore, the introduction of the concept of complexity science should be progressive, stepwise, and demonstrate some tangible gains at each stage. In this case, the mining industry will increasingly engage in both its use and a more systematic application.

4.5.4 Future research

We need to better understand the scope, benefits and challenges of the complexity science applications in the mining industry. It should be investigated through future research works and actual applications. These include, but are not limited to:

- Analyse and define an adequate balance between the use of traditional and novel approaches. It also includes reasonable combinations of those two types of approaches within a global methodology.
- Define and characterize more accurately the nature and strength of interconnections between sub-models and their constituent parts, as well as associated uncertainties.
- Develop a detailed model of mine strategic planning and asset management.
- Pursue detailed studies regarding the sub-systems and constituent parts of the global model in order to achieve a better understanding and refine it.
- Develop a multi-agent simulation-based tool of the model (or by using another technique, or a combination of techniques, mentioned previously), which will provide information upon its behaviour patterns as a mean of changing business and operational environment. This topic also includes determining how we compose multiple interacting adaptive processes within a single comprehensive enterprise system.
- Identify and map in a more detailed way associated characteristics of complexity for both sub-systems and their constituent parts; and

- Conceive and carry out a pilot project with an actual mining enterprise in order to calibrate and validate the model, and to acquire a better understanding of the approach.

Furthermore, it is suggested to include the concept of complexity science (theory) into the curriculum of mining school programs, at least at the graduate levels for further development and applications in the mining sector.

4.6 Conclusion

Facing tough international competition, mining companies worldwide are constantly forced to produce more at a lower cost. They are also confronted with a highly complex business and operational environment which also includes intrinsic uncertainties related to business, natural, technical, technological, organizational, regulatory, political, legal, financial, market, and environmental influential factors. Strategic planning and a sound asset management play a key role in this environment.

In such a context, the mining industry develops various methods and approaches that help addressing these issues. They are often based on traditional approaches that are generally unable to adequately grasp and tackle the above mentioned complexities and uncertainties. It seems that the complexity of the business and operational environment, and associated uncertainties in the mining industry can sometimes overwhelm the ability of mining enterprises to efficiently analyse and manage such increasingly complex issues.

This paper proposes a novel, enhanced approach for a strategic asset management decision-making framework for mining companies considering them as complex adaptive systems (CAS), and based on the concept of complexity science. This science has emerged and evolved over the past several decades in other domains of human activities where complexities generally occur. In this regard, this paper depicts a global, high level model describing the proposed approach by integrating this concept.

The mining industry has not yet developed its own original framework for this purpose contrary to some achievements and experience with complexity science applications gained in other human activities or industries. This paper indicates that there are significant benefits and potential for further studying, understanding and expanding this concept to the mining industry.

This way, it may assist decision-makers in key decision-making processes and asset management by providing more realistic insights. The proposed approach complements existing traditional approaches and also intends to integrate them into a holistic process.

This method is envisioned to maximize the overall performance of a mining enterprise. It also enables designing a robust, sustainable and resilient organization which is economically viable. It may be particularly useful in order to optimize several mining sites belonging to the same company.

This approach will be undoubtedly beneficial for mining companies facing a fierce competition on the international scale. It also goes along with modern developments worldwide. The ultimate success of such an endeavor requires careful and adequate adaptation of the proposed high-level ideas with regard to operational and business context of the mining industry. This paper also provides a discussion upon challenges and recommended future research and applications of this concept in the mining industry.

It is also worth emphasizing that similar approaches may be developed for other industrial branches.

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CHAPITRE 5 – ARTICLE 2

RISKS OF EXTREME AND RARE EVENTS IN ASSET MANAGEMENT

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Safety Science, 2016, *88*, 129-145.

Highlights

- The occurrence of extreme and rare events in complex systems has been analyzed.
- The risks of those events in asset management have been studied.
- A methodology is proposed to integrate them in a holistic asset management decision-making.
- A methodology is proposed to integrate them in asset management.
- Two case studies are carried out in order to illustrate the proposed approach.

Abstract

Modern companies operate in a complex business and operational environment, which generates new types of risks that were relatively unknown just a few decades ago (e.g. cyber security), and creates favorable conditions for the emerging of extreme and rare events that may seriously perturb the current and long-term performance of enterprises. Current practices generally neglect taking into account those risks. Analyzing and managing them through traditional methods has recently shown to be less efficient. Advice and input from technical experts, strategic planners or knowledgeable managers may be insufficient or too narrowly focused to adequately manage the complexity of the systems and structures in a constantly changing and barely predictable environment. It is generally due to a lack of knowledge regarding the type and range of uncertainties, the nature of interconnections, the level of complexity, as well as our low ability to predict future events. Consequently, enterprises need alternative and enhanced methods and tools in order to better understand and model the complex business and operational environment and the associated risks.

This paper proposes a high level Risk-Informed Decision-Making framework in asset management that integrates risks extreme and rare events as part of an overall risk assessment and management activity. The research focuses on the methodology aimed at identifying, assessing and managing those risks in asset management. We believe that this approach may support organizations in becoming more resilient and robust in a changing and complex environment. We expose two case studies that demonstrate the applicability of the proposed model.

Keywords: asset management, extreme and rare events, complex adaptive systems, uncertainties, risk-informed decision-making.

5.1 Introduction

Globalization and strong competition are part of a typical operational and business environment. The ability of enterprises to create and implement innovative concepts is decisive to meet the demands regarding competitiveness, and to ensure their operations and further development.

During the last decades, Asset Management (AsM) and Business Continuity Management (BCM) have become prevalent approaches among successful organizations as effective tools allowing to deliver value from assets and ensure the sustainability of the business and its operations (Komljenovic *et al.*, 2015; Torabi *et al.*, 2014). The positive evolution of AsM practices, experience and knowledge led to the publication of a new International Standard on AsM, the ISO 55000 (ISO, 2014a). The BCM is an approach used by organizations as an effective precautionary tool aiming at mitigating the consequences of disasters, and making them more resilient against disruptions. Good practices are enacted in an International Standard (ISO, 2012). The business continuity represents the capability of an organization to continue delivering products or services at acceptable predefined levels following disruptive incidents (ISO, 2012; Torabi *et al.*, 2014). Business Impact Analysis (BIA) and Risk Assessment (RA) are the steps in BCM which identify the components of a system and try to define plans to ensure the continuity of the business's critical functions (determined in BIA) in emergency situations (determined in RA) (Torabi *et al.*, 2014). Hence, there are overlapping areas between AsM and BCM. The main focus of the current paper is on AsM, and the BCM concept will be used to support analysis in the former when required (e.g. a less studied issue in AsM relates to emergency situations following various disruptive events or their combination).

AsM is sometimes stereotyped as being upon maintenance and reliability. However, it covers much more than those two areas. The ISO Standard provides the following definition of AsM: *Coordinated activity of an organization to realize value from assets* (ISO, 2014a). The same Standard defines an asset *as an item, thing or entity that has potential or actual value to an organization.*

As per best practices, AsM should not only focus on the asset itself, but also on the value that it can deliver to the organization. It involves the balancing of costs, benefits, opportunities and risks against the desired performance of the assets, in order to achieve the organizational objectives. This balancing activity often involves the consideration of different timeframes and geospatial scales. AsM interacts with virtually all the functions of an organization, and focuses on the total business impact (IAM, 2015).

Enterprises operate in a business and operational environment characterized by significant complexities and intrinsic uncertainties[1] (Komljenovic *et al.*, 2015). The

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[1] There are two types of uncertainty in engineering (Kumamoto, 2007; US NRC, 2013): 1) Aleatory uncertainty: This type of uncertainty arises when an event occurs randomly. This uncertainty can be expressed in terms of probability or frequency. A random equipment failure is a typical example of

risk represents the effect of uncertainties on objectives (ISO, 2009a; Aven and Aven, 2015). This environment has also produced new types of risks that were relatively unknown just a few decades ago (e.g. cyber security), and created favorable conditions for the emerging of extreme and rare events[2] that may seriously perturb the current and long-term performance of enterprises.

Analyzing and managing those risks within AsM through traditional methods has recently shown to be less efficient. Advice and input from technical experts, strategic planners or knowledgeable managers may be insufficient or too narrowly focused to adequately manage the complexity of the systems and structures in a constantly changing and barely predictable environment (Glouberman and Zimmerman, 2002; Rzevski and Skobelev, 2014). It is generally due to a lack of knowledge regarding the type and range of uncertainties, the nature of interconnections, the level of complexity, as well as our low ability to predict future events (Aven, 2015a,b, 2014; Chopra and Khanna, 2015; Leveson, 2011; Makridakis *et al.*, 2009; Makridakis et Taleb, 2009a,b; Miller, 2010; OECD, 2011; Orrell and McSharry, 2009; Paté-Cornell, 2012; Taleb, 2005, 2010, 2012).

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an aleatory uncertainty. This type of failure is defined as a failure occurring at a predictable rate, but at an unpredictable (i.e. random) time; 2) Epistemic uncertainty: This type of uncertainty has been referred to as a state-of-knowledge uncertainty. There are three types of epistemic uncertainties: parameter, model, and completeness uncertainty. Epistemic uncertainties arise when we make statistical inferences from data and/or from incompleteness in the collective state of knowledge. Epistemic uncertainties relate to the degree of belief that an analyst has in the representativeness or validity of a model and in its predictions. ISO notes that the uncertainty is the state, even potential, of information related to the understanding or the knowledge of an event, its consequences, or its likelihood (ISO, 2009).

2 Extreme and rare events include, but are not limited to, natural disasters, financial and market crashes, pandemics, major failures of critical assets, major industrial accidents, prolonged shortage of power/energy supply, political changes, unrest and instability, armed conflicts or terrorist attacks, radical changes in a regulatory framework, extremely negative treatment in mass-media creating an unfavorable business environment, major legal pursuits, payment defaults or loss of major customers, etc.

Considering that AsM is an organization's long-term activity, forecasting all relevant influential factors of their business and operational environment is vital for practically all technical and business decisions. The forecasting represents a key part of risk assessment/management (RA&M) and sound decision-making in AsM. Our understanding is that it should also consider the risks of extreme and rare events (E&RE) as part of an overall risk assessment and management activity in AsM (ISO 2014b,c; ISO 2009). Consequently, assessing and managing risks of E&RE in AsM becomes vital. However, there are almost no significant research works related to RA&M of ER&E in asset management, despite the importance of this topic (Komljenovic and Abdul-Nour, 2015). Consequently, enterprises need alternatives and enhanced methods and tools in order to better understand and model the complex business and operational environment in AsM, and its associated risks.

The present study aims at developing a holistic approach for the identification, characterization and treatment of the risks of extreme and rare events in asset management that takes into account a complex business and operational environment.

The remainder of the paper is organized as follows: Section 2 provides a comprehensive literature review; Section 3 depicts the methodology of decision-making in AsM, and an approach regarding the risk assessment of extreme and rare events in asset management; Section 4 presents two case studies which illustrate the proposed methodology. The paper ends with conclusions and outlines future research works.

5.2 Literature review

The development of the methodology involves several domains of expertise such as asset management, the analysis of the risks of extreme and rare events, and the theory of complexity. The review presented below summarizes some important contributions in these areas.

5.2.1 Asset Management

The concept of Asset Management is emerging as a 'mainstream' expectation for competent organizations, and it is a relatively young discipline. It has generated significant interest across various industries and is still maturing (El-Akruti *et al.*, 2013; IAM, 2015). The Standard ISO 55000 mentioned above represents an industry-wide consensus in this area and being implemented.

The nuclear power industry has invested significant efforts in elaborating asset management approaches and methods tailored to its needs and particularities. It developed the Nuclear Asset Management (NAM) process aiming to make operational, resource allocation, and risk management decisions at all levels of a nuclear generation business to maximize the nuclear power plant value to stakeholders, while maintaining the public and plant staff safety (EPRI, 2007). The nuclear power industry also elaborated Risk-Informed Asset Management (RIAM), which is a composite financial/engineering method complementary to NAM that uses a risk management approach to support long-term equipment planning and investment decisions at the corporate, fleet, plant, system or equipment levels of nuclear power organizations (EPRI, 2002, 2005).

Some other specific AsM processes were also elaborated. The petrochemical industry has developed its AsM since late 1980s (El-Akruti *et al.*, 2013; IAM, 2015). Power generation, transmission and distribution utilities produced their specific AsM (Adoghe *et al.*, 2013; Bollinger and Dijkema, 2016; Catrinu et Nordgard, 2011; Dashti et Yousefi, 2013; Scheinder *et al.*, 2006). The field of infrastructure management has been using AsM for many years (Bale *et al.*, 2015; Bush *et al.*, 2014; Doman, 2002; Nikolic and Dijkema, 2010; Osman, 2012; Younis and Knight, 2014). The transportation industry also carried out works in this area (Ballis et Dimitriou, 2010; Doman, 2002). The mining industry is starting to elaborate approaches related to asset management as well, but it is at initial stages (Azapagic and Perdan, 2010; Komljenovic et al., 2015; Komljenovic, 2007).

5.2.2 Extreme and Rare Events

The impact and risks related to E&RE have gained growing interest in the recent years. "Black Swan" or rare and surprising events were introduced and analyzed by Taleb in his book on this topic (Taleb, 2010)[3]. He had already discussed this matter in an earlier book on the subject of randomness (Taleb, 2005). Initially thought to cover financial markets, the idea of the "Black Swan" extended the metaphor to events outside of the financial world. He also highlighted that "Black Swan" events generally occur in complex systems (Taleb, 2005, 2010, 2012).

A similar definition is provided by Fowler and Fisher (Miller, 2010). Aven (2014, 2015a) considers a "Black Swan" as a surprising extreme event related to one's knowledge/beliefs that can be of different types: a) unknown-unknowns (events that are completely unknown to the scientific community), b) unknown-knowns (analysts do not have the knowledge upon an issue but others do), and c) events that are on the list of known events, but judged to have a negligible probability of occurrence, and thus are not believed to occur.

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3 Definition of a "Black Swan" event such as provided by Taleb: first, it is an outlier, as it usually lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature tries to elaborate explanations for its occurrence after the fact, making it explainable and predictable (Taleb, 2010).

Their occurrences often yield undesirable cascading effects that are very challenging to deal with. Several authors argue that they should be seriously taken into consideration in engineering and business analyses (Aven 2014, 2015a,b; Cox, 2012; Garret, 2015; Miller, 2010; National Academy of Sciences, 2014; NERC, 2010; OECD, 2011; Paté-Cornell, 2012; Rzevski and Skobelev, 2014).

Researchers and scholars tackle this issue under various angles (Aven, 2014, 2015a,b; Hand, 2014; Miller, 2010; Olson et al., 2012; Orrell and McSharry, 2009; Paté-Cornell, 2012; Taleb, 2010, 2012). The Organization for Economic Co-operation and Development (OECD) has undertaken a study aiming to get better insights regarding the risks and the impact of future global shocks. The study advances understanding of how to improve global capacity to confront sudden and highly disruptive threats, given the unknowns and the uncertainties that lead to their occurrence, causal linkages and the resistance thresholds of the systems they impact upon (OECD, 2011). The NERC has conducted a similar study of the North American bulk power system (NERC, 2010). Mendonça *et al.* (2009) have analyzed ways in which radically uncertain and disruptive events may be introduced into the corporate decision-making structures. They proposed the notion of *"wild cards"* which refers to trend-breaking/trend-creating rare events that are very difficult or even impossible to anticipate, but that should nonetheless be expected in complex and fast-evolving environments.

Paté-Cornell considers that statistics are often insufficient to support risk management of rare events given that samples may be too small, and the system may have changed. She states that "Black Swan" events represent the ultimate epistemic uncertainty or lack of fundamental knowledge. The author asserts that rare events present major risk management challenge in engineering, medicine, geophysics, finances, and many other fields (Paté-Cornell, 2012). This point of view is generally shared by several researchers and scholars (Aven, 2014, 2015a,b; Miller, 2010; OECD, 2011).

It seems that there exists a common understanding that the quantification of the risks of extreme and rare events does not allow the "prediction" of accidents and catastrophes. It is basically impossible to accurately determine low probabilities. Instead, the risk assessment is aimed at supporting effective risk management (Aven, 2015a; Bollinger and Dijkema, 2016; Cox, 2012; Paté-Cornell, 2012). The risk assessment and risk management of E&RE involve the surveillance of warning signals, precursors, and near-misses, as well as the reinforcement of the system (increasing its resilience and robustness), and a thoughtful response strategy. It also implies a careful examination of organizational factors such as the incentive system, which shape human performance and affect the risk of errors (Paté-Cornell, 2012). Cox (2012) claims that the robust and adaptive methods provide genuine breakthroughs for improving predictions and decisions in such cases.

As far as human performance is concerned, several authors argue that we cannot assume that human decision-making is always rational (Kahneman, 2012; Mosey, 2014; Rickards, 2009; Shiller, 2013; Taleb, 2010). In such situations, cognitive and motivational biases are likely to occur in the decision-making process. Those biases could negatively affect the desired outcomes (Kahneman, 2012; Montibeller and Winterfeldt, 2015). It adds to the overall complexity of the operational and business environment, and may ultimately create favorable conditions for the occurrence of extreme and rare events in a system.

Aven (Aven, 2014, 2015, 2016) claims that there is a need to i) extend the current risk conceptualization and treatment frameworks in order to include the "Black Swan" risk, ii) develop a new generation of risk assessment and decision support methods that place more emphasis on the "Black Swan" risk, and iii) better understand what the analysis captures and what lies within the management domain. To confront possible "Black Swans", we need to balance risk-based approaches, cautionary/precautionary (robustness, resilience, adaptive), and discourse-based approaches (Aven, 2015a, 2016; Cox, 2012). It is worth highlighting that this philosophy has already been adopted from the beginning by the nuclear power industry through the concepts of fundamental safety principles and defense-in-depth (IAEA, 1996, 1999, 2006).

It should be stressed that the concept of BCM considers RA&M of disruptive events as a requirement (ISO, 2012; Torabi *et al.*, 2014). However, the Standard also suggests that the opportunities created by those events should also be analyzed.

5.2.3 Complex Adaptive Systems and the Complexity Theory

How do extreme, rare and disruptive events occur? As discussed in the previous Sections, they may be interpreted as a result of a major lack of knowledge upon the nature of the phenomena under study or observation. It implies that epistemic uncertainties related to those events are substantial, but poorly understood. Several research works analyzing the phenomenon of E&RE explicitly or implicitly deem that they mostly happen in complex systems and situations due to their nature and our lack of understanding apropos them (Aven, 2014, 2015a; Hand, 2014; Mendonça *et al.*, 2009; Paté-Cornell, 2012; Rickards, 2009; Rzevski and Skobelev, 2014; Taleb, 2010, 2012).

In principle, a combination of unusual circumstances should come together to produce an extreme or rare event. However, the increasing degree of interconnections in complex organizations, systems and structures is making these circumstances more likely to occur. What are complex systems? How do we describe and model them?

Complex systems or Complex Adaptive Systems (CAS) are dynamic systems able to adapt in and evolve within a changing environment. They exhibit coherence under changes, via conditional action and anticipation, and they do so without a strong central direction. The CAS are self-organizing, evolving, dynamic, non-linear, rarely predictable with emerging behavior. It is important to highlight that there is no definite separation between a complex system and its environment (NISAC, 2015; OECD, 2009, 2011; Rzevski, 2015; Rzevski and Skobelev, 2014).

The CAS function at various time scales (from seconds to years or decades), and at multiple geospatial scales (from less than one millimeter to several kilometers or more). Orrell and McSharry (2009) state that complex systems cannot be reduced to simple mathematical laws and be modeled appropriately. This position is also shared by other researchers (Bukowski, 2016; Farmer, 2012; Rzevski and Skobelev, 2014).

Thus, a new interdisciplinary field called *Complexity Science* or *Complexity Theory* has emerged and evolved over the last few decades seeking to understand, predict, and influence the behavior of complex systems. It develops concepts, methods and tools that transcend specific applications and disciplines (Farmer, 2012). In this context, the Santa Fe Institute was created in the early 1980s aiming at discovering, comprehending, and communicating common fundamental principles in complex physical, computational, biological, and social systems (Santa Fe Institute for Complexity Science, 2015). In the early 1980s, Perrow introduced notions of complexity in analyzing major industrial accidents (Perrow, 1984), followed by Leveson in the 2000s (Leveson, 2011).

This discipline deals with issues that traditional science had difficulty addressing such as non-linearity and discontinuities, self-organization, emergence, aggregate macroscopic patterns rather than microscopic causal events, probabilistic rather than deterministic outcomes and predictions, change instead of equilibrium. In fact, the complexity science helps reframe our views of CAS which are only partially understood by traditional modeling techniques (Bukowski, 2016; Gaha, 2012; Kremers, 2012; NISAC, 2015; OECD, 2009, 2011; Rzevski and Skobelev, 2014; Complexity Science Focus, 2015).

To perform analyses, several methods and tools have been developed and used such as Multi-Agent Based Models and Network Analyses. Additional complexity-related techniques are also employed although their use is not unique to the complexity science: Data Mining, Scenario Modeling, Dynamical Systems Modeling, Artificial Intelligence, Neural Networks, Evolutionary Game Theory (Bukowski, 2016; EPRI, 2004; Farmer, 2012; Gaha, 2012; Kremers, 2012; NISAC, 2015; OECD, 2009, 2011; Rzevski and Skobelev, 2014).

5.3 Model for characterizing the risks of extreme and rare vents in asset management

For the purpose of the risk analysis of E&RE in AsM, it is necessary to firstly develop a holistic model for a decision-making process that is able to capture the overall complexity of the business and operational environment. In this research we opted for the concept of Risk-Informed Decision-Making (RIDM) as the best suited approach.

The RIDM is a concept elaborated in the U.S. nuclear power industry in the 1990s. An initial idea was presented in the White paper of the U.S. Nuclear Regulatory Commission (Travers, 1999). There is no unique definition of the RIDM, and several ones may be found across references. A cumulative experience related to its development and application led to a generic framework for an integrated RIDM (IAEA, 2011). In the aftermath, the RIDM has been embraced by other industries and activities at risk (Elliott, 2010; FERC, 2015; NASA, 2010). Hansson and Aven

(2014) present a chain value approach while discussing the relationship between facts and values in RIDM.

The RIDM is not an exact science, it is rather a discipline which involves considering, appropriately weighting, and integrating a range of often complex inputs and insights resulting from "traditional" engineering analyses, deterministic and probabilistic risk analyses, operational experience, cost-benefit considerations, regulatory requirements, allowed "time at risk", and any other relevant quantitative, qualitative and/or intangible influential factors and considerations (Bujor et al., 2010).

For the purpose of this research, the following, technology neutral, definition is proposed[4].

Risk-Informed Decision-Making: Decision-making in which the decision maker takes into account all pertinent factors, including relevant uncertainties that have a potential impact on the resolution of the issue under consideration. These factors include both quantitative and qualitative factors that are weighted in the risk-informed decision-making process in accordance with the decision-maker's judgment and experience. The "risk" component constitutes an adequately weighted input among others, whose significance is situation-specific. It is opposed to a risk-based approach where decision-making is solely based on the numerical results of a risk assessment.

Thus, the proposed RIDM approach in the AsM model also aims at integrating the risks of extreme and rare events on the overall performance of asset management.

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4 The proposed definition is mainly inspired by the COG definition of RIDM (COG, 2005)

5.3.1 Global RIDM Model in Asset Management

The asset management strategy is composed of an array of interacting and interdependent activities and constituent elements within a multilevel structure. As per best practices, it should be closely linked to the strategic planning of an enterprise (ISO 2014a; IAM, 2015). We believe that new concepts and approaches should take into account more systematically the overall complexity of the business and operating environment.

As depicted in Figure 5.1, there are elements that enterprises may efficiently predict and control (*level of technological system* where aleatory uncertainties are dominant). Other elements at the *enterprise level* may be efficiently influenced and managed, but not necessarily closely controlled (e.g. enterprise-wide structure and organization, ways of performing business activities). Epistemic uncertainties usually appear here. Finally, there are all other elements belonging to the *external environment* of enterprises (e.g. natural, business, legal, regulatory and political environment, market factors, etc.). It cannot be accurately predicted, controlled, nor strongly influenced. Its complexity is high. Epistemic uncertainties and opacity dominate the external environment. Nevertheless, it usually exercises a major impact on the strategy of AsM. Figure 5.1 illustrates the hierarchy of this global operational and business context.

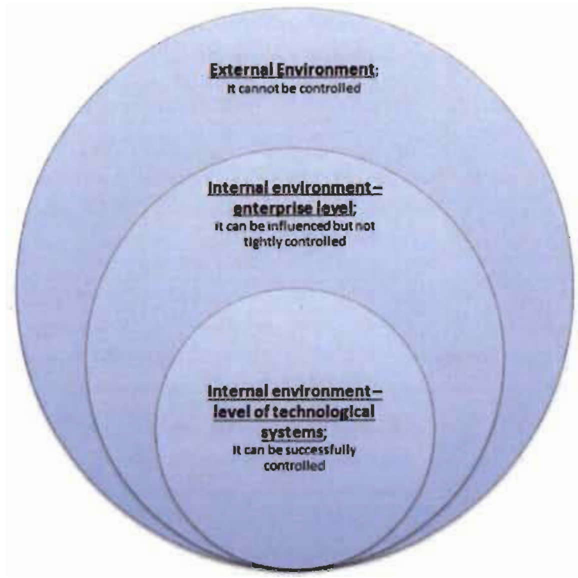

Figure 5.1. The business and operational environment of an enterprise

Thus, it is necessary to develop a holistic model for the asset management strategy that identifies and captures key constituent elements and influential factors, as well as their relationship, interdependencies and complexity.

We claim that in such a complex operational and business context of AsM, contemporary enterprises should be considered as complex adaptive systems (CAS). The methods and tools of the complexity science (theory) are recommended in such circumstances in order to help better understanding their behavior, grasp associated uncertainties and risks, and design appropriate management policies (Farmer 2012; Komljenovic *et al.*, 2015; Kremers, 2012; OECD, 2009, 2011; Rzevski, 2015; Rzevski and Skobelev, 2014; Stacey and Mowles, 2016). Consequently, we argue that the overall asset management strategy should be considered and analyzed as a CAS. Some scholars and researchers have already discussed this orientation with regard to AsM (Bale *et al.*, 2015; Bollinger and Dijkema, 2016; Bush *et al.*, 2014; Komljenovic *et al.*, 2015; Nikolic and Dijkema, 2010; Osman, 2012).

As previously discussed, we propose a global RIDM model (framework) in AsM which integrates into a decision-making process all relevant influential factors, complexity and uncertainties in a structured and systematic manner.

In addition, the model intrinsically takes into account a continuous improvement process based on various feedback from the sub-models and other relevant sources during an organization and asset life cycle (e.g. internal and external audits and/or operating experience). This way, we create conditions for a learning organization which increase its resilience and robustness to unanticipated and surprising events. This attribute is also called "Antifragility" by some scholars (Aven, 2014, 2015b; Taleb, 2012). The key words here are adaptability and co-evolution of enterprises with a continuously changing internal and external context.

The proposed approach is also able to take into account the risks of extreme and rare events in the overall strategy and asset management decision-making. The fundamental principles of a risk assessment process as outlined in ISO 31000 remain.

The methodology is intended to be generic, applicable and adaptable to any size and any type of companies. However, we should emphasize that it is suggested for the strategic and asset management decision-making process affecting both mid and long-term performance, and the sustainability of an enterprise.

Figure 5.2 depicts a proposed global RIDM model in AsM, which is composed of seven sub-models.

Figure 5.2. Global Risk-Informed Decision-Making model in asset management

The main characteristics of the sub-models (constituent elements of the global model) are as follows:

1. *Market sub-model*; it is usually external to an organization/enterprise. It has a major impact on its global performance; items of this sub-model (constituent element) cannot be efficiently controlled nor influenced by an enterprise; epistemic uncertainties are significant. It typically includes:
   - Prediction of the markets, their risks and their volatility
   - Constraints related to new competitors, new products, new technologies
   - Financial market conditions, risks and variations
2. *Sub-model of reliability, availability and maintenance (RAM) factors*; mainly internal to an enterprise; in principle, it may be efficiently controlled and influenced. Aleatory uncertainties are dominant here. The RAM sub-model integrates the following items:
   - Asset selection and utilization

- Criticality of the systems, components and equipment (assets), their reliability, availability and maintenance
- Optimization of the balance between reliability and availability
- Renewal and disposition of assets; Life Cycle Management (LCM)
- Aging and obsolescence management
- RAM information management (RAM-IT)
- Other relevant RAM factors (e.g. work planning and configuration management, materials and services, procurement, etc.)
- Performance and condition monitoring, Key performance indicators (KPI)

3. *Sub-model of operations and operational constraints*; mainly internal to an enterprise; it may be efficiently controlled and strongly influenced, this sub-model includes the following elements:
   - Availability of space
   - Supply and delivery
   - Quality of products and raw materials
   - Value chain and its integration with the concept of AsM
   - Supply of energy and other resources
   - Transportation
   - Overall operational efficiency requirements
4. *Revenue and cost sub-model*; it is both internal and external to an enterprise; it may be partly controlled and influenced to some extent; the revenue and cost sub-model incorporates the following elements:
   - Product prices and revenue, and their volatility
   - Operation & Maintenance costs
   - Manpower costs
   - Capital expenditure
   - Energy costs

- Financial costs
- Raw material costs
- Administrative costs
- Any other relevant costs

5. *Organizational and business sub-model*; it is mainly internal to an enterprise; it may be partly controlled and efficiently influenced; this sub-model usually includes:
   - The overall organization's management, performance criteria, and business continuity management (BCM)
   - Manpower management
   - Knowledge management
   - Human performance management
   - Reward system
   - Organization-wide information management (IT)
   - Enterprise Risk Management (ERM)
   - Organizational performance and enterprise culture improvement, communications
   - Other relevant factors related to the organizational aspect
6. *Sub-model of impact regarding other influential factors and constraints*. These are mainly external to an organization, but they may have a major impact on its global performance; normally, these factors cannot be efficiently controlled or influenced by an enterprise. Epistemic uncertainties are significant. This sub-model includes elements such as:
   - Legal and regulatory requirements
   - Occupational safety and health (OS&H) constraints and requirements
   - Customer satisfaction
   - Socio-economic impact
   - Political factors, changes or conflicts

- Environment protection; impact of climate changes
- Natural perturbations, major events or catastrophes
- Security considerations (physical and cyber security, theft, terrorist threats or attacks)
- Pandemics
- Emergency preparedness and management
- Public risk perception and societal acceptance of risk
- Media treatment, etc.;

7. *Sub-model of impact regarding the strategic plan of an organization.* The strategic plan is described as an overall long-term plan for an organization that is derived from, and embodies, its vision, mission, values, business policies, stakeholders' requirements, objectives, and risk management (BSi, 2008). It is internal to an organization at the enterprise level. Given its direct link to AsM, the orientations defined in a strategic plan are of chief importance.

Table 5.1 portrays the relationship between the sub-models and their attributes in the overall RIDM model in AsM. We present the whole picture in a tabular form instead of graphically for simplicity purpose.

Thus, Table 5.1 contains the main elements and attributes of the global RIDM model in AsM:

a) Sub-models of the global model (element A);
b) Types of environment (attribute B);
c) Level of impact between the constituent elements and strength of the links between them (attribute C);
d) Impact of the variations of the characteristics of the constituent elements on AsM (attribute D);

e) Types of interdependency (connection) between the constituent elements in AsM (attribute E);

f) Pace of the change in the characteristics of the constituent elements (attribute F);

g) Precursors/Warning time (attribute G);

h) Likely duration of the impact (attribute H);

i) Levels of complexity of the sub-models (attribute K).

Table 5.1. Relationship between the constituent sub-models of the global RIDM process in AsM

Sub-model/constituent element (A)	Level of complexity (K)	Type of environment (B)	Impact of changes in constituent elements on AsM (D)	Likely duration of the impact (H)	Pace of change in characteristics of constituent elements (F) / Precursors/Warning time (G)	Sub-model/ constituent element (A)	Attributes (C) and (E)	SubM 1	SubM 2	SubM 3	SubM 4	SubM 5	SubM 6	SubM 7
SubM 1	HCS	EXTL	St	Medd to Vlod	Sd to Es	SubM 1	Level of impact/strength of links between constituent elements (C)		L/M	L/M	M/H	L/H	M/H	M/H
					Shw to Mdw		Type of interdependence (connection) (E)		I,V,VI	I,V,VI	I,V,VI	I,IV,V,VI	I,IV,VI	I,IV,V,VI
SubM 2	WCS	INTL	Mo to St	Vshd to Medd	Sd to Ef	SubM 2	Level of impact/strength of links between constituent elements (C)	N/A		M/H	M/H	L/H	N	L/M
					Shw to Mdw		Type of interdependence (connection) (E)	I,V,VI		I,II,III,IV,V,VI	I,II,IV,V	I,II,III,IV,V,VI	I,II,III,IV,V,VI	I,II,III,IV,V,VI
SubM 3	WCS to MCS	INEL	Mo to St	Vshd to Medd	Ef to Es	SubM 3	Level of impact/strength of links between constituent elements (C)	N/A	M/H		M/H	M/H	L/M	M/H
					Shw to Mdw		Type of interdependence (connection) (E)	I,V,VI	I,II,III,IV,V,VI		I,II,IV,V	I,II,III,IV	I,II,III,IV,V,VI	I,II,III,IV,V,VI
SubM 4	WCS to MCS	EXTL/ INEL	Mo to St	Medd to Vlod	Sd to Es	SubM 4	Level of impact/strength of links between constituent elements (C)	N	M/H	M/H		M/H	N/L	M/H
					Shw to Mdw		Type of interdependence (connection) (E)	I,V,VI	I,II,IV,V	I,II,IV,V		I,II,IV,V,VI	I,V	I,II,IV,V,VI
SubM 5	MCS to HCS	INEL	Mo to St	Medd to Vlod	Ef to Es	SubM 5	Level of impact/strength of links between constituent elements (C)	N/A	M/H	M/H	M/H		L/M	M/H
					Mdw to Lgw		Type of interdependence (connection) (E)	I,IV,V,VI	I,II,III,IV,V,VI	I,II,III,IV	I,II,IV,V,VI		I,II,III,IV,V,VI	I,II,III,IV,V,VI
SubM 6	HCS	EXTL	Ng to St	Medd to Vlod	Sd to Es	SubM 6	Level of impact/strength of links between constituent elements (C)	N/A	L/M	L/M	M	L/M		L/M
					Shw to Lgw		Type of interdependence (connection) (E)	I,IV,VI	I,II,III,IV,V,VI	I,II,III,IV,V,VI	I,V	I,II,III,IV,V,VI		I,II,III,IV,V,VI
SubM 7	MCS to HCS	EXTL/ INEL	St	Vlod	Es	SubM 7	Level of impact/strength of links between constituent elements (C)	N/A	M	M/H	M/H	H	N/L	
					Lgw		Type of interdependence (connection) (E)	I,IV,V,VI	I,II,III,IV,V,VI	I,II,III,IV,V,VI	I,II,IV,V,VI	I,II,III,IV,V,VI	I,II,III,IV,V,VI	

Table 5.2 displays all seven sub-models which compose the global model. Tables 5.3 to 5.10 provide details upon the attributes used in Table 5.1.

Table 5.2. Element (A) in Table 5.1. Sub-models/constituent elements in AsM

SubM 1	Market sub-model
SubM 2	Sub-model of reliability, availability, maintainability (RAM) factors
SubM 3	Sub-model of operations and operational constraints
SubM 4	Revenue and cost sub-model
SubM 5	Organizational and business sub-model
SubM 6	Sub-model of the impact of other factors
SubM 7	Sub-model of the impact of a strategic plan
Note: See also Figure 5.2.	

Table 5.3. Attribute (B) – Types of environment

EXTL	External to an enterprise (organization)
INEL	Internal to an enterprise (organization) (enterprise level)
INTL	Internal to an enterprise (organization) (technical/technological system level)
Note: See also Figure 5.1.	

Table 5.4. Attribute (C) – Level of impact between the sub-models (constituent elements) and strength of the links between them

H	High (strong)
M	Medium (moderate)
L	Low
N	No tangible impact/very weak connections
N/A	Not applicable

Table 5.5. Attribute (D) – Impact of the variations of the characteristics of the sub-models (constituent elements) on AsM

St	Strong
Mo	Moderate
Mi	Minor
Ng	Negligible

Table 5.6. Attribute (E) – Types of interdependence (connection) between the constituent elements in AsM

I. Physical	Reliance mostly of an engineering type between physical assets and/or systems of assets
II. Informational	Information transfer or control requirements between AsM elements (sub-models)
III. Geospatial	Geospatial distance
IV. Policy/procedural	Interdependency caused by a policy or procedure that relates constituent elements in AsM
V. Financial/Monetary	Interdependency caused by financial/cost/revenue relationship between AsM constituent elements
VI. Societal	The effect that an activity or AsM strategy may have on the public opinion, fear, confidence, acceptability, etc.

Table 5.7. Attribute (F) – Pace of the change in the characteristics of the constituent elements

Sd	Sudden (immediate; less than one hour) (e.g. major equipment failure, earthquake, major cyber-attack)
Ef	Emerging quickly (hours, days) (e.g. political unrests, market crashes)
Es	Emerging slowly (weeks, months or years) (e.g. pandemics, climate changes, new technologies)

Table 5.8. Attribute (G) – Precursors/Warning time

Shw	Short (less than one day) (e.g. vibration or overheat of equipment before failure)
Mdw	Medium (one day to four weeks) (e.g. significant market variations/volatility before a market crash)
Lgw	Long (one month or more) (e.g. some unusual behavior of weather indicators, and steady increase of temperature indicating climate changes)

Table 5.9. Attribute (H) – Likely duration of the impact

Vshd	Instant or less than one day (very short)
Shod	Several days (short)
Medd	Several weeks (medium)
Lond	Several months (long)
Vlod	One year or more; permanent impact (very long)

Table 5.10. Attribute (K) – Levels of complexity of the sub-models

Level of complexity of the system / Attributes of complexity	Highly complex system (HCS)	Moderately complex system (MCS)	Weakly complex system (WCS)
Connectivity between the elements of the system (*1*)	High to very high	Moderate to high	Weak to moderate
Degree of autonomy of the elements of the system (*2*)	High to very high	Moderate to high	Weak to moderate
Strength of the connections between the elements of the system (*3*)	Weak to moderate	Moderate to high	High to very high

Legend (adapted from Rzevski and Skobelev, 2014):
(*1*) – Denotes the degree to which an element is connected to other elements of the system. If an element is connected to every other element of the system, its connectivity is 100 %. A higher connectivity creates a greater complexity of the system, which is an important cause for the uncertainty of their behavior.
(*2*) – The autonomy of the elements indicates the degree of freedom given to them to decide what to do. A higher autonomy of the constituent elements produces a greater complexity of the system because of the unpredictability of its global behavior. In complex systems, the autonomy of the elements is always restricted, if not this yields the chaos.
(*3*) – The strength of the connections between the elements of the system designates the degree of breakability of the connections. The lack of connections has a value of zero, and a permanent connection has a value of 1. In complex systems the strength of the connections is between 0 and 1. Weaker connections are easier to break and replace them by new ones. This attribute increases the complexity and, therefore, the unpredictability of the system global behavior. The weaker the connection between the elements yields the greater the complexity of the system is. Weak connections that can be broken when the system self-organizes to adapt to an event are a key attribute of complexity. Strong connections resist self-organization, and very strong connections may prevent the system from self-organizing (Rzevski and Skobelev, 2014).

We can observe in Table 5.1 that the highest complexity is present in the sub-models 1, and 6 (attribute K). Consequently, epistemic uncertainties are most important there, and those activities hold the highest potential of occurrence of E&RE. We find a moderate to high complexity in the sub-models 3, 4, 5 and 7. The sub-model 2 has a weak (low) level of complexity due to a good understanding of the technical systems, and their behavior.

These sub-models and their internal constituent parts interact in a complex manner, and lead to the behavior of the whole process that is not obvious from the individual behavior of each sub-model and its elements. The sub-models are also complex themselves as far as their internal structure, management and functioning are concerned. Consequently, the complexity produces the opacity of a system, and may then create hidden risks due to the presence of significant epistemic uncertainties.

Thus, the AsM of an enterprise may be considered to be an emergent phenomenon integrating several functional, operational, and management layers. It implicates numerous feedback loops reacting to influence their environment, and the behavior of other sub-models and constituent parts. It generally creates the non-linear, emergent and adaptive behavior of the whole system. If any of the interacting sub-processes or elements changed or experienced significant variations, the functioning and performance of other elements and the entire system could be seriously altered.

The proposed global RIDM model also enables to define and characterize the following elements:

- Identifying and mapping the type and strength of the connections between the sub-models and their constituent parts, as well as the degree of their complexity. This activity also enables identifying uncertainties (particularly epistemic ones) within the sub-models. A higher degree of complexity typically signifies larger epistemic uncertainties. These uncertainties and the lack of knowledge may create an overall opacity in the system/process, and could obscure precursors/warning signals/near-misses pointing out to the occurrence of extreme and rare events;

- An approach to identify and characterize the risks of extreme and rare, but plausible events (natural and human-made) which may affect an organization's performance or even endanger its existence. In this activity, motivational and cognitive biases may have a negative impact regarding the obtained outcomes.

An example of how to read the information in Table 5.1 is shown through the analysis of the sub-model 2 presented below regarding the level of impact (Table 5.11) and the types of interdependence (Table 5.12).

Therefore, the proposed global RIDM model in AsM enables to continuously take into consideration and integrate the overall feedback and insights from its sub-models and their constituent parts. It also includes the impact of the organization's strategic orientation, the risks of extreme and rare events, as well as stakeholders' requirements and expectations (Figure 5.2). Given that the RIDM model in AsM is generic and aims at covering all types and sizes of enterprises, the variations of some attributes may appear relatively large (e.g. attributes C and E). Meanwhile, they would be narrowly defined and modeled in specific and actual applications (e.g. power grids, infrastructures, factories, services etc.).

Table 5.11. Level of impact of the SubM 2 on the other sub-models

SubM 1	SubM 3	SubM 4	SubM 5	SubM 6	SubM 7
N/A Changes in the sub-model 2 do not generate changes in the sub-model 1.	**M/H** Links between the sub-models 2 and 3 have a medium to high level of strength. Changes in sub-model 2 generate moderate to high changes in the sub-model 3.	**M/H** Links between the sub-models 2 and 4 have a medium to high level of strength. Changes in sub-model 2 generate moderate to high changes in the sub-model 4.	**L/H** Links between the sub-models 2 and 5 may have a low to high level of strength. Changes in sub-model 2 may generate low to high changes in the sub-model 5.	**N** Links between the sub-models 2 and 6 have a low level of strength. Changes in sub-model 2 generate no tangible changes in the sub-model 6.	**L/M** Links between the sub-models 2 and 7 have a low to medium level of strength or changes in sub-model 2 could generate low to moderate changes in the sub-model 7.

Table 5.12. Interdependence (connection) between the SubM 2 and the other sub-models

SubM 1	SubM 3	SubM 4	SubM 5	SubM 6	SubM 7
II, V, VI There are informational financial and societal links between the sub-models 2 and 1.	**I, II, III, IV, V, VI** There are physical, informational, geospatial and policy/procedural, financial and societal links between the sub-models 2 and 3.	**II, III, IV, V** There are informational, geospatial and financial/monetary links between the sub-models 2 and 4.	**I, II, III, IV, V, VI** There are physical, informational, geospatial and policy/procedural, financial and societal links between the sub-models 2 and 5.	**I, II, III, IV, V, VI** There are physical, informational, geospatial and policy/procedural, financial and societal links between the sub-models 2 and 6.	**I, II, III, IV, V, VI** There are physical, informational, geospatial and policy/procedural, financial and societal links between the sub-models 2 and 7.

5.3.2 Model for Assessing Risks of Extreme and Rare Events in Asset Management

For the purpose of this study, the proposed approach will take into account the overall philosophy and key steps defined in ISO 31000, namely: **I)** establishment of the context, **II)** risk assessment, and **III)** risk treatment (ISO, 2009). Risk assessment integrates the steps of the **IIa)** risk identification, **IIb)** risk analysis, and **IIc)** risk evaluation. ISO 55000 and ISO 22301 also relate to ISO 31000 regarding risk assessment and management (ISO, 2012, 2014a,b,c).

The overall context (step **I)** has been established through the model presented in the previous Section (Figure 5.2, Table 5.1).

5.3.2.1 Risk Assessment

The steps of the risk assessment (**II**) will be further expanded below. The current research proposes a global AsM RIDM model in which we identify and assess potential risks related to E&RE. They typically arise through complex relationships between its sub-models and elements in presence of huge epistemic uncertainties in the system (Figure 5.2, Table 5.1). The discussion on future research presented later portrays ways to elaborate sophisticated simulation models for this purpose using various methods of the complexity science. Meanwhile, the proposed global RIDM model provides a solid basis in this regard.

As far as the identification of risks is concerned **(IIa)**, in the present study we identify 24 various types of potential extreme and rare events which may pose risks for AsM (natural, technological, technical, market, and human made). They are compiled in Table 5.13. The same Table also lists the relationship to the corresponding sub-models depicted in Figure 5.2 and Table 5.1. The list of those events is obtained through both a comprehensive literature review and internal discussions by various experts. In a specific enterprise context, we suggest to proceed to a revision of the list every three to five years or anytime a significant event which may have an important impact to the existing list occurs.

It is worth highlighting that a broad review of different combinations of various E&RE is also strongly suggested. The experience has shown that coincidences of typically rare events are possible, and may create an effect of aggregation which the impact may exceed a mere sum of individual impacts (Hand, 2014; Taleb, 2010). Paté-Cornell speaks there of "Perfect Storms" (Paté-Cornell, 2012).

While analyzing the E&RE, we should also identify potential precursors/warnings/near-misses which may indicate a possibility of occurrence of those events, as well as thresholds to which an event may be considered as an extreme or rare one. Those thresholds should be expressed in physically measurable terms as far as possible. Although significant efforts have been employed to elaborate the set of E&RE presented in Table 5.13, we emphasize that the list may not be exhaustive, and could be extended (or reduced) as a part of a specific organization's context. Moreover, the risk analysis has to take into account the complexities and relationships between the sub-models (Figure 5.2, Table 5.1) for the purpose of a meaningful risk assessment. In the absence of quantitative simulation models, detailed qualitative analyses through a multidisciplinary team may deliver satisfactory results in initial stages. As discussed by various authors, new methods should be elaborated in order to assess the risks of E&RE (Aven, 2014, 2015a; Paté-Cornell, 2012).

At the present stage of development, we encounter two situations while conducting the risk analysis **(IIb)** and the risk evaluation **(IIc)**:

a) Relevant data upon extreme events are available

b) No reliable data or no data at all (rare events)

Ad a) Relevant data upon extreme events are available

In this case, the statistics of extreme value may be applied to calculate the probability of occurrence of extreme events. Once those probabilities are determined, we may develop corresponding risk matrices in order to estimate the levels of risk. When new data become available, information could be updated through Bayesian probability calculations for example, and used in reassessing the risks of E&RE in AsM.

As far as consequence classes are concerned, we propose nine categories. Table 5.14 provides a detailed description of each consequence category and the four levels of impact (catastrophic, severe, major, and minor). Again, the categories are determined through both a broad literature review and discussions of numerous experts.

Ad b) No reliable data or no data at all

In this situation we propose a consequence-based approach. The experience and various research works discussed above have shown that it is basically impossible to truthfully calculate extremely small probabilities of occurrence related to E&RE. They are grossly either overestimated or underestimated because of various human cognitive and/or motivational biases (Hand, 2014; Kahneman, 2012; Montibeller and Winterfeldt, 2015; Rickards, 2009; Shiller, 2013; Taleb, 2010). How could we precisely determine whether the likelihood is 10^{-8}, 10^{-9} or 10^{-10}? We may easily miss several orders of magnitude due to the huge epistemic uncertainties involved there. In this case, we should define a comprehensive list of E&RE, their meaningful combinations, and their relationships against which an organization wants to be reasonably protected while remaining economically viable. The events shown in Table 5.13 may serve as a starting point for the analysis. The consequence categories presented in Table 5.14 are applicable for this purpose.

5.3.2.2 Risk Treatment

Risk treatment measures (step **III** above) are not discussed in detail here since they depend on the type of organizations, and should be tailored to a specific context. However, the general principles of robustness, resilience, continuous improvement (learning organization), and ALARA/ALARP always apply (Aven, 2014, 2015a; Cox, 2014; Paté-Cornell, 2012; Rzevski and Skobelev, 2014). The requirements of Business continuity management (BCM) such as a maximum tolerable period of disruption (MTPD) and a minimum business continuity objective (MBCO) should be taken into consideration (ISO, 2012).

Following the risk assessment, senior management gets meaningful insights and makes a risk-informed decision regarding the course of action in addressing the risks of E&RE in AsM. The risk input is the one among many other inputs and influential factors in a holistic RIDM (also see Figure 5.2).

Table 5.13. Categories of extremes and rare events

N	Main extreme event (hazard)	Description	Sub-Model (Figure 5.2; Table 5.1)	No	Main extreme event (hazard)	Description	Sub-Model (Figure 5.2; Table 5.1)
1	Natural disasters	Earthquake	6	9	Industrial spying causing loss of intellectual properties		6
		Volcano	6	10	Loss of key expertise (technical or management)		5
		Tsunami	6	11	Major labor conflict		4, 5
		Landslide	6	12	Loss of key suppliers		3, 4, 5
		Geomagnetic storms	6	13	Unavailability of key raw materials or water (extreme supply disruption)		3, 4
		Other	6	14	Prolonged loss of power or energy supply		3, 4
2	Severe/extreme weather conditions	Hurricanes	6	15	Development of entirely new technologies or products by competitors		1, 4, 7
		Winds	6	16	Advent of new strong competitors		1, 6, 7
		Tornadoes	6	17	Major legal pursuits		6, 7
		Droughts/Heat waves	6	18	Payment default of major customers		3, 4, 6
		Lightning	6	19	Loss of major customers		3, 4, 5, 7
		Rain	6	20	New laws and regulations radically changing regulatory/legal environment		6, 7
		Floods	6	21	Extremely negative treatment in mass-media causing an unfavorable business environment		6
		Global warming/ climate change in general	6	22	Extreme public opposition to activities (project)		6
		Other	6	23	Political changes and conflicts	Lasting political turmoil	6, 7

Table 5.13. Categories of extremes and rare events (suite)

N	Main extreme event (hazard)	Description	Sub-Model (Figure 5.2; Table 5.1)	No	Main extreme event (hazard)	Description	Sub-Model (Figure 5.2; Table 5.1)
3	Financial and market crashes		1, 4			Terrorist attacks	6, 7
4	Major economic crisis/depression		1, 4			Wars and armed conflicts	6, 7
5	Major industrial accident		2			Economic sanctions	6, 7
6	Major failure/loss of critical assets		2			Major shift in economic policies	6, 7
7	Major technical difficulties		2, 3	24	Pandemics		3, 4, 5, 6, 7
8	Major cyber attack		6				

Table 5.14. Severity of the consequences

Category of impact	Impact on:	Severity of consequences			
		Catastrophic (CT)	Severe (SV)	Major (MJ)	Minor (MI)
A	People's security and health (workers and/or general population)	Death of one or several persons	Severe injuries and/or permanent disability	Injuries without permanent disability; major and observable loss of quality of life	Minor injuries, minor loss of quality of life
B	Environment	Destruction of habitats, and death of numerous animals	Mass destruction or contamination of habitats. No death of animals or very little	Destruction or contamination of habitats near the site	Minor contamination of habitats with no destruction

Table 5.14. Severity of the consequences (suite)

Category of impact	Impact on:	Severity of consequences			
C	Material goods, physical assets (own and/or others, population) – damage (or reconstruction costs)	Destruction of properties over an area exceeding the limits of the site	Significant damage to own physical assets, destruction of private properties off the site	Substantial damage to the site and minor to moderate off-site damage	Minor to moderate damage to the site
		Damage of more than $10M	Damage between $2M and $10M	Damage between $100k and $2M	Damage f Less than $100k
D	Increased costs/work schedules	Increase in cost / schedule 100 % and more	Increase in cost / schedule between 50 % and 100 %	Increase in cost / schedule between 15 % and 50 %	Increase in cost / schedule less than 15 % (covered by the contingency plan)
E	Impact on the reputation and image of the company	Very negative impact at national or international level	Local or regional considerable negative impact	Local, limited negative impact	Little or no negative impact
		Focus of national and international media more than 5 days	Focus of national and regional media for several days	Focus of regional media for several days	Local complaint or a single article in a local media
F	Regulatory impact	Non-compliance or non-respect of applicable laws and regulation	Violation of an article or a regulation that could lead to a fine	Violation of an article or a regulation without fines	Small regulatory impact or no impact
		Civil litigation, criminal accusations			
G	Loss of production	Three weeks or more of downtime	Downtime between three days and three weeks	Downtime less than 3 days	No downtime
		Production cuts of more than 60 %	Production cuts between 40 % and 60 %	Production cuts between 15 % and 40 %	Production cuts of less than 15 %
H	Impact on the strategic plan	Completely or almost completely invalidates the strategic plan	Major changes needed in the strategic plan	Moderate and limited changes needed in the strategic plan	No significant impact on the strategic plan

Table 5.14. Severity of the consequences (suite)

Category of impact	Impact on:	Severity of consequences			
I	Level of implementation of emergency measures	Activation of large-scale emergency measures; evacuation of the population at regional level	Activation of emergency measures at local level; evacuation of the very limited population (local population)	Activation of emergency preventive measures or warnings; no evacuation of people	Activation of emergency measures not necessary

5.4 Case Studies

The risks of extreme and rare events in asset management will be analyzed through two cases of some Hydro-Québec's assets. Hydro-Québec is one of the largest North American companies which generates, transmits and distributes electricity. Its sole shareholder is the government of Quebec. It uses mainly renewable generating sources, in particular large hydro units, and supports the development of other technologies such as wind energy and biomass (Hydro-Quebec, 2015a).

Firstly, we analyze extreme interruptions in its power grid where reliable historical data are available (case **a)** of the risk analysis step **IIb)** presented above). They will be statistically characterized through the extreme value theory. The risks and impacts of such large interruptions will be discussed in terms of operational and asset management challenges.

Secondly, we conduct an analysis with regard to the impact of rare, surprising events which led to the abandoning of the Gentilly-2 Nuclear Power Plant (NPP) Refurbishment Project, where no data were available (case **b)** in the analysis of risks step **IIb)** previously depicted).

5.4.1 Risks of Extreme Power Interruptions in the Grid

The Hydro-Quebec's distribution grid is generally composed of overhead lines. Its underground grid is mainly installed in large urban areas such as Montreal and Quebec City, and represents a smaller part of the overall installations. Overhead lines are exposed to external events. Those events are typically weather generated ones, and usually cause tree or tree branch falls on power grid lines which trigger unplanned power interruptions. Furthermore, there are accidental animal, bird or human made interruptions which are comparatively low. Some other unplanned interruptions may come from the transmission grid disturbances which are small in numbers, but affect a large number of customers, and may last for a long time (Table 5.15 and Table 5.16).

There are also interruptions caused by equipment failures, but they are relatively minor. All the power interruptions are recorded as CHI (Customer Hours of Interruption) on a daily basis in an enterprise database. Other performance indicators are also calculated and used as per common practices (IEEE, 2012)[1].

The enterprise records data upon all the interruption events, including extreme ones. In this case, we may apply the theory of extreme value to characterize them (case **a)** presented above). Such external perturbing events usually originate from **the sub-model 6** (Figure 5.2, Tables 5.1 and 5.13). However, they primarily fell within investigations related to the **sub-model 2** of the global RIDM model. Those extreme events affect the assets' ability to fulfill their intended function. Obviously, perturbations within **the sub-model 2** also touch other sub-models as per interdependencies and attributes shown in Tables 5.1 and 5.11.

In such context, it is important to characterize the risks of extreme interruptions in the power grid since they negatively affect expected customer service, and mobilize important enterprise resources (human, material and financial) in order to get the service restored.

Knowledge upon the risks of the extreme grid events is of key importance from the asset management point of view regarding the continuity of service after a major interruption. The enterprise management team has to adequately plan the necessary

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1 SAIDI: System Average Interruption Duration Index; CAIDI: Customer Average Interruption Duration Index; CAIFI: Customer Average Interruption Frequency Index; ASAI: Average Service Availability Index, etc.

resources in order to successfully handle such interruptions (contingency planning) to ensure the continuity of the service.

The analysis presented here aims at characterizing the risks of such extreme events, and discusses their impact on the overall asset management. It covers the timeframe from 1987 to 2015 inclusively (29 years in total), and takes into consideration unplanned power interruptions only.

The investigation of the interruptions indicates that approximately 93 % of the power interruption occurrences are inferior to 100 kCHI/day. However, the interruptions of 100 kCHI/day and over contributed to 65 % of the total interruption duration over the analyzed period of time. It gives the following ratios:

- 35 % (durations)/93 % (number of days with less than 100kCHI/day) = 0.38;
- 65 % (durations)/7 % (number of days with 100kCHI+/day) = 9.28.

The interruptions of 1 million CHI/day (MCHI+/day) and more represent approximately 0.6 % of the total number of interruptions. Meanwhile, they contributed to 42 % of the total interruption durations. Those values highlight the ratios:

- 58 % (durations)/99.4 % (number of days with less than 1MCHI/day) = 0.58;
- 42 % (durations)/0.6 % (number of days with 1MCHI+/day) = 66.86.

These values mean that each percentage in the number of interruptions of less than 100kCHI/day contributes 0.38 % of the total interruption duration (0.58 % for less than 1MCHI/day). On the other hand, each percentage in the number of interruptions for 100kCHI+/day contributes to 9.28 % regarding the total interruption duration (66.86 % for 1MCHI+/day).

The above numbers clearly demonstrate that the power interruptions of large magnitudes are less frequent, but their impact to the interruption durations is substantial. Thus, the above facts show the importance of adequate preparations in handling extreme interruption events. These findings will be analyzed more in depth below.

5.4.1.1 Statistical Distribution of Extreme Power Interruptions

Table 5.15 displays the maximal daily interruptions in $(CHI/day)_{max}$ on an annual basis (one maximal value per year is selected for the calculations). The maximal observed value is more than 46.35MCHI/day in 1998, and the minimal one is 380,606 CHI/day in 2004 (ratio of 122). It represents a range of almost 46MCHI/day. Table 5.16 provides selected causes that have been at the origin of some extreme interruptions based on HQ's records.

Table 5.15. Maximal daily interruptions in $(CHI/day)_{max}$ on an annual basis

No	Year	Maximum daily value $(CHI/day)_{max}$	No	Year	Maximum daily value $(CHI/day)_{max}$
1	1987	2,755,441.62	16	2002	1,299,914.09
2	1988	5,097,409.68	17	2003	961,733.37
3	1989	21,718,294.52	**18**	**2004**	**380,606.17**
4	1990	1,026,633.01	19	2005	2,681,306.03
5	1991	3,516,996.94	20	2006	6,869,109.36
6	1992	1,690,853.85	21	2007	2,965,983.00
7	1993	1,433,390.82	22	2008	4,704,245.14
8	1994	1,262,054.87	23	2009	597,603.00
9	1995	711,193.02	24	2010	1,058,969.00
10	1996	1,081,331.11	25	2011	4,780,598.00
11	1997	6,284,228.66	26	2012	3,356,084.00
12	**1998**	**46,350,129.63**	27	2013	10,356,982.78
13	1999	9,015,671.30	28	2014	605,955.45
14	2000	1,837,730.90	29	2015	1,526,397.32
15	2001	2,274,439.01			

The daily CHIs represent the total count of interruptions recorded starting on a given day. Consequently, the interruptions occur at the event date, but can be closed sometime after several days following the initial day of the event.

Table 5.16. Selected causes of some major interruptions

Date	**Event**	**Division at the origin of interruptions**
18-Apr-88	Ice storm	Transmission/distribution
13-Mar-89	Solar eruption/geomagnetic storm	Transmission
05-Jan-97	Ice storm	Distribution
06-Jan-98	Ice storm	Transmission/distribution
01-Aug-06	Tornadoes	Distribution
10-Jun-08	Violent storms	Distribution
28-Aug-11	Hurricane Irene	Distribution
19-Jul-13	Violent storms	Distribution
01-Nov-13	Violent storms	Distribution

Note: It should be highlighted that Hydro-Quebec has undertaken major corrective measures following solar eruption and ice storms in order to increase the robustness of its power grid. Thus, it is less likely that events of such magnitude may affect the grid again. These causes correspond to the types of hazard 1 (natural disasters) and 2 (extreme weather) presented in Table 5.13.

The statistical characterization of maximal daily interruptions has been carried out by using the Gumbel distribution, which has shown the best fit in the current study among extreme value distributions.

In probability theory and statistics, the Gumbel distribution is used to model the distribution of the maximum (or the minimum) of a number of samples of various distributions. This distribution is a particular case of the generalized extreme value distribution. It is useful for example, in predicting the likelihood that an extreme flood or other natural disaster will occur (Gumbel, 1935).

The Gumbel cumulative distribution function (CDF) may be written as follows:

$$F(x;\mu,\theta) = \exp\left\{-\exp\left[\frac{-(x-\mu)}{\theta}\right]\right\} \qquad (5.1)$$

$$x \in (-\infty;+\infty)$$

where:

μ (location parameter, real number) and θ (scale parameter; θ > 0; real number) are the parameters of the Gumbel distribution

Probability density function (PDF)

$$f(x;\mu,\theta) = \frac{1}{\theta}\exp\left\{-\left[\frac{x-\mu}{\theta} + \exp\left(-\frac{x-\mu}{\theta}\right)\right]\right\} \qquad (5.2)$$

Other characteristics and parameters of this distribution may be found in relevant statistical references.

The characterization of the parameters of a Gumbel distribution regarding the maximum power interruptions has been performed as per the approach described by the U.S. National Institute of Standard and Technology, Statistical Engineering Division (2015).

An initial analysis has indicated that the maximal daily values of $(CHI/day)_{max}$ have rather an exponential relationship with the values [-ln(-ln(PV))] used in the method with a high correlation coefficient (R^2 = 0.9931). In order to obtain a linear relationship, the natural logarithm of $(CHI/day)_{max}$ values has been calculated. Thus, the CDF described in equation (1) is modified by expressing it as the natural logarithm.

$$F(x;\mu,\theta)=\exp\left\{-\exp\left[\frac{-(\ln(x_L)-\mu_L)}{\theta_L}\right]\right\} \tag{5.3}$$

Where x_L is the natural logarithm of the variable x $(CHI/day)_{max}$.

Figure 5.3 displays the probability plot.

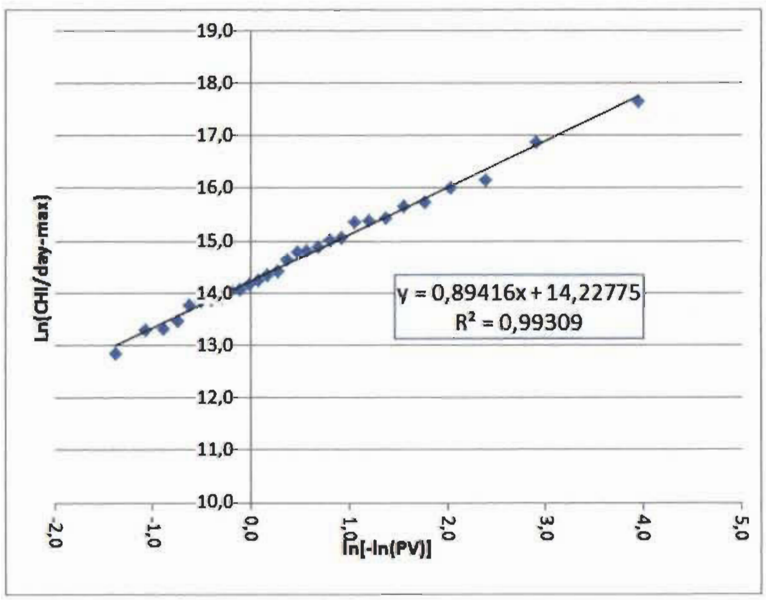

Figure 5.3. Logarithmic probability plot of the Gumbel distribution for $(CHI/day)_{max}$ (1987-2015)

Based on the calculated values of the slope and the intercept (Figure 5.3), we obtain the estimated values of the scale and location parameters:

$\theta_L =$ 0.89416

$\mu_L =$ 14.22775

By inserting these values in equation (5.3), we get an equation for CDF of the maximum daily values of interruptions $(CHI/day)_{max}$ on an annual basis:

$$F(x;\mu,\theta) = \exp\left\{-\exp\left[\frac{-\left(\ln(x_L) - 14.22775\right)}{0.89416}\right]\right\} \tag{5.4}$$

5.4.1.2 Probability of Maximal Daily Interruption

Through equation (5.4) we can calculate the theoretical probability of maximal daily power interruptions of a certain magnitude on an annual basis. Table 5.17 shows the theoretical probability of interruption durations of various magnitudes on an annual basis, and Figure 5.4 depicts them graphically.

Table 5.17. Theoretical probability of maximal daily interruption durations $(CHI/day)_{max}$

$(CHI+/day)_{max}$	**Theoretical probability of a maximum daily power interruption (1-F)**
1.00E+06	0.7952
5.00E+06	0.2306
1.00E+07	0.1137
5.00E+07	0.0198
6.00E+07	0.0161

The above results show that there is a probability of almost 80 % of a maximum daily interruption of 1MCHI/day and over, or 2 % for a maximum interruption magnitude of 50MCHI+/day on an annual basis (Table 5.17).

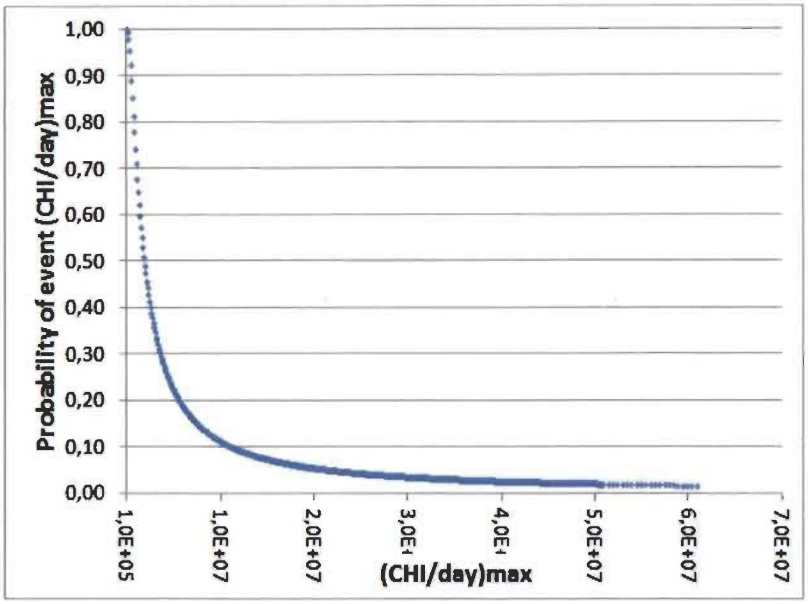

Figure 5.4. Graphical plot of the theoretical probability of events expressed in $(CHI/day)_{max}$

Based on the enterprise's records, the duration of extreme interruptions may vary between 1-2 days up to several weeks, as it was the case of the ice storm in 1998. The consequence categories as per Table 5.14 encompass mainly the category G (loss of production), but other categories are also implicated: A, C, D, E, H and I. Thus, the severity of the consequences varies between major and catastrophic (see Table 5.14). Considering the results of this analysis, we proposed a risk matrix for E&RE with regard to the loss of production, i.e. the category G as a dominant category (Figure 5.5). The probability levels are defined for 5 or less, 15, 40 and 60+ MCHI/day calculated through Equation (4). Theoretically, a maximum daily CHI is around 100 million for the current number of customers in Quebec (Hydro-Quebec, 2015a). It represents a total blackout in Quebec for 24 hours. Consequently, the levels of interruptions considered in the risk matrix reflect the percentages of the loss production for the category G in Table 5.14 (less than 15 %, 40 %, 60 % and more). The risk matrix has four levels of risk: low, moderate, high and very high. For example, an interruption of 60MCHI+/day has a probability of 1.6 %

(Table 5.17), and a catastrophic (CT) severity category for the loss of production (G) (Table 5.14). It should be seen as a moderate risk event (MOR) (Figure 5.5).

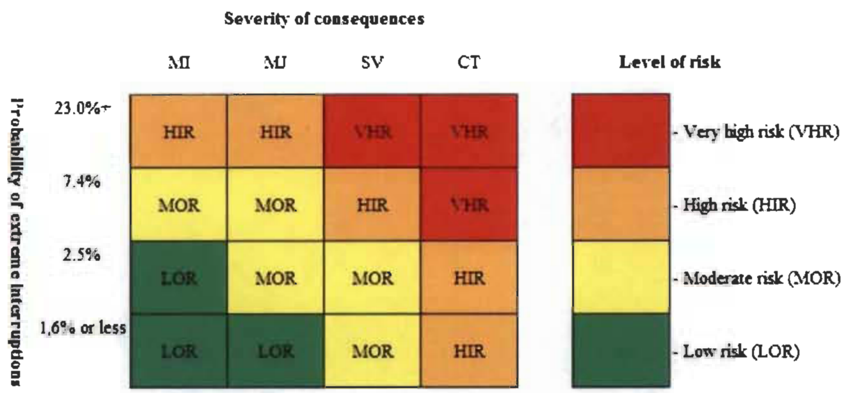

Figure 5.5. Risk matrix for E&RE regarding the loss of production (Category G)

The obtained results can serve as risk insights and input into the holistic RIDM model (Figure 5.2, Table 5.1). They are beneficial in refining the enterprise's approach concerning its contingency planning with regards to the levels of risks, and based on the BCM requirements.

5.4.1 Refurbishment of the Gentilly-2 Nuclear Power Plant

In the second case study, we have performed an analysis with regard to the impact of a series of rare events leading to the abandoning of the Gentilly-2 Nuclear Power Plant (NPP) Refurbishment Project in 2012 (Komljenovic and Abdul-Nour, 2015).

The G2 NPP was the sole Hydro-Quebec's nuclear generating utility. It was a CANDU6 nuclear power plant and had been designed for a 30-year service life, or more accurately 210 000 Equivalent Full Power Hours (EFPH) as it is the case of all CANDU nuclear generating stations (Canteach, 2016). It started its commercial operation in 1983, and should have reached this limit somewhere in 2013. For that reason, Hydro-Quebec has initiated prefeasibility studies in the early 2000s in order to examine the possibility to refurbish the station and to extend its useful life for another 30 years. In these years, a general trend in the nuclear power industry was oriented toward an extension of the operations beyond the initial service life. It was based on an accumulated operational experience and new scientific insights which showed that it was possible. Following these studies, Hydro-Quebec made a positive decision in 2008 to refurbish the station. Required engineering and field works started under the Refurbishment Project. The costs of those activities had been estimated at 1.9B$, and the refurbishment work should have started in March 2011. The restart was foreseen for November 2012 (Hydro-Quebec, 2015b).

However, after initial works began, the Refurbishment Project has been delayed several times. Finally, Hydro-Quebec announced on October 3, 2012 the closure of the Gentilly-2 NPP at the end of 2012, and its decommissioning. It ended its commercial operation on December 28, 2012 (Government of Quebec, 2012; Hydro-Quebec, 2015b,c). What happened within the four years from the initial positive announcement to the abandoning of a project of such magnitude?

A series of unfavorable and rare events occurred over a short period of time which definitely contributed to overturning the initial decision – a "Perfect Storm" as Paté-Cornell (2012) called it. Such events and their combination represent significant epistemic uncertainties for a decision-making process. They are almost impossible to predict, or to mathematically characterize in a complex operational and business environment. Although numerous warning signals and precursors indicating that certain key influential factors went wrong were available, the enterprise's capacity to react was rather limited. Table 5.18 provides a summary overview of the analysis.

Table 5.18. Summary analysis of the risks of rare events of the G2 Refurbishment Project

No	Description	Affected sub-model (Figure5.2, Table 5.1)	Categories of events (Table 5.13) and consequence (Table 5.14)	Comment
1	Extreme market and financial crisis 2008/2009	1; 4; 7	(3, H, MJ)*	This crisis created an unfavorable business environment. The U.S. as an important Hydro-Quebec customer was hit by a recession, which decreased its needs of importing electricity. The crisis also affected many industries in Canada (pulp and paper, aluminum, etc.), and it has slowed the interior demand for electricity (Hydro-Quebec, 2015b).
2	Unforeseen increase of shale gas production in the U.S. in late 2000s, natural gas price decrease (US EIA, 2015; Hydro-Quebec, 2015b)	1; 4; 6; 7	(15, H, MJ) (16, H, MJ)	New and additional unfavorable market conditions; new competitors on the energy market. The most intensive exploitation of shale gas in the late 2000s in the U.S. has decreased the unitary cost of this commodity. It has been increasingly used for electricity generation in the U.S., mainly as a substitute for coal and oil. Combined with the economic crisis, it resulted in fewer needs of importing electricity in the U.S. We can observe that the combined effect of the crisis in the U.S., the price of shale gas, the overcapacity at Hydro-Quebec, and the marginal price of its most recent projects (wind turbines) created a situation in which the improvement of a single factor would not bring significant changes (Hydro-Quebec, 2015b). This means that a fast recovery was implausible.
3	Unexpected major technical difficulties in refurbishment of Point Lepreau NPP and Wolsong NPPs (2008-2012) (Hydro-Quebec, 2015b; WNN, 2010, 2011)	2; 6; 7	(7, D, CT) (21, E, MJ)	A negative feedback/operating experience from industry peers decreased confidence within HQ in the feasibility of the G2 Refurbishment Project. There were also some negative treatments in the media.

Table 5.18. Summary analysis of the risks of rare events of the G2 Refurbishment Project (suite)

No	Description	Affected sub-model (Figure5.2, Table 5.1)	Categories of events (Table 5.13) and consequence (Table 5.14)	Comment
4	Significant cost overruns regarding the G2 Refurbishment Project (from 1.9B$ to 4.3B$) (Hydro-Quebec, 2015b)	2; 3 4; 5; 6; 7	(7, D&H,CT) (22, E, MJ)	Direct negative impact related to cost overruns further eroded the confidence of HQ in the feasibility of the Project. The initial unitary cost of 8.6 ¢/kWh increased to 12.3 ¢/kWh. Thus, the Project was not economically justifiable anymore (Hydro-Quebec, 2015b). It also generated a public opposition to the Project at some extent. This factor may be seen as an epistemic uncertainty of the category "known-unknown". Project cost overruns are relatively common, but it is not usual to anticipate an increase of 226 % for a project of such a magnitude in an unfavorable energy market.
5	Extreme natural disaster (earthquake and tsunami) in Japan resulting, among other things, in Fukushima Daiichi nuclear accident. It resulted in stricter regulation and a wider public opposition to the nuclear power generation (natural, regulatory, economic and public perception influential factors) (INPO, 2012; Hydro-Quebec, 2015b; NAS, 2014)	5; 6; 7	(1,A-I, CT) (20, D, MJ) (21, H, MJ) (22, E, SV)	On the Fukushima site and in Japan, there was an overall negative effect on all the categories of the impact due to both actual damages and public perception. As far as HQ's local context is concerned, this event additionally shrunk the confidence of HQ and the Government of Quebec in the pertinence of the Project.

Table 5.18. Summary analysis of the risks of rare events of the G2 Refurbishment Project (suite)

No	Description	Affected sub-model (Figure5.2, Table 5.1)	Categories of events (Table 5.13) and consequence (Table 5.14)	Comment
6	Political changes: newly elected Government of Quebec in September 2012 was unfavorable to the G2 refurbishment (PQ, 2012). At the first meeting of the Cabinet of ministers, it made a decision to close the G2 NPP and to abandon the Refurbishment Project (Government of Quebec, 2012).	6; 7	(20&23, H, MJ) (20&23, H, CT)	We have here an impact/risk of political factors. Since the G2 NPP production represented 3 % of the HQ's total generating capacity, the severity may be considered as major at the corporate level. The enterprise was able to compensate for the generation loss i.e. it was robust and resilient enough to surmount this situation. The BCM at the corporate level is assured. The impact at the level of the NPP was catastrophic (closure of the NPP and the abandon of the Refurbishment Project). In fact, the sum of the risks of the five previous categories definitely damaged the confidence of the authorities and decision- makers regarding the suitability and feasibility of the Refurbishment Project.

Legend: (3, H, MJ) – (3) – Number of events in Table 13 (Financial and market crashes); (H) – Category of impact in Table 14 (Strategic Plan); (MJ) – Severity of the consequences in Table 14 (Major).

The coincidence and the combination of these six major rare events resulted in a non-linear amplification of their aggregate risk. These events are not all independent between them, which adds to overall complexity and opacity of the context (also see Table 5.1). The aggregate risk is considerably superior to the simple sum of their individual risks and effects. The above analysis shows that the overall operational and business context of the G2 Refurbishment Project as an AsM activity behaved as a CAS, and the proposed model capture this feature. It was practically impossible to mathematically model such risks by using traditional approaches. Consequently, they do not enable to accurately forecast both the occurrence and the gravity of the consequences of such events, and their coincidence. Thus, a major AsM project, initially approved in 2008, was abandoned four years later. This case study illustrates how rare events and their unfavorable combination may generate risks that have the capability to entirely change or disrupt major decisions regarding asset management within a relatively short timeframe.

Even, in having the proposed model for the purpose of the analysis, Hydro-Quebec would have probably not avoided the closure of the NPP, and such scenarios are sometimes inevitable. However, it is worth mentioning that the enterprise has not used a prospective option to submit to the Canadian Nuclear Safety Commission (CNSC) a demand to extend the operation of G2 NPP beyond 210,000 EFPH without refurbishment. This alternative might have enabled an increased resilience and robustness of the overall enterprise through an extended exploitation period of the NPP allowing more time to prepare its closure, and manage organizational and technical challenges involved. The recent CANDU industry experience from Ontario Power Generation (OPG) and Bruce Power (BP) has exposed this possibility. Following detailed studies and clear demonstration of the safety case, CNSC granted an extension to 247,000 EFPH to OPG's Pickering Nuclear Generating Station, and to 245,000 EFPH to the Bruce Power NPPs Bruce B Units 5 and 6 (CNSC, 2014a,b).

5.5 Conclusion

Enterprises worldwide are constantly forced to produce more at lower costs. They are also confronted with a highly complex business and operational environment, and this complexity keeps growing. As per recent industry-wide development, asset management plays a key role in this context.

In such circumstances, industries tend to develop various processes and approaches, which may enable to efficiently address these issues and manage associated risks. They are often based on traditional methods which are generally unable to adequately grasp and tackle the complexities and uncertainties. It is particularly true when considering extreme and rare events which have capabilities to disrupt strategic activities or even jeopardize the survival of enterprises.

We claim that the modern enterprises and their asset management strategy should be considered as Complex Adaptive Systems (CAS), which should be modeled through methods and tools of the complexity science. In such systems, the occurrence of extreme and rare events is very plausible since we do not entirely grasp their scope, nature of associated epistemic uncertainties and risks, and connections between their constituent elements.

This study presents a holistic high level Risk-Informed Decision-Making (RIDM) model (framework) in asset management and initial results on how to tackle the risks of E&RE within this context. Such a methodology may assist decision-makers in key decision-makings by providing more realistic insights. The proposed method may positively complement existing traditional approaches.

The two case studies related to Hydro-Quebec's assets demonstrate the relevance of considering more systematically the complexity and risks of extreme and rare events in asset management.

Future research works should be directed to a deeper understanding of the complexity in AsM, and the development of AsM models using modeling and simulation techniques of the complexity science. This research should also include: the development of adequate stress tests and models for risk exposure from E&RE in AsM and their validation, enhanced risk assessment methods for E&RE in AsM, improved characterization of associated uncertainties, development of algorithms for efficiently generating E&RE in simulation models, efficient ways of improving resilience and robustness in AsM while remaining economically viable, modeling the role of organizational, and human performance, biases and behavior in generating risks from E&RE. Future research works also ought to investigate how to better capture opportunities from E&RE. It is necessary to analyze more in detail the links and complementarities between AsM and BCM as well.

Furthermore, it is indispensable to highlight challenges that the development and application of the proposed approach may encounter. They include, but are not limited to:

- Lack of appropriate analysis and modeling methods, scientific understanding of the complexity and the risks from extreme and rare events in AsM; continuous increase in the overall complexity makes this task more difficult;
- Availability of pertinent data in order to perform the required analyses. Further investigations are needed to determine which data are really needed and whether the quality of the available data is satisfactory. Collecting and preparing them could imply considerable efforts;

- Availability of decision-making support models and tools: they have to be developed and tailored according to the needs of a specific organization/industry. This research may also require an adaptation of existing traditional tools to better fit novel methods and approaches;
- Costs of integrating the complexity framework and new risk assessment methods regarding extreme and rare events in AsM may be consequential (new research, data collection, development of methods and tools, their implementation, training, maintenance, etc.);
- Acceptability of novel approaches by the industry: introduction of new ways of performing analyses or decision-making may face resistance and unwillingness to embrace them.

Acknowledgement

The work has been partly supported by Hydro-Quebec and the Project "ODÉMA" as a part of a larger Asset Management program. We gratefully acknowledge their support. The authors wish to thank an anonymous reviewer for the constructive comments of an early version of the paper.

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CHAPITRE 6 – ARTICLE 3
RISK INFORMED DECISION-MAKING IN ASSET MANAGEMENT AS A COMPLEX ADAPTIVE SYSTEM OF SYSTEMS

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Soumis dans *International Journal of Strategic Engineering Asset Management*

Abstract:

Decision-making is an essential activity in Asset Management. It is influenced by various factors (strategic, technical/technological, economic, organisational, regulatory, safety, markets, etc.). Sound decision-making in AsM ought to take into account relevant factors in order to balance risks, opportunities, performance, costs, and benefits. Additionally, modern organisations evolve in complex operational and business environments and are exposed to significant uncertainties. In such a context, decision-making in AsM becomes more challenging. This study proposes a holistic three-step Risk-Informed Decision-Making (RIDM) methodology developed for AsM, considering it as a Complex Adaptive System of Systems. The methodology is applied in a case study to analyse possible modification strategies for a nuclear power plant's emergency core cooling system. Through the RIDM process, quantitative models and other factors have been taken into account in order to obtain the necessary comprehensive insights regarding the decision to be made.

Keywords: asset management, complex adaptive systems, uncertainties, risk-informed decision-making

6.1 Introduction

Asset Management (AsM) has become widespread among contemporary enterprises and organisations as an effective approach allowing to deliver value from assets and to ensure the sustainability of the business and its operations (The Institute of Asset Management, 2015a; Komljenovic *et al.*, 2016; Hastings, 2010). This concept becomes particularly relevant considering the globalisation and increased competition which characterises markets worldwide.

The advances of AsM experience and the accumulated knowledge across various industries resulted in a new International Standard on AsM, the standard ISO 55000 (ISO, 2014a,b,c).

In practice, AsM is sometimes depicted as being essentially related to maintenance and reliability (The Institute of Asset Management, 2015a). However, AsM covers much more than these two fields. It is defined in this Standard as a coordinated activity of an organisation to realise the value of assets. The ISO Technical Committee for Asset Management Systems, ISO/TC251 clarifies the difference between the concepts of *Managing Assets* and *Asset Management* (ISO, 2017). It highlights that over the years, people, organisations and enterprises have developed whole disciplines to help define the best ways to care for assets throughout their useful lives. As such, they have been *Managing Assets* for a long time. Meanwhile, with the introduction of the formal discipline of *Asset Management* roughly 20 years ago, structured approaches have been developed, which assure stakeholders that those care activities are focused on deriving value for the organisation and not just promoting best asset care arrangements. In this regard, Asset Management and Managing Assets are not alternatives.

Contemporary enterprises operate in a market, natural, technical, technological, organisational, regulatory, legal, political and financial environment (hereafter called "business and operational environment"), which is complex and characterised by significant risks and uncertainties. Furthermore, modern enterprises themselves are complex because of their organisational, management and operational structure (particularly the larger ones), which also increases the overall complexity and uncertainties (Komljenovic *et al.*, 2015; El-Thalji and Liyanage, 2015; Beer and Liyanage, 2014; Harvey and Stanton, 2014; Komljenovic *et al.*, 2016; Stacey and Mowles, 2016; Rzevski and Skobelev, 2014).

In contemporary organizations, assets and their systems, exhibit characteristics of complexity, interdependence, and dynamic emerging behaviour (Chopra and Khanna, 2015; The Institute of Asset Management, 2015a,b; EPRI, 2004). Zio (2016) introduces the notions of the structural and dynamic complexity of modern critical infrastructure such as energy transmission and distribution networks, telecommunication networks, transportation systems, water and gas distribution systems, etc.

Consequently, modern organisations are fairly complex socio-technological-economic entities involving many interacting and interdependent elements with hardly predictable long term behaviours at micro and macro levels. Anticipating and assessing such behaviours and dynamics requires extensive knowledge from multiple disciplines in engineering and beyond.

In this context, the decision-making process related to AsM may reveal very challenging due to significant uncertainties related to the nature and complexity of often conflicting influence factors. There are two types of uncertainties that should be taken into account in engineering and AsM: aleatory (arises when an event occurs randomly) and epistemic (has been referred to as a state-of-knowledge uncertainty). More details may be found in relevant references (Kumamoto, 2007; US NRC, 2013; Komljenovic et al., 2016; EPRI, 2015; ISO, 2009a).

Modern organisations attempt to address these issues by using various models and tools that help decrease uncertainties and better quantify risks within their asset management decision-making process.

Those models and tools are typically based on traditional methods which now show limits in effectively treating the complexities and uncertainties mentioned above (Zio, 2016; Komljenovic et al., 2016; NISAC, 2017; NECSI, 2017; Stacey and Mowles, 2016). The results provided through those models are an important input for the AsM decision-making process. However, it seems that decision makers occasionally give them an overwhelming importance while ignoring their limitations. Such an approach may be misleading and potentially result in mistaken decisions if not all of the important influence factors and complexities are properly considered.

Moreover, there are almost no scientific contributions on how to actually link information and insights obtained from various and sometimes very sophisticated quantitative models in AsM analyses and the needs of the decision maker which are fairly of a qualitative nature. Furthermore, the impact of other barely quantifiable or intangible factors (e.g. public perception, political influence, reputation of an enterprise, etc.) could occasionally become dominant in a final decision-making, but they are quite difficult to be adequately accounted for.

Future challenges require new ways of thinking about and understanding the complex, interconnected and rapidly changing world. When Einstein was asked what was most helpful to him in developing the theory of relativity, he replied, *"Figuring out how to think about the problem."* (Hawking, 2000). There are similar challenges in ways one tackles decision-making in AsM.

This study develops a holistic Risk-Informed Decision-Making (RIDM) approach for AsM in the context of the complexity aiming to address the challenges discussed above. This methodology provides a general framework and offers new insights in the domain of decision-making in AsM contributing to the body of knowledge in this area. The approach is applied in a case study to analyse possible modification strategies for a nuclear power plant's emergency core cooling system (ECCS) at a Canadian Nuclear Generating Station.

The remainder of the paper is organised as follows: Section 2 presents a comprehensive literature review of AsM in different industries; Section 3 depicts the proposed methodology of decision-making in AsM; Section 4 shows a case study which illustrates the applicability of the proposed methodology. The paper ends with conclusions and outlines future research works.

6.2 Asset Management in different industries – a literature review

This section grasps some significant contributions in the field of asset management across various industries and human activities.

The concept of Asset Management has generated significant interest across various industries and is still growing (El-Akruti *et al.*, 2013; The Institute of Asset Management, 2015a). Positive experience in applications of AsM culminated in the ISO 55000 Standard which represents an industry-wide consensus in the area and is being implemented across industries (ISO, 2014a,b,c).

The nuclear power industry has invested significant efforts in developing asset management approaches and methods tailored to its needs and particularities. It developed the Nuclear Asset Management (NAM) and the Risk-Informed Asset Management (RIAM) processes. They aim to guide operational, resource allocation, and risk management decisions at all levels of a nuclear generation business in order to maximise the nuclear power plant value for the stakeholders, while maintaining the public and plant staff safety (EPRI, 2007a,b; EPRI, 2005).

Some other specific AsM processes were also elaborated. The petrochemical industry has developed its own processes at the end of the 1980s (El-Akruti *et al.*, 2013, 2016; The Institute of Asset Management, 2015a; Liyanage, 2010; Love *et al.*, 2017). Power generation, transmission and distribution utilities worked based on specific AsM approaches (Adoghe *et al.*, 2013; Bollinger and Dijkema, 2016; Catrinu and Nordgard, 2011; Dashti and Yousefi, 2013; EPRI, 2007a; Lacroix and Stevenin, 2016; Khuntia *et al.*, 2016). Actors in the field of infrastructure management have been using their specific AsM for many years (Bale *et al.*, 2015; Bush *et al.*, 2014; Nikolic and Dijkema, 2010; Osman, 2012; Younis and Knight, 2014; Park *et al.*, 2016; Shah *et al.*, 2017; Ruitenburg *et al.*, 2014; Katina and Keating, 2015). The transportation industry also carried out works in this area (Ballis and Dimitriou, 2010; Dornan, 2002; Andrews *et al.*, 2014; Yianni *et al.*, 2016). The mining industry is also elaborating approaches related to asset management (Azapagic and Perdan, 2010; Komljenovic *et al.*, 2015; Komljenovic, 2007; Koro, 2013). The above review shows that the application of the AsM concept is gaining momentum across industries, and it seems that it will continue to further evolve in the coming years.

6.3 Risk-Informed Decision-Making Model in Asset Management

In this section an enhanced and holistic methodology regarding decision-making in AsM is proposed. It represents an extension of initial research works carried out in this field (Komljenovic et al., 2016), and integrates several novelties:

- Development of a specific Risk-Informed Decision-Making (RIDM) as a structured and rational decision-making methodology in AsM considering it as a Complex Adaptive System (CAS) or a Complex Adaptive System of Systems (CASoS).
- Structure and relationships between the sub-models of a holistic RIDM in AsM.
- Explicit consideration of the strength of knowledge on outcomes of various quantitative and qualitative models used in decision-making.
- Differentiation of usage of analysis outcomes by analysts and decision makers.
- Definition of the role of deliberation in decision-making, its principles and the roles and responsibilities of various participants in the process.
- Integration of risks of extreme and rare events in the overall risk assessment in AsM decision-making.
- Introduction of the concept of Complex System Governance (CSG) as a way to cope with the complexity of AsM.

The RIDM methodology in AsM is subdivided in three distinct steps: 1) Setting the framework, 2) Performing detailed analyses, and 3) Global analysis, deliberation, decision-making, communication, and implementation. Details are shown below.

6.3.1 Decision-Making in AsM: General Considerations

Asset management is composed of an array of interacting and interdependent activities and constituent parts within a multilevel structure (people, technologies, organisational unities, processes, management, etc.). As per best practices, it should be closely linked to the strategic planning of an enterprise, the so-called "line of sight" which translates organisational objectives into AsM policy, strategy, and objectives (ISO 2014a; The Institute of Asset Management, 2015a).

A comprehensive decision-making in AsM is vital for an organisation which aims to maximise the value realised over the life cycle of its assets. There are various types of decisions made in AsM (The Institute of Asset Management, 2015a,b):

- Capital investment;
- Operation and maintenance;
- Shutdown and outage strategies;
- Life cycle value realisation;
- Resourcing strategy, etc.

In the decision-making process, it is essential to strike the right balance between numerous competing interests and factors such as performance, risks, benefits, costs, opportunities, short-term goals vs. long-term sustainability, etc. New concepts and approaches in modelling AsM and the related decision-making are needed to systematically take into account the overall complexity of the business and operating environment discussed above, as well as to adequately integrate all relevant influence factors. A few research works tackle this subject.

Some new research trends promote approaches where contemporary enterprises/organisations are better characterised and modelled as complex adaptive systems (CAS) or Complex Adaptive Systems of Systems (CASoS) (Stacey and Mowles, 2016; Efatmaneshin *et al.*, 2016; Dekker *et al.*, 2011; Katina *et al.*, 2014; Keating and Katina, 2016; Komljenovic *et al.*, 2016; Pyne *et al.*, 2016; NISAC, 2017; NECSI, 2017; Albino *et al.*, 2016; EPRI, 2004; Rzevski and Skobelev, 2014; Kadiri *et al.*, 2015; Zio, 2016). The scientist S. Hawking highlighted once that the 21st century would be the "century of complexity", and that one has no choice but embrace it (Hawking, 2000).

The CAS or CASoS are dynamical systems comprising a large number of components interacting with each other in nontrivial ways. These systems are able to adapt to and evolve within a changing environment. They exhibit coherence under changes, via conditional action and anticipation, and they do so without a strong central direction. They are self-organising, evolving, dynamic, non-linear, and barely predictable with emerging behaviours influenced by uncertain cause-and-effect relationships, interdependencies, feedback loops and unscheduled discontinuities. It is important to highlight that there is no definite separation between a complex system and its environment. Furthermore, the complexity is associated with the strength of connections between several autonomous constituent elements of a system that make interactions difficult to grasp and anticipate (Komljenovic *et al.*, 2016).

A new interdisciplinary field called *Complexity Science* or *Complexity Theory* has emerged and evolved over the last few decades seeking to understand, predict, and influence the behaviour of complex systems. It develops concepts, methods and tools that transcend specific applications and disciplines. Complexity Science deals with issues that traditional methods have difficulty addressing such as non-linearity and discontinuities, self-organisation, emergence, aggregation of macroscopic patterns rather than microscopic causal events, probabilistic rather than deterministic outcomes and predictions, change instead of equilibrium, etc. In fact, the complexity science helps redefine our views of CAS or CASoS which are only partially modelled by traditional techniques (Komljenovic *et al.*, 2016).

CAS or CASoS function at various time scales (from less than one second to years, decades, or longer), and at multiple spatial scales (from less than one millimetre to several kilometres, or more) (Holling, 2001). Orrell and McSharry (2009) state that complex systems cannot be reduced to simple mathematical laws and be modelled appropriately. The reduction in modelling only introduces new uncertainties.

Following the discussion above, the current research claims that the asset management also has to be considered and analysed as a CAS or CASoS (Komljenovic *et al.*, 2016; Komljenovic *et al.*, 2017a). Some scholars and researchers have already discussed this orientation with regard to AsM (Beer and Liyanage, 2014; Bale *et al.*, 2015; Bollinger and Dijkema, 2016; Bush *et al.*, 2014; Komljenovic *et al.*, 2015; Nikolic and Dijkema, 2010; Osman, 2012; Lacroix and Stevenin, 2016; The Institute of Asset Management, 2015a; Katina and Keating, 2015). However, existing research works in this area can and should be further expanded and enriched in order to provide a more holistic approach.

In this regard, the present study asserts that RIDM in AsM is the best suited approach, and it will be further developed and adapted in this research.

The original RIDM is a concept elaborated by the U.S. nuclear power industry regarding nuclear safety issues in the late 1990s. The initial idea was presented in the White Paper of the U.S. Nuclear Regulatory Commission (Travers, 1999). Its application was further expanded and the framework defined through regulatory documents (US NRC, 2011). There is no unique definition of the RIDM, and several ones may be found across references (Bujor *et al.*, 2010; Elliott, 2010; IAEA, 2011; Komljenovic *et al.*, 2016; NASA, 2010; Travers, 1999; Zio and Pedroni, 2012).

The RIDM involves considering, appropriately weighting, and integrating a range of often complex inputs and insights into decision-making. Inputs and insights considered may come from "traditional" engineering analyses, deterministic and probabilistic risk analyses, operational experience, cost-benefit considerations, regulatory requirements, allowable "time at risk," and any other relevant quantitative, qualitative and/or intangible influence factors and considerations (Bujor *et al.*, 2010, NASA, 2010; Apostolakis, 2004). It is deliberative and iterative. The RIDM is essentially performed by decision makers who consider various inputs from knowledgeable experts (subject matter experts – SMEs, and analysts), as well as relevant quantitative and qualitative models.

Afterwards, the RIDM has been adapted to other industries at risk, such as aerospace (NASA, 2010; Zio and Pedroni, 2012; Stamatelatos *et al.*, 2006), and dam safety (FERC, 2017) to name a few. This concept is opposed to a risk-based approach where decision-making is solely based on the numerical results of quantitative risk assessments (Apostolakis, 2004; Klim *et al.*, 2011; Komljenovic *et al.*, 2016; Travers, 1999; US NRC, 2011; Aven, 2014, 2016a,b).

As discussed above, the novelty of the present research consists in developing a specific RIDM as a structured and rational decision-making methodology in AsM considering it as a CAS or CASoS. The study proposes and introduces a three-step (phase) approach: 1) Setting the framework, 2) Performing detailed analyses, and 3) Global analysis, deliberation, decision-making, communication, and implementation. The steps are closely linked but distinct. Each step is composed of one or several stages. The details are depicted in Figure 6.1.

The proposed methodology is intended to be generic, applicable and adaptable to any size and any type of companies. However, it should be emphasised that it is suggested for key asset management decision-making affecting both mid and long-term performance, as well as the sustainability of an enterprise.

Figure 6.1 also presents participants involved and their functional roles in each step/stage. Key details of the whole process are described below. The methodology integrates key features of decision analysis and analytic-deliberative processes (NASA, 2010; Elliott, 2010; Stamatelatos *et al.*, 2006). The main functional roles in the decision-making process are described below and are inspired by some existing works (NASA, 2010; ISO, 2009a, 2014a):

- Analysts: An analyst is an individual or an organisation that applies probabilistic or other quantitative methods to quantify the performance with respect to various domains such as safety and risk, technical/engineering, revenue and cost, planning, etc.
- Subject Matter Experts (SMEs): A subject matter expert is an individual or an organisation with expertise in one or more specific topics within the domains of interest.
- Decision Maker: A decision maker is an individual with the responsibility to make decisions within a particular organisational scope.
- Management: Management consists of the people who manage an organisation/enterprise.
- Stakeholder: A stakeholder is a person, a group of persons or an organisation that can affect, be affected by, or perceive themselves to be affected by a decision or an activity of the organisation/enterprise.

  Note: A decision maker can be a stakeholder.

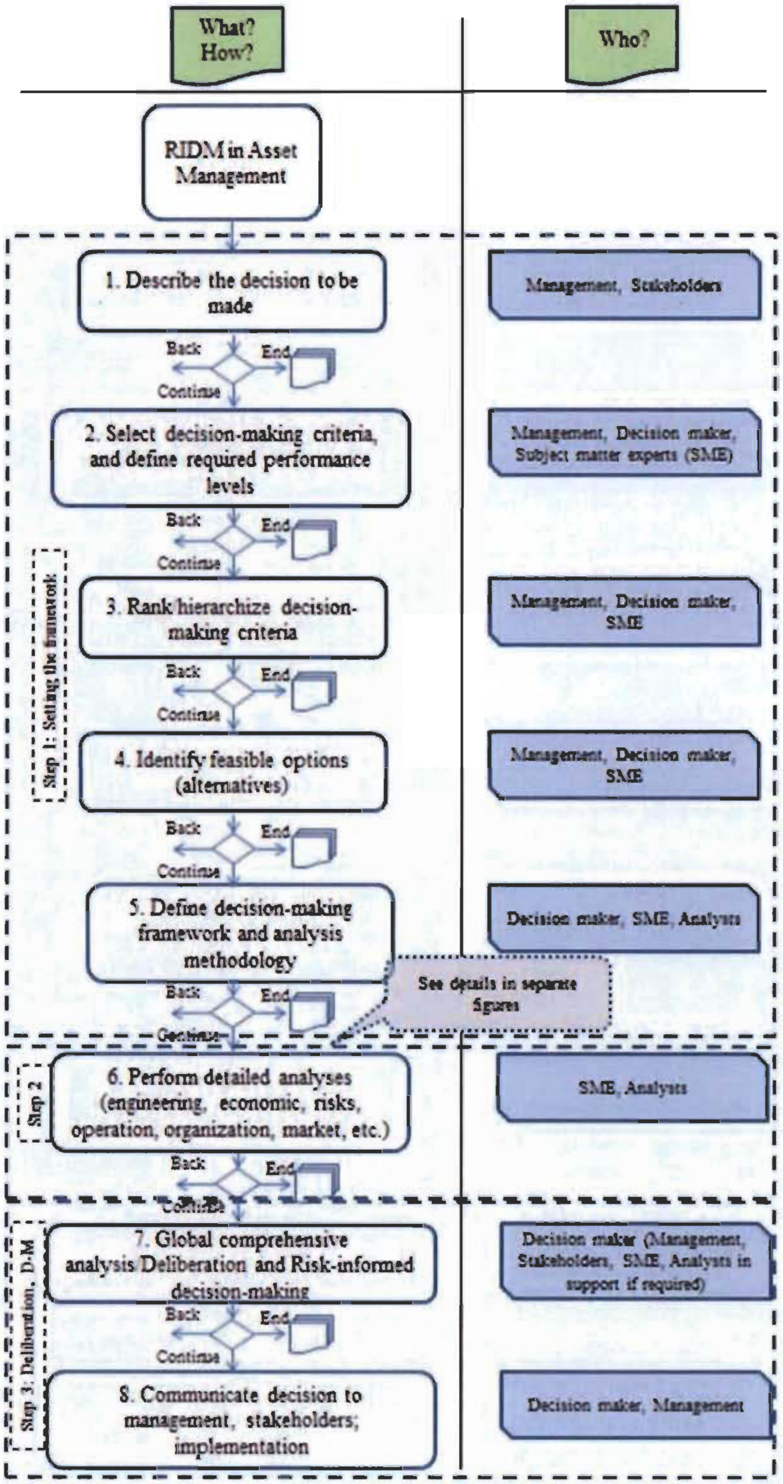

Figure 6.1. Overall RIDM in Asset Management

6.3.2 Decision diamond

The overall AsM decision-making process implies decisions/orientations between stages. They are symbolised by a decision diamond that has three potential outcomes: *Back, End, or Continue* (Figures 6.1 and 6.2).

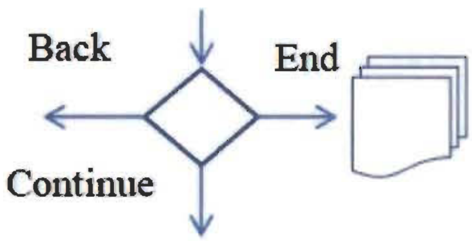

Figure 6.2. Decision diamond in AsM decision-making process

A ***"Back"*** decision requires the repetition of one (or more) previous stages in order to improve assumptions, accuracy, and completeness of information/data or to perform supplementary analyses. It is iterative and enables the continuous improvement of the whole process.

An ***"End"*** decision specifies that the AsM decision-making process does not need to be further pursued. The process can be ended for numerous reasons:

- A situation which prompted the process does no longer exist or the general context has significantly changed. Thus, pursuing the decision-making process is not needed anymore.
- There are sufficient information/insights or the situation is rather straightforward so that the solution is obvious. A comprehensive decision can be made without further analyses.
- It is required to make an immediate decision if it is judged that there is a serious emergency and the organisation lacks time to carry out detailed

analyses. The decision maker has to sufficiently review the situation in order to make sure that the urgent decision would not aggravate the situation. Moreover, the analysis process may continue as emergency actions are being taken.

- Any other reason judged relevant by the management and decision maker.

It is highly important that the decision to end the process and the rationale behind it be duly documented.

A ***"Continue"*** decision involves proceeding to the next stage within the process.

6.3.3 Description of the Decision-Making Steps in Asset Management

6.3.3.1 Step 1: Setting the framework

Step 1 involves five stages, detailed in Figure 6.1. It serves to adequately define the analysed issue, the context, alternatives to be considered, the decision to be made, and suggested methodologies to be used. This phase should not be underestimated, and may be time consuming. Meanwhile, without a comprehensive preparation through this step, the remaining analyses and the resulting decision-making may be almost useless or misleading. The work here involves stakeholders, management, decision maker, subject matter experts (SMEs) and analysts.

The detailed description of the first four stages in Figure 6.1 is omitted given that they are rather obvious. The stage 5 "Define decision-making framework and analysis methodology" outlines how domain-specific analyses are integrated into a multidisciplinary framework to support decision-making under uncertainty. In general, each specific decision domain may have several analysis methodologies available. Various criteria should be taken into account while selecting methods and models such as the criticality of the decision, costs of performing analyses, complexity and time to execute, necessary accuracy of the results, etc.

Asset Management decisions may significantly vary in complexity and criticality. It would not be appropriate to apply the same level of sophistication to all decisions. Simple, non-critical decisions should be made using the results obtained from simpler tools, models or an informed judgement/common sense. Critical and complex decisions require systematic, rigorous, multidisciplinary, and auditable decision-making process (The Institute of Asset Management, 2015a,b). However, the use of more complex evaluation approaches, methods and models is relevant in circumstances where the complexity of the context and the value of the decision justify them, i.e. they should be fit for purpose and provide the knowledgeable decision maker with relevant information and insights.

The selection of evaluation methods and models should also involve a "cultural" aspect, i.e. they have to be accepted and trusted by both the stakeholders and the organisation's management. Ultimately, they should be integrated into a structured asset management system. To remain relevant, approaches and models have to keep pace with the contemporary evolution of organisations, the state-of-the art knowledge, as well as the increasingly complex technological systems and business environment.

On the other hand, excessively complex methods, models and solutions may suffer from being too difficult to understand by analysts, SMEs and decision makers, resulting in the "black box" syndrome which could lead to disinterest, and cause a lack of trust. Moreover, the undue complexity of models and methods could create the opacity of the overall decision-making process and obscure its true rationale. This outcome is potentially risky and may later reveal costly for an effective asset management. Meanwhile, overly simplistic and reductionist models cannot be fit for purpose, and may mislead the decision maker. Consequently, the real challenge is to find the right balance between the adequacy of the methods/models used and the actual decision-making context and needs.

To perform analyses related to the complexity, several methods and tools are available such as Multi-Agent-Based Models, Cellular Automata and Network Analyses. There are also additional complexity-related techniques and methods: Data Mining, Scenario Modelling, Systems Theory, Dynamical Systems Modelling, Artificial Intelligence, Neural Networks, Evolutionary Game Theory, Panarchy Theory, etc. (NISAC, 2017; NECSI, 2017; Komljenovic *et al.*, 2016; Rzevski and Skobelev, 2014; Sayama, 2015; Zio, 2016; Holling, 2001; Homer-Dixon, 2011).

It is common practice to use various assumptions in engineering and other analyses through the steps of the process. Since they usually have a significant impact on the outcomes of those analyses, it is important to reasonably explain and properly document them for subsequent studies and sensitivity analyses.

6.3.3.2 Step 2: Detailed analyses

- Detailed model

  The second step involves performing the required detailed analyses (engineering, risks, and other relevant analyses). It is mainly carried out by subject matter experts (SMEs) and analysts using appropriate methods, models and tools suggested and defined in the previous step. This phase aims at producing results, inputs and insights as well as formulating recommendations for the decision maker. These analyses have to be rigorous, systematic, and technically and scientifically sound.

  A more comprehensive model is required to perform all the required in-depth analyses, characterise uncertainties, and assess the impact of other relevant influence factors. Figure 6.3 depicts more details regarding the model which is referenced as stage 6 in Figure 6.1.

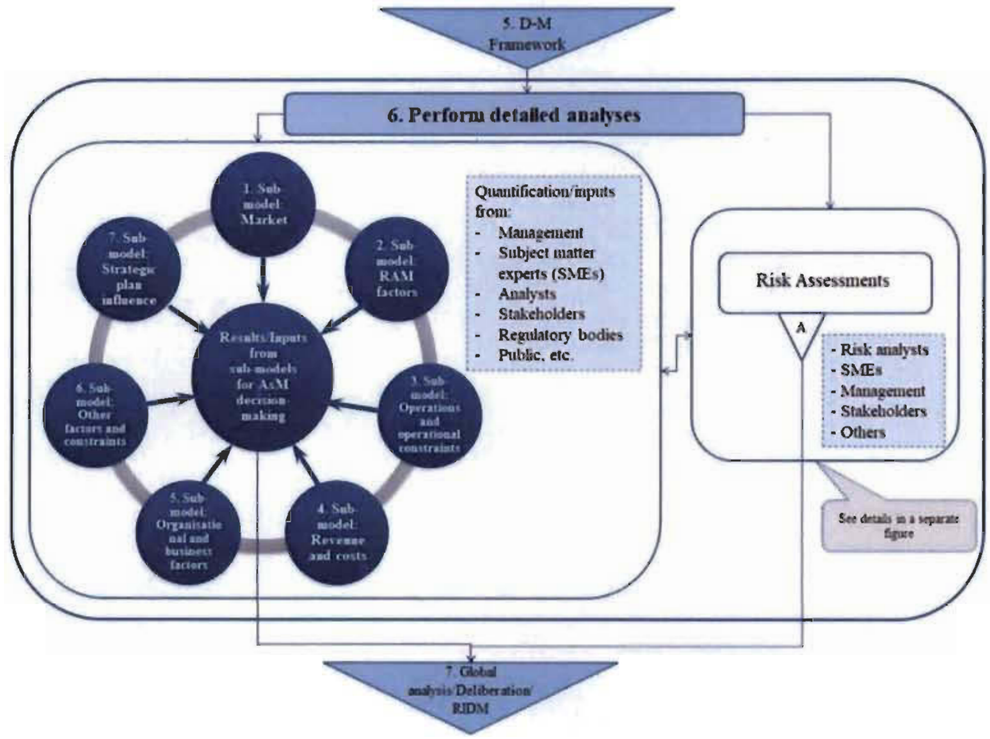

Figure 6.3. Global model for detailed analyses in RIDM in AsM

The detailed analyses are basically carried out by analysts and SMEs. Additional inputs from other actors in the process may be solicited if required (Figure 6.3).

The model is composed of seven sub-models and is presented on the left side in Figure 6.3. Initial research works on this subject are carried out by (Komljenovic *et al.*, 2016). In order to adequately understand the proposed methodology, these sub-models and their interdependencies are presented in detail in Appendix 6.A.

These sub-models and their internal parts interact in a complex manner which leads to the behaviour of the whole process that is not obvious from the individual behaviour of each sub-model and its parts (Tables 6.A1 and 6.A2).

The activities, influence factors, technologies, and constraints depicted and modelled in the seven sub-models are complex as far as their internal structure, management and functioning are concerned. They represent a complex adaptive system (CAS) themselves. Consequently, this overall complexity leads to the opacity of the whole system, and may then breed hidden risks due to the presence of unexpected connections and significant epistemic uncertainties caused by the lack of knowledge upon the true state of the system.

Their assembly, countless interactions and interdependence evolve and become a complex adaptive system of systems (CASoS). Therefore, the AsM of an enterprise may be considered to be an emergent and dynamic phenomenon integrating several technological, functional, operational, and management layers. It implicates numerous feedback loops reacting to the influence of their environment and the behaviour of other sub-models and their parts. It generally creates a non-linear, emergent, and adaptive behaviour of the whole system. If any of the interacting sub-processes or elements would change or experience significant variations, the functioning and performance of other elements and the entire system could be seriously altered (Komljenovic *et al.*, 2016).

The outputs from the sub-models (or from qualitative informed assessments in the absence of models) should be comprehensively aggregated in order to provide meaningful and sufficient insights to the decision maker for the ulterior deliberation and decision-making process. In fact, the nature of these sub-models also integrates relevant decision-making criteria.

– Risk Assessment

The right side of the model in Figure 6.3 depicts the risk assessment process. The details are shown in Figure 6.4. There is a strong relationship between the seven sub-models and associated risks. The activities and influence factors presented in these sub-models generate various types of risks which have to be assessed.

For the purpose of this study, risk assessment takes into account the overall framework defined in the ISO 31000 Standard, namely: **I)** establishment of the context, **II)** risk assessment, and **III)** risk treatment (ISO, 2009a; The Institute of Asset Management, 2016). Risk assessment integrates the following steps: **IIa)** risk identification, **IIb)** risk analysis, and **IIc)** risk evaluation. ISO 55000 also relates to ISO 31000 regarding risk assessment and management (ISO, 2014a). Step 1 of the global RIDM in AsM covers step **I** in risk assessment. Step 2 in the global process and step **II** are also associated, and finally Step 3 and step **III** go along as well.

Meanwhile, it should be stressed that traditional methods of risk analysis are not entirely adequate for complex entities such as AsM. The challenge in risk assessment in complex systems sits in their very nature of non-linearity and emergent behaviour, uncertainties and opacity of actual interdependencies, and interactions of their constituent elements which are difficult to grasp and understand. The aggregation of risks is quite challenging for the same reasons since it almost never represents a mere sum of individual risks.

A traditional view in the risk analysis of an event supposes some linearity (a timeline and a clear cause-effect dependency) which could be representative of the reality to a certain extent. Even if some aspects were not reflected in the analysis, the identification of protective barriers remains good enough to define corrective actions. Today, in most situations, the use of such linear approaches and traditional methods of risk analysis (e.g. FMECA, FTA, ETA, HAZOP, Bow-Tie, What-if, LOPA, etc.) (ISO, 2009b) is insufficient to allow for a complete and suitable understanding of the stakes and challenges regarding risk analyses in complex systems. (Komljenovic *et al.*, 2017b).

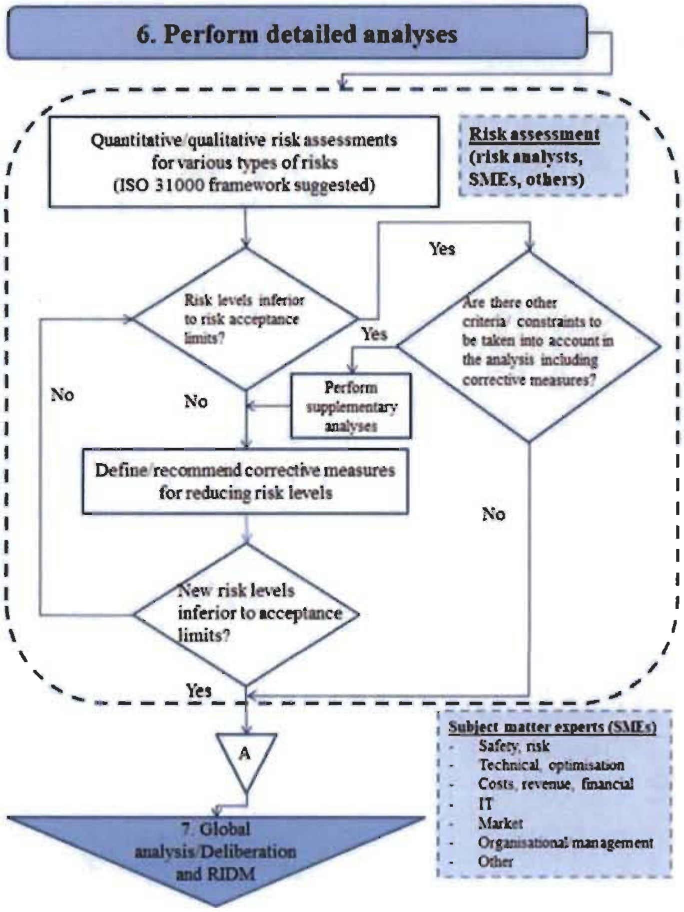

Figure 6.4. Detailed Risk Assessment in RIDM in AsM

Therefore, new methods are needed to understand and model this complexity in the risk analyses. Several authors share this point of view and advocate the development of new approaches (Aven, 2014, 2016a,b; Dekker *et al.*, 2011; Cox, 2012; Haimes, 2017; Harvey and Stanton, 2014; Leveson, 2011a,b; Hollangel, 2012; Jensen and Aven, 2018; NISAC, 2017; NECSI, 2017; Pyne *et al.*, 2016; Zio, 2016). In absence of mature methods and models for a majority of industries, the risk analysis in AsM should exploit or improve existing ones as far as practical. The utilisation of some advanced methods of risk analysis such as *Systems-theoretic accident model and processes (STAMP)* may be helpful in this regard (Leveson, 2011a,b). Also, in various, mature industries at risk with highly complex installations or systems, e.g. nuclear, aviation, one may have a good understanding of risks, and enough data to develop adequate risk models (e.g. Probabilistic Risk Assessment – PRA in the nuclear power industry) (CNSC, 2014a; US NRC, 2011, 2013). In new fields, one might not have a sufficient understanding of the potential risks, data or models to adequately assess risks, e.g. nanotechnology, DNA modifications, artificial intelligence (Komljenovic *et al.*, 2017b). For that purpose, methods and modelling tools taken from the complexity science enumerated earlier may be valuable in characterising risks and improving risk assessment in AsM as CAS/CASoS. Research works in this field are at their beginnings.

Accordingly, analysts, SMEs, and the decision maker need to use all available information, knowledge and models to grasp and assess risks associated with the complexity and make an informed judgement upon their influence on the outcomes of analyses in decision-making in AsM. The knowledge of their limitations is essential (Apostolakis, 2004; Klim *et al.*, 2011). Failing to adequately consider that may likely cause serious consequences for the whole RIDM process in AsM.

Risk assessment in AsM also has to take into account extreme and rare events. In today's modern world, one should understand that those events are more likely to occur due to the complexity of assets and operational and business environment. It is no longer acceptable to consider those events as external to the design, analysis and operation of contemporary complex technological systems and organisations. Epistemic uncertainties are significant there (Komljenovic *et al.*, 2016). It exists a common understanding among risk experts that the quantification of the risks of extreme and rare events does not allow the "prediction" of accidents and catastrophes. It is basically impossible to accurately determine very low probabilities; one could miss several orders of magnitude. Instead, the risk assessment is aimed at supporting an effective risk management (Aven, 2014, 2016b; Cox, 2012; Paté-Cornell, 2012). Risk assessment and risk management of those events basically involve the surveillance of warning signals, precursors, and near-misses, as well as the reinforcement of the system (increasing its resilience and robustness), and a thoughtful response strategy (Albino *et al.*, 2016; Zio, 2016; Haimes, 2017; Jensen and Aven, 2018). It also implies a careful examination of organisational factors such as the incentive system, which shape human performance and influence the risk of errors (Paté-Cornell, 2012; Kahneman, 2012). Within this activity, motivational and cognitive biases may generate wrong perceptions or irrational thinking, and have a negative impact on the outcomes (Montibeller and Winterfeldt, 2015; Kahneman, 2012; Komljenovic *et al.*, 2016). Cox (2012) claims that robust and adaptive methods provide genuine breakthroughs for improving predictions and decisions in such cases. The categories of impact with regard to risk assessment may vary in function of the specific context of an organisation. As per common practices, they may encompass the following types of impact: a) Safety and health of people (workers and public), b) Environment, c) Loss of material goods or other physical assets (company's own or others), d) Financial losses, e) Increased costs of operation and maintenance or delays in a project schedule, f) Loss of reputation and deterioration of the image of the enterprise, etc.

The levels of gravity of the impact should also be tailored to the specific needs of the analysis such as I) Catastrophic, II) Severe, III) Major, IV) Minor, or any other meaningful scale expressed in relevant measurable units ($, % of production loss, number of production days lost, etc.).

The same applies to the categories of likelihood. They should be defined in accordance to the needs of the analysis, as well as per usual practices in enterprise risk management. The scale may be either descriptive (in the absence of reliable data) or numerical (where pertinent data are available). Estimating likelihood is also a challenging task in complex systems. Several authors highlighted it, including the need to elaborate new risk analysis approaches for complex systems. Characterising impacts and likelihood enables the construction of corresponding risk matrices which assist a risk analysis (item **IIb** above). Risk acceptance levels should be defined at the enterprise level for allowing risk evaluation (item **IIc** above).

– Strength of background knowledge

Before and during detailed analyses in Step 2, it is highly important that the participants evaluate their strength of background knowledge with regard to the issue/phenomena analysed. Given the opacity of complex systems, this is particularly important when analysing such systems. Some scholars consider this element very important in the risk analyses (Aven 2014, 2016a,b; Askeland *et al.*, 2017). Background knowledge also includes undocumented data, information and beliefs, with the latter articulated as assumptions (Askeland *et al.*, 2017). A weaker knowledge basis introduces more uncertainties in analyses and causes a lower confidence regarding their outcomes.

In the context of health and safety, Health and Safety Executive (HSE) in the United Kingdom utilise the *factor of gross disproportion* in their cost-benefit analysis (CBA) to compensate for uncertainties and ensure sufficient margins of both safety and operations. HSE have not formulated any algorithm which can be used to determine, in any case, when the degree of disproportion can be judged as 'gross.' The judgement is made on a case-by-case basis. However, they use a rule of thumb stating that a factor of up to 3 (i.e., costs three times larger than benefits) would indicate risks to workers; a factor of 2 would indicate low risks to members of the public, and a factor of 10 would indicate high risks. Moreover, HSE suggest performing sensitivity analyses to further grasp the impact of uncertainties, and to assess the robustness of the CBA's outcomes (HSE, 2017).

The current study extends the requirement to consider the strength of knowledge to all specific analyses in the seven sub-models performed for the AsM decision-making process depicted in Figure 6.3, including risk assessment (Figure 6.4). A stronger knowledge basis means fewer epistemic uncertainties and higher confidence regarding the obtained results, and vice-versa. This fact has to be taken into account in the deliberation and final decision-making (Step 3) by providing sufficient operating, management and safety margins in order to compensate for epistemic uncertainties.

A qualitative scale for the strength of the knowledge basis is proposed in this research: *weak, satisfactory (moderate), and strong*. A similar scale is suggested by Askeland *et al.* (2017).

In summary, the proposed detailed model allows to define and characterise the following features:

- Identifying and mapping the type and strength of the connections between the sub-models and their parts, as well as the degree of their complexity. Generally, this activity also allows to identify uncertainties (particularly epistemic ones) within the sub-models. A higher degree of complexity typically corresponds to larger epistemic uncertainties. These uncertainties and a lack of knowledge may likely create an overall opacity in the system/process, and could obscure precursors/low level intensity events/warning signals/near-misses pointing out to the likely occurrence of extreme, disruptive events. In many regards, the CAS/CASoS are opaque and their behaviour is hardly predictable. Risk assessment in those systems is more difficult and requires new methods and paradigms because traditional methods are not entirely adequate for this purpose (Haimes, 2017; Komljenovic *et al.*, 2016; Jensen and Aven, 2018; Aven, 2014, 2016b; Katina *et al.*, 2014; NISAC, 2017; NECSI; 2017; Hollangel, 2012; Komljenovic *et al.*, 2017b; Leveson, 2011a,b; Zio, 2016).

- Identifying and understanding the risks of extreme and rare, but plausible events (natural and human-made) which may seriously affect an organisation's performance or even endanger its existence.

6.3.3.3 Step 3: Deliberation, decision-making, communication, and implementation

The third step of RIDM in AsM is mainly performed by the decision maker, supported by SMEs, analysts, and stakeholders. This step is rather qualitative aiming to grasp all relevant insights for a satisfactory decision-making. This step is presented as the stages 7 and 8 in Figure 6.1, and involves a high-level analysis and deliberation. The decision maker has to make a comprehensive usage of the outcomes of various quantitative analyses with the level of detail appropriate for the decision to be made, and to integrate other relevant influence factors often intangible and hardly quantifiable as discussed above. A similar approach is used in certain practices in risk analysis and management (NASA, 2010; Elliott, 2010, Aven, 2014, 2016a,b).

An organisation, through the RIDM process, gives the decision maker the authority and responsibility to make critical decisions. While the ultimate responsibility for alternative selection belongs to the decision maker, their evaluation can be performed within a number of deliberation forums which may be held before the final selection is made. As discussed above, the decision-making is supported by relevant results of appropriate quantitative and qualitative analyses performed by analysts and SME. They have to provide a comprehensive compilation of insights and information sufficient for the decision-making. All relevant interdependencies ought to be taken into consideration (see Tables 6.A1 and 6.A2).

The final decision in AsM can be made only after a deliberation takes place (that is one of the differences between a risk-*informed* rather and risk-*based* process). Deliberations are necessary because there may be aspects of the particular decision that cannot be considered in a formal way or through modelling (Tuler and Webler, 1999; NASA, 2010; Shattan, 2008; Elliott, 2010; Stamatelatos *et al.*, 2006; Apostolakis, 2004). Some discussion in this regard is presented in previous sections. The analytic deliberation, then, is a structured deliberation among those people interested and affected by a decision, such as management, decision maker, stakeholders, SME, analysts, etc. The deliberation process should imply enough members to achieve a "critical mass" of knowledge, interest and motivation. The members should be selected on a case-by-case basis. The Analytic Deliberative Decision-Making Process (ADP) was developed at MIT, and has been used to study various decision-related problems (Elliott, 2010). It is useful for making decisions when there is adequate time for analysis and collective discussion. Deliberations can be formal or informal, and may lead to the conclusion that none of the original alternatives is acceptable. The ADP is not appropriate for real-time decision-making (Elliott, 2010). To be mutually supportive, analysis and deliberation have to be integrated and iterative.

It is important to understand that deliberations do not delegitimise the use and importance of scientific understandings and various quantitative analyses. The insights gained from Step 2 may eventually lead to the formulation of additional decision alternatives, in which case one should go back to Step 1 as indicated by the feedback loop (decision diamond in Figures 6.1 and 6.2). If the deliberation concludes that the original decision alternatives were satisfactory, then a decision is made and documented. The options (alternatives) from Step 1 are evaluated and one of them is selected. Relevant analysis, in quantitative or qualitative form, strengthens the knowledge base for deliberations. Without good analyses from

Step 2, deliberative processes can lead to agreements that are unwise, misleading, or not feasible.

There are no algorithms developed to perform deliberations before decision-making. However, the following principles should be taken into account while conducting them in the AsM context:

- Human performance: Several authors argue that we cannot assume that human decision-making is always rational. In such situations, cognitive and motivational biases are likely to occur in the decision-making process. Those biases could negatively affect the desired outcomes (Kahneman, 2012; Montibeller and Winterfeldt, 2015; Paté-Cornell, 2012). It adds to the overall complexity of the operational and business environment, and may ultimately create favourable conditions for the occurrence of extreme and disruptive events in a system through an induced fragility. It is necessary to take into account the actual structure of the organisation its advantages, constraints and limitations, and its impact on the strategy of AsM. Therefore, these aspects have to be accounted for in deliberations and decision-making.

- The overall comprehensive assessment and analysis by a decision maker is rather qualitative, and based on all relevant inputs. The results obtained from quantitative assessments (risk and other models) represent a very strong guidance in decision-making, but they are not a definite panacea. These analyses are chiefly model-based and fact-based, but the decision maker should also offer a value-based approach (Hansson and Aven, 2014; Askeland et al., 2016). It is up to the decision maker to adequately commensurate the importance, weight and limits of quantitative inputs. This overall analysis has to go beyond the results of quantitative analyses.

- Deliberations should aim at grasping the overall picture, key interdependencies and relationship between the main influence factors (Figures 6.1, 6.3, 6.4. Tables 6.A1 and 6.A2). The total business impact should be considered by balancing short and long term goals and strategies of the organisation, and align with "Line-of-sight" which translates organisational objectives into AsM policy, strategy and objectives.

- The decision maker, with the help of SMEs, analysts, management, and stakeholders should properly identify and evaluate the importance of intangible or unquantifiable influence factors for a final decision-making. These are "soft issues" which are often hard to grasp, understand and integrate into the final decision-making.

- The strength of knowledge of the analysts and subject matter experts involved should be qualitatively assessed, and taken into account in the final decision-making (Hansson and Aven, 2014; Aven, 2014, 2016a; Askeland *et al.*, 2016). Weaker background knowledge asks for extra compensation margins due to larger epistemic uncertainties.

  The complexity of the constitutive parts, influence factors, their interdependence and relationship in AsM, as well as the operational and business environment should be properly understood and assessed (Tables 6.A1 and 6.A2). The assumption of the independence and linear behaviour of these factors are most likely no longer applicable in such a context. The right understanding of this aspect is of chief importance for adequate decision-making and management (Stacey and Mowles, 2016, Komljenovic *et al.*, 2016; Efatmaneshnik *et al.*, 2016).

  One of the possible ways of coping with the complexity in AsM in a general sense consists in tailoring and expanding the concept of *Complex System Governance (CSG)*. Its generic framework has been developed at the Old

Dominion University, Norfolk, VA, USA. The CSG is an emerging field aiming to develop control, communication, coordination, and integration functions necessary to produce and sustain desirable levels of system performance in complex systems. It is defined as the *design, execution, and evolution of the metasystem functions necessary to provide control, communication, coordination, and integration of a complex system*. The proposed reference model with conceptual foundations is based on the system theory and management cybernetics (Keating *et al.*, 2014; Keating and Bradley, 2015; Keating and Katina, 2016).

Pyne *et al.* (2016) further explore concepts, methods, and tools that may help managers to cope with constantly increasing complexity issues. They use the CSG and the System Thinking to propose a framework enabling managers to better handle the complexity which is a *"new normal"* in the contemporary business world. The authors argue that effective problem solving in complex domains needs a different level of "more systemic" approaches capable of matching the uncertain, complex, and dynamic behaviour which characterise today's context. The authors explore the challenges in moving the CSG from the theoretical/conceptual formulation to practice.

The potential adaptation of the CSG to AsM specificities should be further studied in areas where it could help in determining how to deal with the constantly increasing complexity of the operational and business environment.

- Methods of multi-attribute decision-making (MADM) or multi-criterion decision-making (MCDM) may be useful while performing deliberations and decision-making. Any MADM may be used, and there are many mature methods available (Analytic Hierarchy Process – AHP, Fuzzy AHP, ELECTRE, PROMETHEE, VIKOR, Multi-attribute utility theory – MAUT, etc.). Meanwhile, it is important to recognise the strengths, weaknesses, and limits of those methods in order to use them adequately. There are plenty of high-quality contributions in the literature regarding this topic (e.g. Parnell et al., 2013). The outputs of these methods help a decision maker to make a final decision. Nevertheless, these methods and their results should be perceived as a structured guidance and support of the analysis documenting the reasoning behind the analysis. In the end, the machines/models do not make decisions – humans do

It is worth highlighting that classical MADM methods have very limited capabilities in capturing and characterising complexity. New research works are needed to elaborate new approaches and overcome this weakness.

– Key uncertainties (especially epistemic ones) have to be identified, mapped and assessed. Basic principles in treating and managing them at this stage of AsM decision-making are the following:

  Case 1. Aleatory (or dominantly aleatory uncertainties) – usually present with well-defined technological systems that an organisation is capable to efficiently control; traditional scientific/engineering methods and models of analysis may deliver adequate insights (e.g. sub-model 2).

  Case 2. Dominantly epistemic uncertainties where an organisation has a capacity to strongly influence the environment without having the ability to exercise a strong control (enterprise-level activities and internal organisational structure and functioning): the complexity is fairly present here and quantitative models or qualitative assessments based on the complexity theory may be helpful. Decision-making and management of these elements should be based more on the concept of agility, resilience, and robustness of the organisation in order to offer a better flexibility and efficiency, and compensate for the emergent behaviour of the whole system (Komljenovic et al., 2016) (e.g. the sub-models 3, 4, 5, 7).

  Case 3. Predominantly epistemic uncertainties where an organisation does not have the capacity to strongly influence or control the environment (all external influence factors relevant to AsM): the complexity clearly prevails here, and the risk of extreme, disruptive events is relatively high. The quantitative models or qualitative assessment should capture it. Those models may use methods related to the complexity science. Decision-making and management of these elements should also be based more on robustness, resilience, and "antifragility" in order to offer a better flexibility and efficiency, and compensate for surprising (emergent) events and behaviour. This approach represents a part of a continuous improvement. Some authors even advocate the concept of "anticipatory" systems where organisations foresee and avoid shocks and perturbations, and seize opportunities from them when pertinent (Albino *et al.*, 2016). The AsM strategy should enable the survival of the organisation in the case of extreme shocks/perturbations from both the internal and external environment (Komljenovic *et al.*, 2016) (e.g. the sub-models 1 and 6).

– Risk treatment

Risk treatment measures (Step **III** above) are not discussed in detail here since they depend on the type of organisations, and should be tailored to the specific context of the organisation, which should have established its risk acceptance levels. The general principles of robustness, resilience, and continuous improvement (learning organisation), and the concept of "As Low as Reasonably Practical – ALARP" apply (Aven, 2014, 2016a; Cox, 2012; HSE, 2017; Paté-Cornell, 2012; Rzevski and Skobelev, 2014). If the activities of an organisation show a potential of large scale disruptions or represent a public risk of global harm, it is worth examining whether the principle of precaution (PP) should apply (Taleb *et al.*, 2014). If so, those analyses should be duly performed and documented, and conclusions should be drawn. The requirements of Business continuity management (BCM) such as a maximum tolerable period of disruption (MTPD) and a minimum business continuity objective (MBCO) should be taken into consideration (Komljenovic et al., 2016).

A few other aspects have to be considered while analysing risk reduction measures:

- Allowable "Time-at-risk" (ATR): it represents the time a system/installation is allowed to operate in a degraded condition before implementing temporary or permanent corrective measures. In the case of high-risk levels, the ATR is very short.
- The weight of the Cost/Benefit Analysis (CBA) argument: its weight decreases with increasing risks, i.e. in the case of high levels of risks its importance is small in defining relevant risk reduction measures.
- Integral risk picture: it is necessary to consider the overall risk portrait and interdependencies between various types of risks to ensure that risk reduction measures do not generate new risks or increase existing ones elsewhere. Measures that reduce several types of risks should be favoured.
- Background knowledge and uncertainties: conservative approaches are required in the case of weak background knowledge and larger uncertainties regarding the analysed risk, and vice-versa.

– Communication and implementation

Once deliberations are completed and the final decision is made and accordingly documented, the organisation has to provide the necessary resources to implement it. This activity may be carried out as part of regular activities or as a specific distinct project, using internal or external manpower. This orientation depends on the scale and size of the activities to be carried out, as well as on the internal governing rules of the enterprise. Key stakeholders have to be informed.

Thus, with the main elements of the RIDM in AsM defined, an enhanced decision-making framework becomes available, which will be illustrated next through a case study.

6.4 Case Study

This case study illustrates the application of the proposed methodology depicted in Figures 6.1, 6.3 and 6.4, and described in Section 6.3. It was developed for a particular circumstance in the nuclear power industry. Decision-making concerns aspects related to operations and maintenance, shutdown and outage strategy, and life cycle value realisation, discussed at the beginning of Section 6.3.1.

The nuclear power industry is a complex but mature sector at risk with a very strong knowledge basis. It belongs to the so-called High-Reliability-Organisations (Leveson, 2011a). The plant staff and technical managers are highly qualified with strong technical skills and knowledge. For some employee categories, there is a very rigorous licensing process managed by the relevant regulatory body (e.g. shift supervisor and first operator of the control room). This way, uncertainties and risks related to the strength of knowledge (or lack of) are greatly minimised.

The sophisticated methods and models are mature and available for deterministic and probabilistic analyses validated through a strict quality assurance program. There are also extensive industry-wide networks of information exchange accessible (at the national and international levels) which support an efficient continuous improvement program. Moreover, the nuclear power industry is heavily regulated. This aspect also significantly contributes in minimising the risks related to their operations. The application of the three-step RIDM methodology in AsM is depicted below.

6.4.1 Step 1: Setting the framework

This section describes the stages 1.1 – 1.5 which are part of Step 1 (Figure 6.1). Possible design modification strategies in a Canadian CANDU nuclear power plant's emergency core cooling system (ECCS) are analysed. The ECCS is one of four special safety systems in CANDU nuclear power plants. The conception of this system is fairly complex. It functions in three phases after its initiation. They consist of a) high pressure, b) mid-pressure, and c) low pressure phases (including associated components and equipment) with corresponding involvement of control logic, instrumentation, and various support systems (air, electricity, water) (Figure 6.5). It is credited as a key mitigating system in numerous nuclear accident scenarios (e.g. Large Loss of Cooling Accident – LLOCA, Small Breaks in the Primary Circuit, End Fitting Failure, Loss of Forced Circulation to name a few). This system is subject to strict regulatory performance requirements and scrutiny. Its minimum allowable performance standards shall be defined by the regulator and operators, and properly referenced in the Safety Report and the Operating Policies and Principles (OPP). For example, the ECCS shall be designed and operated in such manner that its unavailability is less than 1E-03 year/year (AECB, 1991; Canteach, 2017).

In this study, the RIDM methodology in AsM is applied to determine the best strategy in order to implement the necessary correction measures regarding a weakness in the design discovered in the ECCS during an operators' training preparation.

Throughout the phase of mid-pressure of the ECCS, water is drawn from the dousing tank (red arrow in Figure 6.5). The two pneumatic valves (PV) should close at the end of this stage before initiating a long-term low-pressure phase (blue rectangle in dashed line in Figure 6.5). Previously, it was understood that those valves were redundant for the closure. However, operators discovered that they are not. Failure to close one of the two valves leads to the aspiration of air into the ECCS pumps (blue oval dashed line in Figure 6.5), and consequently results in their failure. Thus, the function of the ECCS low pressure cannot be fulfilled, and the system fails its mission. Such a situation violates the basic safety principle stating that *the ECCS design shall have sufficient redundancy such that no failure of any single component of the systems can result in its impairment to an extent that the system will not meet its minimum allowable performance standards under accident conditions* (AECB, 1991). This requirement is based on the basic requirements of the defence-in-depth philosophy which is one of the key pillars of the safe operation of nuclear power plants (IAEA, 1996). As such, the situation was rather complex, and could not be tolerated on a permanent basis. Adequate corrective measures were required, although the failure of the ECCS during the Large Loss of Coolant Accident (LLOCA) as the worst case scenario is a situation analysed in the Safety Report. This report details all required deterministic analyses which demonstrate that the plant is back to a safe state following such an accident, even if it represents a significant challenge for operators (CNSC, 2014b). Safety Report is one of the key documents in support of the PROL (Power Reactor Operating Licence).

Initially, operators tested various manoeuvring scenarios aiming to avoid the loss of the system through operational procedures, but the time available to do it revealed insufficient. Afterwards, an analysis of possible design changes in the ECCS was performed. The whole process has involved the following participants:

- Lead analyst: Risk and reliability engineer
- Decision maker: Chief Nuclear Officer/Nuclear Generation Station Manager
- Operation: Shift Supervisor and First Operator the Control Room (two members)
- Maintenance: Maintenance engineer

- Subject matter experts (SME):
  - Nuclear Safety: Nuclear safety engineers (operational safety, emergency operating procedures' specialist, and nuclear safety analyses: four members);
  - Reliability: Plant reliability engineers and probabilistic risk analysis specialists (three members);
  - Engineering: ECC System Engineer and an engineer responsible for the design modifications (two members).

All the people involved had many years of relevant experience in their respective field of expertise. Among stakeholders, one finds the management of the enterprise and the regulatory body, Canadian Nuclear Safety Commission (CNSC).

Following an overall review of the situation carried out by the plant management and knowledgeable experts, the retained solution consisted in installing two other pneumatic valves in series with the existing ones (red rectangle in solid lines, Figure 6.5). This way, an adequate redundancy would be ensured, and no single equipment failure could cause the impairment of the system. Given the strict performance requirements for the ECCS, the engineering work, testing, and procurement of required equipment represented a cumbersome and lengthy process (roughly one year in total). It should also be highlighted that the studied plant was going to undergo a major refurbishment project three years later, aiming to extend its useful life for another 30 years. The acceptance of the solution also involved thorough discussions with the Regulatory Body.

Three modification options were proposed to the Regulatory Body:

- Option 1: PV installation during a 6-week specific shutdown foreseen uniquely for installing the PV two years before the refurbishment. Considering engineering work and procurement delays, it represents one year of "time-at-risk" before the installation;

- Option 2: PV installation during a planned shutdown one year before the refurbishment. The installation of the PV extends the planned shutdown state for approximately two weeks. It represents two years of "time-at-risk";
- Option 3: PV installation during the refurbishment. This activity would not be on the refurbishment critical path. It represents three years of "time-at-risk".

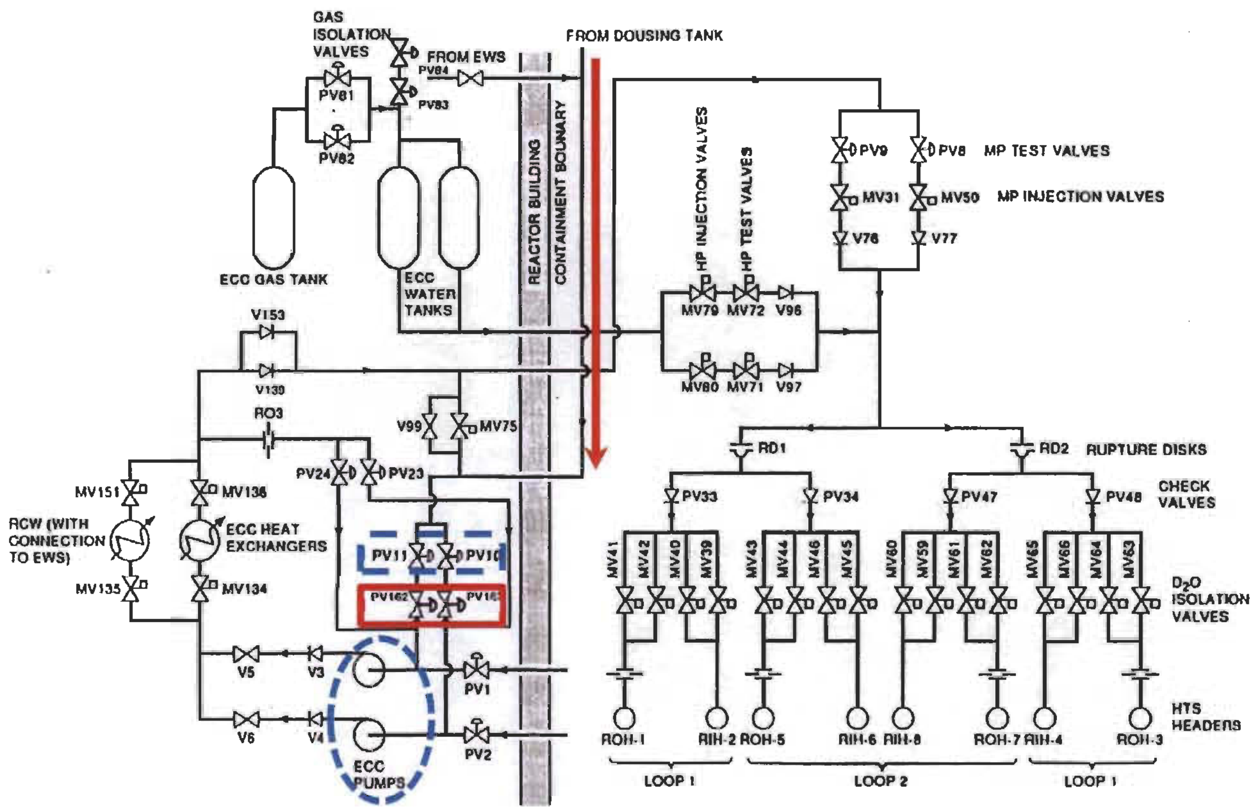

Figure 6.5. Simplified ECCS schema with PV installed in series (Canteach, 2017)

The context represents a complex decision-making situation in AsM. This decision can be tackled using the RIDM methodology presented in Section 6.3. The methodology has been tailored to better fit the actual circumstance. Figure 6.6 presents the decision-making criteria obtained through the analysis and discussions among the participants mentioned above. These decision-making criteria are associated with the sub-models depicted in Figure 6.3. There are five groups of decision criteria considered (Figure 6.6), and associated to generic the sub-models shown on the left side in Figure 6.3. Some decision criteria are further detailed in their sub-criteria. For example, the main criterion 1) "Nuclear Safety Requirements" involves three sub-criteria: a) requirements regarding deterministic analyses, b) requirements regarding probabilistic analyses, and c) risk impact. The risk impact includes three relevant categories of risks for this analysis: i) Radiological Risk to Public at a Design Basis Accident (DBA), ii) Severe Accidents Risks, and c) Risk of Negative Impact on Safety.

6.4.2 Step 2: Detailed analyses

The impact of each decision criterion and sub-criterion listed above is evaluated using relevant quantitative and qualitative analyses. The complexity of the decision-making context increases knowing that the above criteria are not entirely independent. Tables 6.1 and 6.2 present the characteristics and interdependencies of the criteria as per the descriptions in Tables 6.A1 and 6.A2. The interdependencies among them are of various types in accordance with the aspects labelled in Tables 6.A3-6.A10. These outcomes are important for the deliberation to be carried out in the next step.

For example, in Table 6.1, the main criterion 1) "Nuclear Safety Requirements" has a high level of complexity (HCS for attribute K), it is both internal and external to the organisation (EXTL/INTL for attribute B), its changes have a strong impact on the AsM (**St** for attribute D), its duration of the impact is very long given that those attributes do not change frequently (**Vlod** for attribute H), its pace of change is typically slow and known in advance since plant operators also take part in any changes made to those requirements (**Es** for attribute F), and finally, its precursor/warning time is long because of slow changes and involvement of plant operators in this activity (**Lgw** for attribute G).

Example for Table 6.2 regarding the same criterion 1) Nuclear safety requirements: it has a high (H) or moderate to high (M/H) impact on other criteria (attribute C). It has a policy and societal interdependency with the criteria 2 and 3 (IV, VI for attribute E), all type of interdependencies from Table 6.A6 with the criterion 4 (I, II, III, IV, V, VI for attribute E), and an informational and policy/procedural/functional interdependency with the criterion 5 (II, IV for attribute E).

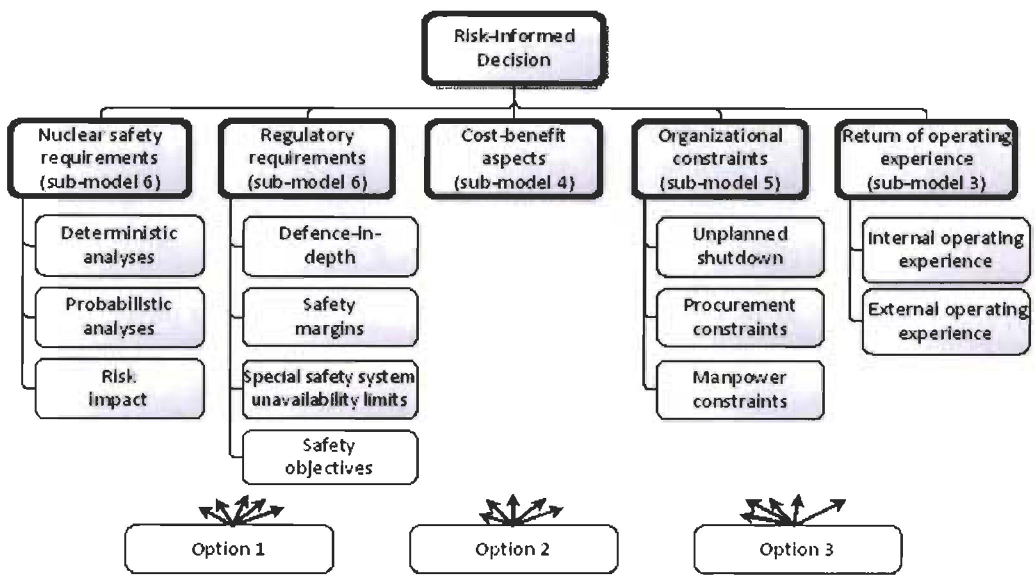

Figure 6.6. Risk-informed decision-making in the case study

Table 6.1. Characteristics of main decision criteria

Decision criterion/Constituent element (A)	Level of complexity (K)	Type of environment (B)	Impact of changes in constituent elements on AsM (D)	Likely duration of the impact (H)	Pace of change in characteristics of constituent elements (F) / Precursors/Warning time (G)
1. Nuclear Safety Requirement/Impact	HCS	EXTL/INEL	St	Vlod	Es / Lgw
2. Regulatory requirements	MCS	EXTL	St	Vlod	Es / Lgw
3. Cost-Benefit Aspect	MCS	EXTL/INEL	Mo to St	Vlod	Es / Lgw
4. Organizational Constraints	MCS	EXTL/INEL	Mo	Medd	Ef to Es / Mdw to Lgw
5. Return of Operating Experience (OPEX)	WCS	EXTL/INEL	Mo	Shodd to Medd	Es / Lgw

Table 6.2. Interdependencies between main decision criteria

Decision criterion/Constituent element (A)	Attributes (C) and (E)	Decision criterion/Constituent element (A)				
		1. Nuclear Safety Requirements/ Impact	**2. Regulatory Requirements**	**3. Cost-Benefit Aspect**	**4. Organizational Constraints**	**5. Return of Operating Experience (OPEX)**
1. Nuclear Safety Requirements/ Impact	Level of impact between constituent elements (C)		H	M/H	M/H	M/H
	Type of interdependence (connection) (E)		IV, VI	IV, VI	I, II, III, IV, V, VI	II, IV
2. Regulatory Requirements	Level of impact between constituent elements (C)	H		M/H	M/H	M
	Type of interdependence (connection) (E)	IV, VI		IV, VI	I, II, III, IV, V, VI	II, IV
3. Cost-Benefit Aspect	Level of impact between constituent elements (C)	N/L	N/L		M/H	L/M
	Type of interdependence (connection) (E)	II, IV, V	II, IV, V		I, II, III, IV, V	II, IV, V
4. Organizational Constraints	Level of impact between constituent elements (C)	N/L	N/L	M/H		L/M
	Type of interdependence (connection) (E)	II, IV, V, VI	II, IV, V,VI	I, II, III, IV, V		I, II, III, IV, V, VI
5. Return of Operating Experience (OPEX)	Level of impact between constituent elements (C)	M	M	M/H	M/H	
	Type of interdependence (connection) (E)	II, IV	II, IV	II, IV, V	I, II, III, IV, V, VI	

The overall ranking of the decision criteria and sub-criteria was performed using Analytic Hierarchy Process (AHP) (Saaty, 1990). The AHP theoretical background is not presented here given that it is an MCDM method which is mature and well documented in numerous high quality references and examples. Table 6.3 presents the results.

Table 6.3. Ranking of decision criteria and sub-criteria

Criterion	Second order criteria	Weight
1. Nuclear Safety Requirements		**36.1 %**
	1.1 Deterministic analyses	40.0 %
	1.2 Probabilistic analyses	40.0 %
	1.3 Risk Impact	20.0 %
2. Regulatory Requirements		**36.1 %**
	2.1 Defence-in-Depth	34.7 %
	2.2 Special Safety System unavailability limits	24.6 %
	2.3 Safety Margins	20.4 %
	2.4 Safety Objectives	20.4 %
3. Cost-Benefit Aspects		**15.8 %**
4. Organisational constraints		**7.2 %**
	4.1 Unplanned shutdown	25.0 %
	4.2 Procurement constraints	50.0 %
	4.3 Manpower constraints	25.0 %
5. Return of Experience (OPEX)		**4.8 %**
	5.1 Internal OPEX	75.0 %
	5.2 External OPEX	25.0 %

The results show that the criteria 1 and 2 have the highest ranking (weight) of 36.1 % each, and both represent a total weight of 72.2 %. This outcome goes along with the general philosophy in the nuclear power industry where nuclear safety has a prevailing importance in the decision-making.

Once all the characteristics, interdependencies, and decision criteria ranking are completed, the analysis continued with a detailed assessment of three options against the decision criteria and sub-criteria (Figure 6.6).

The main details regarding the importance and limits of the probabilistic risk assessment (PRA) insights in the decision-making process (Criteria 1 and 2) are presented. Its results provide the risk level assessment required to establish an allowable "time-at-risk" (within the "Nuclear safety requirements" and "Safety Objectives" within "Regulatory requirements" in Figure 6.6). It should be stressed that the PRA input is one of the key influence factors in the final decision-making.

The probabilistic risk assessment (PRA) or probabilistic safety assessment (PSA) is a sophisticated risk evaluation technique. In the nuclear power industry, it consists in a comprehensive and integrated assessment of the safety (or risk) of a nuclear reactor facility (CNSC, 2014a). The assessment involves the probability, progression, and consequences of equipment failures or transient conditions to derive numerical estimates that provide a consistent measure of the risk of the reactor facility, as follows:

- In a level 1 PRA, the sequences of events that may lead to the loss of the reactor's core structural integrity and massive fuel failures are identified and their probabilities are quantified.
- In a level 2 PRA, the level 1 PRA results are used to analyse the containment behaviour, evaluate the radionuclides released from the fuel failures, and quantify the releases into the environment.

The process allowing to fully assessing the level 2 PRA is typically a three-tier approach which progressively leads the assessment into additional detail layers. The evaluation includes the grouping of event sequences to provide risk estimates of

Severe Core Damage, Large Releases, Small Releases, Wide-spread Fuel Damage, etc. for the at-power and shutdown states. The PRA is typically structured into operational assessment models for various Plant Damage States (PDS). For example, PDS0, PDS1 and PDS2 represent Severe Core Damage Frequency (SCDF). In this study, the risk quantification is limited to Severe Core Damage Frequency (SCDF) and Large Release Frequency (LRF) assessment as a metric for the risk increase in the full power state. The results obtained are presented in Table 6.4. The PRA results show that the decrease of risk resulting from a PV installation quantified by both metrics (SCDF and LRF) is relatively small. With and without PV, the values obtained are inferior to the corresponding quantitative safety limits of 1E-04 for SCDF and 1E-05 for LRF (CNSC, 2009; US NRC, 2011). These safety limits or safety objectives are integrated within "Regulatory requirements" in Figure 6.6. Based on the quantitative PRA results only, the design modification may not seem justifiable given that the risk levels are below the quantitative safety limits. Thus, the RIDM process (Figures 6.1, 6.3 and 6.4) was used to identify all other relevant fundamental insights necessary to make a final decision (Figure 6.6, Table 6.3). The criteria such as "defence-in-depth" and "absence of a single point of vulnerability" (AECB, 1991) emphasised the necessity to install the PV in order to meet regulatory requirements, and to comply with the fundamental safety principles.

Table 6.4. PRA quantification results with and without PV installed

Metric	With PV installed (y/y)	Without PV installed (y/y)	ΔSCDF ΔLRF (increase)
Severe Core Damage Frequency (SCDF)	3.83E-05	4.01E-05	1.80E-06
Large Release Frequency (LRF)	9.47E-08	1.22E-07	2.73E-08

The uncertainties are mostly related to the limits of the model, the assumptions made, as well as the quality of the data. Sensitivity analyses were performed to assess the impact of those uncertainties. These analyses showed that the safety objectives are always met.

Thus, the results of the PRA show the compliance with quantitative safety limits, but were unable to demonstrate regulatory compliance with regard to the "defence-in-depth" and "absence of a single point of vulnerability" requirements. Detailed analyses and deliberations were carried out by the decision maker, plant management, SMEs, and the analyst in order to integrate insights regarding the decision criteria depicted in Figure 6.6, and Tables 6.3 and 6.4 in order to identify the most favourable option.

The ranking of the options for each decision criterion and their overall ranking is presented in Figure 6.7. The AHP was used again to complete this analysis. The vertical axis shows the weight of each option against each decision criterion and the overall weight.

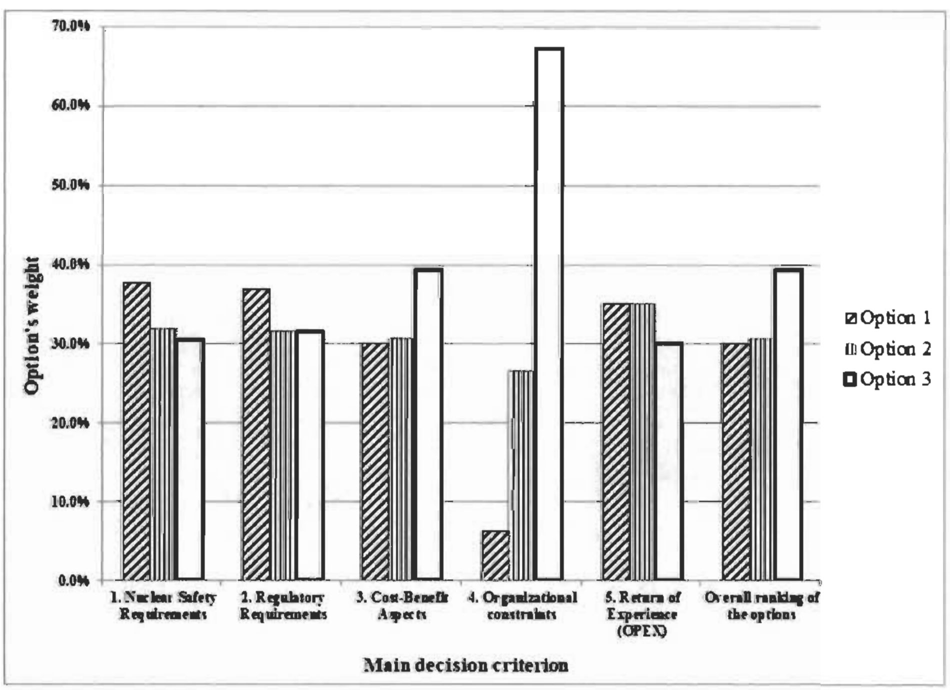

Figure 6.7. Final ranking of the options

For example, following a detailed Cost-Benefit Analysis (CBA), the Options 1 and 2 showed a negative NPV (Net Present Value), and the Option 3 had a positive NPV. The Option 3 was also the most favourable regarding the criterion 4) "Organisational constraints." A sensitivity analysis was performed for the criteria where the option 3 did not dominate (1, 2 and 5) in order to verify the robustness of the solution. This analysis showed that the solution is robust given that the change in the final solution follows only after a very large modification of the weight of those criteria.

6.4.3 Step 3: Deliberations, decision-making, communication, and implementation

The Option 3 (installation during the refurbishment of the plant) was retained after deliberations and discussions among the members. The strength of knowledge of all the participants was evaluated as very strong, as per the rationale presented above. All relevant factors, including the complexity of the overall context and the results of various technical, uncertainties, and economic analyses were factored in. Since the "time-at-risk" was three years for that option, it was judged acceptable. The above process was used to build a final safety and business case, and to obtain regulatory approval for the proposed strategy. The Regulator body was informed upon the final decision through the official communication channels. It approved the proposed solution, and the PVs were installed three years later. It should be highlighted that the other CANDU plants have completed this installation through other design modification projects (Criterion 5 regarding external return of operating experience).

6.5 Conclusions

This paper introduces a holistic three step Risk-Informed Decision-Making (RIDM) as a structured and rational decision-making methodology in AsM considering it as a Complex Adaptive System (CAS) or a Complex Adaptive System of Systems (CASoS). It takes into account the complexity of the assets, the operational and business environment, and the internal structure of the organisations. The methodology systematically integrates several other aspects which have an impact on the final outcomes such as the associated risks (including risks of extreme and rare events), results of various quantitative and qualitative analyses, cost-benefit analysis, impact of the intangible influence factors, and strength of knowledge of participants involved in the analyses, deliberations, as well as decision-making.

In such a decision-making process, insights from quantitative models are rather important. However, the study shows that they do not constitute a sufficient base of information to address complex issues in asset management. Those tools are usually unable to capture intangible influence factors (e.g. non-quantitative regulatory requirements) which may become dominant in a final decision-making process.

The case study carried out at a CANDU nuclear power plant illustrates the applicability of the methodology. It also demonstrates the limits of the inputs resulting from quantitative analyses. For example, the insights from the Probabilistic Risk Assessment (PRA) tool were insufficient to demonstrate both the regulatory compliance and the compliance with fundamental safety principles in the case of a major activity related to the installation of additional equipment within the Emergency Core Cooling System. It confirmed the compliance with the quantitative safety limits, but was not able to show the acquiescence with the requirements of defence-in-depth and the absence of the single point of vulnerability. Other factors and measures have been used to demonstrate it, although the input from PRA was of chief importance in the decision-making process. This example illustrates the need to cautiously consider quantitative inputs in a decision-making process in order to avoid wrong decisions.

This illustrative case from the nuclear power industry may serve as an example for other industries where an overwhelming reliance on quantitative models may sometimes be misleading in the decision-making process.

Meanwhile, the current research demonstrates the need for future research works in this area which would further contribute to the body of knowledge in asset management. The main points are enumerated below:

- Improve the understanding of the impact of the strength of background knowledge on the outcomes of analyses and decision-making in AsM.
- Enhance the understanding of the impact of human and organisational performance on both the AsM performance and decision-making.
- Increase the understanding and characterisation of interdependencies between sub-models and their constituent parts.
- Develop detailed individual sub-models and a global decision-making model using the tools of the Complexity Science.
- Study the potential of adaptation and application of the Complex system governance (CSG) concept to AsM specific needs.
- Enhance MCDM methods in order to better integrate the impact of complexity to their outcomes.
- Improve risk analysis and risk aggregation methods in the context of the complexity, including the characterisation of the risks of extreme and rare events in AsM.
- Enhance the integration of new IT technologies and analytics into the AsM.
- Further applications of the methodology in different industries in order to improve it.
- Examine the methodology through inclusion of emerging concepts (e.g., vulnerability, resilience, susceptibility, fragility) and development of variations of the proposed approach.

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Appendix 6.A

Main characteristics of the seven sub-models depicted in Figure 6.3

The description below represents an extension of earlier research works performed by (Komljenovic *et al.*, 2016).

Main features of the sub-models

1. *Market*: Usually external to an organisation/enterprise. It has a major impact on an organisation's global performance. Items of this sub-model (constituent elements) cannot be efficiently controlled nor influenced by an enterprise and epistemic uncertainties are significant. It typically includes:
   - prediction of the markets, their risks and their volatility;
   - constraints related to new competitors, new products, new technologies;
   - financial market conditions, risks and variations.
2. *Reliability, availability and maintainability (RAM) factors*: Mainly internal to an enterprise. In principle, these elements may be efficiently controlled and influenced. Aleatory uncertainties are dominant here. The RAM sub-model integrates following items:
   - asset selection and utilisation;
   - criticality of the systems, components and equipment (assets), their reliability, availability, and maintainability; diagnostic and prognostic;
   - optimisation of the balance between reliability and availability;
   - renewal and disposition of assets; Life Cycle Management (LCM);
   - aging and obsolescence management;
   - RAM information/data management and analytics (RAM-IT);
   - other relevant RAM factors (e.g. work planning and configuration management, materials and services, procurement, etc.);

- performance and condition monitoring, asset, health and maintenance strategies;
- key performance indicators (KPI).

3. *Operations and operational constraints*: Generally internal to an enterprise. These aspects may be efficiently controlled and strongly influenced, but epistemic uncertainties are quite significant here due to the internal complexity of organisations. This sub-model includes the following elements:
    - availability of space;
    - delivery of products and services;
    - quality assurance;
    - supply of energy, raw material and other resources;
    - value chain and its integration to the concept of AsM;
    - transportation;
    - overall operational efficiency/performance requirements.
4. *Revenue and costs*: Both internal and external to an enterprise. It may be partly controlled and influenced to some extent; epistemic uncertainties are substantial here due to unpredictability of external factors and the impossibility of the organisation to control them. The revenue and cost sub-model incorporates the following features:
    - product/service pricing and revenue, and their volatility;
    - capital expenditure;
    - energy, operation, maintenance, manpower, financial, raw material, administrative costs;
    - any other relevant costs.
5. *Organisational and business factors*: Primarily internal to an enterprise. These are "soft" factors, difficult to characterise and model, but usually have an important impact on the overall performance of an enterprise. They may be

partly controlled and efficiently influenced; a mix of aleatory and epistemic uncertainties is present here. This sub-model usually includes:

- the overall organisation's management, budget, performance criteria, and business continuity management (BCM);
- manpower and knowledge management;
- R&D, Innovation, new technologies and processes;
- human, organisational performance and enterprise culture improvement, communications;
- reward system;
- quality assurance;
- enterprise Risk Management (ERM);
- organisation-wide information/data management and analytics (IT);
- other relevant factors related to the organisational aspect.

6. *Other factors and constraints*: Mainly external to an organisation, but may have a major impact on its global performance. Epistemic uncertainties are significant. Typically, these factors cannot be efficiently controlled or influenced by an enterprise. This sub-model includes elements such as: legal and regulatory requirements, occupational safety and health (OS&H) constraints and requirements, customer satisfaction, socio-economic impact, political changes or conflicts, environmental protection, impact of climate changes, natural perturbations, major events or catastrophes, security considerations, public risk perception, media treatment, etc.
7. *Strategic plan influence*: The strategic plan is described as an overall long-term plan for an organisation that is derived from, and embodies, its vision, mission, values, business policies, stakeholders' requirements, objectives, and risk management. It is internal to an organisation. Given its direct link to AsM ("Line of sight"), the orientations defined in the strategic plan are of chief importance.

Connections between the sub-models and their constituent elements

The connections between the sub-models and their constituent elements (management, stakeholders, workers, customers, operation requirements and constraints, assets and asset management, supply chains, legal and regulatory environment, markets, public perception, natural conditions, political environment, etc.) are of different strengths and types, such as physical, informational, cyber, geospatial, functional, logical, policy/procedural, financial, market, societal, etc. (Katina *et al.*, 2014; Komljenovic *et al.*, 2016).

Table 6.A1 portrays the main characteristics of the sub-models and their attributes in the overall RIDM model in AsM. Table 6.A2 depicts the attributes of interdependencies between the sub-models. For simplicity purpose, the whole picture is presented in a tabular form instead of graphically. The sub-models are depicted as *"Constituent element (A)"* in Tables 6.A1 and 6.A2.

Table 6.A1. Characteristics the sub-models in the AsM model

Constituent element (A)	**Level of complexity (K)**	**Type of environment (B)**	**Impact of changes in constituent elements on AsM (D)**	**Likely duration of the impact (H)**	**Pace of change in characteristics of constituent elements (F)**	**Precursors/Warning time (G)**
1. Market	HCS	EXTL	St	Medd to Vlod	Sd to Es	Shw to Mdw
2. RAM Factors	WCS	INTL	Mo to St	Vshd to Medd	Sd to Ef	Shw to Mdw
3. Operations and operational constraints	WCS to MCS	INEL	Mo to St	Vshd to Medd	Ef to Es	Shw to Mdw
4. Revenue and costs	WCS to MCS	EXTL/INEL	Mo to St	Medd to Vlod	Sd to Es	Shw to Mdw
5. Organizational and business factors	MCS to HCS	INEL	Mo to St	Medd to Vlod	Ef to Es	Mdw to Lgw
6. Other factors and constraints	HCS	EXTL	Ng to St	Medd to Vlod	Sd to Es	Shw to Lgw
7. Strategic plan influence	MCS to HCS	EXTL/INEL	St	Vlod	Es	Lgw

Table 6.A2. Interdependencies between the sub-models in AsM

Constituent element (A)	Attributes (C) and (E)	Constituent element (A) 1. Market	2. RAM Factors	3. Operations and operational constraints	4. Revenue and costs	5. Organizational and business factors	6. Other factors and constraints	7. Strategic plan influence
1. Market	Level of impact/strength of the links between constituent elements (C)		L/M	L/M	M/H	L/H	M/H	M/H
	Type of interdependence (connection) (E)		II, V, VI	II, V, VI	II, V, VI	II, IV, V, VI	II, IV, VI	II, IV, V, VI
2. RAM Factors	Level of impact/strength of the links between constituent elements (C)	N/A		M/H	M/H	L/H	N	L/M
	Type of interdependence (connection) (E)	II, V, VI		I, II, III, IV, V, VI	II, III, IV, V	I, II, III, IV, V, VI	I, II, III, IV, V, VI	I, II, III, IV, V, VI
3. Operations and operational constraints	Level of impact/strength of the links between constituent elements (C)	N/A	M/H		M/H	M/H	L/M	M/H
	Type of interdependence (connection) (E)	II, V, VI	I, II, III, IV, V, VI		II, III, IV, V	I, II, III, IV	I, II, III, IV, V, VI	I, II, III, IV, V, VI
4. Revenue and costs	Level of impact/strength of the links between constituent elements (C)	N	M/H	M/H		M/H	N/L	M/H
	Type of interdependence (connection) (E)	II, V, VI	II, III, IV, V	II, III, IV, V		II, III, IV, V, VI	II, V	II, III, IV, V, VI

Table 6.A2. Interdependencies between the sub-models in AsM (suite)

Constituent element (A)	Attributes (C) and (E)	Constituent element (A)						
		1. Market	**2. RAM Factors**	**3. Operations and operational constraints**	**4. Revenue and costs**	**5. Organiza-tional and business factors**	**6. Other factors and constraints**	**7. Strategic plan influence**
5. Organizational and business factors	Level of impact/strength of the links between constituent elements (C)	N/A	M/H	M/H	M/H		L/M	M/H
	Type of interdependence (connection) (E)	II, IV, V, VI	I, II, III, IV, V, VI	I, II III, IV	II, III, IV, V, VI		I, II, III, IV, V, VI	I, II, III, IV, V, VI
6. Other factors and constraints	Level of impact/strength of the links between constituent elements (C)	N/A	L/M	L/M	M	L/M		L/M
	Type of interdependence (connection) (E)	II, IV, VI	I, II, III, IV, V, VI	I, II, III, IV, V, VI	II, V	I, II, III, L/NIV, V, VI		I, II, III, IV, V, VI
7. Strategic plan influence	Level of impact/strength of the links between constituent elements (C)	N/A	M	M/H	M/H	H	N/L	
	Type of interdependence (connection) (E)	II, IV, V, VI	I, II, III, IV, V, VI	I, II, III, IV, V, VI	II, III, IV, V, VI	I, II, III, HIV, V, VI	I, II, III, IV, V, VI	

Tables 6.A3 to 6.A10 provide details regarding the attributes used in Tables 6A1 and 6A2.

Table 6.A3. Attribute (B): Types of environment

EXTL	External to an enterprise (organisation)
INEL	Internal to an enterprise (organisation) (Enterprise level)
INTL	Internal to an enterprise (organisation) (Technical/technological system level)

Table 6.A4. Attribute (C): Level of impact between the sub-models (constituent elements) and strength of the links between them

H	High (strong)
M	Medium (moderate)
L	Low
N	No tangible impact/very weak connections
N/A	Not applicable

Table 6.A5. Attribute (D) – Impact of the variations of the characteristics of the sub-models (constituent elements) on AsM

St	Strong
Mo	Moderate
Mi	Minor
Ng	Negligible

Table 6.A6. Attribute (E): Types of interdependence (connection) between the constituent elements in AsM

I. **Physical**	Reliance mostly of an engineering type between physical assets and/or systems of assets. It also includes material, energy, and other physical resource circulation
II. **Informational/cyber**	Information transfer or control requirements between AsM elements (sub-models)
III. **Geospatial**	Geospatial interconnections and distances
IV. **Policy/procedural/functional**	Interdependency caused by a policy, procedure or functioning that relates constituent elements in AsM. It also includes relevant logical interdependencies.
V. **Financial/Monetary**	Interdependency caused by financial/cost/revenue relationships between AsM constituent elements
VI. **Societal**	The effect that an activity or an AsM strategy may have on the public opinion, fear, confidence, acceptability, etc.

Table 6.A7. Attribute (F): Pace of changes in the characteristics of the constituent elements

Sd	Sudden (immediate; less than one hour) (e.g. major equipment failure, earthquake, major cyber-attack)
Ef	Emerging quickly (hours, days) (e.g. political unrest, market crashes)
Es	Emerging slowly (weeks, months, years or longer) (e.g. pandemics, climate changes, advent of new technologies)

Table 6.A8. Attribute (G): Precursors/Warning time

Shw	Short (less than one day) (e.g. vibration or overheat of the equipment before failure)
Mdw	Medium (one day to four weeks) (e.g. significant market variations/volatility before a market crash)
Lgw	Long (one month or more) (e.g. some unusual behaviour of weather indicators, and steady increase of temperature indicating climate changes)

Table 6.A9. Attribute (H): Likely duration of the impact

Vshd	Instant or less than one day (very short)
Shod	Several days (short)
Medd	Several weeks (medium)
Lond	Several months (long)
Vlod	One year or more; permanent impact (very long)

Table 6.A10. Attribute (K): Levels of complexity of the sub-models

Level of complexity of the system / Attributes of complexity	Highly complex system (HCS)	Moderately complex system (MCS)	Weakly complex system (WCS)
Connectivity between the elements of the system (*1*)	High to very high	Moderate to high	Weak to moderate
Degree of autonomy of the elements of the system (*2*)	High to very high	Moderate to high	Weak to moderate
Strength of the connections between the elements of the system (*3*)	Weak to moderate	Moderate to high	High to very high

Legend (adapted from Rzevski and Skobelev, 2014):

(*1*) – Denotes the degree to which an element is connected to other elements of the system. If an element is connected to every other element of the system, its connectivity is 100 %. A higher connectivity creates a greater complexity of the system, which is an important cause for the uncertainty of their behaviour.

(*2*) – The autonomy of the elements indicates the degree of freedom given to them to decide what to do. A higher autonomy of the constituent elements produces a greater complexity of the system because of the unpredictability of its global behaviour. In complex systems, the autonomy of the elements is always restricted, if not this yields the chaos.

(*3*) – The strength of the connections between the elements of the system designates the degree of breakability of the connections. The lack of connections has a value of zero, and a permanent connection has a value of 1. In complex systems, the strength of the connections is between 0 and 1. Weaker connections are easier to break and replace them with new ones. This attribute increases the complexity and, therefore, the unpredictability of the system's global behaviour. The weaker the connection between the elements yields the greater the complexity of the system is. Weak connections that can be broken when the system self-organises to adapt to an event are a key attribute of complexity. Strong connections resist self-organisation, and very strong connections may prevent the system from self-organising (Rzevski and Skobelev, 2014).

It may be observed in Table 6.A1 that the highest complexity is present in the sub-models 1 and 6 (attribute K). Consequently, it contributes to the presence of epistemic uncertainties, which are most important there. Those activities hold the highest potential of occurrence of extreme and rare events. A moderate to high complexity may be found in the sub-models 3, 4, 5 and 7. The sub-model 2 has a weak (low) level of complexity due to a good understanding of the technical/technological systems, and of their behaviour. If more efforts were devoted to study more complex sub-models, there would be fewer epistemic uncertainties.

CHAPITRE 7 – CONCLUSIONS

7.1 Discussion générale

Les entreprises contemporaines sont constamment contraintes de produire plus à moindre coût. Elles sont également confrontées à un environnement opérationnel et d'affaires très complexe et cette complexité ne cesse de croître. Selon des développements récents à des industries à fort intensité du capital, la gestion des actifs joue un rôle clé dans ce contexte pour leur permettre d'améliorer leur compétitivité et leur performance. Le fait que l'environnement opérationnel et d'affaires soit complexe n'est pas toujours bien reconnu dans les analyses, la gestion des actifs ou les processus de prise de décision. Les entreprises utilisent souvent des méthodes traditionnelles et des modèles réductionnistes qui ne sont pas nécessairement capables de saisir cette complexité globale.

Les systèmes ou problèmes complexes ne peuvent être déconstruits en leurs composants et modélisés par des modèles réductionnistes. Lorsque cela est fait, plus d'inconnus et d'incertitudes sont introduits. La vision et l'approche classiques de la gestion d'actifs sont remises en question dans le contexte de systèmes technologiques très complexes opérant dans un environnement opérationnel et d'affaires complexe. Le présent travail de recherche fait valoir que ces systèmes devraient être considérés comme des systèmes adaptatifs complexes ou des systèmes de systèmes complexes adaptatifs.

Le but du présent travail de recherche était de développer une méthodologie de prise de décision en gestion des actifs en tenant compte de la complexité de l'environnement d'affaires et opérationnel. Le concept de la science de la complexité est introduit et adapté pour le contexte spécifique de la gestion des actifs.

Certaines méthodes et techniques de modélisation de la science de la complexité sont suggérées pour capturer cette complexité.

Dans cette thèse, une méthodologie intégrale de prise de décision en GDA en tenant compte des risques en trois étapes a été développée. La GDA est considérée comme un système de systèmes complexes adaptatifs. Une méthode d'intégration des risques d'événements extrêmes et rares dans le processus décisionnel en GDA a également été élaborée.

7.2 Contributions scientifiques

Dans son ensemble, le travail de recherche apporte plusieurs contributions scientifiques :

- La méthodologie de prise de décision spécifique pour la GDA en tenant compte des risques (RIDM) en considérant la GDA comme un système de systèmes complexes adaptatifs.
- La définition de la structure et des relations entre les sous-modèles du modèle décisionnel global.
- Une considération explicite du niveau de connaissances sur les résultats des divers modèles quantitatifs et qualitatifs utilisés dans la prise de décision.
- La différenciation de l'utilisation des résultats d'analyse par les analystes et les décideurs.
- La définition du rôle de la délibération dans la prise de décision, ses principes incluant les rôles et responsabilités des différents participants impliqués dans le processus décisionnel.
- L'intégration des risques d'événements extrêmes et rares dans l'évaluation globale des risques lors de la prise de décision.

- L'introduction du concept de gouvernance de système complexe comme moyen de faire face à la complexité en GDA.

En général, la thèse propose un changement majeur dans la manière d'analyser et de modéliser le processus de la gestion des actifs. Cette recherche contribue à l'état des connaissances par l'introduction de la théorie de la complexité en GDA et son processus décisionnel. Elle fait aussi la démonstration de l'importance d'y inclure les risques des événements extrêmes, disruptifs et rares à cause de l'environnement opérationnel et d'affaires complexe qui est susceptible de créer de tels événements. Par conséquent, les méthodes traditionnelles d'analyse et de modélisation ont atteint leur limite d'efficacité et de capacité de représenter adéquatement le processus de la gestion des actifs. Il devient clair que celui-ci ne peut être strictement contrôlé et des approches améliorées doivent être conçues pour assurer son efficience dans le contexte de la complexité. Naturellement, le travail de recherche ne vise pas à remplacer entièrement les méthodes traditionnelles. Il propose d'utiliser des méthodes et concepts novateurs basés sur la théorie de complexité pour complémenter ceux traditionnels. Par conséquent, ils aideront à améliorer la compréhension des éléments constitutifs de la GDA, leurs caractéristiques et leur comportement et finalement, l'élaboration des modèles plus réalistes.

En fait, il est nécessaire de répondre aux questions suivantes : que peut offrir le concept de science de la complexité aux entreprises modernes et en quoi ses idées diffèrent-elles des idées traditionnelles existantes? Certaines réponses sont suggérées ci-dessous :

- La science de la complexité permet aux utilisateurs de rapprocher les sciences naturelles, techniques, socioéconomiques et de gestion en offrant soit des explications sur les phénomènes rencontrés, soit un guide pour une meilleure compréhension du problème analysé et des actions à réaliser.

- Grâce à une meilleure compréhension des *patterns* du comportement par lesquels des changements imprévisibles, inconnus et émergents se produisent, la science de la complexité offre de nouvelles manières d'analyser les entreprises en tant que systèmes adaptatifs complexes incluant des problèmes qui y émergent. L'objectif de la science de la complexité est de générer des idées qui aident à comprendre des problèmes complexes de manière plus réaliste et intégrale.
- La meilleure compréhension du contexte, des défis et des problèmes peut permettre d'embrasser ce que l'on perçoit comme des « réalités désordonnées et incontrôlables ». En fait, le concept de science de la complexité peut être utilisé de manière flexible et en combinaison avec des approches traditionnelles. Ceci pourrait permettre des comparaisons entre des scénarios, des cas et des systèmes qui semblaient auparavant non liés, en aidant à définir des actions efficaces.
- La science de la complexité suggère de nouvelles façons de réfléchir sur des problèmes connus ou anticipés et de nouvelles questions qui devraient être posées et répondues. Elle se concentre sur l'identification et l'analyse des tendances, des *patterns* de comportement ainsi que des incertitudes associées, plutôt que de chercher à prédire des événements spécifiques.

Ainsi, la recherche fournit un cadre de référence amélioré pour des stratégies de la GDA plus efficaces. Le processus global de prise de décision en tenant compte des risques intègre également de façon structurée et systématique les intrants de l'orientation stratégique d'une entreprise, les incertitudes associées (aléatoires et épistémiques) et les contraintes liées à la gestion globale du risque. En outre, le modèle incorpore intrinsèquement le processus d'amélioration continue basé sur divers retours d'expérience interne et externe pertinents au cours du cycle de vie de l'entreprise et des actifs (par exemple, audits internes et externes et/ou expérience d'exploitation).

7.3 Bénéfices anticipés

La méthodologie proposée a le potentiel d'apporter des bénéfices tangibles aux entreprises contemporaines. Ceux-ci incluent, mais ne sont pas limités à :

- le modèle décisionnel en gestion d'actifs cohérent et intégral ayant une base scientifique et technique rigoureuse. La science de la complexité offre de nouvelles perspectives pour mieux comprendre et modéliser l'environnement d'affaires et opérationnel complexe et aider ainsi à concevoir un processus de prise de décision en GDA plus efficace;
- robustesse, résilience et flexibilité accrues des entreprises confrontées à de nombreux scénarios futurs incertains, y compris des événements plausibles extrêmes, rares et potentiellement disruptifs;
- retour sur investissement et croissance optimisés;
- planification à long terme et la performance durable grâce à des modèles plus réalistes. L'une des forces les plus importantes des modèles est sa capacité à évaluer de nombreux scénarios afin de déterminer quelles conditions pourraient conduire à un événement ayant des conséquences indésirables (ou souhaitables). Ainsi, des stratégies adéquates peuvent être conçues pour promouvoir des scénarios favorables;
- la capacité de démontrer le meilleur rapport qualité-prix dans un régime de financement contraint;
- démonstration plus facile du respect des normes et de la législation en vigueur;
- amélioration des performances en matière de santé, de sécurité et d'environnement dans le contexte global de l'entreprise;
- amélioration de la réputation et de l'image de l'entreprise, ce qui peut inclure une valeur accrue pour les actionnaires, une meilleure satisfaction du personnel, la chaîne d'approvisionnement plus efficiente, une meilleure

capacité de démontrer que le développement durable est activement pris en compte dans la gestion des actifs tout au long de leur cycle de vie.

7.4 Défis futurs et limites de la méthodologie

Il est indispensable de mettre en évidence les défis et limites que le développement et l'application de l'approche proposée peuvent rencontrer. Ils incluent, mais ne sont pas limités à :

- le manque de méthodes d'analyse et de modélisation appropriées, compréhension scientifique de la complexité et des risques liés aux événements extrêmes et rares en GDA; l'augmentation continuelle de la complexité globale rend cette tâche plus difficile;
- la disponibilité des données pertinentes pour effectuer les analyses requises. Des investigations supplémentaires sont nécessaires pour déterminer quelles sont les données réellement nécessaires et si la qualité des données disponibles est satisfaisante. Les rassembler et les préparer pourrait impliquer des efforts considérables;
- la disponibilité de méthodes d'aide à la décision capables de capturer la complexité : elles doivent être développées et adaptées en fonction des besoins d'une organisation/industrie spécifique. Cette recherche peut également nécessiter une adaptation des outils traditionnels existants pour mieux s'adapter à de nouvelles méthodes et approches;
- les coûts d'intégration du concept de complexité et des nouvelles méthodes d'évaluation des risques concernant les événements extrêmes et rares en GDA peuvent être conséquents (nouvelles recherches, collecte de données, développement de méthodes, mise en œuvre, formation, maintien, etc.);

- l'acceptabilité de nouvelles approches par l'industrie : l'introduction de nouvelles méthodes d'analyse ou de prise de décision peut faire face à une résistance et/ou à un refus de les adopter.

7.5 Recherches futures

Les recherches futures doivent s'attaquer aux lacunes, limites et défis identifiés. Ainsi, les travaux de recherche futurs devraient être orientés vers une compréhension plus approfondie de la complexité dans la GDA et le développement de modèles en utilisant des techniques de modélisation et de simulation employées dans la science de la complexité. On doit également mieux comprendre la portée, les bénéfices et les défis de leur application en gestion d'actifs. Cela devrait être étudié par de futurs travaux de recherche et applications réelles. Il est nécessaire d'analyser et de définir un équilibre adéquat entre l'utilisation de nouvelles approches et des approches traditionnelles. Les recherches futures devraient améliorer la compréhension de l'impact des niveaux de connaissances sur les résultats des analyses et la prise de décision en GDA. À cet égard, il est aussi nécessaire d'améliorer les méthodes de prise de décision multicritères afin de mieux intégrer l'impact de la complexité.

Il est essentiel d'améliorer la compréhension de l'impact de la performance humaine et organisationnelle sur la performance de la GDA et la prise de décision dans le contexte de la complexité opérationnelle et d'affaires. Ce sujet comprend l'étude des biais cognitifs et motivationnels qui pourraient avoir un impact significatif sur cette performance. De ce point de vue, il est également nécessaire d'étudier le potentiel d'adaptation et d'application du concept de gouvernance du système complexe aux besoins spécifiques de gestion des actifs.

Il est recommandé d'élaborer des modèles basés sur la simulation multi-agents (ou en utilisant une autre technique de modélisation, ou une combinaison de techniques issues de la science de la complexité), qui fourniront des informations sur leurs *patterns* de comportement comme un moyen d'exprimer les changements dans l'environnement opérationnel et d'affaires. Cela permettra de mieux comprendre et caractériser les interdépendances entre les sous-modèles et leurs parties constituantes. Ce sujet comprend également la détermination de la manière pour intégrer plusieurs processus adaptatifs interactifs au sein d'un seul modèle intégral d'entreprise. Cela peut être réalisé en poursuivant des études détaillées sur les sous-modèles et les parties constitutives du modèle global afin de parvenir à une meilleure compréhension et de l'améliorer.

Cette recherche devrait également inclure le développement de tests de stress appropriés et de modèles de l'exposition aux risques des événements extrêmes et rares en GDA et leur validation. Il est nécessaire d'élaborer des méthodes plus performantes et mieux adaptées à l'évaluation des risques des événements extrêmes et rares en GDA et des méthodes d'agrégation des risques dans le contexte de la complexité. Cette étude comprend aussi une caractérisation améliorée des incertitudes associées et le développement d'algorithmes pour générer efficacement des événements extrêmes et rares dans des modèles de simulation. Il convient d'étudier des moyens efficaces d'une entreprise d'améliorer la résilience et la robustesse en GDA tout en restant économiquement viable. Il s'agit d'améliorer la méthodologie par l'inclusion de concepts émergents (par ex., vulnérabilité, résilience, robustesse, antifragilité, etc.) et le développement de différentes variantes de l'approche proposée dans cette thèse.

La méthodologie est appliquée et validée avec succès dans le cas de trois industries : minière, nucléaire et une utilité électrique. Elle démontre un grand potentiel des applications dans diverses industries lors de recherches futures.

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ANNEXE 1
ARTICLES PRODUITS DURANT LA RECHERCHE

Catégorie 1. Articles de revue avec comité de lecture directement liés à la recherche

1. Komljenovic, D., Abdul-Nour, G., & Boudreau, J.F. (2018). Risk-informed decision-making in asset management as a complex adaptive system of systems. *International Journal of Strategic Engineering Asset Management (IJSEAM)*, soumis pour la revue des pairs en janvier 2018.
2. Komljenovic, D., Gaha, M., Abdul-Nour, G., Langheit, C., & Bourgeois, M. (2016). Risks of extreme and rare events in asset management. *Safety Science, 88*, 129-145.
3. Komljenovic, D., Abdul-Nour, G., & Popovic, N. (2015). Approach for strategic planning and asset management in mining industry in the context of business and operational complexity. *International Journal of Mining and Mineral Engineering (IJMME)*, *6*(4), 338-360.

Catégorie 2. Articles de conférences directement liés à la recherche (avec comité de lecture)

1. Blancke, O., Komljenovic, D., Tahan, A., Amyot, N., Hudon, C., Boudreau, J.F., & Lévesque, M. (2018). From data to asset health management in the context of hydropower generation: A holistic concept. *13th World Congress on Engineering Asset Management*, Stavanger, Norvège (soumis).
2. Blancke, O., Combette, A., Amyot, N., Komljenovic, D., Hudon, C., Tahan, A., & Zerhouni, N. (2018). Predictive maintenance approach for complex equipment based on petri net failure mechanism propagation model. *4th European Conference of the Prognostic and Health Management Society*, 3-6 juillet 2018, Ultrecht, Pays-Bas (accepté).

3. Komljenovic, D., Abdul-Nour, G., & Boudreau, J.F. (2017). Decision-making in asset management under regulatory constraints. *12th World Congress on Engineering Asset Management*, Brisbane, Australie.

4. Gaha, M., Komljenovic, D., Langheit, C., De Guise, N., Zinflou A., & Bourgeois, M. (2016). Probabilistic Monte-Carlo simulation to assess distribution network reliability. *Conseil international de Grands Réseaux Électricques (CIGRÉ)*, Paris, France.

5. Blancke, O., Tahan, A., Komljenovic, D., Amyot, N., Hudon, C., & Lévesque, M. (2016). A hydrogenerator model-based failure detection framework to support asset management. *Conference: Prognostics and Health Management (PHM), 2016 IEEE Conference*, Ottawa, Canada.

6. Komljenovic, D., & Abdul-Nour, G. (2015). Impact of rare events on the strategy of asset management. *11^{e} Congrès international de génie industriel*, Québec.

Catégorie 3. Articles de revue avec comité de lecture indirectement liés à la recherche

1. Blancke, O., Tahan, A., Komljenovic, D., Amyot, N., & Hudon, C. (2018). A holistic multi-failure mode prognosis approach for complex equipment. *Reliability Engineering and System Safety*, (accepté, en révision).

2. Komljenovic, D., Loiselle, G., & Kumral, M. (2017). Organization: A new focus on mine safety improvement in a complex operational and business environment. *International Journal of Mining Science and Technology*, *27*, 617-625.

3. Kassem, A., Al-Haddad, K., & Komljenovic, D. (2017). Concentrated solar thermal power in Saudi Arabia: Definition and simulation of alternative scenarios. *Renewable and Sustainable Energy Reviews*, *80*, 75-91.

4. Hassan, A.G., Kassem, A., Awasthi, A., Komljenovic, D., & Al-Haddad, K. (2016). A multicriteria decision making approach for evaluating renewable

power generation sources in Saudi Arabia. *Sustainable Energy Technologies and Assessments*, *16*, 137-150.

5. Kassem, A., Al-Haddad, K., Komljenovic, D., & Schiffauerova, A. (2016). A value tree for identification of evaluation criteria for solar thermal power technologies in developing countries. *Sustainable Energy Technologies and Assessments*, *16*, 18-32.
6. Komljenovic, D. (2014). An approach of asset management in the mining industry. *Journal of Faculty of Mining, Geology and Civil Engineering*, University of Tuzla, *2014/2*, 15-22, ISSN:2303-5145.

Catégorie 4. Articles des conférences indirectement liés à la recherche (avec comité de lecture)

1. Demir, S., Kumral, M., & Komljenovic, D. (2017). Effects of cognitive and motivational biases on mine safety. *6th International Symposium on Occupational Health and Safety in Mining 2017*, Adana, Turkie.
2. Kassem, A., Al-Haddad, K., & Komljenovic, D. (2016). Multi criteria evaluation for concentrated solar thermal power collecting technologies. *Conference on Modern Engineering & Technological Advances*, Toronto, Canada.
3. Loiselle, G., Komljenovic, D., & Kumral, M. (2016). From operational hazards to organizational weaknesses: Changing the focus for improvement. *3rd International Symposium on Mine Safety Science and Engineering*, Montréal, Canada.