UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

Cadre global pour la prise de décision en gestion d'actifs industriels : Evaluation et gestion des risques liés aux technologies émergentes et aux événements imprévisibles à fort impact

THÈSE PAR ARTICLES PRÉSENTÉE COMME EXIGENCE PARTIELLE DU DOCTORAT EN INGÉNIERIE (CONCENTRATION GÉNIE INDUSTRIEL)

PAR

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DÉDICACE

À mon père, disparu, pour les valeurs de persévérance qu'il m'a transmises ;

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RÉSUMÉ

La gestion de la sécurité et des risques associés aux actifs physiques industriels adopte de plus en plus une perspective systémique, où la performance est perçue comme un phénomène complexe et émergent, résultant de l'interconnexion de multiples facteurs. Contrairement aux méthodes traditionnelles, centrées sur l'analyse des causes racines pour résoudre des erreurs isolées, cette approche systémique reconnaît que la sécurité et les risques résultent des interactions entre les différents éléments du système. Elle insiste sur l'importance de comprendre la dynamique globale du système afin d'assurer une adaptation efficace dans des environnements en constante évolution.

C'est dans ce cadre que s'inscrit cette thèse, qui propose une étude exploratoire et qualitative en gestion des actifs physiques industriels (GDA-PI). L'objectif est de développer un cadre intégré de prise de décision, permettant d'évaluer la variabilité des performances face aux risques technologiques émergents, ainsi qu'aux événements extrêmes, rares et perturbateurs. Afin d’atteindre cet objectif, nous intégrons deux outils robustes de support à la décision : la méthode d'analyse fonctionnelle *(FRAM – Functional Resonance Analysis Method)* et la méthode d’analyse des processus selon la théorie des systèmes *(STPA – System-Theoretic Process Analysis)*.

La méthode FRAM se distingue par sa flexibilité et son approche centrée sur les fonctions, permettant des modifications sans remodéliser tout le système. Contrairement aux modèles traditionnels (matrice de risques, AMDEC, arbres de défaillances, etc.), la méthode FRAM ne se limite pas à un diagramme fixe et permet d'explorer une large gamme de scénarios *(Instantiations of the FRAM Model)*. Cela offre une meilleure compréhension des systèmes complexes et dynamiques en tenant compte des conditions de travail réelles et des interactions entre différents facteurs. Cependant, bien que la méthode FRAM soit efficace, elle ne prend pas toujours en compte les défaillances technologiques. Il est donc important de la considérer comme un complément aux méthodes d'analyse conventionnelles, et non comme une solution autonome.

Par ailleurs, la méthode STPA, basée sur la modélisation et l'analyse des accidents à partir de la théorie des systèmes (STAMP – System-Theoretic Accident Model and Processes), analyse la sécurité et les risques comme un problème de contrôle dynamique, en tenant compte des interactions dangereuses, même en l'absence de défaillances de composants. STPA élargit les modèles linéaires de causalité pour inclure des boucles de rétroaction (boucles de contrôle) et des interactions multiples, intégrant des facteurs humains, organisationnels, techniques et technologiques. La sécurité et les risques sont perçus comme une propriété émergente, résultant des interactions entre les composants du système.

Ces deux méthodes sont complémentaires pour l'analyse des systèmes. Leur combinaison permet de créer un cadre puissant de soutien à la décision, en exploitant leurs capacités collectives en tant qu'outils intégrés pour l'analyse des systèmes complexes.

Pour démontrer la valeur pratique et l'efficacité de ce cadre intégré de prise de décision dans des environnements sociotechniques complexes, nous allons mener une étude de cas sur le LineDrone de la compagnie Hydro-Québec[*], un octocoptère équipé de huit moteurs et hélices, faisant partie de la flotte de véhicules aériens sans pilote *(UAV – Unmanned Aerial Vehicle),* qui inspecte les lignes de transmission à haute tension sans nécessiter d'interaction humaine directe. Les fonctions essentielles au bon fonctionnement du système sont identifiées et classifiées avec l'aide des experts d'Hydro-Québec et des spécialistes universitaires.

Cette thèse représente une première exploration et ouvre la voie à de futurs développements théoriques et pratiques. In fine, l'examen de l'intégration possible de ce cadre avec un cadre de prise de décision fondé sur les risques *(RIDM – Risk-Informed Decision-Making Framework)* apporte une dimension supplémentaire intéressante. L'ampleur de cette intégration dépendra du contexte spécifique de l'analyse.

MOTS-CLÉS – Stratégie de gestion des actifs, Risques émergents, Évènements extrêmes rares et perturbateurs, Industrie 4.0, FRAM (functional resonance analysis method), STAMP (system-theoretic accident model and processes), STPA (system-theoretic process analysis), RIDM (risk-informed decision-making framework).

[*] Hydro-Québec est une grande entreprise canadienne spécialisée dans la production, le transport et la distribution d'électricité hydroélectrique, offrant une énergie fiable et durable aux clients résidentiels, commerciaux et industriels.

ABSTRACT

The management of safety and risks associated with industrial physical assets is increasingly adopting a systemic perspective, where performance is viewed as a complex and emergent phenomenon resulting from the interconnection of multiple factors. Unlike traditional methods focused on root cause analysis to solve isolated errors, this systemic approach recognizes that safety and risks arise from interactions among different system elements. It emphasizes the importance of understanding the overall system dynamics to ensure effective adaptation in constantly evolving environments.

This thesis falls within this framework, proposing an exploratory and qualitative study in the management of industrial physical assets. The goal is to develop an integrated decision-making framework that enables the assessment of performance variability in the face of emerging technological risks, as well as extreme, rare, and disruptive events. To achieve this objective, we integrate two robust decision-support tools: the Functional Resonance Analysis Method (FRAM) and the System-Theoretic Process Analysis (STPA) method.

The FRAM method stands out for its flexibility and function-centered approach, allowing modifications without the need to re-model the entire system. Unlike traditional models (risk matrices, FMEA, FTA, etc.), FRAM is not limited to a fixed diagram and allows for exploring a wide range of scenarios (Instantiations of the FRAM Model). This provides a better understanding of complex and dynamic systems by considering real working conditions and interactions among different factors. However, while the FRAM method is effective, it does not always account for technological failures. Therefore, it should be considered as a complement to conventional analysis methods rather than a standalone solution.

Moreover, the STPA method, based on accident modelling and analysis from the System-Theoretic Accident Model and Processes (STAMP), analyses safety and risks as a dynamic control problem, taking into account hazardous interactions even in the absence of component failures. STPA expands linear causality models to include feedback loops (control loops) and multiple interactions, integrating human, organizational, technical, and technological factors. Safety and risks are perceived as an emergent property resulting from interactions among system components.

These two methods are complementary for system analysis. Their combination allows the creation of a powerful decision-support framework, leveraging their collective capabilities as integrated tools for the analysis of complex systems.

To demonstrate the practical value and effectiveness of this integrated decision-making framework in complex sociotechnical environments, we will conduct a case study on Hydro-Québec's LineDrone, an octocopter equipped with eight motors and propellers, part of an Unmanned Aerial Vehicle (UAV) fleet used to inspect high-voltage transmission lines without requiring direct human interaction. The essential functions for

the proper functioning of the system are identified and classified with the assistance of experts from Hydro-Québec and academic specialists.

This thesis represents an initial exploration and paves the way for future theoretical and practical developments. Ultimately, examining the potential integration of this framework with a Risk-Informed Decision-Making (RIDM) framework provides an additional interesting dimension. The extent of this integration will depend on the specific context of the analysis.

KEYWORDS – Asset Management Strategy, Emerging Risks, Extreme-Rare-And-Disruptive-Events, Industry 4.0, Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP), System-Theoretic Process Analysis (STPA), Risk-Informed Decision-Making Framework (RIDM).

TABLE DES MATIÈRES

Page

LISTE DES TABLEAUX

Page

LISTE DES FIGURES

LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

AI	Artificial Intelligence
AM	Asset Management
AMBoK	Asset Management Body of Knowledge
AM-Council	Australian Asset Management Council
AMPs	Asset Management Plans
AMS	Asset Management System
AMDEC	Analyse des Modes de Défaillance, de leurs Effets et de leur Criticité
ATHENA	A Technique for Human Event Analysis
BCM	Business Continuity Management
BSI	British Standards Institution
CAST	Causal Analysis based on System Theory
CAS	Complex Adaptive System
CREAM	Cognitive Reliability and Error Analysis Method
CSG	Complex system governance
CPS	Cyber-Physical Systems
ERM	Enterprise Risk Management
ETA	Event Tree Analysis
FHA	Fault Hazard Analysis
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FRAM	Functional Resonance Analysis Method
FTA	Fault Tree Analysis
GDA	Gestion des Actifs
GDA-PI	gestion des actifs physiques industriels
GFMAM	Global Forum on Maintenance and Asset Management
GSC	Gouvernance des Systèmes Complexes
HAZOP	Hazards and Operability Analysis
HEP	Human Error Probability

HFACS	Human Factors Analysis and Classification System
HILF	High-Impact Low-Frequency Events
HQ	Hydro-Quebec
HRA	Human Reliability Assessment
HCR	Human Cognitive Reliability Correlation
I.4.0	Industry 4.0
I.5.0	Industry 5.0
IA	Intelligence Artificielle
IIOT	Industrial Internet of Things
IAM	Institute of Asset Management.
LIHP	Low-Impact High-Probability Events
ML	Machine Learning
MORT	Management Oversight and Risk Tree
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
RCA	Root-Cause Analysis
RCM	Reliability-Centered Maintenance
RE	Resilience Engineering
RIDM	Risk-Informed Decision-Making
SAC	Système Adaptatif Complexe
SAM	Strategic Asset Management
SoS	Systems of Systems
STAMP	System-Theoretic Accident Model and Processes
STPA	System-Theoretic Process Analysis
STPA-sec	System-Theoretic Process Analysis for Security
STS	Systèmes Sociotechniques (Sociotechnical systems)
THERP	Technique for Human Error-Rate Prediction
UAV	Unmanned Aerial Vehicle

INTRODUCTION

La gestion des actifs physiques industriels (GDA-PI) est définie par la norme ISO 55000 comme des activités coordonnées d'un organisme visant à créer de la valeur à partir d'actifs (ISO-55000, 2024, 2014). Cette définition met en lumière la nécessité d'un équilibre entre avantages, coûts, risques, opportunités et performances, ainsi que l'importance d'une approche systématique intégrant planification et mise en œuvre. La GDA-PI permet aux dirigeants d'entreprise de saisir la valeur des actifs et de comprendre leur rôle central dans l'atteinte des objectifs organisationnels (IAM, 2015, ISO-55000, 2024). Bien que déjà bien établie dans des secteurs comme l'aviation et les compagnies d'électricité, la GDA-PI est confrontée à des défis croissants liés à la complexité de la gestion des risques dans un contexte de concurrence internationale, d'imprévisibilité et de contraintes accrues.

Cette complexité entraîne inévitablement à une montée rapide des risques émergents liés aux nouvelles technologies (risques nouveaux et inconnus) (Leveson, 2016). Elle est exacerbée par des évolutions telles que l’industrie 4.0, qui a introduit une pléthore de technologies de pointe, telles que l’Internet des objets (IoT), l’intelligence artificielle (IA), la robotique et les systèmes cyber-physiques (CPS). Ces innovations offrent des avantages significatifs en matière d'automatisation et de prise de décision basée sur les données, mais elles apportent également des risques uniques et des incertitudes que les approches traditionnelles de gestion d'actifs peinent à adresser. Keating et al. (2022) et Katina et al. (2021) ont identifié ces défis pour la gouvernance des systèmes complexes. Les effets de ces risques sur la GDA-PI doivent être étudiés en tenant compte de l'environnement externe et interne de l'organisation. Dans cet environnement dynamique et incertain, la résilience des systèmes sociotechniques devient cruciale (Komljenovic, 2018). Cette incertitude est intrinsèque à la situation de l'économie mondiale, ainsi qu'à la précarité de la situation politique due aux récents conflits armés et aux pandémies, qui pourraient perturber la performance des organisations.

En réponse à ces défis, des méthodologies innovantes ont émergé, notamment la modélisation de la dynamique des systèmes, l'ingénierie de la résilience (Hickford et al., 2018; Praetorius et al., 2015 ; Woods, 2015), et l'analyse systémique des risques, ainsi que la gestion des risques émergents (ISO-31000, 2018, ISO-31050, 2023, CEN, 2013). Des méthodes telles que FRAM (Functional Resonance Analysis Method) (par exemple, Diop et al., 2022b; Patriarca et al., 2020 ; Gattola et al., 2018 ; De Carvalho, 2011), STAMP (System-Theoretic Accident Model and Processes) (par exemple, Leveson, 2023 ; Leveson & Thomas, 2018; Allison et al., 2017 ; Leveson, 2016 ; Ouyang et al., 2010), ainsi que le RIDM (Risk-Informed Decision-Making) (par exemple, Gaha et al., 2021 ; Dezfuli et al., 2010c ; Komljenovic et al., 2016; Zio et al., 2012) ont également été développées pour mieux analyser les systèmes complexes, comprendre leur comportement, et gérer la variabilité de performance ainsi que les risques pour la santé et la sécurité.

La perspective systémique en gestion des risques des actifs industriels transforme l'approche traditionnelle en considérant la performance comme un phénomène complexe et émergent. Elle met l'accent sur l'interaction de multiples facteurs, tels que la culture organisationnelle, la technologie et le comportement humain, plutôt que sur les erreurs isolées. L'ingénierie de la résilience valorise la variabilité pour encourager un fonctionnement adaptatif, au-delà de la simple prévention des défaillances isolées, comme dans l'analyse des causes racines (Hollnagel, 2012). L'efficacité de ces outils réside dans leur capacité à aborder les interdépendances et les interactions entre les divers composants du système, englobant à la fois les éléments technologiques et humains. De plus, ils prennent en compte les effets de cascade potentiels et les risques émergents qui peuvent survenir au sein des systèmes sociotechniques complexes.

C'est dans ce contexte que cette thèse prend toute sa pertinence. Elle propose un cadre de prise de décision intégrée pour évaluer la variabilité des performances en fonction des risques associés aux technologies émergentes et aux événements extrêmes. Ce cadre combine les méthodologies FRAM et STAMP afin de mieux appréhender les complexités des systèmes sociotechniques modernes. L'objectif principal est d’améliorer la compréhension et la gestion de la variabilité de performance des systèmes complexes.

CHAPITRE 1

CONTEXTE ET STRUCTURE DE LA RECHERCHE

1.1 Contexte et motivation de la recherche

Les services publics d'électricité, tels qu'Hydro-Québec, gèrent de vastes portefeuilles d'actifs, où la gestion des actifs physiques industriels (GDA-PI) joue un rôle crucial dans la performance des infrastructures (voir Figure 1.1). Considérée comme une approche décisionnelle clé, la GDA-PI aide ces entreprises capitalistiques à anticiper des risques complexes liés aux technologies émergentes et à des événements extrêmes susceptibles de perturber leurs opérations. Pour Hydro-Québec, cela implique de suivre en permanence l'état, l'emplacement et la disponibilité des actifs afin d'optimiser leur productivité, de minimiser les interruptions de service et d'assurer la sécurité.

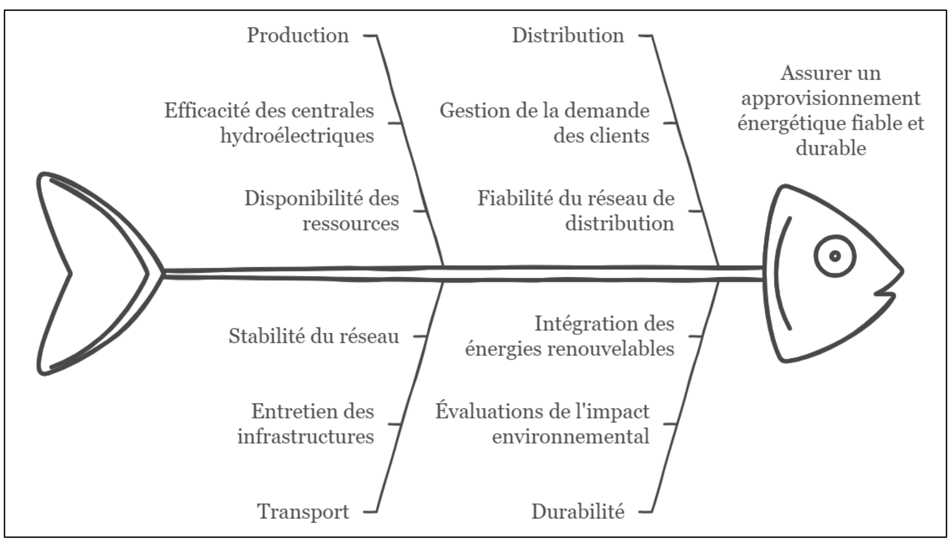

Figure 1.1. Gestion de l'électricité chez Hydro-Québec
(Source : élaboration personnelle)

Dans un paysage en constante évolution, l'intégration des technologies émergentes présente une myriade de défis et de risques qui doivent être méticuleusement évalués et gérés. Les experts d'Hydro-Québec ont mis en lumière plusieurs lacunes techniques critiques dans leur évaluation de l'état actuel des services publics d'électricité, en particulier dans le contexte de la transition énergétique et de la numérisation accrue (Komljenovic, 2024).

Alors que les services publics passent à un réseau décarboné, ils doivent faire face aux complexités de l'intégration des sources d'énergie renouvelable telles que l'éolien et le solaire, qui sont par nature variables et imprévisibles. Cela nécessite le développement de modèles mathématiques avancés et d'outils informatiques pour mieux comprendre et gérer le comportement dynamique de ces ressources au sein du réseau.

L'introduction rapide des technologies numériques et des systèmes d'automatisation a élargi la surface d'attaque pour les cybermenaces. La dépendance aux systèmes intensifs en logiciels augmente la vulnérabilité du réseau aux cyberattaques, qui peuvent avoir des implications graves pour la fiabilité et la sécurité du système. La résolution de ces vulnérabilités nécessite le développement de mesures de cybersécurité robustes, ainsi que des méthodologies pour évaluer et améliorer la fiabilité des systèmes technologiques opérationnels.

Le changement climatique introduit des incertitudes supplémentaires, à la fois aléatoires et épistémiques, qui compliquent l'environnement opérationnel des services publics d'électricité. Les événements météorologiques extrêmes, tels que les ouragans, les tornades et les tempêtes de verglas[†], posent des risques importants pour l'intégrité des infrastructures de transmission et de distribution. Le développement de modèles climatiques probabilistes à haute résolution et de modèles de dégradation des actifs est essentiel pour comprendre et atténuer ces risques.

De plus, le passage aux réseaux intelligents et à l'automatisation accrue nécessite des outils sophistiqués basés sur les données pour optimiser la gestion en temps réel du réseau et améliorer les processus de prise de décision. L'utilisation de l'intelligence artificielle (IA) et de l'apprentissage automatique *(Machine Learning, ML)* dans les opérations du réseau, bien que prometteuse, nécessite une validation et une vérification rigoureuses pour garantir la fiabilité et la sécurité de ces technologies dans des applications critiques.

Les Figures 1.2 et 1.3 offrent respectivement un aperçu non exhaustif des facteurs influençant la gestion des actifs dans les services publics d'électricité modernes et des défis associés à la gestion des infrastructures de ces services.

Pour plus de détails sur les lacunes techniques à combler pour les services publics d'électricité *("Remaining Technical Gaps For Electric Power Utilities")*, le lecteur est invité à se référer aux travaux de Komljenovic (2024).

[†] Par exemple, en janvier 1998, une tempête de verglas au Québec a gravement endommagé les infrastructures d'Hydro-Québec, avec l'effondrement de 1 000 pylônes et la destruction de 30 000 poteaux. Plus de 1,4 million de foyers ont été privés d'électricité, certains pendant plus de trois semaines, et les réparations ont coûté plus de 1 milliard de dollars.

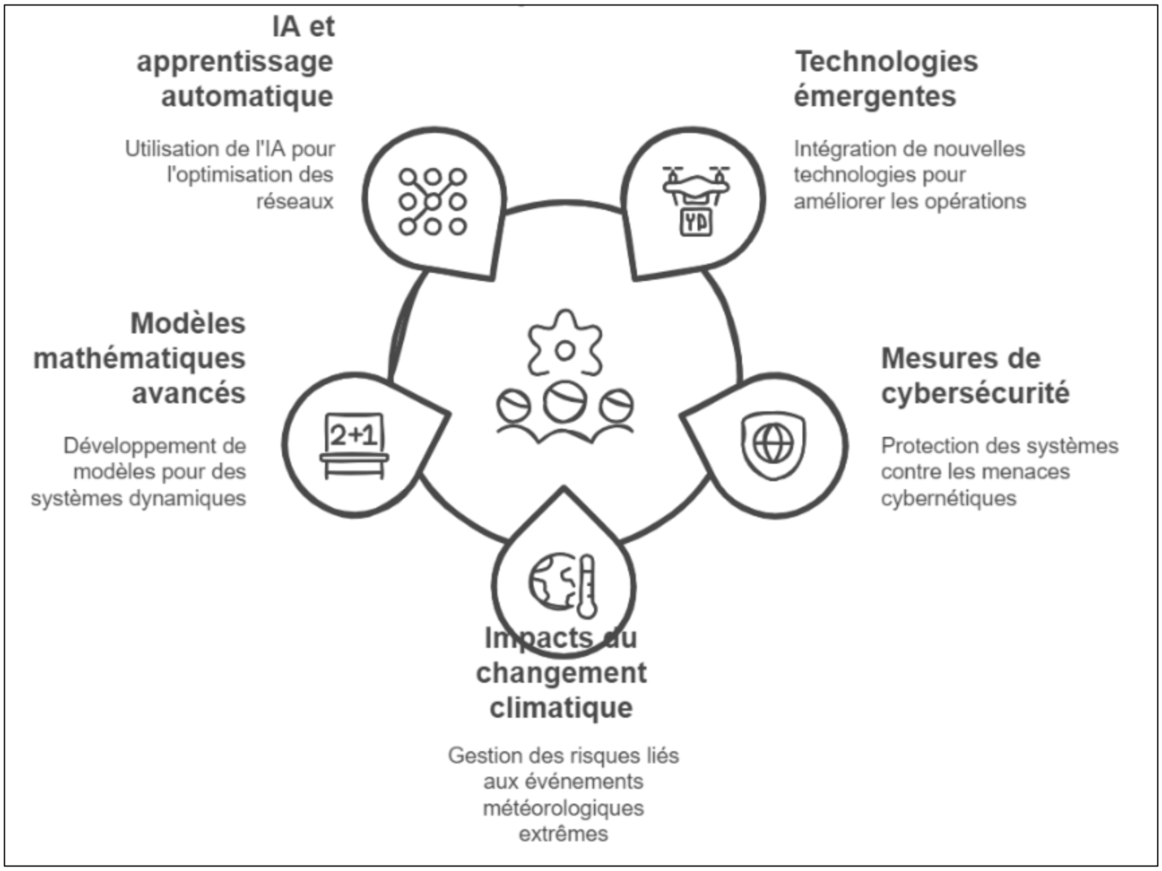

Figure 1.2. Facteurs de la GDA-PI dans l'électricité

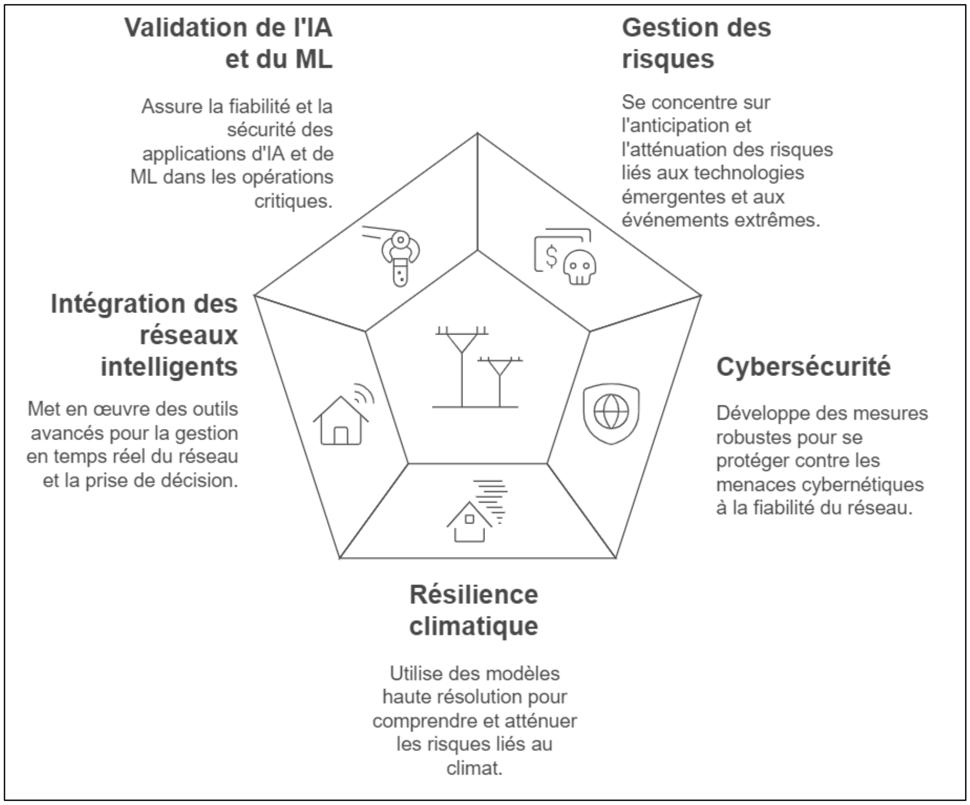

Figure 1.3. Figure 1.3 : Défis de gestion des infrastructures électriques

1.2 Structure de la recherche

Afin de guider le lecteur à travers les différentes étapes de cette recherche, la thèse est structurée de manière à développer progressivement les éléments clés de l'étude (voir Figure 1.4). Chaque chapitre joue un rôle crucial dans la construction de l'argumentation et la démonstration des résultats. La structure de la thèse est donc organisée comme suit :

- CHAPITRE 1 : ce chapitre expose le contexte général et la motivation de la proposition de recherche, ainsi que la structure de celle-ci.

- CHAPITRE 2 : ce chapitre propose une revue critique et synthétique de la littérature, couvrant les recommandations scientifiques sur les systèmes complexes et socio-techniques modernes, l'industrie 4.0 et 5.0, la non-linéarité et l'incertitude des systèmes socio-techniques, la gestion des actifs industriels, l'ingénierie de la résilience, la gestion des risques industriels, ainsi que les méthodes d'évaluation de risques (FRAM et STAMP) et la méthode de prise de décision en tenant compte des risques (RIDM).

- CHAPITRE 3 : ce chapitre est dédié à l'énoncé de la problématique et des questions de recherche.

- CHAPITRE 4 : ce chapitre décrit le but et les objectifs de la recherche, la portée de celle-ci, ainsi que les concepts, les mesures de performance et les mots-clés.

- CHAPITRE 5 : ce chapitre présente la méthodologie de recherche visant à atteindre le but et les objectifs de recherche.

- CHAPITRE 6 : ce chapitre décrit la contribution de la recherche et les retombées scientifiques attendues.

- CHAPITRE 7 : ce chapitre présente le premier article de revue avec comité de lecture, publié dans le International Journal of Engineering Research & Technology (IJERT) : *« Overview of Strategic Approach to Asset Management and Decision-Making »*.

- CHAPITRE 8 : ce chapitre présente le deuxième article de revue avec comité de lecture, publié dans le American Journal of Industrial and Business Management (AJIBM) : *« The Functional Resonance Analysis Method: A Performance Appraisal Tool for Risk Assessment and Accident Investigation in Complex and Dynamic Sociotechnical Systems ».*

- CHAPITRE 9 : ce chapitre présente le troisième article de revue avec comité de lecture, publié dans le American Journal of Industrial and Business Management (AJIBM) : « A High-Level Risk Management Framework as Part of An Overall Asset Management Process for The Assessment of Industry 4.0 Related New Emerging Technological Risks ».

- CHAPITRE 10 : ce chapitre présente le quatrième article de revue avec comité de lecture, accepté avec corrections dans le journal International Journal of Production Research (IJPR) : *« A Comprehensive Decision-Making Approach: Evaluating and Managing Risks Associated with Emerging Technologies – A LineDrone Technology Case Study ».*

- Les ANNEXES contiennent les résumés des deux chapitres de livre et des cinq articles présentés dans des conférences avec comité de lecture.

- Enfin, en CONCLUSION, nous présentons une synthèse générale et des recommandations, servant de point de départ pour de nouvelles avenues de recherche.

Figure 1.4. Canevas de la recherche : du contexte à la conclusion

CHAPITRE 2

REVUE CRITIQUE DE LITTÉRATURE

2.1 Méthodologie de la revue

Ce chapitre propose une revue de littérature ciblée, alignée avec les questions et objectifs de recherche. Diverses recommandations scientifiques en lien avec la gestion des actifs physiques industriels (GDA-PI), ainsi que la complexité et la non-linéarité dans les systèmes sociotechniques contemporains, sont examinées en profondeur. Plutôt que de couvrir tous les sous-modèles en GDA-PI, ce chapitre se concentre sur le développement original de méthodologies et de méthodes de prise de décision, spécifiquement pour évaluer et gérer les risques liés aux technologies émergentes et aux événements imprévisibles à fort impact.

La revue s'articule en quatre étapes clés. Elle débute par une exploration des systèmes complexes et de la théorie de la complexité, suivie d'une analyse des systèmes sociotechniques modernes, intégrant l'Industrie 4.0 et 5.0, la non-linéarité et l'incertitude. Elle se penche ensuite sur la GDA-PI et la résilience, pour finalement proposer une approche systémique de gestion des risques en s'appuyant sur des méthodes telles que RIDM, RIAM, FRAM et STAMP.

2.2 Systèmes sociotechniques et théorie de la complexité

2.2.1 Systèmes sociotechniques

Un système sociotechnique (STS) est une approche qui met en lumière l'interaction entre les éléments humains (sociaux) et technologiques (techniques) au sein d'une organisation (Stranks, 2007; Long, 2018; University of Leeds, 2024). La théorie sociotechnique stipule que les performances organisationnelles reposent sur cette interaction, qui peut être linéaire et prévisible ou non linéaire, complexe et imprévisible. Son objectif principal est l'optimisation conjointe des dimensions humaines et techniques afin d'améliorer la performance globale, la satisfaction au travail et l'adaptabilité (Cooper et al., 1971).

Cette approche reconnaît que les interactions, qu'elles soient prévues ou imprévues, peuvent avoir un impact positif ou négatif sur les résultats, et insiste donc sur la participation active des individus dans la conception et la mise en œuvre des systèmes (Winter et al., 2014). Optimiser un aspect en négligeant l'autre tend à renforcer les interactions imprévisibles, souvent préjudiciables à la performance globale, ce qui souligne l'importance d'une conception et d'une optimisation conjointes (Winter et al., 2014, Cooper et al., 1971).

2.2.2 Systèmes complexes et théorie de la complexité

La complexité des systèmes évolue avec le temps et dépend des connaissances et des outils disponibles. Bien que le terme « système complexe » soit couramment employé, il reste souvent mal défini. Cette difficulté tient au caractère non statique de la complexité : ce qui était considéré complexe il y a des décennies ne l'est souvent plus aujourd'hui, grâce aux avancées en outils et en savoirs. Par ailleurs, la complexité ne se limite pas à une seule propriété, mais regroupe plusieurs dimensions (Leveson, 2024). Par exemple:

- La complexité interactive concerne les interactions entre composants du système.
- La complexité dynamique est liée aux changements temporels.
- La complexité décompositionnelle survient lorsque les décompositions structurelle et fonctionnelle du système ne correspondent pas.
- Enfin, la complexité non linéaire apparaît lorsque les relations entre cause et effet ne sont ni directes ni évidentes, compliquant ainsi la prévision des comportements.

Une caractéristique majeure qui entrave la prédiction du comportement des systèmes est le couplage entre leurs composants (Komljenovic, 2018). Une définition utile de la complexité repose sur le degré et les types de couplages ou dépendances entre les composants (Leveson, 2024). Ces dépendances peuvent être directes ou indirectes. Les dépendances indirectes sont plus difficiles à identifier. Comprendre et anticiper le comportement global d'un système, ainsi que celui de ses composants individuels, exige une maîtrise de toutes ces dépendances, en particulier les indirectes (Leveson, 2024).

Autrement dit, ces systèmes complexes[‡] sont des ensembles constitués de nombreux éléments interconnectés et interdépendants, dont les interactions produisent des comportements globaux imprévisibles (Anish et al., 2010; Mitleton-Kelly, 2003). Ils se caractérisent par des dynamiques non linéaires, des effets de rétroaction et une adaptabilité continue. La complexité augmente leur vulnérabilité, entraînant des interactions imprévues et des défaillances en cascade, ce qui empêche l'atteinte d'un équilibre stable (Komljenovic, 2018).

La complexité reste la principale source d'incertitude et de non-linéarité dans les systèmes sociotechniques modernes (Diop et al., 2023). Elle découle des interactions entre les nouvelles technologies issues de l'industrie 4.0, des incertitudes liées aux chaînes d'approvisionnement, de la conformité réglementaire, de la gestion financière, des exigences en matière de santé et de sécurité, ainsi que de l'imprévisibilité des catastrophes naturelles ou des événements exceptionnels à venir. En d'autres termes, ces menaces sont intrinsèquement liées à la continuité des opérations nécessaires pour fournir les services requis dans un environnement incertain.

Aujourd'hui, la complexité des systèmes s'accroît rapidement, en grande partie à cause de l'explosion de l'utilisation des logiciels dans les systèmes de contrôle (Leveson,

[‡] Ces systèmes complexes, indispensables au bon fonctionnement des sociétés, incluent notamment les services publics d'électricité, les centrales nucléaires, les réseaux de transport, les plates-formes pétrolières, ainsi que les réseaux de distribution d'eau, de gaz et de communication.

2024). Cette situation impose une amélioration substantielle des pratiques de conception et de gestion de la sécurité des systèmes.

La théorie de la complexité est un domaine interdisciplinaire qui vise à comprendre et gérer les comportements des systèmes complexes, là où la science traditionnelle se heurte à des limites (Katina et al., 2021; Keating et al., 2022; Diop et al., 2023). Elle s'intéresse aux interactions imprévisibles, aux défaillances en cascade et à l'adaptation continue des systèmes dans des environnements dynamiques. La science de la complexité utilise divers outils comme la modélisation multi-agents et la simulation de systèmes pour mieux appréhender ces systèmes. Bien que cette approche soit prometteuse, son application spécifique à la gestion des actifs reste encore peu explorée, ouvrant ainsi des perspectives pour de futures recherches. Elle offre une perspective complémentaire aux analyses traditionnelles en se concentrant sur des systèmes adaptatifs et interconnectés, et en fournissant des outils pour anticiper et gérer leurs comportements complexes dans des environnements incertains.

2.2.3 Systèmes sociotechniques modernes

Dans les systèmes sociotechniques modernes, la complexité est le principal moteur de la non-linéarité et de l'incertitude. Cette complexité découle des interactions complexes entre les technologies émergentes issues de l'Industrie 4.0. De plus, les incertitudes liées aux catastrophes naturelles potentielles ou aux événements extraordinaires, ainsi que les menaces organisationnelles contemporaines et les biais dans la prise de décision humaine, contribuent davantage à la complexité globale de ces systèmes. Reconnaître et traiter efficacement cette complexité est essentiel pour assurer la résilience et l'adaptabilité des systèmes sociotechniques face aux défis évolutifs et dynamiques.

- *Industrie 4.0*

La quatrième révolution industrielle (aussi appelée industrie 4.0) ou industrie du futur est une initiative du gouvernement allemand visant à stimuler la compétitivité et la productivité de l'industrie manufacturière (Blanchet, 2014). En 2006, le gouvernement allemand a présenté sa « Stratégie de haute technologie » *(High-Tech Strategy)* à la Foire de Hanovre, le plus grand salon mondial des technologies industrielles. Pour la première fois, l'industrie 4.0 a été mentionnée en lien avec l'avènement d'une révolution industrielle. En 2011, à la même Foire de Hanovre, trois représentants du monde des affaires, de la politique et de la science ont montré comment le changement de paradigme basé sur les systèmes cyber-physiques et de nouveaux modèles d'affaires se réaliserait dans les décennies à venir (Kagermann et al., 2011). Ce groupe d'experts, dirigé par le Dr Kagermann et le Dr Wolfgang Wahlster du Centre allemand de recherche en intelligence artificielle ainsi que le Dr Wolf-Dieter Lukas du ministère fédéral de la Recherche et de l'Éducation, a présenté les résultats de leurs travaux sur l'industrie 4.0. Leur publication décrit trois axes principaux autour desquels s'articulent les caractéristiques de l'ingénierie de production industrielle du futur, à savoir (i) un haut degré de personnalisation des produits avec une production flexible, (ii) l'implication des clients et des partenaires commerciaux dans les processus de conception et de création de valeur, (iii) la relation entre production et services de qualité pour créer des produits hybrides.

Au cours des dernières années, le concept de l'industrie 4.0 s'est développé rapidement et est devenu un terme adopté mondialement dans les pays technologiquement avancés. Les technologies habilitantes de l'industrie 4.0 jouent un rôle clé dans la transformation numérique des industries, offrant des outils avancés pour améliorer l'efficacité, la productivité et la flexibilité. Ces technologies, en interagissant et en se complétant, soutiennent la transformation numérique et permettent aux entreprises de répondre aux défis de l'industrie 4.0, en renforçant la compétitivité et la résilience dans un environnement industriel en constante évolution. Voici quelques-unes des principales technologies habilitantes de l'industrie 4.0.

Systèmes cyber-physiques : Un CPS est un système informatique dans lequel un mécanisme est contrôlé ou surveillé par des algorithmes informatiques (Bartodziej, 2017). Ces systèmes intègrent des composants physiques et numériques pour permettre une interaction et une adaptation en temps réel. Ils offrent une plateforme pour le suivi automatisé et le contrôle des processus industriels complexes, et sont essentiels pour les usines intelligentes. Khaitan et al. (2014) mentionne que les CPS représentent une nouvelle classe de systèmes d'ingénierie offrant une interaction étroite entre les composantes cybernétiques et physiques. Le matériel *(Hardware)* et les logiciels *(Software)* de ces systèmes sont interconnectés et capables de fonctionner à différentes échelles spatio-temporelles, pouvant interagir entre eux pour s'adapter au contexte (Khaitan et al., 2014; Shafiq et al., 2015). En d'autres termes, les CPS représentent la convergence des mondes physique et numérique en établissant des réseaux mondiaux pour l'intégration des systèmes de fabrication, des machines et des systèmes d'entreposage (Shafiq et al., 2015; Wang et al., 2016). Des exemples de CPS incluent les réseaux intelligents, les systèmes de contrôle industriel, les systèmes robotiques et le pilote automatique des avions, les voitures autonomes et la surveillance médicale. En effet, les capteurs et actionneurs de ces systèmes et machines sont contrôlés par des microcontrôleurs de systèmes cyber-physiques qui échangent des informations et des données via des terminaux informatiques embarqués, des applications sans fil ou le cloud (Lu, 2017). Les systèmes CPS ont été déployés à travers trois générations de technologies (Wang et al., 2016)): (1) des technologies telles que la RFID permettant l'identification unique des objets à l'aide de codes-barres avec une gestion centralisée des données (stockage et analyse), (2) des technologies équipées de capteurs et d'actionneurs avec un ensemble limité de fonctions, (3) des technologies équipées de capteurs et d'actionneurs en réseau capables de stocker et d'analyser des données.

Internet des objets (IoT) : Le concept de l'IoT décrit le réseau d'objets physiques intégrés de technologies telles que des capteurs et des logiciels permettant la connexion et l'échange de données avec d'autres systèmes via Internet (Erboz, 2017; Wang, 2016). Autrement dit, l'IoT relie des dispositifs et capteurs physiques à Internet, permettant une collecte et un échange de données en temps réel. Cette connectivité facilite le suivi, l'analyse et la prise de décision basée sur les données, notamment dans la gestion des actifs et le contrôle de production. Les systèmes IoT reposent sur des infrastructures de cloud computing et des CPS. En d'autres termes, l'IoT se réfère à un système de dispositifs informatiques, de machines mécaniques et numériques, d'objets, d'humains ou d'animaux interconnectés avec des identifiants uniques (Unique Identifiers, UIDs) capables de transférer des données sur un réseau sans nécessiter d'interaction humaine *(Human-to-Human Interaction, H2H; Human-to-Computer Interaction, H2C).* L'IoT comprend également des logiciels d'application pour le contrôle des processus, la collecte de données en temps réel à partir de sites distants afin de contrôler les équipements et les conditions, et l'extension spontanée de la supervision et de l'acquisition de données *(Supervisory Control and Data Acquisition, SCADA)*. Le SCADA intègre des composants matériels qui collectent et alimentent les données dans un ordinateur équipé du logiciel SCADA pour un traitement et une présentation en temps voulu (Rouse, 2020). Les systèmes de fabrication flexible (FMS) et les systèmes de fabrication reconfigurable (RMS) sont de plus en plus dotés d'intelligence permettant la communication entre les machines *(Machine to Machine, M2M)*, le système et l'opérateur humain *(Machine to Human, M2H*

/ System to System, S2S). M2M fait référence à la connexion d'un appareil au cloud pour la gestion et la collecte de données (Rouse, 2020; Rouse, 2016). Le concept de l'IoT a évolué à partir de la communication M2M, c'est-à-dire des machines se connectant entre elles via un réseau sans interaction humaine. Le succès de l'IoT repose sur sa capacité à acquérir et identifier des données pour leur utilisation tout en garantissant la confidentialité et la sécurité (ITU-T-Y.4000, 2016).

Cloud Computing : Le terme Cloud Computing ou disponibilité des ressources informatiques à la demande est une technologie généralement associée à l'accessibilité des services informatiques pour de nombreux utilisateurs via le cloud d'un fournisseur. Le cloud désigne principalement la puissance de calcul et le stockage dans le cloud (stockage de données) sans gestion active directe de l'utilisateur (Montazerolghaem et al., 2020; Mell & Grance, 2011). Le cloud permet le stockage et le traitement de données à distance, accessible de manière sécurisée et en temps réel. Cette technologie soutient les infrastructures IoT et Big Data en offrant un accès à la puissance de calcul et au stockage, sans nécessiter de gestion directe de l'utilisateur. Trois modèles de services standards de solutions de cloud computing sont proposés par les fournisseurs de cloud (Mell & Grance, 2011) : *(1) Software-as-a-Service (SaaS),* tel que les logiciels de gestion intégrée, les ERP (Enterprise Resource Planning), les CRM (Customer Relationship Management), les courriels, les bureaux virtuels, la communication, les jeux, etc., disponibles sur Internet plutôt que localement sur un PC unique. Les utilisateurs utilisent les applications du fournisseur fonctionnant sur une infrastructure cloud. *(2) Platform-as-a-Service (PaaS),* permettant aux clients d'accéder aux applications dans le cloud (exemples : environnement d'exécution, bases de données, serveur web, outils de développement, etc.). Le client gère les applications implémentées, par exemple, les paramètres de configuration, tandis que le fournisseur gère l'infrastructure cloud comprenant le réseau, les serveurs, les systèmes d'exploitation ou le stockage. *(3) Infrastructure-as-a-Service (IaaS)* pour le stockage de données, les machines virtuelles, les serveurs, les réseaux et autres ressources informatiques essentielles. Le client peut installer et exécuter des logiciels comprenant des systèmes d'exploitation et des applications. Le client gère et contrôle les applications, les systèmes d'exploitation, le stockage, etc., tandis que l'infrastructure cloud sous-jacente est contrôlée par le fournisseur de cloud computing. Parmi les géants du marché en termes de disponibilité des ressources informatiques à la demande, citons : Amazon Web Services (AWS), Google Drive, Microsoft Azure, et IBM avec Blue-Cloud (Haug et al., 2016). Aujourd'hui, il est courant de stocker des données dans le cloud grâce à l'explosion des fournisseurs de cloud qui soutiennent la prise de décision axée sur les données.

Intelligence artificielle (IA), apprentissage automatique et Big Data : L'IA repose sur des algorithmes avancés pour analyser des données, identifier des motifs et prédire des résultats. Grâce à l'apprentissage automatique, les systèmes peuvent s'améliorer de manière autonome et s'adapter aux évolutions des données et des environnements. La capacité de collecter et d'exploiter de vastes volumes de données est essentielle pour optimiser les opérations, anticiper les défaillances et analyser les tendances de production. L'analyse des Big Data permet aux entreprises de prendre des décisions éclairées, basées sur des preuves concrètes, et d'améliorer leurs performances globales.

Informatique Cognitive (CC) : Le CC vise à reproduire les processus de pensée humaine dans les machines, permettant de créer des systèmes autonomes capables de résoudre des problèmes complexes. Ce domaine s'appuie sur des technologies d'intelligence artificielle (IA) et de traitement des signaux, intégrant des systèmes d'auto-apprentissage *(Self-Learning Systems)* utilisant le data mining, la reconnaissance de formes et le traitement du langage naturel pour imiter le fonctionnement du cerveau humain (Rouse, 2016; Kelly III, 2016). Grâce à des algorithmes d'apprentissage automatique, ces systèmes acquièrent et améliorent continuellement leurs connaissances à partir des données analysées via des modèles statistiques et mathématiques. L'objectif est de développer des solutions automatisées capables d'extraire des informations, d'exécuter des tâches et de résoudre des problèmes sans intervention humaine.

Jumeaux numériques (Digital Twins, DT) : Les DT sont des représentations virtuelles d’actifs ou de systèmes physiques, conçues pour la surveillance en temps réel, la simulation et l’analyse prédictive. Ils permettent de tester des scénarios virtuels avant leur mise en œuvre, aidant ainsi à prendre des décisions éclairées. Un DT agit comme l’équivalent numérique en temps réel d’un objet physique. La Simulation Digital Twins (SDT) offre aux gestionnaires d’actifs la capacité de réagir aux perturbations en temps réel, tout en augmentant la visibilité des impacts à long terme de leurs décisions, favorisant ainsi une meilleure résilience. Selon IoT-Analytics (2020), le DT peut être défini comme une abstraction numérique des attributs ou du comportement d’un système physique, structurée autour de trois dimensions : (1) le niveau hiérarchique (sa structure organisationnelle); (2) les phases du cycle de vie (les étapes où il est appliqué); (3) l’utilisation pratique (les données d’entrée et leur exploitation). La SDT repose sur trois avancées majeures pour une prise de décision optimale : (i) vue holistique à 360° (répliquer l’ensemble d’un écosystème); (ii) simulation dynamique (prédire l’évolution future d’une organisation); (iii)connexion en temps réel (l’IoT alimente le DT avec des données en temps réel, facilitant l’automatisation des décisions) (Bantel, 2021).

L'industrie 4.0 ne découle pas d'une fracture numérique comme les trois révolutions précédentes, à savoir : (1) la mécanisation de la production par la machine à vapeur et l'eau au XVIIIe siècle, (2) la production de masse (Henry Ford) et la création de la chaîne d'assemblage grâce à l'électricité au XIXe siècle, (3) l'automatisation de la production par les technologies de l'information et l'électronique au XXe siècle. L'industrie 4.0 façonne l'avenir des organisations en provoquant des changements profonds dans les façons de faire des affaires. Le passage à des systèmes de plus en plus numériques sera inexorablement accompagné par une multitude de nouveaux défis et de risques émergents associés aux contraintes et exigences de la santé et sécurité au travail (SST) ainsi qu'à la gestion des risques d'entreprise (ERM), tels que les cyberattaques majeures, l'interconnexion des technologies numériques, l'interopérabilité des systèmes, la réingénierie et la standardisation des processus, produits et services, ainsi que l'acquisition et le stockage de données massives (Big Data), la gouvernance numérique, la maintenance et l'acquisition, la formation et la rétention des talents en milieu de travail. Les décideurs qui comprennent pleinement ces évolutions et les avantages associés aux technologies numériques seront les mieux préparés à relever les divers défis liés à l'industrie 4.0. Ainsi, il n'est pas nécessaire de réinventer la roue à chaque fois, mais chaque entreprise pourrait devoir adapter son modèle économique spécifique, potentiellement plus approprié dans ce contexte de numérisation (European-Asset-Management-Committee, 2017).

- *Industrie 5.0*

L'Industrie 5.0, également appelée cinquième révolution industrielle, est une initiative de la Commission Européenne (CE), l'organe exécutif de l'Union Européenne (UE) (De Nul et al., 2021). Lancée à l'occasion du dixième anniversaire de l'industrie 4.0, cette vision complète et élargit son prédécesseur en mettant l'accent sur une transition vers une industrie durable, centrée sur l'humain et résiliente.

Contrairement à l'industrie 4.0, axée sur la technologie, l'industrie 5.0 se concentre sur les valeurs humaines et sociétales. Elle vise à intégrer des processus respectueux de l'environnement à chaque étape de la chaîne de production, tout en plaçant le bien-être et la sécurité des employés au centre des préoccupations. Ses objectifs incluent : *(1) Centrage sur l'humain* (prioriser le confort, la sécurité et l'équité sociale des travailleurs); (2) *Durabilité* (respecter les limites planétaires grâce à des pratiques écologiques); (3) *Résilience* (promouvoir une prospérité durable face aux défis sociétaux. En d'autres termes, l'industrie 5.0 déplace l'attention de la création de valeur pour les actionnaires vers une approche centrée sur les parties prenantes, renforçant la responsabilité de l'industrie envers la société (Xu et al., 2021). Elle s'appuie sur les outils et technologies de l'industrie 4.0 tout en les orientant vers des objectifs sociétaux, durables et équitables. La Figure 2.1 illustre ces valeurs fondamentales (humain, durable et résilient), confirmant la vision de l'industrie 5.0 comme un modèle industriel axé sur les valeurs.

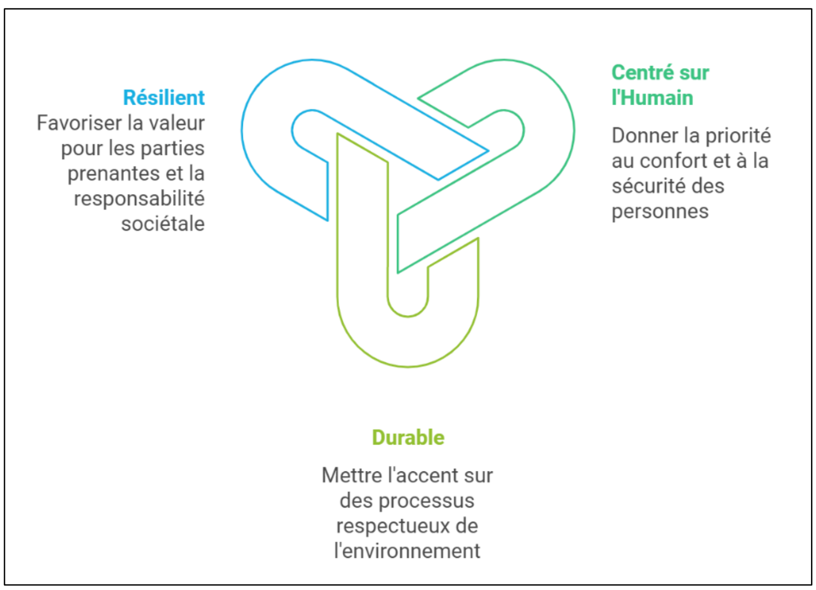

Figure 2.1. Principes directeurs de l'industrie 5.0

- *Non-linéarité et incertitude dans les systèmes sociotechniques modernes*

La complexité des systèmes sociotechniques est intrinsèquement liée aux risques émergents de l'industrie 4.0, à l'intensification des événements extrêmes et perturbateurs, ainsi qu'aux risques organisationnels et aux biais cognitifs et motivationnels propres aux dynamiques humaines. Ces systèmes évoluent dans un contexte d'incertitude persistante, exacerbée par l'instabilité politique mondiale, les récents conflits armés et les pandémies, menaçant ainsi la performance et la résilience des organisations. Komljenovic et al. (2015) met en évidence que l'interaction complexe entre facteurs humains, techniques et organisationnels accentue l'imprévisibilité des comportements dans les systèmes sociotechniques modernes, compliquant la gestion des risques et de la sécurité. Les incertitudes dans ces systèmes se répartissent en deux grandes catégories : *(1) aléatoires*, liées aux variations naturelles des opérations, et *(2) épistémiques*, issues des limites de la connaissance et des hypothèses de modélisation. Pourtant, aucun modèle scientifique n'intègre de manière exhaustive ces dimensions. Cela met en lumière l'urgence de développer des approches novatrices et systémiques capables de répondre aux menaces croissantes posées par la complexité et l'incertitude dans les systèmes sociotechniques modernes.

Abdul-Nour et al. (2021) proposent un cadre décisionnel pour la gestion des risques, des incertitudes et de la résilience dans les systèmes socio-techniques complexes, comme illustré dans la Figure 2.2. Ce cadre évalue les incertitudes, les classant en trois niveaux (mineures, modérées, significatives) et adapte les stratégies de gestion en conséquence : gestion traditionnelle, gestion sous incertitude ou gestion axée sur la résilience. Le processus se conclut par une révision globale et une prise de décision éclairée, soulignant l'importance d'approches différenciées pour renforcer la sécurité et la résilience, particulièrement dans des contextes où la variabilité des performances est essentielle.

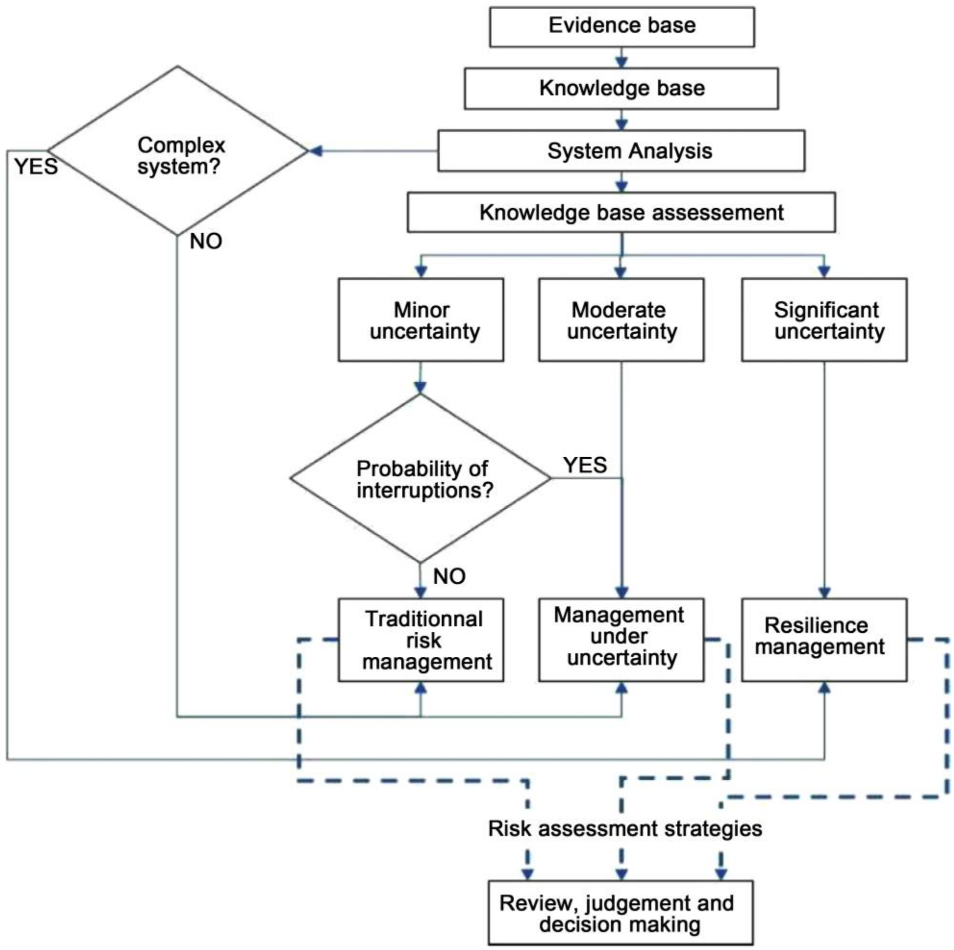

Figure 2.2. Cadre décisionnel pour la gestion des risques, des incertitudes et de la résilience dans les systèmes complexes *(Source: Abdul-Nour et al. (2021))*.

2.3 Gestion des actifs physiques industriels et processus de prise de décision

Dans cette section, il est proposé une revue synthétique des contributions majeures de la communauté scientifique sur le concept de gestion des actifs physiques industriels (GDA-PI) et les processus décisionnels qui y sont associés. Ces thématiques suscitent un intérêt croissant dans divers secteurs industriels et gagnent en maturité. Plutôt que d'aborder l'ensemble des sous-modèles existants, la revue mettons l'accent sur le développement original de méthodologies et de méthodes décisionnelles en GDA-PI. Les articles de revue avec comité de lecture, publiés dans des journaux internationaux, fournissent des détails approfondis sur la littérature. Alors, cette section offre ainsi un aperçu ciblé de la recherche en GDA-PI.

2.3.1 Une Approche Intégrée et Multidisciplinaire

La gestion des actifs est définie comme l'activité de coordination d'une organisation pour tirer de la valeur[§] des actifs, couvrant aussi bien les actifs physiques qu'immatériels (données, propriété intellectuelle, réputation) (ISO-55000, 2024, 2014). La Figure 2.2 illustre l'intégration progressive de la gestion des actifs dans la gestion globale de l'organisation (IAM 2024, 2015), conformément aux principes des normes ISO-55000 (2024, 2014). La représentation en couches montre les différents niveaux

[§] « La réalisation de valeur suppose normalement de parvenir à un équilibre entre les bénéfices des coûts, des risques, des opportunités et des performances » (ISO-55000, 2014).

d'interaction (cf. Figure 2.3) : *(1) Portefeuille d'actifs* – actifs gérés au sein du système de gestion, *(2) Système de gestion des actifs* – cadre structuré définissant les politiques, objectifs et processus, *(3) Gestion des actifs* – activités coordonnées pour maximiser la valeur des actifs, *(4) Gestion globale de l'organisation* – alignement stratégique pour atteindre les objectifs organisationnels. Cette structure garantit une gestion holistique des actifs, optimisant leur performance et alignant les décisions avec les objectifs stratégiques. Par exemple, elle s'applique à des secteurs comme l'énergie ou les transports, où elle permet de réduire les coûts, d'augmenter la résilience et d'atteindre des objectifs à long terme.

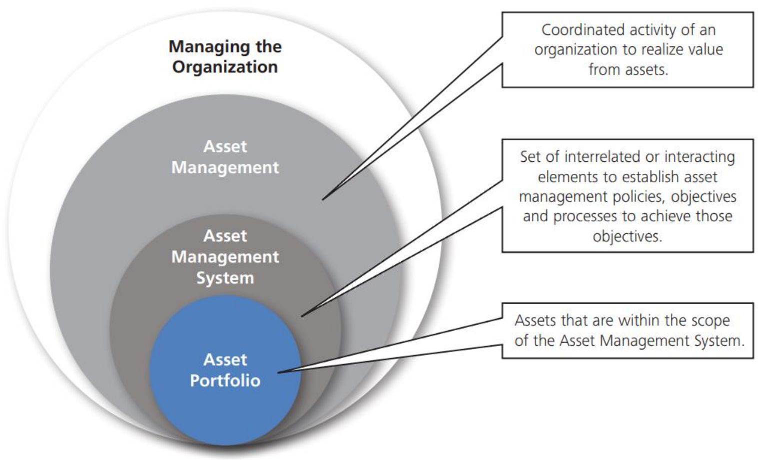

Figure 2.3 Relation entre la gestion des actifs et les autres entités

(Source: IAM, 2024)

Bien que la problématique de la gestion des actifs physiques industriels (GDA-PI) ne soit pas nouvelle, elle est au cœur des pratiques des organisations à forte intensité d'actifs, telles que les compagnies aériennes ou les entreprises d'électricité, depuis des décennies (Bulita, 1994). Devenue une tâche cruciale et de plus en plus complexe, la GDA-PI exige une gestion rigoureuse des incertitudes et des risques multidimensionnels, qu’ils soient stratégiques, opérationnels, financiers, technologiques ou techniques, impactant directement les processus d’affaires. Confrontée à des défis majeurs tels que la concurrence internationale, la volatilité des marchés et la sophistication des systèmes sociotechniques modernes, la GDA-PI doit également répondre à des risques émergents, comme la cybersécurité, le terrorisme et le changement climatique. Ces menaces croissantes augmentent significativement la probabilité d’événements extrêmes susceptibles de compromettre la performance des organisations. Pour renforcer leur compétitivité à l’échelle mondiale, les décideurs et praticiens de la GDA-PI développent des stratégies innovantes en s’appuyant sur les outils de l’industrie 4.0, tels que l’Internet industriel des objets (IIoT), l’intelligence artificielle (IA), le cloud computing, les systèmes cyber-physiques (CPS) et l’analyse de données massives (Big Data). Ces technologies permettent une gestion optimisée des données et facilitent des prises de décision éclairées.

Dans le secteur électrique canadien, par exemple, les services publics assurent environ 92 % de la production totale d’électricité. Ces entreprises doivent gérer le remplacement d’une part significative de leurs actifs en fin de cycle de vie, souvent rendus obsolètes par les avancées technologiques ou la transition vers des énergies alternatives (vertes, propres et sans carbone) plus efficaces (Komljenovic, 2018).

La nouvelle normalité, marquée par la complexité des systèmes industriels et l’émergence d’un large éventail de technologies, pousse les organisations à repenser et optimiser leurs modèles de gestion stratégique pour répondre aux exigences actuelles et futures.

2.3.2 Normes et Cadres Référentiels en GDA

- *Série de normes ISO 55000*

La série de normes ISO-55000 (2024, 2014) (comprenant ISO 55000, 55001 et 55002) établit les concepts fondamentaux d'une approche holistique de la GDA. Ces normes succèdent au guide PAS 55 (BSI, 2013, 2008), devenu obsolète depuis 2015, bien qu'il conserve une utilité pédagogique pour certaines organisations. La Figure 2.4 montre les différents niveaux de la norme PAS 55 utilisée comme modèle de base pour ISO 55000. La norme ISO-55001 (2014) définit les exigences pour l'établissement, la mise en œuvre, la maintenance et l'amélioration d'un système de gestion des actifs (SGA). Quant à ISO 55002, elle fournit des lignes directrices pour l'application de ces exigences (ISO-55002, 2014, 2018).

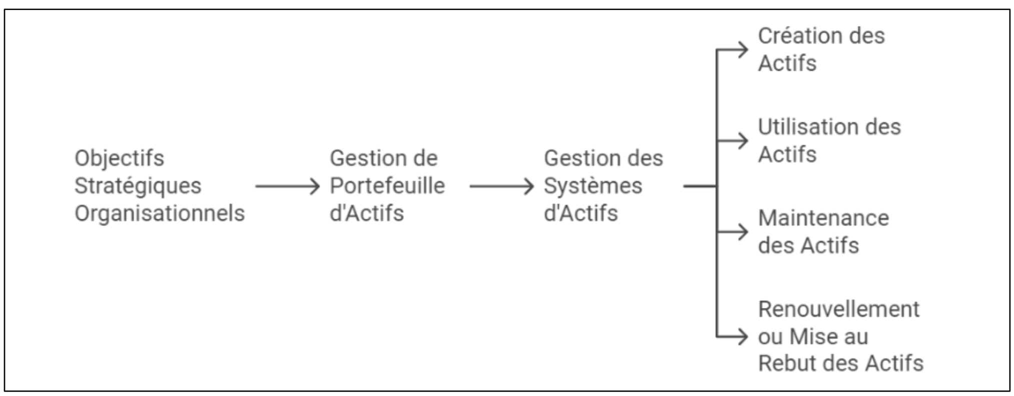

Figure 2.4. Système de gestion des actifs PAS 55
(Source : élaboration personnelle basée sur BSI, 2008)

- *Contributions du GFMAM*

En 2011, le Global Forum on Maintenance and Asset Management (GFMAM (2011)) a été fondé par des experts et professionnels pour enrichir les pratiques en GDA.

Contrairement aux normes ISO, les thèmes du GFMAM couvrent un spectre plus large de connaissances en GDA (Campbell et al., 215). Le GFMAM a identifié 39 sujets, regroupés en six thématiques : (1) Stratégie et planification, (2) Prise de décision en GDA, (3) Gestion du cycle de vie, (4) Informations sur les actifs, (5) Organisation et personnes, (6) Risque et examen. Ces thématiques sont alignées sur les normes ISO et servent à évaluer la maturité des pratiques en GDA.

- *Modèle Conceptuel de l'IAM*

L'Institute of Asset Management (IAM) a publié un modèle conceptuel (Asset Management – An Anatomy (IAM-2015)) regroupant les mêmes thématiques identifiées par le GFMAM. Ce cadre référentiel met en évidence l'interconnexion entre les activités, leur alignement stratégique et l'importance d'une intégration optimale des processus. L'IAM a développé un cadre conceptuel pour la gestion des actifs, comprenant six groupes de thèmes qui couvrent les 39 sujets initialement publiés par le GFMAM (IAM, 2015; GFMAM, 2014). Ce cadre, intitulé *IAM Asset Management - An Anatomy*, permet d'évaluer la *maturité* en gestion des actifs. Aligné avec les principes des normes de la série ISO-55000 (2014), il détaille les activités de gestion des actifs au sein d'une organisation. Les 39 sujets sont regroupés en 6 thèmes, ce qui illustre : l'ampleur de la gestion des actifs, les interrelations entre les différentes activités, la nécessité de les intégrer, et l'importance de l'alignement avec les objectifs et la stratégie organisationnelle. La Figure 2.5 présente le modèle de l'IAM incluant les 6 groupes thématiques. Les niveaux de maturité, qui qualifient le degré de progrès d'une organisation, reposent sur les définitions adoptées par l'IAM.

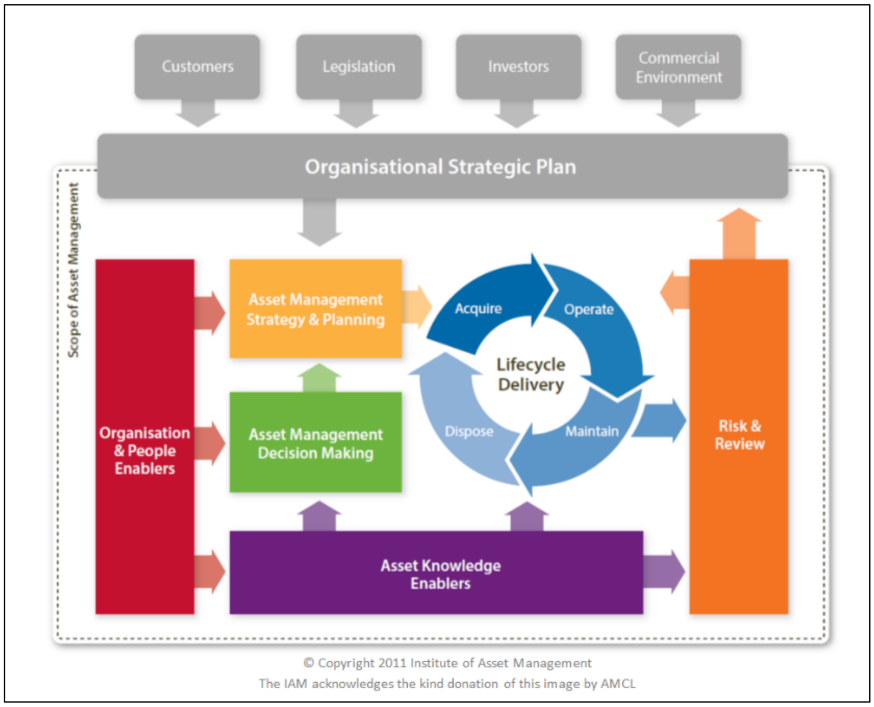

Figure 2.5. Modèle conceptuel de gestion des actifs

(Source: (IAM, 2015))

La Figure 2.6 illustre le cheminement vers l'excellence en gestion d'actifs. La maturité est évaluée sur une échelle de 0 à 5, où le niveau 3, correspondant au degré de *Compétence*, reflète les exigences de la certification ISO-55001 (2014). À ce niveau, les processus de gestion des actifs sont en place, ils sont documentés, communiqués et contrôlés à l'échelle de l'organisation, ils produisent les résultats attendus. Il est courant d'observer un niveau de maturité initial qualifié de *Sensibilisation (Awareness)* chez les organisations réalisant leur première évaluation des pratiques de gestion d'actifs. Ce niveau constitue souvent le point de départ vers l'adoption des meilleures pratiques, un processus continu et évolutif fondé sur le principe d'amélioration continue.

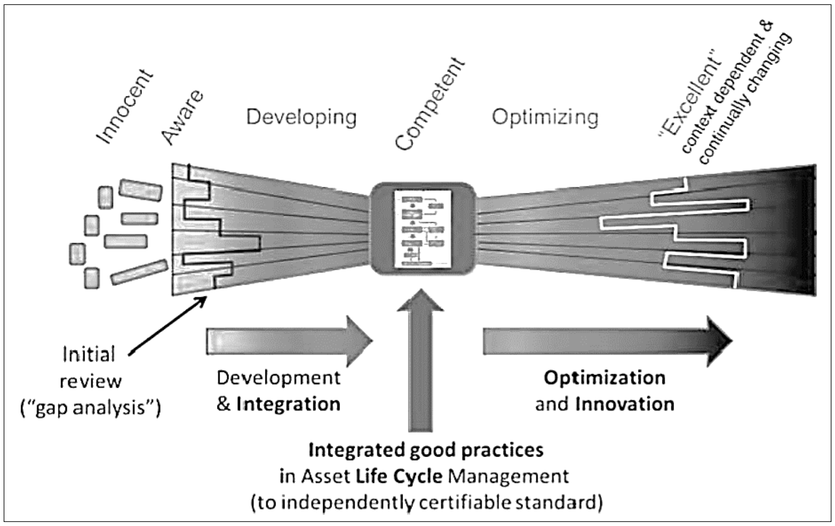

Figure 2.6. Échelle de maturité en gestion des actifs
(Source: IAM (2015))

- *AMBoK de l'AM-Council*

En 2014, l'AM-Council (Australian Asset Management Council (AM Council, 2014) a développé l'AMBoK (Asset Management Body of Knowledge), un cadre complet pour la prise de décision stratégique, tactique et opérationnelle en GDA. L'AMBoK offre des modèles et des définitions pratiques pour structurer et optimiser la gestion des actifs. La Figure 2.7 illustre les différents modèles développés au sein de l'AMBoK et leurs niveaux d'implication dans la GDA.

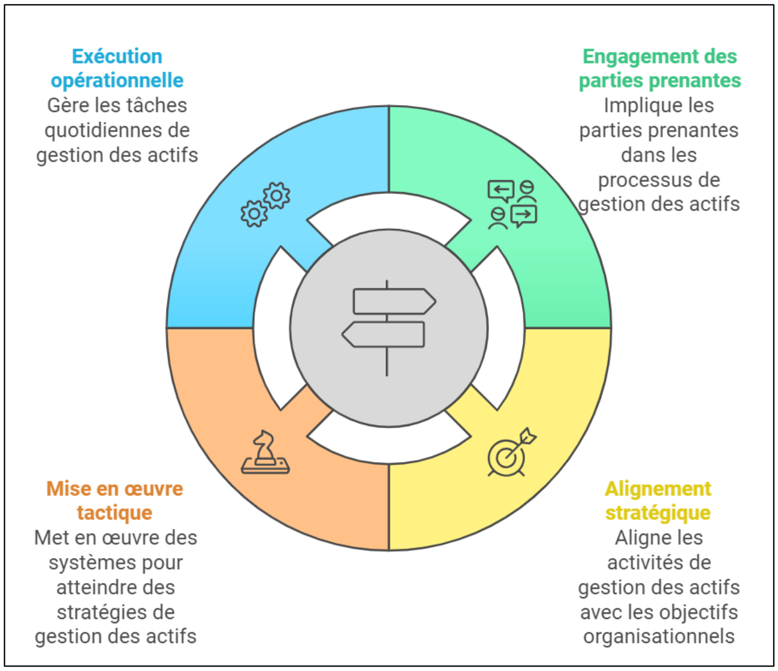

Figure 2.7. Modèles du corpus de connaissances en gestion des actifs (AMBoK)
(Source : adapté de AM Council, 2014)

- *Contribution du CIGRÉ au Secteur Électrique*

Créé en 1921, le Conseil International des Grands Réseaux Électriques (CIGRÉ) est une organisation mondiale dédiée aux aspects techniques, économiques, environnementaux et réglementaires des réseaux électriques haute tension CIGRÉ (2013, 2014). Selon le CIGRÉ, la GDA consiste à maximiser les bénéfices à long terme tout en maintenant un service de qualité et des risques acceptables (Bartlett, 2002 ; Khuntia et al., 2016). Le CIGRÉ a élaboré un modèle conceptuel pour la prise de décision en GDA, structuré en trois niveaux d'exigences d'information : (1) Niveau Corporate, (2) Niveau Réseau et (3) Niveau Composant. Ce modèle est illustré par la Figure 2.8, qui détaille les niveaux d'informations nécessaires pour une gestion des risques optimale dans le secteur électrique.

Pour une analyse détaillée des approches stratégiques en GDA et des processus décisionnels, le lecteur est invité à consulter les articles évalués par des pairs de Diop et al. (2021, 2022, 2023, 2024) et leurs références bibliographiques.

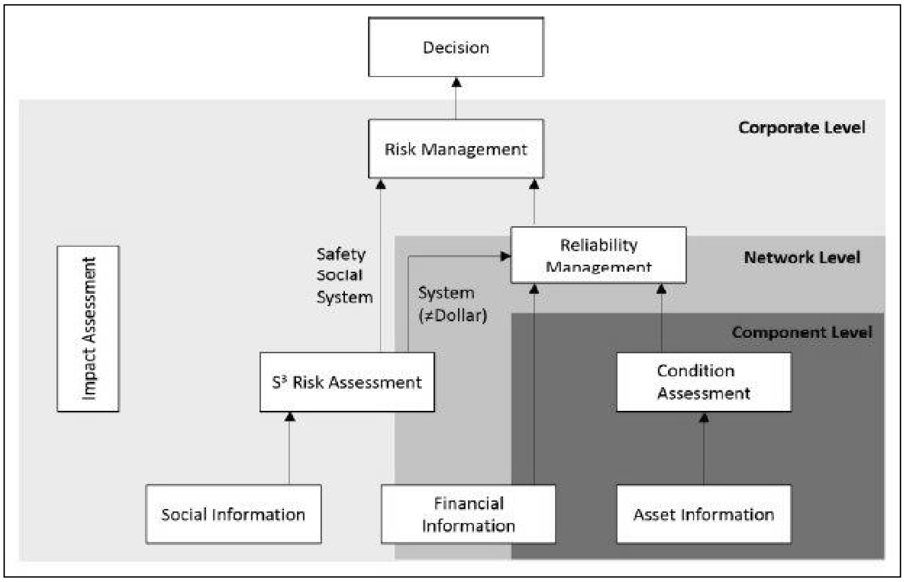

Figure 2.8. Modèle conceptuel de prise de décision pour la GDA
(Source: CIGRÉ, 2013)
** Note: S3 stands for Safety, Social, and System Oriented Risks.*

2.3.3 Ingénierie de la Résilience en GDA-PI

La gestion des actifs physiques industriels (GDA-PI) joue un rôle essentiel pour permettre aux actifs de s'adapter aux environnements organisationnels externes et internes. Ces environnements incluent la concurrence croissante, la déréglementation des marchés, l'innovation technologique, ainsi que des risques majeurs tels que les attaques terroristes, les catastrophes naturelles, les perturbations géopolitiques, les grandes tempêtes géomagnétiques et les cyberattaques (Gavrikova et al., 2020). La Figure 2.9 présente la hiérarchie de ces environnements. En raison de sa complexité et de son incertitude profonde, l'environnement externe demeure difficilement prévisible, et ni précisément contrôlable ni influençable (Komljenovic et al., 2015). Pour répondre à ce type d’environnement, la gestion de la résilience constitue une approche largement reconnue dans l’analyse des risques et des incertitudes. La littérature scientifique propose une vaste gamme de définitions du concept de résilience (Hollnagel, 2017; Hickford et al., 2018, Hosseini et al., 2016; Albino et al., 2016; Zio, 2016), ce qui peut compliquer son interprétation et sa mesure (Henry et al., 2012). Ces variations s’expliquent par les aspects spécifiques du système étudié (Lofquist, 2017). Vugrin et al. (2010) a identifié plusieurs aspects interconnectés pour évaluer la résilience des systèmes, notamment : (i) technique, (ii) organisationnel, (iii) social, (iv) économique, (v) écologique et (vi) environnemental. Par exemple, l’ingénierie de la résilience, promue comme un concept moderne de gestion de la sécurité, aborde les systèmes sociotechniques complexes (Hollnagel et al., 2017 ; Righi et al., 2015, Hickford et al., 2018).

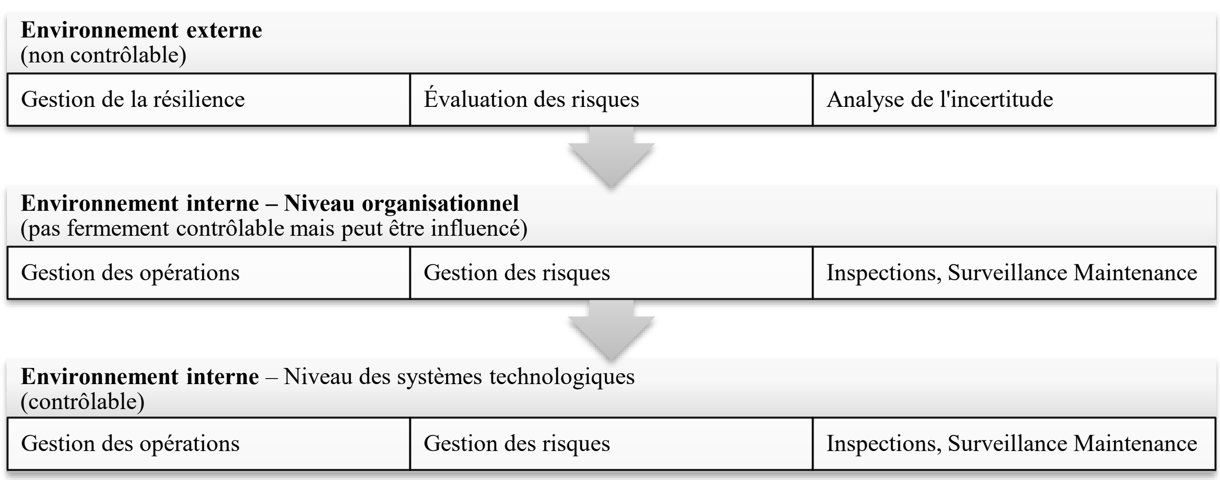

Figure 2.9. Hiérarchie des environnements organisationnels pour la GDA-PI
(Source: adapté de Komljenovic et al. (2015))

Quatre principes communs émergent de la revue de la littérature, comme le montre la Figure 2.10. Ces principes incluent la capacité à survivre au changement, soit en atténuant les effets de la perturbation, en s'y adaptant ou en s'en remettant. Il est important de noter que la rapidité de la récupération est un aspect central de la résilience. Les organisations performantes se distinguent par leur résilience, car elles sont capables d'anticiper et de réagir efficacement aux menaces et opportunités dans un environnement complexe et en constante évolution.

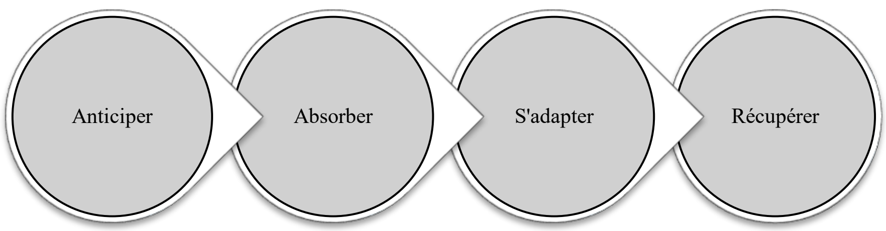

Figure 2.10. Quatre principes fondamentaux de la résilience
(Source: adapté de Hickford et al., 2018)

Il convient de souligner que la résilience, en tant qu'approche pour faire face à la complexité et aux incertitudes, ne devrait pas être envisagée au niveau des composants, mais plutôt comme une caractéristique du système dans son ensemble, capable de résister à des conditions sévères (Hickford et al., 2018: Martorell et al., 2013). Le concept général de résilience, tel qu'illustré dans le cas d'une tempête de neige au Québec, peut être expliqué à travers les quatre phases principales (Figure 2.11): planification (préparer), absorption, récupération, et adaptation.

- *Planification*: cette phase prépare et anticipe l'arrivée d'un événement défavorable (e.g., tempête de neige).
- *Absorption*: cette phase reflète la perte de performance subie lors de l'occurrence d'un événement défavorable. Elle reflète une meilleure préparation ou robustesse, entraînant une réduction de l'impact.
- *Récupération*: cette phase consiste à rétablir les performances après un événement défavorable. La durée nécessaire pour une récupération complète est d'autant plus longue que la perte de performance est importante ou que les ressources nécessaires pour réparer les dommages ne sont pas disponibles. Selon ces facteurs, plusieurs trajectoires de récupération sont possibles.
- *Adaptation*: cette phase permet de recueillir des informations, d'acquérir de l'expérience sur l'événement défavorable et de continuer à améliorer la résilience du système.

La résilience implique une amélioration continue et une adaptation persistante, car plusieurs niveaux de performance peuvent être atteints après la récupération. Ce concept de résilience repose sur quatre propriétés principales (Komljenovic et al., 2020; Hickford et al., 2018; Martorell et al., 2013):

- *Robustesse* : la capacité d'absorber un choc, de maintenir des fonctions critiques et de survivre après un événement défavorable, notamment par l'absorption et l'adaptation.
- *Redondance* : La présence de systèmes ou de ressources alternatifs pour garantir le fonctionnement en cas de défaillance.
- *Ingéniosité* : La capacité à planifier, se préparer et être prêt à résister à une perturbation.
- *Récupération* rapide : La capacité à reprendre rapidement les opérations et à fonctionner efficacement après un accident (Hickford et al., 2018 ; Martorell et al., 2013).

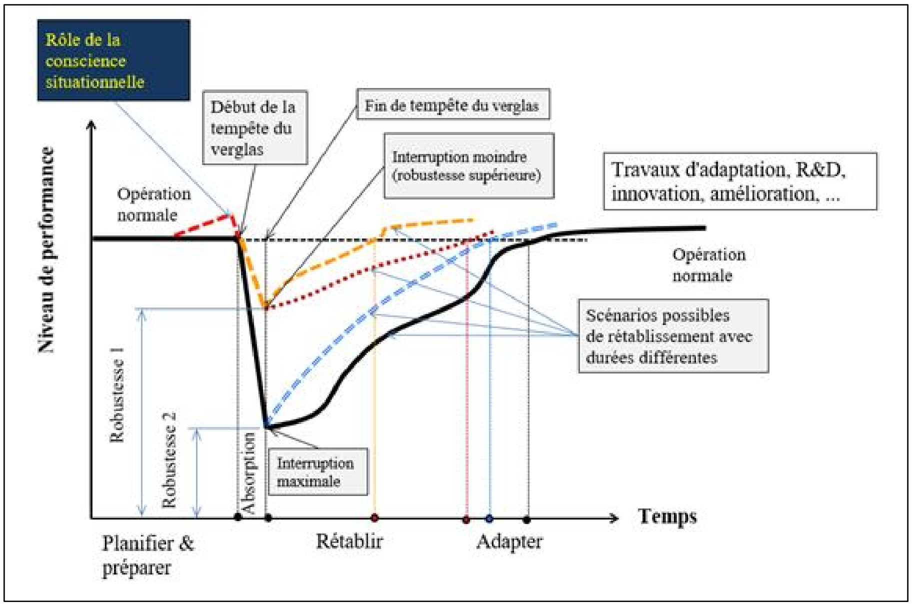

Figure 2.11. Concept général de résilience illustré dans le cas d'une tempête de neige au Québec *(Source:Komljenovic et al. (2020))*

2.3.4 Fiabilité et résilience des systèmes de systèmes (SoS)

L'étude de Dersin et al. (2024) met en lumière les défis uniques associés à la fiabilité et à la résilience des systèmes de systèmes *(Systems of Systems, SoS)*, définis comme des ensembles d'entités interconnectées présentant des comportements émergents, des interdépendances complexes et une vulnérabilité accrue aux événements extrêmes. Alors que la fiabilité vise principalement à prévenir les défaillances, la résilience élargit cette perspective en intégrant la capacité d'un système à anticiper, absorber, s'adapter et récupérer efficacement après des perturbations majeures, qu'elles soient prévisibles (événements à faible impact et forte probabilité : LIHP (low-impact high-probability events)) ou exceptionnelles (événements à fort impact et faible probabilité: HILF (high-impact low-frequency events), comme les catastrophes naturelles).

Dersin et al. (2024) propose deux études de cas illustratives :

(1) *Le réseau électrique Beauharnois-Les Cèdres de Hydro-Québec :* Cette étude intègre des approches de modélisation multi-couches, incluant des simulations Monte Carlo et des analyses probabilistes, pour évaluer la capacité du réseau à gérer les inondations en tant que système électrique de déversement. Une version résiliente du réseau est proposée, avec une topologie améliorée permettant d'augmenter la capacité d'évacuation des eaux en cas d'événements perturbateurs majeurs. Les résultats montrent une meilleure gestion des risques, avec un impact minimal sur la génération d'énergie et les ressources hydriques.

(2) *Les réseaux de transport urbains multimodaux :* En utilisant la théorie des graphes, cette étude modélise les interactions entre les réseaux de bus et de trains pour évaluer leur résilience face à des défaillances, comme la fermeture de stations. Les résultats montrent que l'intégration des réseaux permet de réduire les interruptions de trajet et les retards, démontrant l'importance des couplages intermodaux pour renforcer la résilience globale.

L'article souligne également la complémentarité de la fiabilité et de la résilience, suggérant que des systèmes optimisés exclusivement pour l'efficacité tendent à être plus fragiles face aux perturbations. Une approche holistique est préconisée, prenant en compte les dimensions techniques, économiques, organisationnelles et sociales des infrastructures critiques. Enfin, l'article propose des perspectives prometteuses, comme l'intégration de l'intelligence artificielle et des réseaux neuronaux graphiques, pour mieux modéliser les interdépendances et améliorer la gestion des risques et la résilience des SoS.

Ces travaux offrent des perspectives précieuses pour l'analyse et l'optimisation des infrastructures vieillissantes. Ils mettent en lumière des approches novatrices visant à renforcer la résilience face à des perturbations complexes, tout en garantissant la continuité des services essentiels. Cette thématique constitue une avenue particulièrement prometteuse à approfondir dans le cadre de recherches futures.

2.4 Plaidoyer pour une approche systémique en GDA-PI

Cette section passe en revue les principales méthodes de gestion systématique des risques industriels, notamment les méthodes RIDM (Risk-Informed Decision-Making), RIAM (Risk-Informed Asset Management), FRAM (Functional Resonance Analysis Method) et STAMP (System-Theoretic Accident Model and Processes), qui occupent une place significative dans la recherche scientifique en raison de leur pertinence pour l'analyse des risques.

2.4.1 Processus de prise de décision éclairée par les risques (RIDM)

Autrefois, l'évaluation des risques et des incertitudes reposait principalement sur des analyses probabilistes, connues sous les appellations d'évaluation probabiliste des risques *(Probabilistic Risk Assessment, PRA)* ou d'évaluation quantitative des risques *(Quantitative Risk Assessment, QRA)*. Ces méthodes permettaient aux gestionnaires d'actifs d'obtenir une base quantitative pour la prise de décision. Cependant, cette dernière nécessite une variété de données d'entrée, à la fois qualitatives (comme les jugements d'experts) et quantitatives (comme les résultats des analyses de risques).

Aujourd'hui, une évolution se dessine, on passe d'une approche de gestion de la sécurité basée sur les risques *(Risk-Based)* à une approche éclairée par les risques *(Risk-Informed)*. Dans cette dernière, les résultats des PRA et QRA sont intégrés comme éléments fondamentaux du processus décisionnel (Komljenovic et al., 2016 ; Zio, 2012). Cette approche, appelée prise de décision informée par les risques (RIDM –Risk-Informed Decision-Making (RIDM), s'applique particulièrement à la prise de décision dans des contextes liés à la sécurité (Dezfuli, 2010c). Initialement développée par l'industrie nucléaire des États-Unis pour faire face aux défis de sécurité de l'énergie nucléaire, elle a également été adoptée par l'industrie aérospatiale, notamment la NASA (Travers, 1999).

Dans ce cadre, la gestion des risques *(Risk Management, RM)* englobe à la fois le processus RIDM et la gestion continue des risques *(Continuous Risk Management, CRM)* (Dezfuli, 2010c). Ces deux approches sont complémentaires et doivent être intégrées dans un cadre unique pour assurer une gestion efficace des risques. Une gestion proactive combine ainsi le RIDM, qui se concentre sur la sélection d'une alternative parmi plusieurs options pour atteindre les objectifs, et le CRM, qui veille à l'exécution et au suivi de la décision choisie.

Comme le souligne Zio (2012), les résultats quantitatifs des évaluations de risques ne sont qu'une composante du processus décisionnel. Ils doivent être intégrés à d'autres critères tels que les préférences sociales, les contraintes budgétaires ou encore les préoccupations politiques. Dans le même sens, Dezfuli et al. (2010c) met en garde contre une dépendance excessive à l'information technique, en insistant sur l'importance du jugement humain dans la prise de décision. De son côté, Komljenovic (2018) rappelle que le RIDM nécessite une perspective plus large, intégrant des analyses couvrant l'ingénierie, l'économie, la société, l'environnement, et les cadres réglementaires.

Les exigences de gestion des risques de la NASA (NPR 8000.4) structurent le processus de RIDM en trois parties principales, comportant six étapes (voir Figure 2.12): *(1) Identification des alternatives* (reconnaître les opportunités en fonction des objectifs); *(2) Analyse des risques* (développer une base technique pour la délibération); (3) *Délibération et sélection* (choisir une alternative et ses engagements de performance en s'appuyant sur les analyses réalisées). Ces étapes permettent d'intégrer les dimensions techniques, humaines et organisationnelles nécessaires à une prise de décision éclairée et efficace.

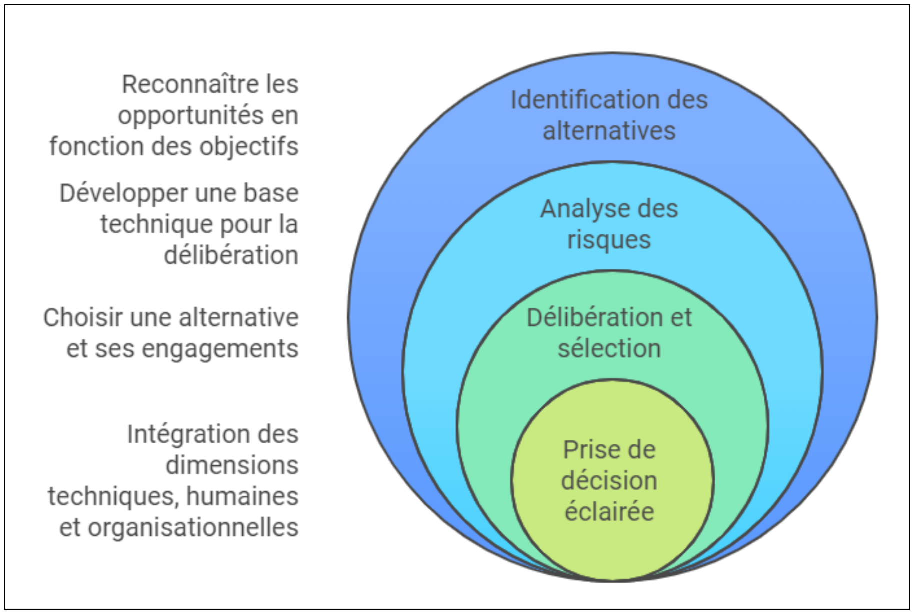

Figure 2.12. Processus RIDM
(Source: adapté de NASA/SP-2010-576)

Komljenovic et al. (2019) proposent une approche adaptée aux grands projets, axée sur la gestion stratégique des actifs, en tenant compte de la performance à long terme et de la durabilité. Cette approche se décline en trois étapes principales, comme illustré à la Figure 2.13: (1) établir le cadre décisionnel, (2) réaliser des analyses approfondies, et (3) délibérer et prendre les décisions finales. Cependant, les auteurs précisent que ce processus est inadapté pour les décisions quotidiennes, en raison de sa complexité et de son orientation stratégique.

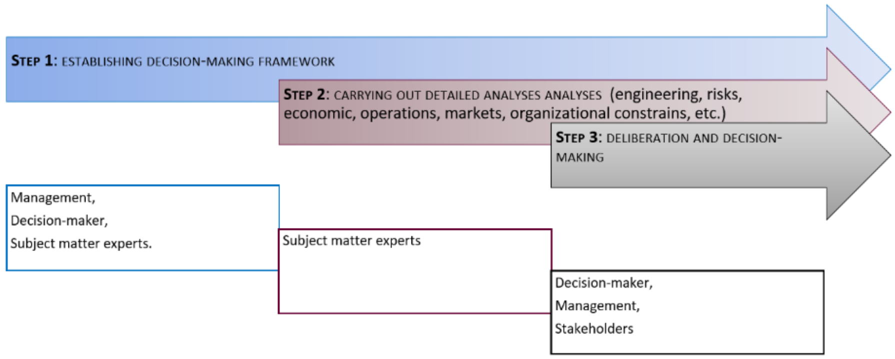

Figure 2.13. Processus global RIDM en gestion des actifs
(Source : adapté de Komljenovic et al., 2019)

2.4.2 Gestion des actifs éclairée par les risques (RIAM)

Le concept de processus de gestion des actifs éclairée par les risques (Risk-Informed Asset Management, RIAM) est un outil d'analyse décisionnelle basé sur les risques, initialement développé pour les centrales nucléaires, mais adapté aux industries orientées par le marché (EPRI, 2002). En termes simples, le processus RIAM offre aux gestionnaires d'actifs un instrument permettant de planifier les priorités des projets, de gérer le cycle de vie des actifs, de développer des plans d'entretien à long terme, d'élaborer des budgets et de prendre en compte les risques économiques, ainsi que la fiabilité et la disponibilité des systèmes.

La Figure 2.14 illustre, de manière conceptuelle et à un haut niveau, le modèle de RIAM basé sur le rapport technique du plan de développement de l'Electric Power Research Institute (EPRI, 2002). La méthode RIAM vient compléter la méthode de gestion des actifs nucléaires *(Nuclear Asset Management, NAM)*, qui utilise la gestion des risques et définit des objectifs stratégiques pour soutenir la prise de décisions d'investissement dans une perspective de planification à long terme, tout au long du cycle de vie des actifs (EPRI, 2002).

Le processus RIAM repose sur l'établissement de plusieurs modèles de rentabilité et de mesures de performance ou indicateurs d'aide à la décision (coût, sécurité, revenus, calendrier, etc.), afin d'aider les décideurs à allouer et optimiser les ressources. Par conséquent, le RIAM s'inscrit également dans une approche axée sur la performance (Liming, 2002).

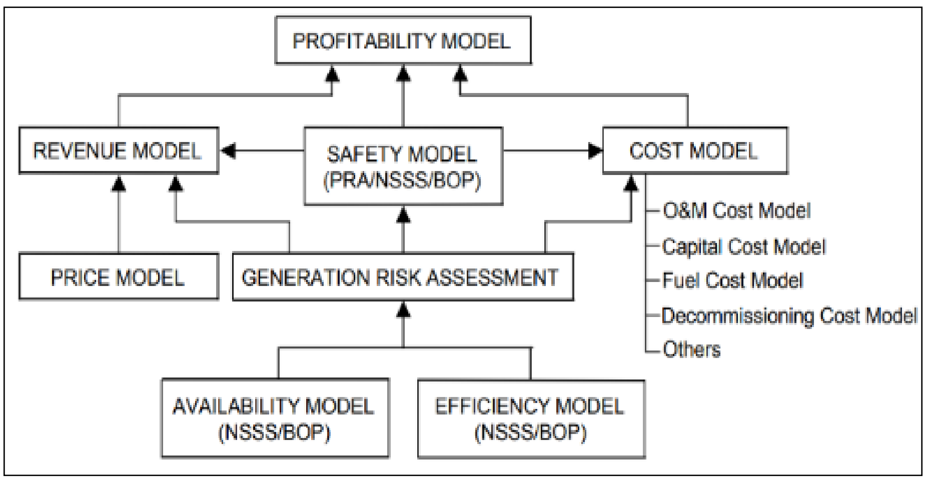

Figure 2.14. Risk-Informed Asset Management process (RIAM)
(Source: EPRI, 2002)

2.4.3 Functional Resonance Analysis Method (FRAM)

Le concept de Sécurité I, appliqué dans des méthodes traditionnelles comme l'AMDEC (Analyse des Modes de Défaillance, de leurs Effets et de leur Criticité) et le HAZOP (Hazard and Operability Analysis), met l'accent sur l'identification des défaillances potentielles. Ces approches, basées sur des modèles linéaires et ascendantes (par exemple, AMDEC, HAZOP, FTA, ETA ou Bowtie), sont efficaces pour identifier les dangers au sein de systèmes complexes. Toutefois, elles présentent des limites, notamment leur incapacité à prendre en compte les risques résultant des interactions entre composants, pouvant entraîner des défaillances systémiques (Lee et al., 2020).

Le concept de Sécurité II met l'accent sur ce qui fonctionne bien, en identifiant les fonctions essentielles à la réalisation des objectifs du système. C'est dans cette perspective que la méthode FRAM a été introduite en 2004 pour surmonter les limites des approches déterministes et probabilistes dans l'analyse des systèmes complexes (Hollnagel, 2004). Aujourd'hui, la méthode FRAM est largement utilisée pour modéliser des systèmes sociotechniques dynamiques, en examinant non seulement les causes des échecs, mais aussi les facteurs contribuant aux succès (Hollnagel, 2012).

Alignée avec la philosophie de l'ingénierie de la résilience, cette méthode relativement récente d'évaluation des performances, de gestion des risques et d'investigation des accidents s'inscrit pleinement dans le cadre de la Sécurité II, par opposition au paradigme traditionnel de la Sécurité I (Hollnagel, 2012, 2014, 2018). La méthode se concentre sur la variabilité des performances quotidiennes dans les systèmes sociotechniques, dépassant le cadre des erreurs humaines et des défaillances isolées. Il modélise les fonctions nécessaires à la performance, en identifiant les interactions et dépendances complexes au sein du système. Cette approche, inspirée de la théorie de la résonance stochastique en physique, aide les gestionnaires et décideurs à anticiper où et comment la variabilité des performances peut se produire avant qu'elle ne se propage. Sun et al. (2022) soulignent que les systèmes sociotechniques doivent posséder une résilience adéquate pour absorber les variabilités des sous-systèmes.

2.4.4 *System-Theoretic Accident Model and Processes (STAMP)*

Leveson (2024, 2016) propose une approche systémique innovante en ingénierie de la sécurité, appelée STAMP, pour analyser la causalité des accidents. Cette méthode descendante *(Top-Down)*, fondée sur la théorie générale des systèmes, s'avère plus efficace que les méthodes traditionnelles d'analyse des risques pour évaluer des systèmes complexes. Les systèmes sont envisagés comme des composants interdépendants maintenus en équilibre dynamique par des boucles de contrôle et de rétroaction.

Le modèle STAMP élargit les modèles linéaires classiques de causalité en intégrant des processus complexes et des interactions dangereuses entre les composants, représentés par des boucles de causalité (boucle de contrôle) et divers facteurs contributifs (Aven, 2022). Cette approche prend en compte des éléments tels que les opérateurs humains, les considérations organisationnelles, ainsi que les aspects techniques et technologiques. Contrairement aux approches axées sur la prévention des défaillances ou la fiabilité, STAMP décrit la sécurité comme un problème de contrôle dynamique *(Dynamic Control Problem)*. Cela permet de réguler le comportement des composants et du système dans son ensemble, afin de garantir que les exigences et contraintes de sécurité sont respectées en opération.

CHAPITRE 3

PROBLÉMATIQUE ET QUESTIONS DE RECHERCHE

3.1 Problématique de recherche

La complexité des systèmes sociotechniques modernes, résultant des interactions entre les technologies de l'industrie 4.0, les incertitudes liées aux catastrophes et les biais humains, pose des défis majeurs en termes de résilience et d'adaptabilité. Pour répondre à ces enjeux, les chercheurs recommandent d'étudier ces systèmes en tant que Systèmes Adaptatifs Complexes (SAC), en s'appuyant sur la théorie de la complexité (Checkland, 1981; Farmer, 2012).

Par ailleurs, la Gouvernance des Systèmes Complexes (GSC) est proposée comme une approche efficace pour améliorer la gestion et la performance de ces systèmes (Katina et al., 2021; Keating et al., 2022). Elle permettrait d'intégrer la gestion des risques et de la complexité tout en tenant compte des spécificités des SAC.

Ainsi, il devient impératif de développer une stratégie globale en Gestion des Actifs (GDA) qui intègre ces approches. Cette stratégie devra également aborder les limites actuelles de la Gestion des Risques d'Entreprise (GRE) et de la Santé et Sécurité au Travail (SST) afin de garantir une gestion adaptée aux défis contemporains.

À ce jour, aucun modèle intégrant ces différents aspects n'a été exploré de manière exhaustive au sein de la communauté scientifique. Par conséquent, il est essentiel de développer des approches innovantes et efficaces, capables d'aborder cette problématique dans une perspective systémique, afin de mieux répondre aux menaces engendrées par la complexité et l'incertitude des systèmes sociotechniques.

3.2 Questions de recherche

La problématique de recherche précédemment évoquée soulève les questions de recherche suivantes :

- Comment développer un cadre holistique de prise de décision en gestion des actifs physiques industriels (GDA-PI), permettant l'évaluation et la gestion des risques technologiques émergents, ainsi que des événements extrêmes, rares et perturbateurs ?

- Comment, dans un tel cadre, intégrer de manière structurée des approches systématiques pour gérer la complexité des systèmes sociotechniques, étroitement liée aux risques émergents de l'industrie 4.0, aux événements extrêmes, rares et perturbateurs, ainsi qu'aux risques organisationnels et aux biais cognitifs et motivationnels propres à la logique humaine ?

CHAPITRE 4

OBJECTIFS ET PORTÉE DE LA RECHERCHE

4.1 But de la recherche

L'objectif ultime de cette recherche est de concevoir un cadre holistique et optimal visant à faciliter la prise de décision en gestion des actifs industriels. Ce cadre permettra d'évaluer et de gérer les risques associés aux technologies émergentes ainsi qu'aux événements extrêmes, rares et perturbateurs. Il aura pour vocation de soutenir les gestionnaires d'actifs dans leur capacité à relever les défis liés à la complexité et à l'incertitude des systèmes sociotechniques modernes, tout en promouvant durablement des lieux de travail sains et sécuritaires pour les employeurs et les travailleurs.

Dans un premier temps, le projet se concentrera sur le développement d'un modèle, s'appuyant sur les cadres recommandés dans la littérature scientifique, et sur la démonstration de sa faisabilité à travers une preuve de concept. Par la suite, des recherches futures seront nécessaires pour approfondir la validation et optimiser le modèle, en intégrant l'expertise des professionnels et des données issues du terrain.

4.2 Objectifs spécifiques

L'objectif général de cette recherche est subdivisé en quatre objectifs spécifiques, conçus pour faciliter la résolution de chaque sous-problème identifié. Ces sous-problèmes servent de « véhicules » permettant de répondre à la problématique globale et d'atteindre l'objectif ultime de cette recherche grâce à un processus d'élicitation d'experts, notamment par la méthode Delphi. Les principaux axes de recherche se déclinent comme suit :

- Explorer l’approche stratégique de la gestion des actifs et de la prise de décision.
- Examiner les approches systémiques de gestion des risques en gestion d’actifs, dans le contexte des risques émergents et des événements extrêmes, rares et perturbateurs.
- Concevoir un cadre holistique, robuste et flexible pour faciliter la prise de décision en gestion des actifs industriels. Ce cadre devra permettre l’évaluation et la gestion des risques technologiques émergents ainsi que des événements extrêmes, soutenu par un processus d’élicitation d’experts.
- In fine, réaliser une étude de cas basée sur un processus d’élicitation d’experts et une consultation consensuelle de chercheurs et de gestionnaires d’actifs industriels via la méthode Delphi. Cette étude visera à approfondir et valider la faisabilité et l’efficacité de l’approche proposée lorsqu’elle est appliquée à des systèmes sociotechniques complexes réels.

Cette structuration méthodique permettra d’atteindre les objectifs de recherche tout en répondant efficacement aux défis associés à la gestion des systèmes sociotechniques complexes. La Figure 4.1 décrit l'objectif principal de recherche qui est subdivisé en quatre (4) objectifs spécifiques de recherche.

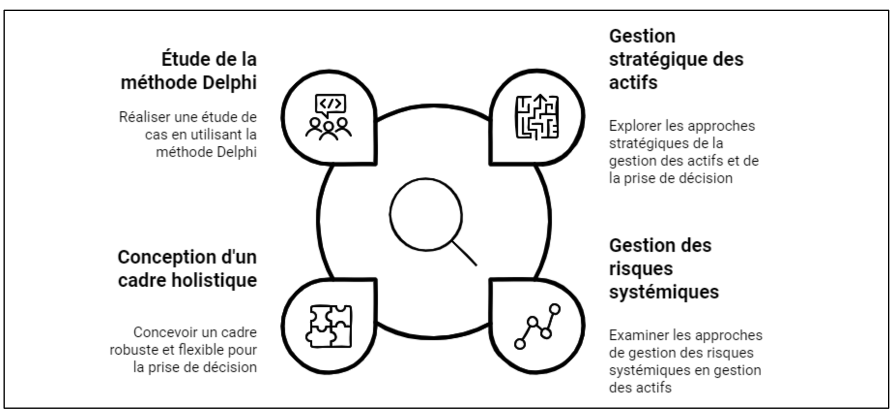

Figure 4.1. Objectif principal subdivisé en quatre objectifs spécifiques

4.3 Concepts, Mesures de performance, Mots clefs

Les Figures 4.2, 4.3 et 4.4 illustrent respectivement une proposition des concepts, des mesures de performance et des mots-clés alignés avec les axes de recherche. La Figure 4.2 présente les principaux concepts mobilisés dans cette recherche. Ces concepts sont regroupés autour d'un cadre systémique intégrant :

- Les systèmes sociotechniques,
- Les technologies émergentes,
- Les événements extrêmes,
- Les approches systémiques,
- La gestion des risques complexes,
- La prise de décision éclairée par les risques,
- La stratégie de gestion des actifs,
- Et le processus d'élicitation d'experts.

Ces éléments représentent les piliers conceptuels d'un environnement complexe où interagissent les dimensions techniques, humaines et organisationnelles dans la gestion des actifs industriels.

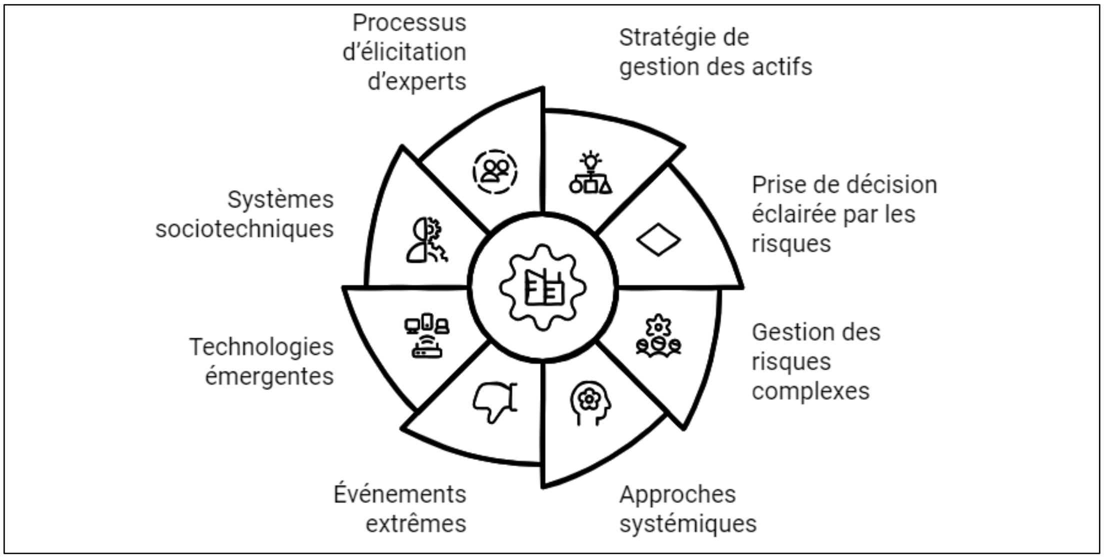

Figure 4.2. Concepts

La Figure 4.3 propose une série de mesures de performance permettant d'évaluer l'efficacité et la résilience des systèmes analysés. Ces mesures incluent :

- La validation empirique (par les cas et preuves du terrain),
- La continuité opérationnelle,
- La préparation aux risques,
- La résilience,
- L'adaptabilité,
- Et l'efficacité de la prise de décision.

Ces indicateurs sont essentiels pour juger de la robustesse des stratégies mises en place face aux incertitudes et aux défis opérationnels.

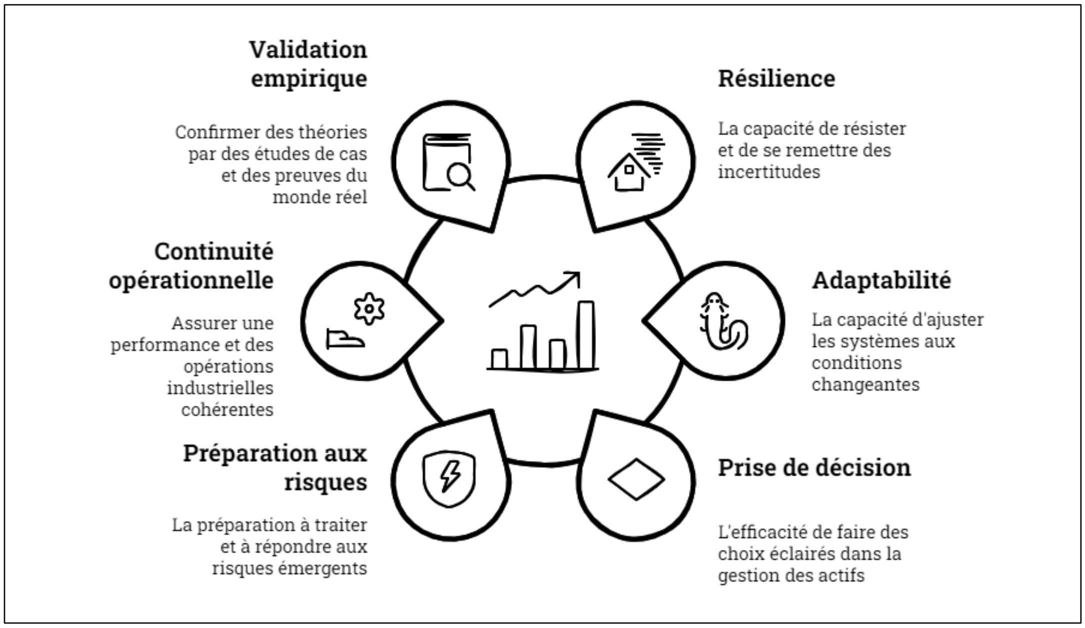

Figure 4.3. Mesures de performance

La Figure 4.4 structure les mots-clés de la recherche selon une logique causale menant à l'objectif global : naviguer dans des défis systémiques complexes. Les mots-clés sont regroupés en branches thématiques. D'une part, les avancées technologiques (Industrie 4.0, technologies émergentes) et les enjeux de sécurité et de résilience. D'autre part, les approches systémiques, la gestion des risques d'entreprise, et les processus de prise de décision. L'ensemble de ces mots-clés illustre l'interdisciplinarité et la transversalité nécessaires à la compréhension et à la maîtrise des systèmes complexes modernes.

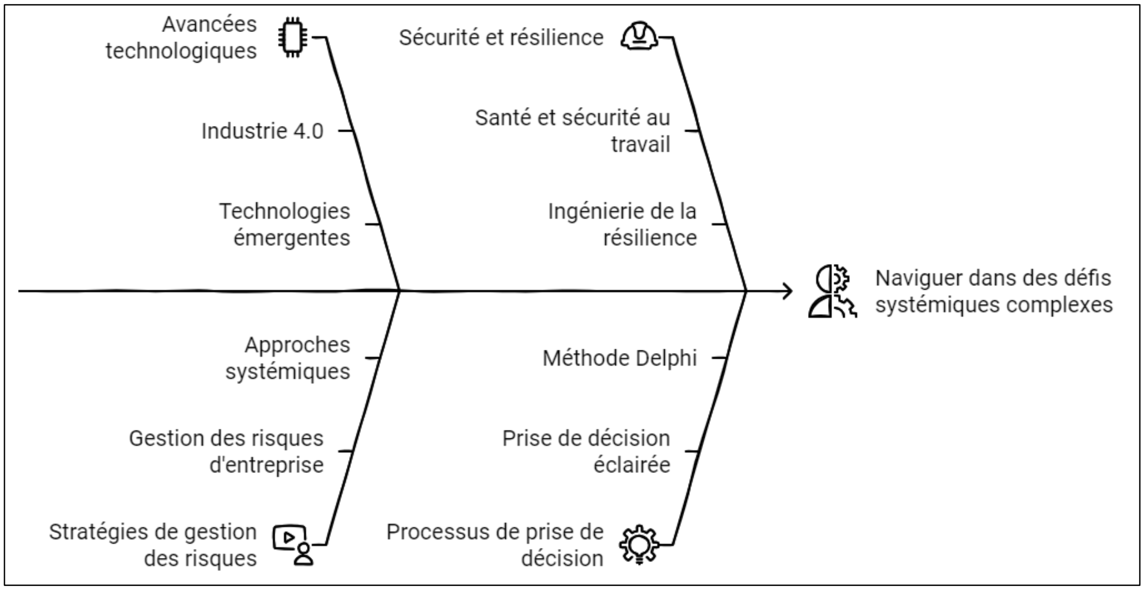

Figure 4.4. Mots-clés

CHAPITRE 5

MÉTHODOLOGIE DE LA RECHERCHE

5.1 Introduction à la méthodologie de recherche

Ce chapitre présente la méthodologie de recherche, développée à partir des questions, du but et des objectifs clairement définis. L'objectif principal est de concevoir un cadre holistique et optimal pour faciliter la prise de décision en lien avec les risques en gestion des actifs industriels. Pour atteindre cet objectif, la méthode Delphi, reposant sur un processus d'élicitation d'experts, est proposée comme un outil essentiel.

Ce cadre s'appuie sur une combinaison des méthodes FRAM (Functional Resonance Analysis Method) et STAMP (System-Theoretic Accident Model and Processes), intégrées dans un processus global de gestion des actifs physiques industriels (GDA-PI). Il est conçu pour évaluer et gérer efficacement les risques associés aux technologies émergentes, aux événements extrêmes, rares et perturbateurs, ainsi qu'aux menaces organisationnelles contemporaines et aux biais dans la prise de décision humaine.

La Figure 5.1 fournit une vue d'ensemble des principales méthodes d'analyse systémique. Les méthodes FRAM, STAMP et RIDM se situent dans le quadrant 2, regroupant les concepts développés pour des systèmes particulièrement complexes et difficiles à maîtriser.

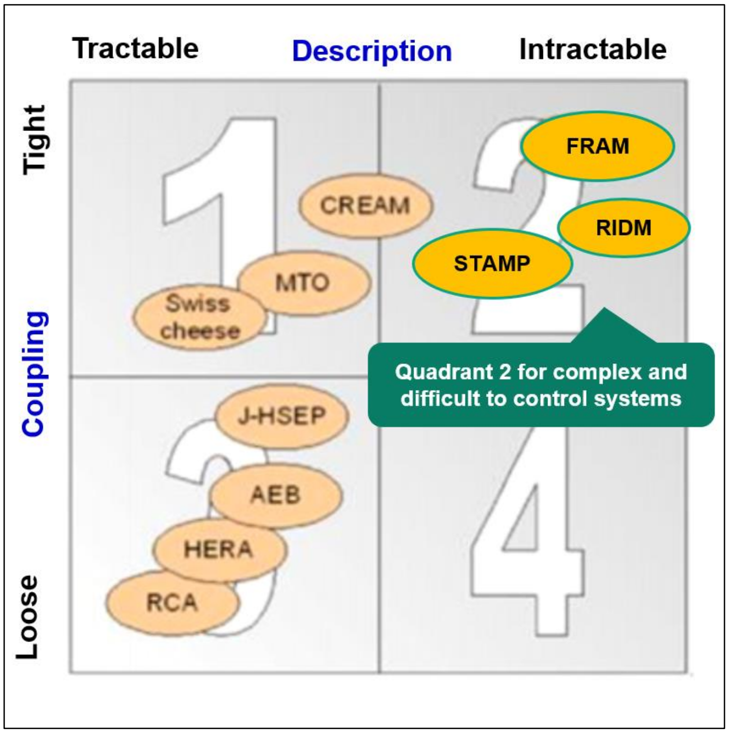

Figure 5.1. Méthodes d'évaluation de risque des systèmes
(Source: adapté de Hollnagel et al. (2008))

5.2 Structuration des Axes de la Recherche

L'approche proposée peut être subdivisée en trois (3) grands axes principaux:

5.2.1 Axe 1: Bâtir le modèle FRAM

L'objectif de cet axe est de concevoir un modèle d'évaluation des risques en s'appuyant sur le processus FRAM (Functional Resonance Analysis Method). Ce processus permet de représenter les couplages ou le maillage entre les modules fonctionnels du système sociotechnique, en mettant en lumière leurs interactions et leurs dépendances. Le modèle met en évidence la variabilité des performances des modules fonctionnels amont *(Variability of Upstream Functional Modules)* et leur impact sur les modules fonctionnels aval *(Downstream Functional Modules)* via un couplage amont-aval *(Up-Down Coupling)*.

Dans le cadre du processus FRAM, des risques peuvent émerger en raison de la variabilité des performances des modules fonctionnels, de leurs interactions et de leurs dépendances, générant un phénomène de résonance fonctionnelle. Ce concept correspond à une combinaison de circonstances inhabituelles menant à un événement extrême ou rare en gestion des actifs physiques industriels (GDA-PI). En effet, la complexité croissante des systèmes sociotechniques modernes constitue une source majeure d'incertitude et de non-linéarité, et demeure la principale cause des variabilités de performance identifiées.

Le processus FRAM fournit une description détaillée de chaque module fonctionnel d'un système sociotechnique complexe au niveau macro, ainsi que de la variabilité de performance potentielle associée à six aspects clés de ces modules *(Input, Output, Preconditions, Resources, Control et Time)*. Pour approfondir cette analyse, le processus STAMP (System-Theoretic Accident Model and Processes), est ensuite utilisé. Ce dernier, qui constitue l'objet de l'axe 2 de la méthodologie de recherche, fournit une description détaillée du fonctionnement interne des modules ciblés au niveau micro. Ainsi, tandis que le processus FRAM est particulièrement adapté à une analyse macro des systèmes sociotechniques complexes, le processus STAMP le complète en permettant une analyse approfondie des composants du système à une échelle micro.

5.2.2 Axe 2: Bâtir le modèle STAMP

L'objectif de cet axe est de concevoir un modèle d'évaluation des risques en utilisant le processus STAMP, afin de fournir une description détaillée du fonctionnement interne des modules fonctionnels susceptibles de présenter des variabilités de performance. Pour cela, la démarche débute par définir l'objectif de l'étude STAMP. Les limites du système sont ensuite déterminées, ainsi que les dangers et les pertes à considérer dans l'analyse. Sur la base de ces informations, les contraintes de sécurité sont identifiées, permettant ainsi de définir le niveau de sécurité souhaité pour le système.

La structure de contrôle du système sociotechnique *(Safety Control Structure)* est ensuite modélisée pour identifier les potentielles actions de contrôle dangereuses *(Unsafe Control Actions, UCAs)* au sein des mécanismes de contrôle et de rétroaction. Nous identifions également les scénarios de perte *(Loss Scenarios)*. Ainsi, des scénarios de causalité d'accident liés aux actions de contrôle dangereuses (UCAs) peuvent être générés. Cela permet de déterminer comment chaque UCA peut se produire, comment elle se propage, et comment elle peut causer des pertes au sein du système sociotechnique. Ces scénarios tiennent particulièrement compte des accidents liés aux défaillances de composants, aux interactions dangereuses entre composants, aux opérateurs humains, au comportement des logiciels, aux erreurs de conception, aux exigences de sécurité, aux procédures, et autres facteurs.

Cette modélisation permet de contrôler à la fois le comportement des composants du système et celui du système dans son ensemble, afin de garantir que les exigences et contraintes de sécurité sont correctement mises en œuvre dans le système en fonctionnement.

5.2.3 Axe 3: Étude de cas

L'axe 3 de la recherche consiste à réaliser une étude de cas s'appuyant sur un processus d'élicitation d'experts et une consultation collaborative impliquant des chercheurs universitaires, des experts industriels et des gestionnaires d'actifs, menée à l'aide de la méthode Delphi. Cette étude a pour objectif d'approfondir et de valider la faisabilité ainsi que l'efficacité du cadre proposé lorsqu'il est appliqué à des systèmes sociotechniques complexes réels. Pour illustrer cette démarche, le cadre est appliqué à un cas pratique, le LineDrone, une technologie de drone autonome développée par Hydro-Québec pour l'inspection des lignes de transmission haute tension sans intervention humaine directe. Cette application démontre la capacité du cadre à réduire la variabilité des performances, à renforcer la résilience et à optimiser la sécurité opérationnelle.

5.2.4 Axe 4: Faisabilité de l'intégration du cadre au processus RIDM

L'objectif de cet axe est d'étudier la faisabilité de l'intégration du cadre, issu de l'analyse conjointe FRAM et STAMP, à un processus global de prise de décision informée par les risques (RIDM – Risk-Informed Decision-Making) dans le cadre de recherches futures, suivant cette thèse. Cette intégration vise à renforcer l'efficacité et l'adaptabilité du cadre.

Un processus d'élicitation d'experts peut être utilisée pour identifier des stratégies de prévention et d'atténuation face aux impacts des risques liés aux événements extrêmes, rares et perturbateurs sur la performance globale d'un programme de gestion des actifs physiques industriels (GDA-PI) et pour gérer les incertitudes.

Le processus RIDM contribuera à soutenir la performance à long terme et la durabilité des systèmes sociotechniques dans un environnement en constante évolution et difficilement prévisible. Il permettra de prendre en compte les risques liés aux événements extrêmes, rares et perturbateurs dans le cadre d'une stratégie globale de gestion des actifs physiques industriels (GDA-PI) et du processus décisionnel associé.

5.3 Vue d’ensemble de la structure méthodologique de la recherche

La Figure 5.2 présente une vue d’ensemble de la méthodologie de recherche, mettant en lumière les différentes phases du projet. Les Figures 5.3 et 5.4 illustrent les étapes clés des deux méthodes utilisées – la méthode FRAM et la méthode STAMP-STPA – dans le cadre de la création d’un cadre holistique et optimal visant à faciliter la prise de décision en gestion des actifs industriels.

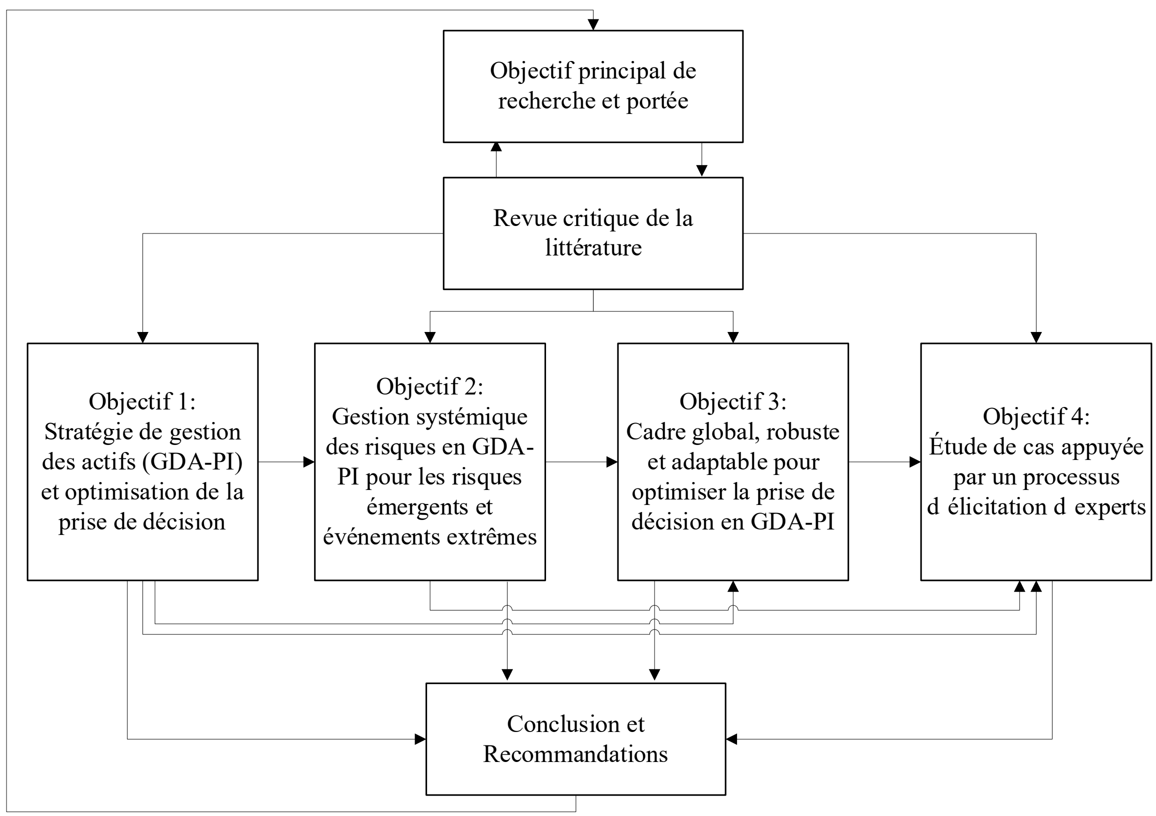

Figure 5.2. Vue d’ensemble de la structure méthodologique de la recherche

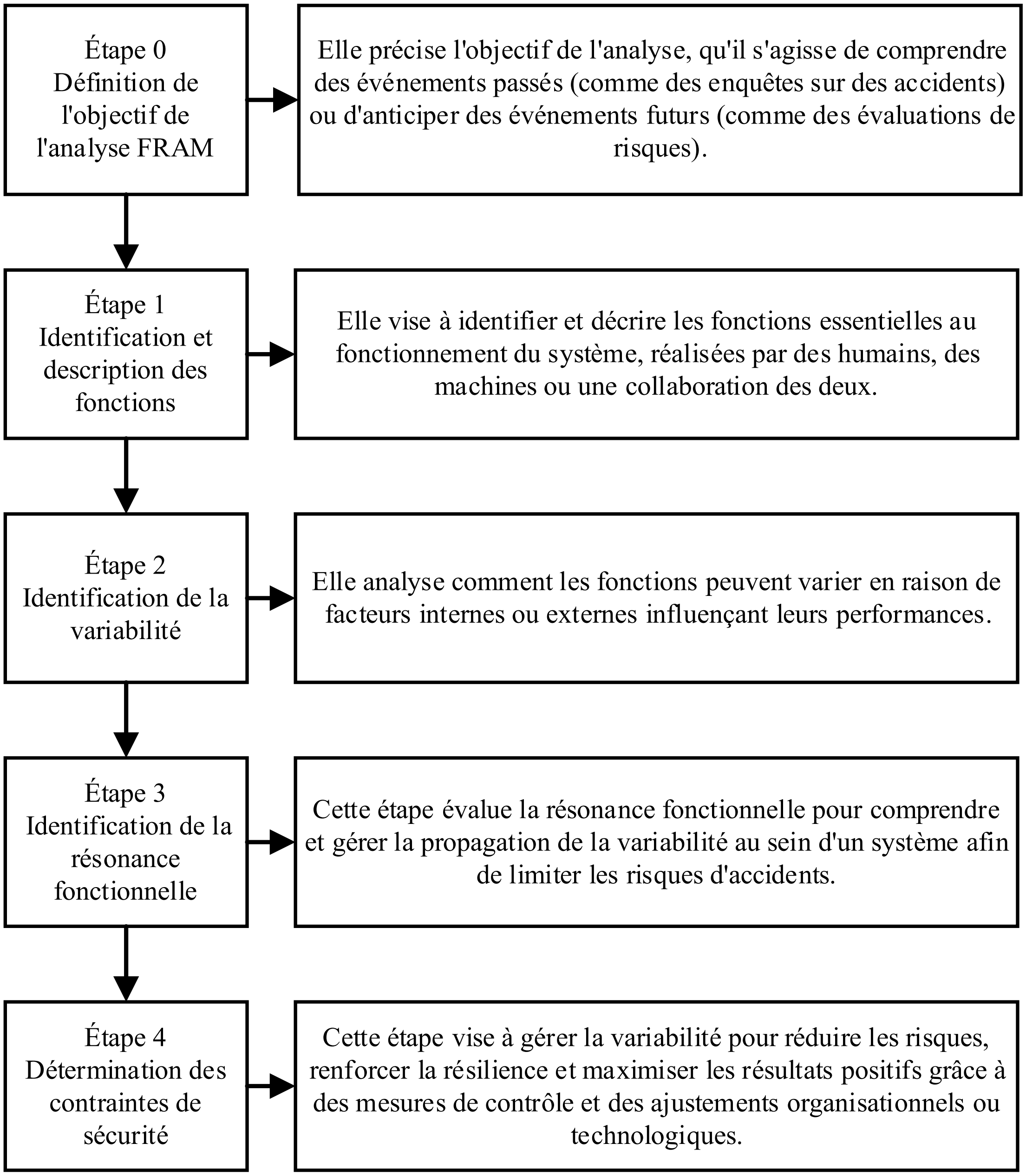

Figure 5.3. Étapes clés de la méthode FRAM

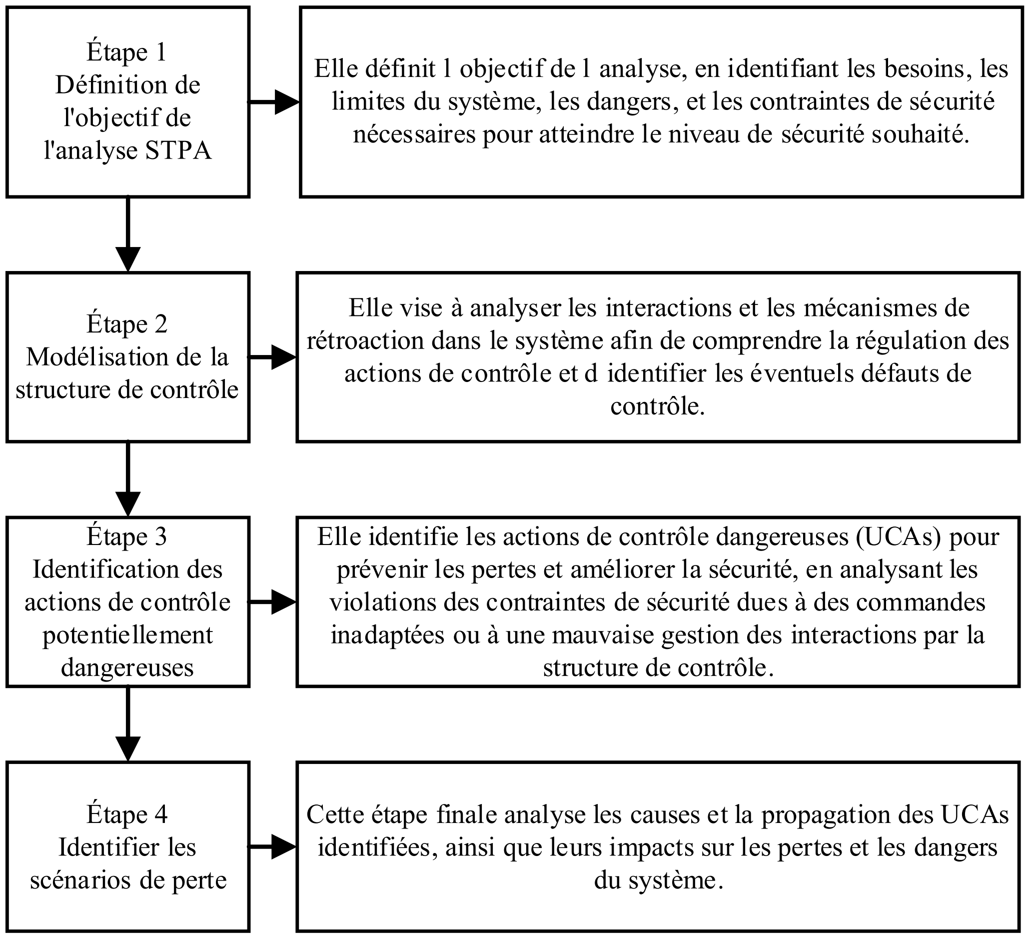

Figure 5.4. Étapes clés de la méthode STPA

CHAPITRE 6

RETOMBÉES ET CONTRIBUTION DE LA RECHERCHE

6.1 Alignement de la recherche avec les objectifs de la chaire Hydro-Québec

Cette thèse s'inscrit dans les axes de recherche de la Chaire Hydro-Québec en gestion des actifs à l'Université du Québec à Trois-Rivières (UQTR)[**]. Les axes de recherche se concentrent sur trois grands thèmes. La Figure 6.1 illustre ces trois thèmes en vue d'une gestion intégrée des actifs.

- Le premier thème porte sur la modélisation et l'optimisation du processus global de gestion des actifs, avec pour objectif de développer un concept intégré permettant la conception, l'optimisation et la prise de décision dans ce processus.
- Le deuxième thème s'attache à l'optimisation du cycle de vie des actifs, en visant l'élaboration d'une méthodologie globale pour modéliser et optimiser ce cycle dans un contexte de gestion des actifs.
- Enfin, le troisième thème se concentre sur la modélisation des risques liés aux événements extrêmes et aux facteurs externes dans la gestion des actifs complexes, avec pour objectif de concevoir une méthodologie globale pour

[**] Hydro-Québec, la société d'État québécoise responsable de la production, du transport et de la distribution de l'électricité au Québec, a lancé, en partenariat avec l'Université du Québec à Trois-Rivières (UQTR) et le Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG), la Chaire de recherche Hydro-Québec sur la gestion des actifs (GDA).

évaluer l'impact de ces événements rares et des facteurs externes sur les stratégies de gestion des actifs.

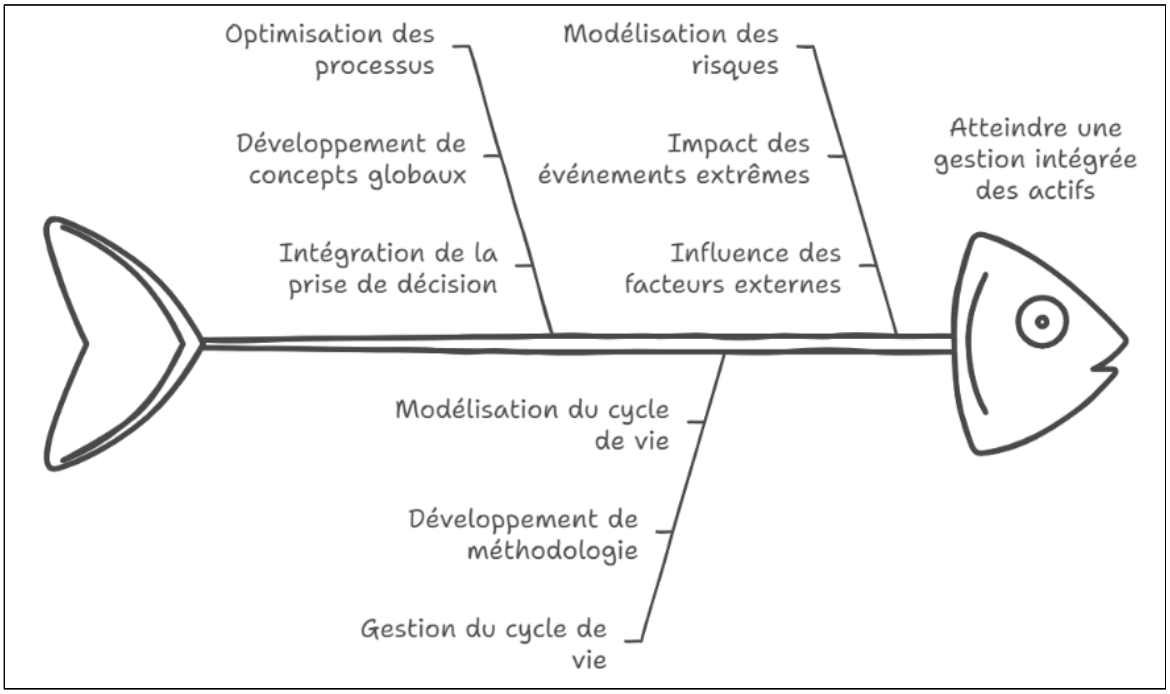

Figure 6.1. Concordance de la recherche avec les objectifs de gestion des actifs

6.2 Contributions scientifiques des articles

La contribution de la thèse se matérialisera par la publication d'articles dans des revues avec comité de pairs (RAC), par la présentation et la publication d'articles de conférence lors de congrès internationaux avec comité de pairs (CAC), ainsi que par la participation à des activités de vulgarisation, notamment à travers des séminaires de doctorat et des présentations au comité de la chaire Hydro-Québec/UQTR.

Article 1: Overview of Strategic Approach to Asset Management and Decision-Making

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2021). Overview of strategic approach to asset management and decision-making. International Journal of Engineering Research & Technology, 10, 64-89.

L'article 1 analyse les approches stratégiques de gestion des actifs et leur alignement avec les objectifs organisationnels, tout en explorant les méthodologies émergentes et les technologies de l'industrie 4.0. Il démontre que l'intégration des risques dans la planification stratégique améliore la gouvernance et renforce la résilience organisationnelle. Par ailleurs, il met en évidence comment des technologies émergentes peuvent optimiser la gestion des actifs, réduire les incertitudes et renforcer la résilience, en soulignant leur rôle crucial dans l'anticipation des imprévus au sein d'environnements complexes. Cette contribution se distingue par sa capacité à proposer un cadre novateur reliant la gestion stratégique des actifs, les innovations technologiques et les méthodologies de gestion des risques. Ce cadre permet aux entreprises d'intégrer ces éléments dans leurs processus stratégiques afin de moderniser leurs infrastructures et de renforcer leur résilience. Cependant, s'appuyant principalement sur une revue de la littérature, l'article met en évidence la nécessité de valider empiriquement ses propositions au moyen d'études de cas et de tests pratiques dans divers contextes industriels. Enfin, il recommande d'explorer des approches interdisciplinaires combinant ingénierie de la résilience, intelligence artificielle et analyse prédictive.

Article 2: The Functional Resonance Analysis Method A Performance Appraisal Tool for Risk Assessment and Accident Investigation in Complex and Dynamic Socio-Technical Systems

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2022). The functional resonance analysis method: A performance appraisal tool for risk assessment and accident investigation in complex and dynamic sociotechnical systems. American Journal of Industrial and Business Management, 12(2), 195-230.

L’article 2 propose une revue systématique des publications consacrées au développement et à l'application de la méthode FRAM sur une période d'une décennie. En s'appuyant sur la méthodologie PRISMA pour le recueil des données, 47 documents issus de la base de données Scopus ont été analysés. Cette contribution met en évidence la nécessité de méthodes d'évaluation systémiques pour comprendre comment la variabilité des performances peut influencer la sécurité des systèmes sociotechniques complexes. Elle souligne que des variabilités inattendues dans les performances peuvent se combiner de manière imprévisible, générant ainsi des risques significatifs pour la sécurité. Reconnue pour sa capacité à modéliser la complexité des systèmes et à intégrer la variabilité des performances, la méthode FRAM s'impose comme un outil clé pour l'évaluation des risques dans des systèmes dynamiques complexes. Toutefois, l'absence d'une approche quantitative limite son application dans certaines analyses spécifiques, telles que l'évaluation de la sensibilité. L'article propose des méthodes complémentaires, telles que FMEA, STAMP et AcciMap, et recommande d'étendre les applications empiriques afin de valider les principes de la méthode FRAM. Il préconise également l'exploration d'approches combinées avec des méthodologies quantitatives pour renforcer son utilité dans divers secteurs, tout en appelant à des recherches futures pour surmonter ses limitations.

Article 3: A High-Level Risk Management Framework as Part of An Overall Asset Management Process for The Assessment of Industry 4.0 Related New Emerging Technological Risks

Diop, I., Abdul-Nour, G. G., & Komljenovic, D. (2022). A high-level risk management framework as part of an overall asset management process for the assessment of industry 4.0 and its corollary industry 5.0 related new emerging technological risks in sociotechnical systems. American Journal of Industrial and Business Management, 12(7), 1286-1339.

L'article propose un cadre innovant pour la gestion des risques dans les systèmes sociotechniques complexes, en réponse aux défis posés par les technologies émergentes de l'industrie 4.0. Ce cadre intégré combine trois méthodologies avancées : la méthode Functional Resonance Analysis Method (FRAM), la méthode System-Theoretic Accident Model and Processes (STAMP) et la prise de décision informée par les risques (RIDM – Risk-Informed Decision-Making). Il prend en compte les interactions dynamiques et complexes entre les dimensions technologiques, humaines et organisationnelles, en intégrant des outils modernes pour renforcer la résilience organisationnelle et assurer la continuité des opérations. Cette contribution aborde les limites des approches traditionnelles de gestion des risques et propose des solutions adaptées pour faire face aux événements extrêmes, aux cyberattaques et aux incertitudes économiques. Il est recommandé de mener des études empiriques pour valider l'efficacité du cadre et d'explorer des approches interdisciplinaires afin d'améliorer les capacités de gestion des risques et des incertitudes. Ce travail contribue de manière significative à la gestion stratégique des actifs en proposant des solutions innovantes adaptées aux défis des environnements modernes.

Article 4: A Comprehensive Decision-Making Approach: Evaluating and Managing Risks Associated with Emerging Technologies – A LineDrone Technology Case Study

Diop, I., Abdul-Nour, G. G., & Komljenovic, D. (2024). A Comprehensive Decision-Making Approach: Evaluating and Managing Risks Associated with Emerging Technologies – A LineDrone Technology Case Study. Manuscript submitted for publication in the International Journal of Production Research (IJPR).

L'article propose un cadre méthodologique intégré pour améliorer la gestion des actifs industriels dans des systèmes sociotechniques complexes, en réponse aux défis posés par les technologies émergentes, telles que l'intelligence artificielle et les systèmes cyber-physiques, ainsi qu'aux événements disruptifs caractéristiques de l'industrie 4.0. Il met en lumière l'importance de stratégies adaptées pour gérer les risques associés à ces nouvelles technologies. Ce cadre combine deux outils d'évaluation avancés : la méthode

Functional Resonance Analysis Method (FRAM), qui examine la variabilité des performances et les interconnexions des systèmes, et la méthode System-Theoretic Process Analysis (STPA) issue du paradigme System-Theoretic Accident Model and Processes (STAMP), qui identifie les dangers et évalue les contraintes de sécurité. Le cadre est appliqué à un cas pratique, le LineDrone, une technologie de drone autonome développée par Hydro-Québec pour inspecter les lignes de transmission haute tension sans intervention humaine directe. Cette application démontre l'efficacité du cadre à réduire la variabilité des performances, renforcer la résilience et optimiser la sécurité. Cette contribution permet d'améliore les processus décisionnels tout en renforçant la sécurité, la résilience et les performances des infrastructures critiques dans des environnements dynamiques. L'article préconise également d'étendre son application à d'autres contextes industriels pour enrichir la gestion des risques et optimiser les outils d'analyse.

6.3 Énumération des contributions scientifiques lors de la recherche

Les contributions scientifiques de cette étude sont présentées dans la section suivante.

Articles de revue avec comité de lecture :

Diop, I., Abdul-Nour, G. G., & Komljenovic, D. (2024). A Comprehensive Decision-Making Approach: Evaluating and Managing Risks Associated with Emerging Technologies – A LineDrone Technology Case Study. Manuscript submitted for publication in the International Journal of Production Research (IJPR).

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2022). A High-Level Risk Management Framework as Part of an Overall Asset Management Process for the Assessment of Industry 4.0 and Its Corollary Industry 5.0 Related New Emerging Technological Risks in Socio-Technical Systems. American Journal of Industrial

and Business Management, 12, 1286-1339. https://doi.org/10.4236/ajibm.2022.127071

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2022). The Functional Resonance Analysis Method: A Performance Appraisal Tool for Risk Assessment and Accident Investigation in Complex and Dynamic Socio-Technical Systems. American Journal of Industrial and Business Management, 12(2), 195-230.

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2021). Overview of Strategic Approach to Asset Management and Decision-Making, International Journal of Engineering Research & Technology (IJERT) Volume 10, Issue 12 (December 2021).

Livres et chapitres de livres :

Diop, I., Abdul-Nour, G., Komljenovic, D. (2024). A Framework for Assessing Emerging Technology Risks in Industrial Asset. In: Crespo Márquez, A., Seecharan, T.S., Abdul-Nour, G., Amadi-Echendu, J. (eds) Advances in Asset Management: Strategies, Technologies, and Industry Applications. Engineering Asset Management Review, vol 3. Springer, Cham. https://doi.org/10.1007/978-3-031-52391-5_4.

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2024). Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks. In 17th WCEAM Proceedings. Cham: The Springer eBook series is indexed by Scopus and Ei. Series: Lecture Notes in Mechanical Engineering. Ho Chi Minh City, Vietnam, 18-20 October 2023.

Articles de comptes-rendus de conférences avec comité de lecture :

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2024). Assessing and Managing Risks Linked to Emerging Technologies. “The 6th IEEE International Conference on Technology Management, Operations and Decisions (IEEE ICTMOD), 2024”. Sharjah-Dubai, United Arab Emirates November 4–November 6, 2024, hosted by American University of Sharjah. Published by IEEE Xplore Digital Library as well as other Abstracting and Indexing (A&I) databases (Scopus, Web of Science, ProQuest, IET, NLM, CrossRef).

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2024). System-Theoretic Process Analysis (STPA): An Innovative Top-Down Hazard Assessment Method Based on the System-Theoretic Accident Model and Processes (STAMP) – A bibliometric Review. Proceedings of the American Society of Mechanical Engineers (ASME 2024): Asset Integrity Management – Critical Infrastructure Conference (AIM-CI). Delta Marriott Orlando Celebration on February 5-6, 2024, Orlando, FL, USA. AIM-CI2024-110532.

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2023). Assessment of Performance Variability in Complex Sociotechnical Systems. A case study using the Functional Resonance Analysis Method and the System-Theoretic Process Analysis. «The 50th International Conference on Computers and Industrial Engineering. Sharjah-Dubai, United Arab Emirates October 30–November 2, 2023, hosted by American University of Sharjah. Series sponsored by Computers & Industrial Engineering: An International Journal, published by Elsevier.

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2023). Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks. In 17th WCEAM Proceedings. Cham: The Springer eBook series is indexed by Scopus and Ei. Series: Lecture Notes in Mechanical Engineering. Ho Chi Minh City, Vietnam, 18-20 October 2023.

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2023). Asset and Risk Management Approach in the Context of Complexity in Industry 4.0/5.0 Systems. In 16th WCEAM Proceedings (pp. 508-520). Cham: Springer International Publishing. Series: Lecture Notes in Mechanical Engineering. Sevilla, Spain, 5-7 October 2022.

Comités scientifiques:

Membre de l'équipe éditoriale, Fabrication Avancée (Editorial Team Member, Advanced Manufacturing). 2024.

Rédacteur invité pour la revue Sustainability (Guest Editor for the open access journal Sustainability (ISSN 2071-1050)). 2024.

Reviewer for the book series Engineering Asset Management Review (EAMR), Volume 4: Case Studies in Digital Transformation: Integration of Digital Technologies to Enhance Asset Management Processes. Volume Editors: Turuna

Seecharan (University of Minnesota Duluth), Adolfo Crespo (University of Seville, Spain), Georges Abdul-Nour (University of Quebec in Trois-Rivières), Joe Amadi-Echendu (University of Pretoria, South Africa), Jay Lee. 2024

Conférencier au Symposium Gestion des actifs IREQ (Institut de recherche en électricité du Québec), Hydro-Québec. Été 2024

Harmonisation des matrices de risques chez Hydro-Québec Production, Transmission et Distribution (Mandat de 15h par semaine / 4 mois). Printemps 2024.

Présentation devant le comité scientifique de la Chaire de recherche Hydro-Québec pour la gestion des actifs. Automne 2023, Printemps 2023, Hiver 2022, Automne 2021.

CHAPITRE 7

ARTICLE 1

Overview of Strategic Approach to Asset Management and Decision-Making

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Article de revue avec comité de lecture publié au journal International Journal of Engineering Research & Technology (IJERT).

Abstract – This article explores the critical elements of Strategic Asset Management (SAM), emphasizing its integration within organizational strategies at corporate, business, and functional levels. It reviews physical Asset Management (AM) models, defined as coordinated organizational activities aimed at maximizing asset value, and highlights the pivotal role of SAM in aligning these activities with broader strategic objectives. Adopting a holistic approach, the review examines decision-making models and risk management strategies. It underscores the importance of enhancing AM governance through effective risk identification, characterization, and treatment, while identifying promising research directions to advance the field.

Keywords – Strategic asset management; risk assessment and management; resilience engineering; maintenance 4.0; industry 4.0; decision-making.

7.1 Introduction

The ISO 55000 standard defines Asset Management (AM) as *"the coordinated activity of an organization to realize value from assets"* (ISO 55000, 2014). AM strategies must align with various levels of organizational strategy, including corporate, business, and functional levels. The growing complexity of managing assets stems from intensifying international competition, increasing unpredictability, volatility, and security concerns. Organizations today face significant uncertainties and diverse risks, including strategic, operational, organizational, financial, technological, and technical challenges, all of which can severely impact business processes. Consequently, businesses face mounting pressure to reduce unexpected and harmful equipment failures, which places high expectations on maintenance activities (Baglee et al., 2016). They must increasingly anticipate potential futures in a dynamic and challenging market characterized by resource shortages, environmental liabilities, and climate change (Brown et al., 2014).

For instance, Komljenovic (2018) highlights the case of power utilities, which must manage the replacement of substantial portions of their assets as they reach the end of their lifecycle, become obsolete due to technological advancements, or are replaced by more efficient and carbon-free alternatives. AM is not a new concept; asset-intensive industries, such as aviation and electrical power companies, have been managing assets since the beginning of modern industrial practices (Bulita, 1994). However, contemporary AM decision-makers and stakeholders are often required to deliver more value at a lower cost. Asset Management Systems (AMS) must establish effective connections between the Strategic Asset Management Plan (SAMP) and the activities of various organizational departments, including human resources, operations, maintenance, and engineering (IAM, 2015). AM also plays a critical role in helping business leaders understand the value of their assets and their importance in achieving organizational objectives (ISO 55000, 2014).

This review adopts a holistic approach to explore strategic asset management (SAM) and decision-making models, focusing on risk management strategies to address emerging technological risks associated with Industry 4.0, as well as extreme and rare events. It emphasizes improving AM governance through effective risk identification, characterization, and treatment. The paper is structured as follows: PART 2 details the methodology for literature selection, PART 3 reviews decision-making models and their alignment with organizational strategies, PART 4 discusses emerging trends in Strategic Asset Management (SAM), and PART 5 concludes with gaps in the literature and directions for future research.

7.2 Methodology for the systematic literature review

To map the state of the art on this topic, a systematic and critical literature review was conducted to quantify the scientific output and evaluate its quality and impact. The search methodology involved the following steps: (i) identifying appropriate and relevant keywords for database searches, (ii) querying the Scopus online database, (iii) collecting relevant articles, (iv) assessing the relevance of each paper, (v) applying a snowballing technique to identify additional relevant papers, and (vi) performing inverse searches using the Web of Science (WoS) core collection and Google Scholar. The following paragraphs detail each step.

- *Keywords definition, online database search and paper selection*

The literature review process began by defining relevant keywords, grouped into four categories: *(a) Strategic asset management* (e.g., “strategic approach to asset management” or “physical assets management framework”); *(b) Risk-informed decision-making* (e.g., “risk-informed asset management”); *(c) Industry 4.0 and maintenance* (e.g., “intelligent maintenance” or “condition-based maintenance”), and *(d) Resilience engineering* (e.g., “system resilience” or “resilience modeling”).

Keywords from these categories were combined to query the Scopus database for articles published between 2010 and 2021. Articles were screened for relevance based on their title, abstract, and keywords, with potentially pertinent articles selected for full-text analysis. The review retrieved 96 references for (a), 103 for (b), 122 for (c), and 650 for (d). A snowballing approach was used to analyze the bibliographies of selected articles, identifying additional relevant works. An inverse search was also conducted via Web of Science (WoS) and Google Scholar to locate articles citing the selected studies. This comprehensive search provided 971 references, which were further analyzed bibliometrically to map the field's growth, identify leading authors and papers, and understand structural and dynamic aspects such as country contributions and key trends.

- *Results*
  - *Descriptive Analysis and conceptual structure for (a) keywords*

The figures and data visualize the scientific landscape of the subject matter based on the keywords related to (a) *strategic asset management*. Table 7.1 reveals that the majority of publications are conference papers (51.50%), followed by journal articles (39.00%) and book chapters (3.90%). Figure 7.1 illustrates the annual total references published from 2010 to 2021 and the annual growth rate of publications. The data show a significant decrease in references in 2012, followed by fluctuations from 2013 to 2019. A sharp peak occurred in 2020, but this was followed by a decline in 2021. These trends suggest that the volume of publications in this research area during the survey period was inconsistent, indicating instability in publication activity (Afuye et al., 2021; Ellegaard & Wallin, 2015). Table 7.2 highlights the most frequent and relevant keyword co-occurrences within the intellectual domain of asset management, identifying key research hotspots in the field.

Table 7.1. Document type for string (a)

Rank	Document Type	Number of Documents
1	Article	49
2	Conference Paper	41
3	Book	02
4	Review	02
6	Book Chapter	01
8	Note	01

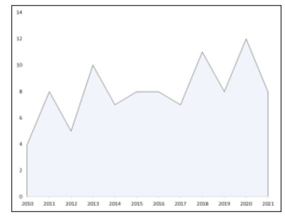

Figure 7.1. The number of annual referencesfor string (a)

Table 7.2. Co-word analysis through keyword co-occurrences for string (a)

Rank	Keyword	Occurences
1	Asset management	52
2	Asset management strategy	25
3	Strategic asset managements	20
4	Maintenance	17
5	Risk assessment	12
6	Decision making	10
7	Life cycle	9
8	Investments	9
9	Budget control	7
10	Decision support systems	6

Figure 7.2. Density visualization map for Co-word Analysis through Keyword co-occurrences for string (a)

The co-word analysis of keyword co-occurrences identifies clusters of keywords, providing insights into the intellectual structure of the research field. For further details on co-word analysis, readers can refer to Cobo et al. (2011) and its bibliographic references. The analysis revealed five clusters grouped into four main areas of research, as outlined in Table 7.3. Table 7.4 highlights the most productive authors and the most cited references in the field. According to Afuye et al. (2021), the number of publications in a research area is a valuable metric for quantifying an author’s impact within that domain. Similarly, Wang et al. (2018) emphasize that an author’s publication volume reflects their influence and the relevance of their research. Alegre H. and Vlok P.J. are tied as the most productive authors, each with three publications. In terms of citations, Velasquez-Contreras J.L. leads with 42 citations, followed by Roshani E. with 28 citations, and Caradot N. with 22 citations.

Table 7.3. Top keyword clustered into 4 areas of research for string (a)

Cluster 1 *(4 items)*	Cluster 2 *(8 items)*	Cluster 3 *(6 items)*	Cluster 4 *(3 items)*	Cluster 5 *(1 items)*
Management practice Strategic asset management Strategic approach Strategic planning	Costs Decision making Decision support systems Investment Life cycle Reliability analysis Risk Risk assessment	Budget control Electrical utilities Human resource management Maintenance Reliability Repair	Asset management Asset management strategy Project management	Risk management

The citation analysis reveals the structure of the field by examining linkages between nodes, such as co-citation networks, which illustrate interactions among cited references and journals. Aria et al. (2017) note that key dimensions for analyzing co-citation networks include: (i) centrality and peripherality of nodes, (ii) proximity and distance, (iii) strength of ties, (iv) clusters, and (v) bridging contributions. Table 7.5 presents the top 10 countries ranked by the number of papers published and citations received. During the survey period, the United States ranked first in the number of publications, followed by the United Kingdom and Australia. The country collaboration network further highlights how countries interact and collaborate within this research area.

Table 7.4. Top 10 authors for string (a)

Most Productive-Authors			Most Cited-Author References	
Rank	Author	Documents	Author	Citations
1	Alegre H.	3	Velasquez-Contreras JL	42
2	Vlok, P.J.	3	Roshani E.	28
3	Brito , R.S.	2	Caradot N.	22
4	Brown, K .	2	Joseph T.	21
5	Dray, A.	2	Morrison N.	13
6	Hamilto n, M.	2	Ten Veldhuis JAE	13
7	Keast, R.	2	Alegre H.	13
8	Laue, M .	2	Vreeburg JHG	9
9	Mahmood, M.N .	2	Haynes B.	8
10	Rødseth, H.	2	Clements D.	7

Table 7.5. Top 10 most productive country for string (a)

Rank	Country	Documents	Citations
1	United states	23	22
2	U. kingdom	16	65
3	Australia	11	32
4	Netherlands	7	33
5	Norway	4	2
6	South Africa	4	6
7	Canada	4	29
8	Portugal	4	13
9	Colombia	3	2
10	France	3	26

Table 7.6. Country collaborations clustered into 5 research groups for string (a)

Cluster 1 *(6 countries)*	Cluster 2 *(3 countries)*	Cluster 3 *(2 countries)*
Canada	Australia	France
Iran	United states	Germany
Netherlands	Colombia	
Norway		
South Africa		
U. kingdom		

Table 7.6 highlights the performance of international collaboration between countries, organized into five research groups. The density visualization map illustrates the regular research clusters within this field and their interrelations, providing insights into collaborative dynamics.

- *Descriptive Analysis and conceptual structure for (b) keywords*

The following figures visualize the scientific landscape of the subject matter using the (b) keywords: *"Risk-informed decision-making"* and *"Risk-informed asset management"* in database searches. Table 7.7 reveals that the majority of manuscripts were published as conference papers (69.90%) and journal articles (26.20%). Figure 7.3 illustrates the annual total references published between 2010 and 2021, along with the annual growth trend. A sharp decline is observed around 2013–2014, followed by a significant peak in 2019. These metrics indicate considerable fluctuations in publication volume throughout the survey period, reflecting instability in the research activity within this field.

Table 7.7. Document type for string (b)

Rank	Document type	# Documents ~ %
1	Conference Paper	72~69.90%
2	Article	27~26.20%
3	Book Chapter	1~1.00%
4	Erratum	1~1.00%
5	Review	1~1.00%
6	Short Survey	1~1.00%

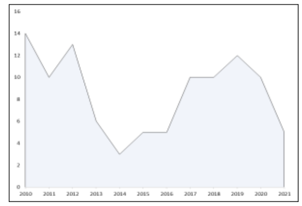

Figure 7.3. The number of annual references for string (b)

Table 7.8. Co-word analysis through keyword co-occurrences for string (b)

Rank	Keyword	Occurences
1	Decision making	72
2	Risk-informed decision making	70
3	Risk assessment	56
4	Safety engineering	42
5	Nuclear power plants	31
6	Risk management	27
7	Probabilistic risk assessment	19
8	Uncertainty analysis	19
9	Nuclear fuels	15
10	Nuclear energy	13

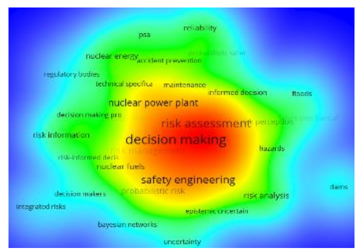

Figure 7.4. Density visualization map for keyword co-occurrences for string (b)

Table 8 highlights the most frequent and relevant keyword co-occurrences within the intellectual domain, identifying key research hotspots in this subject area. For further details on the value and significance of keyword co-occurrences in specific research fields, readers are referred to Zhang et al. (2017), Chen et al. (2019), and Afuye et al. (2021), along with their cited references. The co-word analysis reveals clusters of keywords, indicating thematic groupings in the research. Five distinct clusters were identified, corresponding to five main areas of research, as detailed in Table 7.9.

Table 7.9. Top keyword clustered into 5 areas of research for string (b)

Cluster 1 *(9 items)*	Cluster 2 *(9 items)*	Cluster 3 *(6 items)*	Cluster 4 *(5 items)*	Cluster 5 *(3 items)*
Dams	Accident prevention	Bayesian network	Decision makers	Epistemic uncertainties
Failure (mechanical)	Decision making	Maintenance	Integrated risks	Informed decision
Hazards	Decision making process	Nuclear industry	Nuclear fuels	Reliability
Risk analysis	Nuclear energy	Risk-informed decision making	Probabilistic risk assessment	
Risk assessment	Nuclear power plants	Technical specifications	Risk information	
Risk perception	Probabilistic safety assessment	Uncertainty		
Risk-informed decision making	PSA			
Safety engineering	Regulatory bodies			
Uncertainty analysis	Risk management			

Table 7.10 highlights the most productive authors and the most cited references in the field. Narumiya Y. ranks first in terms of the number of publications with 7 papers, followed by Parry G. with 6 papers. In terms of citations, Dubois D. leads with 45 citations, followed by Vaurio JK with 41 citations and Volkanovski A. with 27 citations. Table 11 provides insights into the most productive countries, ranked by the number of papers published and citations received. During the survey period, the United States ranked first in both document count and citations, followed by Canada and Japan.

Table 7.10. Top 10 authors for string (b)

	Most Productive-Authors		Most Cited-Author Ref.	
Rank	Author	Doc.	Author	Citat.
1	Narumiya Y.	7	Dubois D.	45
2	Parry G.	6	Vaurio JK	41
3	Ferrante F.	5	Volkanovski A.	27
4	Cho N.	4	Ham Y.	20
5	Dube D.	4	Talarico L.	16
6	Jang D.	4	Aven T.	13
7	Lewis S.	4	Fumagalli L.	11
8	Yamaguchi A.	4	Morales-Torres	8
9	Bujor A.	3	Alipour MH	8
10	Carlos, S.	3	Gjorgiev B.	8

Table 7.11. Top 10 country for string (b)

Rank	Country	Documents	Citations
1	US	42	49
2	Canada	12	14
3	Japan	9	1
4	South korea	6	0
5	Spain	4	18
6	Slovenia	3	37
7	Norway	3	18
8	Italy	3	14
9	Germany	3	4
10	China	3	0

- *Descriptive Analysis and conceptual structure for (c) keywords*

The following figures visualize the scientific landscape of the subject matter using the (c) keywords: *“industry 4.0”, “intelligent maintenance”, “predictive maintenance”, or “condition-based maintenance”* in database searches. Table 7.12 indicates that the majority of documents were published as conference papers (55.20%), followed by journal articles (35.10%) and book chapters (3.70%). Figure 7.5 depicts the annual total references published between 2010 and 2021, showing a considerable increase over the period. These metrics indicate a consistently high and stable publication volume, suggesting that this research area has maintained steady growth in terms of the number of publications. Table 7.13 highlights the most frequent and relevant keyword co-occurrences within the intellectual domain, identifying key research hotspots in this subject area. Co-word analysis revealed four distinct clusters, corresponding to four main areas of research, as detailed in Table 7.14.

Table 7.12. Document type for string (c)

Rank	Document type	# Documents ~ %
1	Conference Paper	73~59.80%
2	Article	41~33.60%
3	Book Chapter	5~4.10%
4	Review	2~1.60%
5	Note	1~0.80%

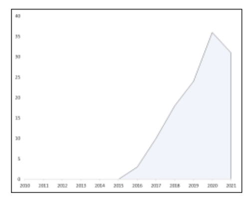

Figure 7.5. Number of annual references for string (c)

Table 7.13. Co-word analysis through keyword co-occurrences for string (c)

Rank	Keyword	Occurences
1	Industry 4.0	102
2	Maintenance	61
3	Predictive maintenance	55
4	Embedded systems	15
5	Machine learning	14
6	Internet of things	14
7	Learning systems	11
8	Artificial intelligence	11
9	Augmented reality	11
10	Decision making	10

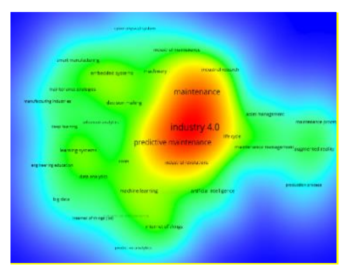

Figure 7.6. Density visualization map for keyword co-occurrences for string (c)

Table 7.14. Top keyword clustered into 4 areas of research for string (c)

Cluster 1 *(11 items)*	Cluster 2 *(8 items)*	Cluster 3 *(7 items)*	Cluster 4 *(7 items)*
Advanced analytics	Artificial intelligence	Asset management	Big data
Cyber physical system	Decsion support systems	Augmented reality	Costs
Data analytics	Industrial maintenance	Industry 4.0	Decision making
Deep learning	Industrial research	Life cycle	Internet of things
Embedded systems	Industrial revolutions	Maintenance	Manufacturing process
Engineering education	Machine learning	Maintenance management	Preventive maintenance
Learning systems	Predictive analytics	Maintenance process	
Machinery	Predictive maintenance		
Maintenance strategies			
Manufacturing industries			
Smart manufacturing			

Table 7.15 highlights the most productive authors and the most cited references in the field. El-Thalji I. and Mentzas G. rank first in terms of the number of publications, each with four articles. In terms of citations, Yan J. leads with 155 citations, followed by Masoni R. with 101 citations, and Sahal R. with 84 citations. Table 7.16 provides insights into the most productive countries based on the number of papers published and citations received. During the survey period, Italy ranked first in both document count and citations, followed by Germany and Greece.

Table 7.15. Top 10 authors for string (c)

Most Productive-Authors			Most Cited-Author Ref.	
Rank	Author	Documents	Author	Citations
1	El-Thalji, I.	4	Yan J.	155
2	Mentzas, G.	4	Masoni R.	101
3	Bousdekis, A.	3	Sahal R.	84
4	Fiorentino, M.	3	Li D.	79
5	Frontoni, E.	3	Ceruti A.	76
6	Gattullo, M.	3	Franciosi C.	46
7	Nordal, H.	3	Scurati GW	42
8	Paolanti, M.	3	Sipsas K.	40
9	Uva, A.E.	3	Zonta T.	39
10	Apostolou, D.	2	Alqahtani AY	39

Table 7.16. Top 10 most productive country

Rank	Country	Documents	Citations
1	Italy	24	432
2	Germany	14	20
3	Greece	10	101
4	Norway	9	91
5	Brazil	8	70
6	United K.	8	115
7	Spain	7	68
8	France	6	91
9	India	6	20
10	USA	6	113

Table 7.17 highlights the performance of international collaboration among countries, organized into four distinct research groups. This clustering provides insights into the collaborative dynamics and partnerships within the field.

Table 7.17. Country collaborations clustered into 4 research groups for string (c)

Cluster 1 *(3 countries)*	Cluster 2 *(3 countries)*	Cluster 3 *(3 countries)*	Cluster 4 *(2 countries)*
Germany	India	France	Brazil
Greece	Norway	Spain	United states
Poland	United kingdom	Italy	

- *Descriptive analysis and conceptual structure for (d) keywords*

The following figures visualize the scientific landscape of the subject matter using the (d) keywords: *"resilience engineering"*, *"system resilience"*, and *"resilience modeling"* in database searches. Table 18 reveals that most manuscripts were published as journal articles (50.00%), followed by conference papers (33.30%) and book chapters (6.70%). Figure 7.7 illustrates the annual total references published between 2010 and 2021, highlighting a significant and steady increase in publications over the survey period. The number of references peaked in 2021 with a total of 114 publications, indicating stability and growth in this research area. Table 7.19 highlights the most frequent and relevant keyword co-occurrences, identifying research hotspots. Co-word analysis revealed five distinct clusters, corresponding to five main areas of research, as detailed in Table 7.20.

Table 7.18. Document type for string (d)

Rank	Document type	# Documents ~ %
1	Article	320~ 49.20%
2	Conference Paper	225~ 34.60%
3	Book Chapter	37~ 5.70%
4	Review	33~5.10%
5	Book	9~ 1.40%
6	Editorial	9~ 1.40%
7	Note	6~ 0.90%
8	Other	8~ 1.80%

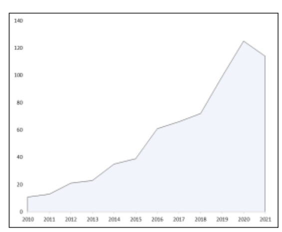

Figure 7.7. The number of annual references for string (d)

Table 7.19. Co-word analysis through keyword co-occurrences for string (d)

Rank	Keyword	Occurences
1	Resilience	192
2	Resilience engineerings	127
3	System resiliences	108
4	Resilience engineerings	98
5	Human	71
6	Safety engineering	63
7	Disasters	53
8	Risk assessment	46
9	Reliability	41
10	Decision making	41
11	Uncertainty analysis	38
12	Electric power transmission networks	34
13	Climate change	33
14	Risk management	32
15	Accident prevention	31

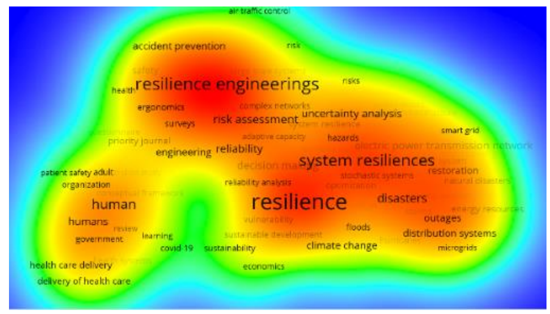

Figure 7.8. Density visualization map for keyword co-occurrences for string (d)

Table 7.20. Top keyword clustered into 5 areas of research for string (d)

Cluster 1 *(25 items)*	Cluster 2 *(23 items)*	Cluster 3 *(17 items)*
Distributed energy resources	System resilience	Risk
Distribution systems	System engineering	Risk assessment
Electric load flow	Resilience metrics	Risk management
Electric power systems	Resilience model	Safety
Electric power transmissions	Adaptative capacity	Safety engineering
Electric power transmissions networks	Uncertainty analysis	Safety management
Electric utilities	Recovery	Sociotechnical systems
Energy resources	Reliability	Health
Disasters	Sensitivity analysis	Accident prevention
Natural disaster	Benchmarking	Resilience engineering
Extremes events	Decision making	Resilience systems
Extreme weather	Critical infrastructure	Advanced traffic management systems
Extreme weather events	Complex networks	Air traffic control
Hurricanes	Complex systems	Dada envelopment analysis
Storms	Bayesian networks	Questionnaire
Power system resilience	Behavioral research	Surveys
System resilience	Large scale systems	Priority journal
Restoration	Information systems	
Intelligent systems	Infrastructure systems	
Investments	Stochastic systems	
Microgrids	Transportation system	
Smart power grid	Water supply	
Optimization	Public works	
Monte Carlo methods		
Integer programming		

Cluster 4 *(11 items)*	Cluster 5 *(15 items)*
Climate change	Conceptual framework
Covid-19	Controlled study
Ecosystem resilience	Government programs
Resilience	Organization
Soial-ecological systems	Economics
Sustainability	Health care
Sustainability development	Health systems
Vulnerability	Health care policy
Floods	Delivery of health care
Flood security	Health care Delivery
Reliability analysis	Patient safety
	Human
	Interview
	Learning
	Review

Table 7.21 identifies the most productive authors and the most cited references. Azadeh A. ranked first in the number of publications with 22 articles, followed by Hollnagel E. with 12 articles. In terms of citations, Hollnagel E. ranked first with 1,395 citations, followed by Hosseini S. with 682 citations. Table 7.22 presents the most productive countries. The United States ranked first with 212 publications and 5,825 citations, followed by the United Kingdom with 65 publications cited 1,691 times. Table 7.23 provides insights into international collaboration performance, identifying six research groups formed through country-level partnerships. These clusters showcase the collaborative dynamics and global interconnectivity within the field.

Table 7.21. Top 10 authors for string (d)

Most Productive-Authors			Most Cited-Author References	
Rank	*Author*	*Documents*	*Author*	*Citations*
1	Azadeh A.	22	Hollnagel E.	1395
2	Hollnagel E.	12	Hosseini S.	682
3	Righi A.	11	Henry D.	456
4	Bie Z.	7	Woods D.	310
5	Panteli M.	7	Panteli M.	309
6	Ranasinghe U	7	Ayyub B.	289
7	Woods D.	7	Li F.	251
8	Patriarca R.	6	Bie Z.	231

Table 7.22. Top 10 most productive country for string (d)

Rank	Country	Documents	Citations
1	US	212	5825
2	UK	65	1691
3	Iran	64	1386
4	China	54	422
5	Australia	40	789
6	France	38	766
7	Germany	37	285
8	Italy	34	340
9	Canada	31	364
10	Brazil	27	544

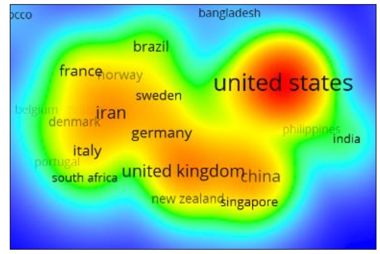

Figure 7.9. Density visualization map for the most productive country for string (d)

Table 7.23. Country collaborations clustered into 6 research groups for string (d)

Cluster 1 *(8 countries)*	Cluster 2 *(8 countries)*	Cluster 3 *(5 countries)*	Cluster 4 *(3 countries)*	Cluster 5 *(3 countries)*	Cluster 6 *(3 countries)*
China	Belgium	Australia	Brazil	United States	France
Germany	Denmark	Canada	Norway	Bangladesh	Japan
Netherlands	Finland	India	Sweden	South Korea	Morroco
New Zeland	Iran	Philippines			
Nigeria	Italy	Poland			
Singapore	Portugal				
Switzerland	South Africa				
United Kingdom	Spain				

In summary, the selection process prioritized papers based on their relevance to the research topic. Specifically, papers were included if they were written in English, categorized as journal or conference papers, and their abstracts indicated a focus on the strategic approach to asset management and/or decision-making. Further screening involved reading each article to confirm its relevance to the review. The selected documents were then organized using the reference management software Endnote. To maintain a concise scope, only the most relevant and appropriate articles were analyzed and discussed in detail, while others were excluded to ensure the paper's length remained within acceptable limits.

7.3 Asset Management Models

The complex and automated environment of industrial systems necessitates optimized strategic models for asset management (AM). Modern AM relies on Industry 4.0 tools like IIoT and AI to process data and enhance decision-making. It plays a crucial role in ensuring long-term asset sustainability amidst market challenges, technological advancements, and external risks (Baglee et al., 2016; Gavrikova et al., 2020). The concept of *"Multi-Unit Systems"* has emerged, expanding AM's scope from simple repairs to the optimization of complex systems (Petchrompo et al., 2019).

The ISO range of standards:

The ISO standards series (ISO-55000, 2024; ISO-55001, 2014; and ISO-55002, 2018) form the foundation of a holistic approach to Asset Management (AM), defining its concepts, implications, and objectives. These standards, along with the International Infrastructure Management Manual, succeed the PAS 55 guide (BSI, 2008, 2013). Although PAS 55 has been obsolete as a formal specification of the British Standards Institution (BSI) since 2015, it remains a valuable resource for educational purposes. ISO-55000 (2024) provides an overview of AM, its principles, terminology, and the context for the ISO 5500x series. ISO-55001 (2014) outlines the requirements for establishing, implementing, maintaining, and improving an Asset Management System (AMS) within an organizational context. ISO-55002 (2018) offers guidelines for applying the requirements of ISO-55001(2014), providing detailed guidance for implementation. This series establishes a comprehensive framework for organizations to achieve effective and sustainable asset management practices.

The GFMAM – Asset Management Landscape Subjects:

In 2011, a group of experts, academics, and professionals in Asset Management (AM) and Maintenance established the Global Forum on Maintenance and Asset Management (GFMAM). Unlike the ISO standards, which focus on specific aspects of AM, the GFMAM provides a more comprehensive scope of AM knowledge (Campbell et al., 2015). In 2014, the GFMAM published a document outlining 39 subjects of AM, organized into six thematic groupings, which represent key components of the broader AM body of knowledge (GFMAM, 2014):

- *Strategy and planning theme*

This theme focuses on aligning Asset Management (AM) activities with the organization's mission and objectives. It encompasses developing AM policies, translating stakeholder expectations into objectives and strategies, and coordinating activities across the asset lifecycle. It consists of five key subjects, as outlined in Figure 7.10.

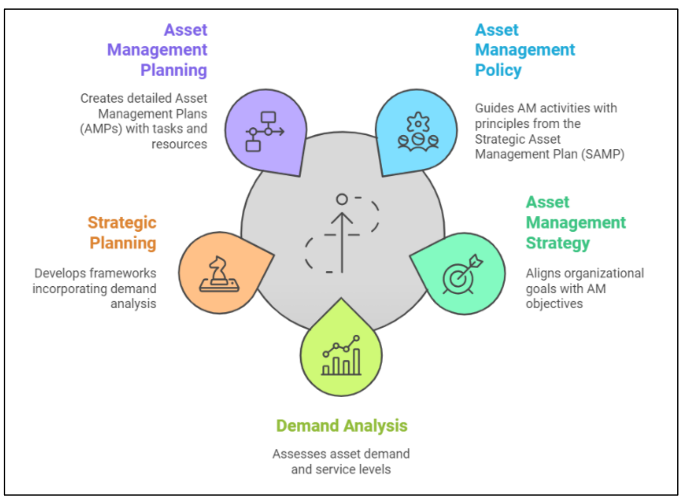

Figure 7.10. Strategy and planning theme *(Source: own representation based on GFMAM (2014))*

- *Asset management decision-making theme*

This theme focuses on identifying processes that enable informed decision-making to maximize value across the asset lifecycle. It evaluates the impact and criticality of decisions related to asset acquisition, operation, maintenance, and disposal, considering performance, risks, and costs. The theme is divided into five key subjects, as outlined in Figure 7.11.

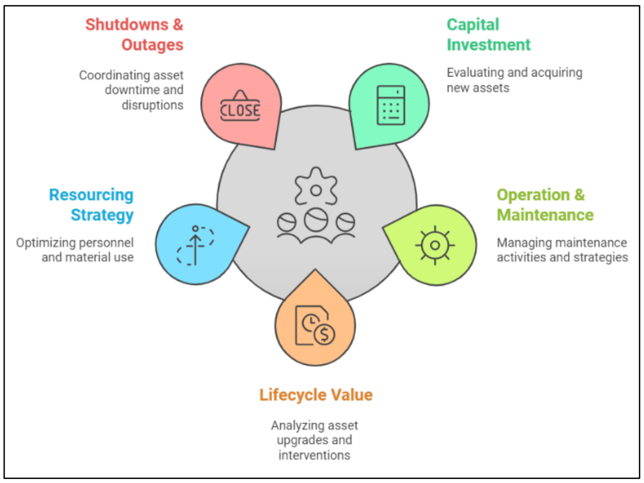

Figure 7.11. Asset management decision-making theme
(Source: own representation based on GFMAM (2014))

- *Lifecycle Delivery theme*

This theme focuses on how organizations execute projects, operate, and maintain assets to deliver the expected level of service throughout the asset lifecycle. It encompasses strategies, activities, and risk management for asset acquisition, operation, maintenance, and disposal. The theme includes 11 subjects, as outlined in Figure 7.12.

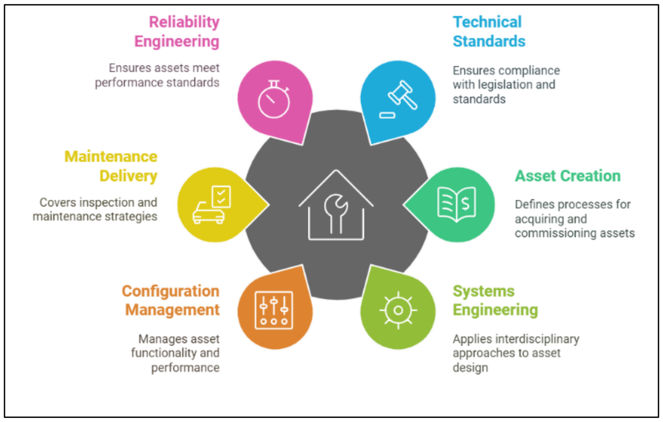

Figure 7.12. Lifecycle Delivery theme
(Source: own representation based on GFMAM (2014))

- *Asset Information theme*

This theme focuses on building a comprehensive understanding of the asset portfolio, including its condition, criticality, and capacity, which serves as a critical input for various Asset Management (AM) processes. It emphasizes the availability, reliability, and accessibility of relevant information, which underpins the quality of decisions related to operations, maintenance, financing, and risk management. It is composed of four key subjects, as outlined in Figure 7.13.

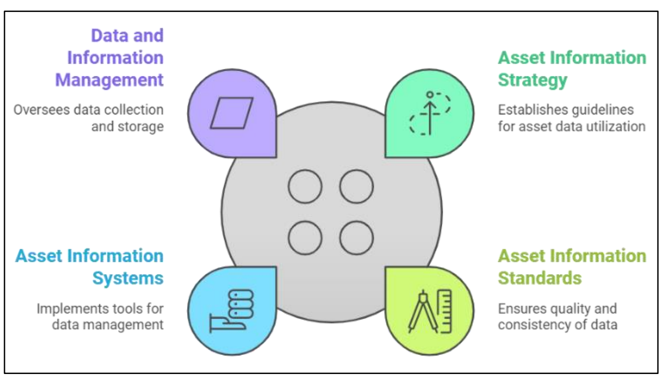

Figure 7.13. Asset Information theme *(Source: own representation based on GFMAM (2014))*

- *Organization and People theme*

This theme focuses on the organizational structure and culture, roles, responsibilities, and key skills related to Asset Management (AM). It explores the extent to which AM principles are adopted by senior management and employees, as well as the alignment of their efforts and behaviors with industry best practices. This theme is comprised of five key subjects, as illustrated in Figure 7.14.

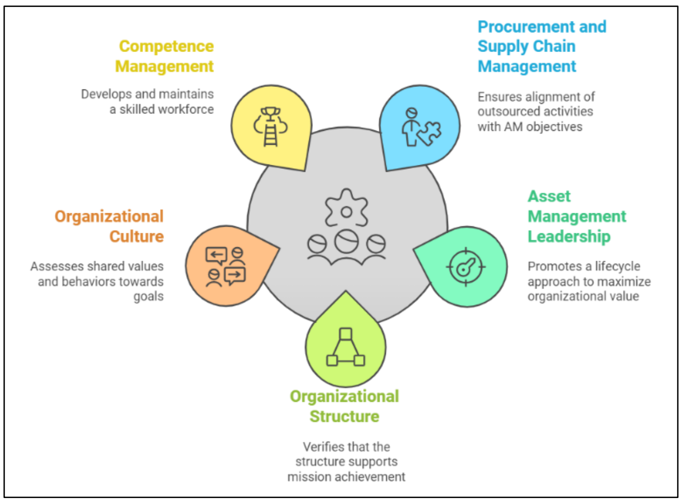

Figure 7.14. Organization and People theme
(Source: own representation based on GFMAM (2014))

- *Risk and Review theme*

This theme is a critical component of strategic planning and decision-making in Asset Management (AM). It addresses the organization's sensitivity to asset failures and its resilience across various business sectors. Key activities within this theme include identifying risks, establishing effective feedback and review mechanisms to ensure objectives are achieved, assessing the physical condition and performance of assets, and driving continuous improvement in AM practices. Additionally, it focuses on ensuring the performance and reliability of the Asset Management System (AMS) through robust feedback and monitoring processes. This theme comprises nine subjects, as illustrated in Figure 7.15.

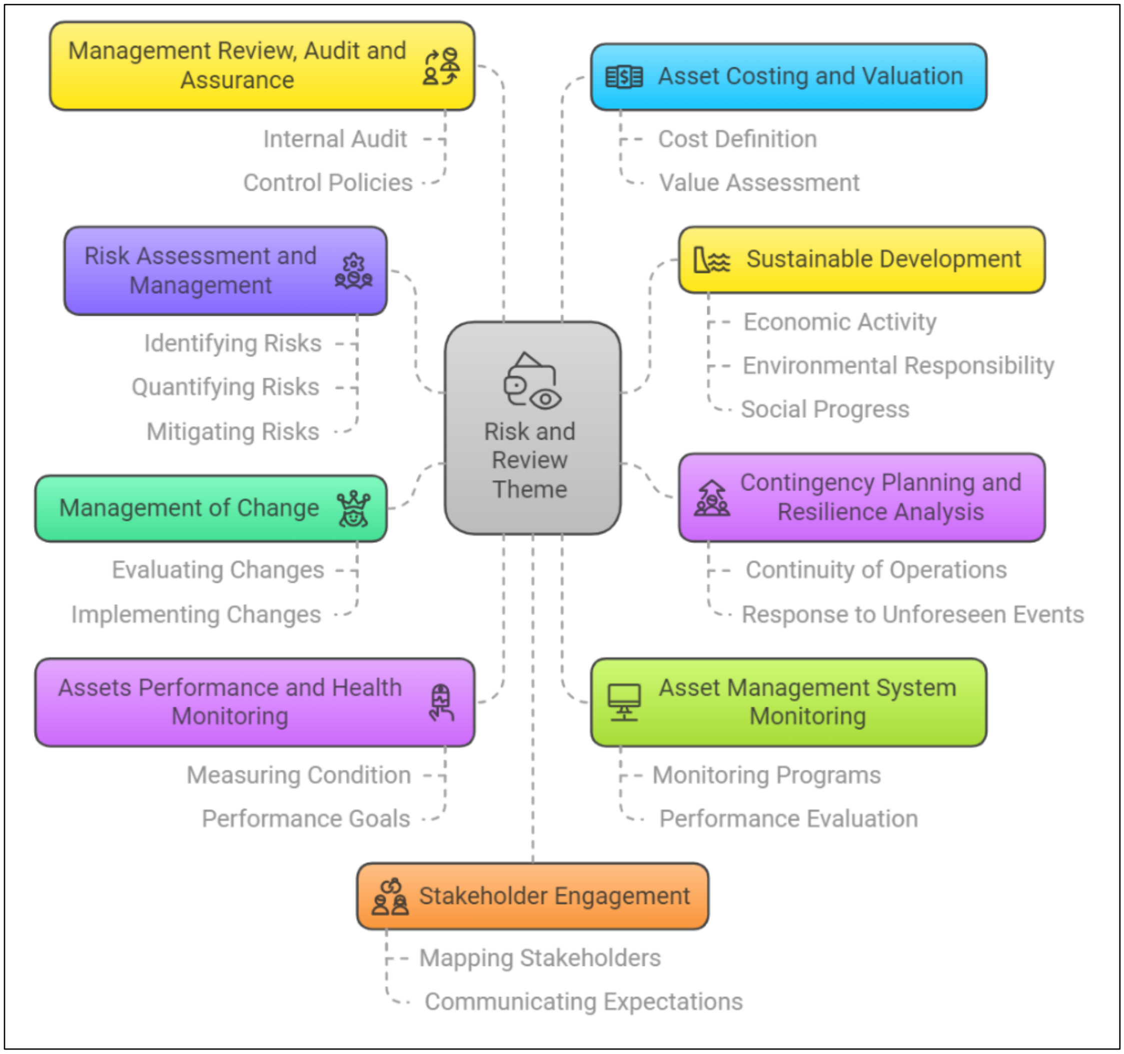

Figure 7.15. Risk and Review theme
(Source: own representation based on GFMAM (2014))

The IAM Conceptual Framework for Asset Management:

The Institute of Asset (IAM) has developed a conceptual model for Asset Management (AM), encompassing six groups of themes that cover the 39 topics initially introduced by the Global Forum on Maintenance and Asset Management (GFMAM, 2014; IAM, 2015). The IAM's framework, outlined in Asset Management – An Anatomy, serves as a tool for assessing maturity in AM practices. This framework aligns with the principles of the ISO 55000 series of standards and provides detailed guidance on the 39 subjects that define AM activities within an organization. These subjects are organized into six key themes, illustrating the broad scope of AM, the interconnection between its activities, and the necessity for their integration. Furthermore, the model highlights the importance of aligning AM activities with the organization's objectives and strategy. Figure 7.16 depicts the IAM model for managing physical assets, including the six thematic groups.

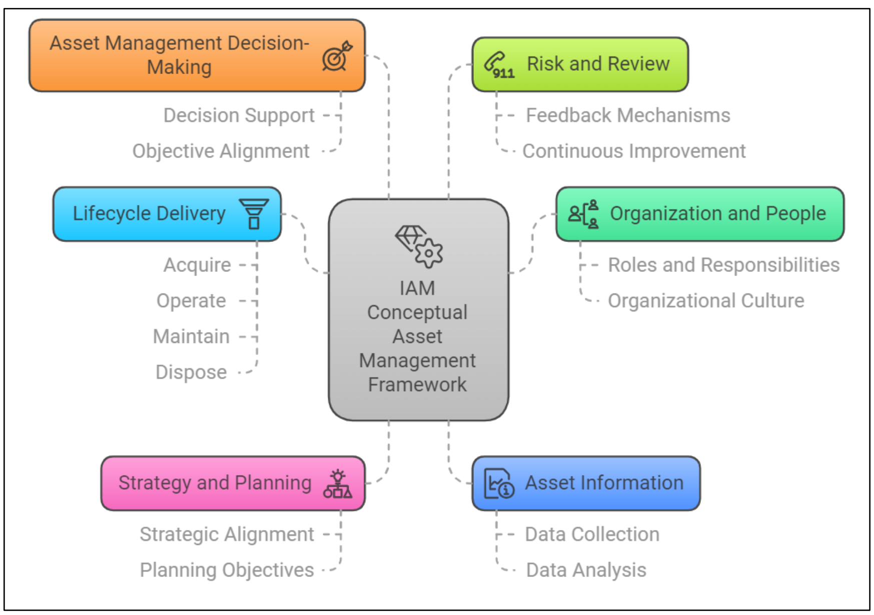

Figure 7.16. Conceptual AM model
(Source: own representation based on IAM, 2015)

The maturity levels used to assess an organization's progress in managing physical assets are based on definitions established by IAM. Figure 7.17 illustrates the pathway toward achieving excellence in AM practices. The maturity rating is measured on a scale from 0 to 5, with level 3 representing the *"Competence"* stage. This level aligns with the certification requirements of the ISO-55001 (2014) standard. Achieving level 3 indicates that processes for AM activities are in place, well-documented, effectively communicated, and consistently controlled across the organization. Furthermore, it demonstrates that these processes are delivering the intended results, thereby meeting organizational objectives. Organizations that conduct an initial assessment of their AM practices often exhibit a maturity level of *"Awareness"*. This stage typically serves as the starting point in their journey toward implementing best practices in AM. The process is inherently continuous and evolves over time, driven by a commitment to ongoing improvement.

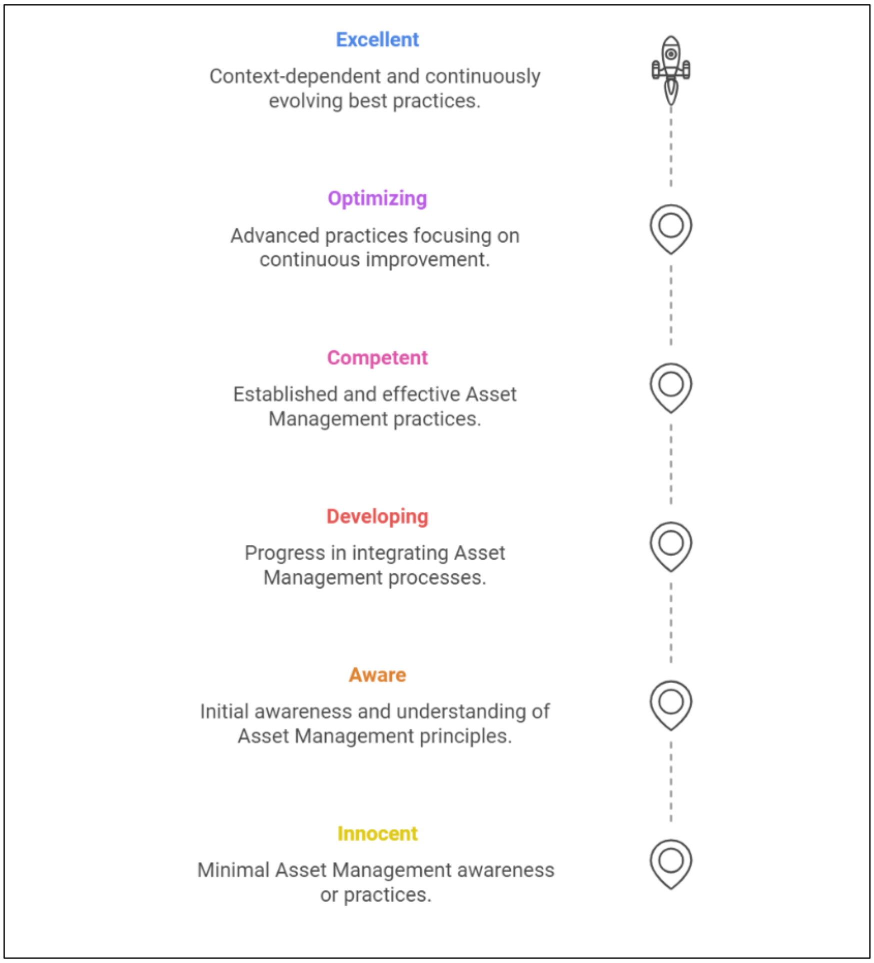

Figure 7.17. IAM Asset Management Maturity Scale
(Source: own representation based on IAM, 2015)

The Asset Management Body of Knowledge (AMBoK)

In 2014, the Australian Asset Management Council (AM-Council) developed a compilation of best practices, referred to by the acronym AMBoK, which constitutes a comprehensive Asset Management (AM) framework (Asset Management Council, 2014). AMBoK encompasses a collection of models – strategic, operational, tactical, and maturity – as well as definitions that collectively form a holistic framework for AM practices. Figure 7.18 illustrates the various models developed and their respective levels of involvement in AM.

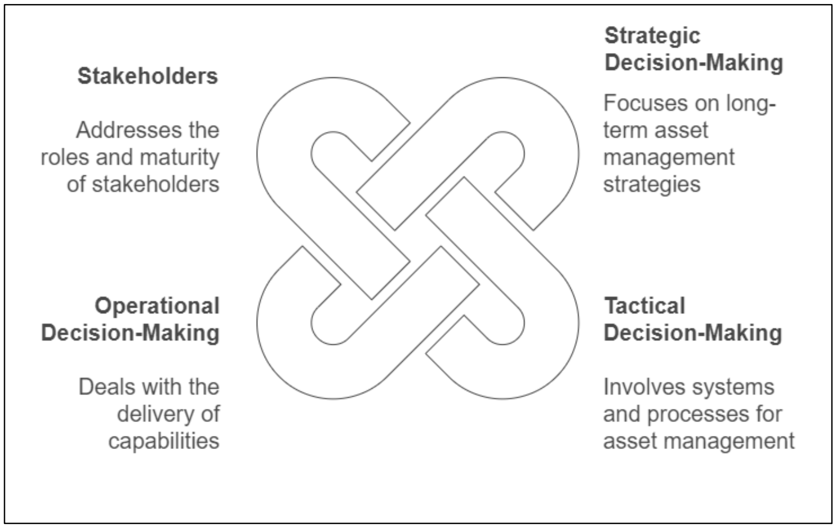

Figure 7.18. Asset Management Body of Knowledge collection of models (AMBoK)
(Source: own representation based on AM Council, 2014)

CIGRE conceptual decision-making process

The International Council on Large Electric Systems (CIGRÉ) is a global nonprofit professional organization specializing in high-voltage electricity. Established in 1921 in France, CIGRÉ has become a key authority in the field of electrical utilities.

In the context of Electrical Utilities, CIGRÉ defines Asset Management (AM) as follows: *"The Asset Management of Transmission and Distribution businesses operating in an electricity market involves central key decision-making for the network business to maximize long-term profits, while delivering high service levels to customers with acceptable and manageable risks" (Khuntia et al., 2016; Bartlett, 2002).*

CIGRÉ has developed a conceptual model of decision-making for AM, known as the *Asset Management Decision Process*. This model consists of three levels of information requirements: *(1) Corporate Level* – high-level decision-making aligned with strategic goals. *(2) Network Level* – focused on operational and tactical decisions for managing the electricity network. *(3) Component Level* – detailed information for managing individual assets and components. Figure 7.19 illustrates this conceptual decision-making process for AM in the power sector, as defined by CIGRÉ (CIGRÉ, 2013, 2014). The model highlights how decision-making is informed by a structured hierarchy of information requirements within a Risk Management framework.

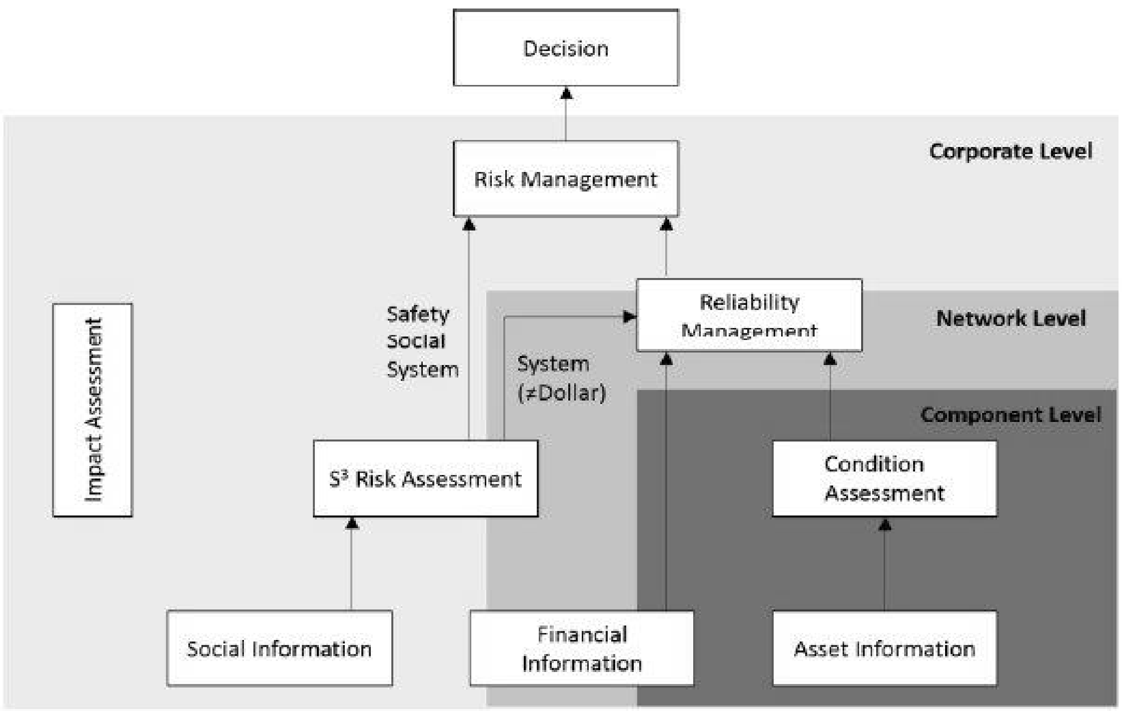

Figure 7.19. Conceptual Model of Decision-Making for Asset Management
(Source: Cigre, 2013)

* Note: S3 stands for Safety, Social, and System Oriented Risks.

7.4 Risk Management and Decision-Making Process in Asset Management

This section provides an overview of the key background concepts related to the research focus, namely risk management (RM) and the decision-making process in asset management (AM). It highlights critical aspects such as risk-informed decision-making (RIDM) and risk-informed asset management (RIAM), which are of significant interest to the scientific community.

Research indicates that RM is increasingly recognized as a tool for enhancing strategic asset management and should be an integral part of an organization's activities and those of its stakeholders (Maletič et al., 2020; Dezfuli et al., 2010c; Olechowski et al., 2016). Outcomes from risk assessment and uncertainty analysis provide asset managers with clear insights and support informed, deliberate decision-making (Khuntia et al., 2016; Komljenovic et al., 2016; Zio, 2012; Aven et al., 2010; Aven, 2010; NASA, 2002).

- *Risk and risk assessment*

The ISO-31000 (2018, 2009) standards define risk management (RM) as *"coordinated activities to direct and control an organization with regard to risk"*. Similarly, Hubbard (2020) describes RM as the process of identifying, evaluating, and prioritizing risks, followed by coordinated actions to either enhance opportunities or mitigate the likelihood and impact of adverse events. Risk, as per ISO-31000 (2009, 2018), is characterized as *"an effect of uncertainty on objectives"*. This effect represents *"a deviation from the expected, which can be positive, negative, or both, addressing, creating, or resulting in opportunities and threats"*. Risk is often expressed in terms of *"risk sources, potential events, their consequences, and their likelihood"*. In practical terms, risk can be understood as the likelihood of an event that negatively impacts an organization's objectives. NASA's procedural requirement NPR 8000.4 defines risk through three components: (1) the scenario(s), (2) the likelihood(s), and (3) the consequence(s) as shown in Figure 7.20 (Dezfuli et al., 2010c). According to these authors, this approach benefits RM by: (i) differentiating high-probability, low-consequence outcomes from low-probability, high-consequence outcomes; (ii) guiding proactive risk management through the identification of risk drivers and the screening of low-probability, low-consequence events; (iii) highlighting areas where investments can reduce uncertainty effectively.

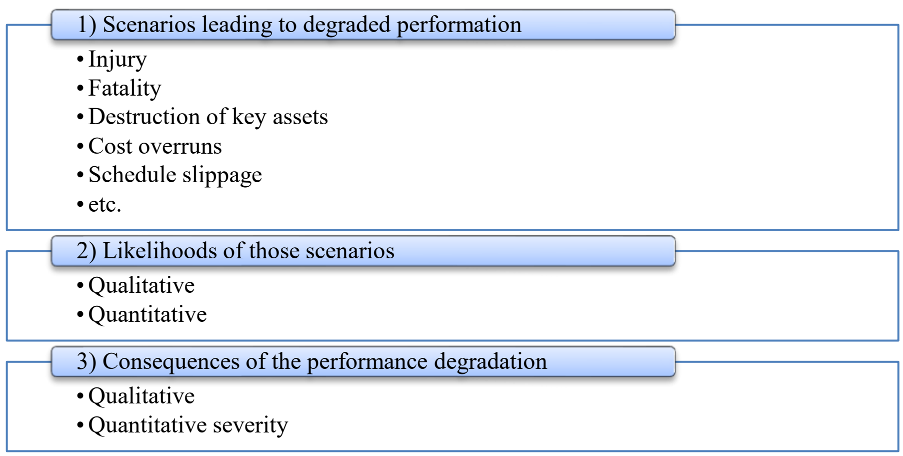

Figure 7.20. Risk defined as a set of triplets
(Source: own representation based on NASA/SP-2010-576 ; ISO-3100 (2018)

Risk is also characterized as the outcome of an organization's objectives, priorities, and actions in addressing environmental uncertainties (Gavrikova et al., 2020). These uncertainties include global market deregulation, legal liabilities, technological advancements, and risks from events such as terrorist attacks, natural disasters, geomagnetic disturbances, and cyberattacks.

Uncertainty, a fundamental aspect of risk, is embedded in the assessment of likelihoods and consequences. It stems from internal and external factors that can disrupt or delay the achievement of corporate objectives (ISO-31000, 2018, 2009; ISO-31010, 2008; Purdy, 2010). The ISO-31000 (2009) standard highlights that *"managing risk is iterative and assists organizations in setting strategy, achieving objectives, and making informed decisions"*. It incorporates risk analysis, evaluation, reduction, and management, particularly when the consequences carry significant societal impacts. For further details on RAC, see Marhavilas et al. (2021) and their references.

The next section examines the *Risk-Informed Decision-Making (RIDM)* process, an essential element of effective RM.

- *Risk-Informed Decision-Making process*

The concept of Risk-Informed Decision-Making (RIDM) was developed primarily by the U.S. nuclear engineering and aerospace industries, including the National Aeronautics and Space Administration (NASA) and the U.S. Nuclear Regulatory Commission (USNRC), to address safety concerns in high-risk domains (Travers, 2015).

Traditionally, risk management (RM) was equated with Continuous Risk Management (CRM). Risk assessment and uncertainty analysis relied heavily on probabilistic methods, such as Probabilistic Risk Assessment (PRA) or Quantitative Risk Assessment (QRA). Decision-making integrates diverse inputs, both qualitative (e.g., expert judgment) and quantitative (e.g., risk analysis). Today, RM encompasses both the CRM process and the RIDM process, forming a comprehensive framework (Maletič et al., 2020; Dezfuli et al., 2010c; Olechowski et al., 2016).

Proactive RM integrates RIDM, which focuses on selecting risk-informed decision alternatives to achieve objectives, and CRM, which ensures the execution of chosen alternatives meets requirements. These complementary processes should be unified into a single framework for effective RM. The trend is shifting from a *risk-based* to a *risk-informed* safety management approach, where PRA/QRA and deterministic methods are fundamental components of decision-making (Khuntia et al., 2016; Zio, 2012; Aven, 2012).

RIDM emphasizes that risk assessment is only one part of the decision-making process, as decisions also involve factors such as social preferences, political considerations, and budgetary constraints (Zio et al., 2012; Dezfuli et al., 2010c). Technical data cannot solely guide decisions; human judgment and broader analyses, including engineering, economic, societal, environmental, and regulatory aspects, are equally critical (Komljenovic, 2018).

NASA's RIDM framework, outlined in procedural requirement NPR 8000.4 (NASA/SP-2010-576), comprises three parts and six process steps as depicted in the Figure 7.21: *(1) Identifying Decision Alternatives* – recognizing opportunities aligned with objectives. *(2) Performing Risk Analysis* – developing an integrated perspective and technical basis for deliberation. *(3) deliberating and Selecting Alternatives* – making performance commitments informed by, but not solely based on, risk analysis.

Zio et al. (2012) analyzed RIDM processes developed by NASA and USNRC, comparing methodologies and identifying commonalities. These structured processes help decision-makers manage complex, high-impact decisions involving uncertainty and multiple objectives. They aim to ensure decisions are made with awareness of associated risks while considering all decision attributes in an integrated manner.

Komljenovic et al. (2019a, 2019b) proposed a RIDM process tailored to large-scale strategic asset management projects, focusing on long-term performance and sustainability. Their approach includes: (1) Establishing the decision-making framework. (2) Performing detailed analyses. (3) Deliberating and making final decisions. However, they noted that this process is unsuitable for routine decision-making. Today, RIDM has been adopted in industries beyond aerospace and nuclear, including infrastructure and dam safety, offering robust decision-support tools for complex challenges (Maletič et al., 2020; Dezfuli et al., 2010c; Komljenovic et al., 2016; Olechowski et al., 2016).

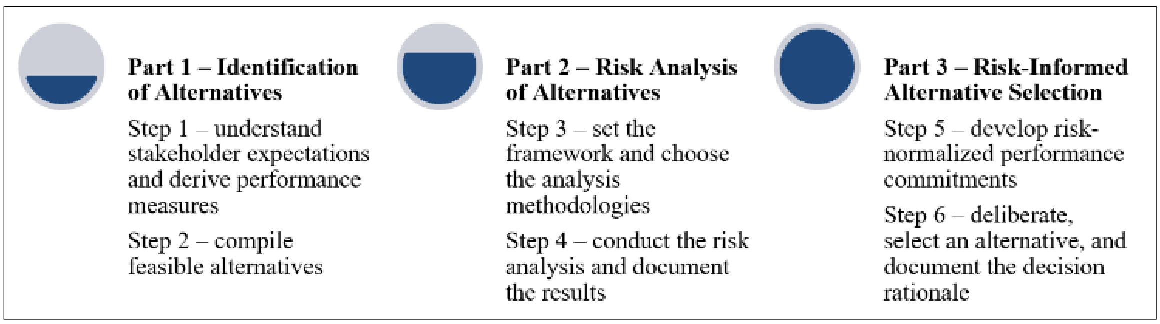

Figure 7.21. Global RIDM process
(Source: own representation based on NASA/SP-2010-576; ISO-3100 (2018))

- *Risk-Informed Asset Management process*

The Risk-Informed Asset Management (RIAM) process is a risk-based decision analysis tool initially developed for nuclear power stations. It is designed to suit market-driven industries by providing plant executives with a comprehensive framework for planning project priorities, lifecycle management, long-term maintenance strategies, budgeting, and managing economic risks. Additionally, it addresses system reliability and availability.

As shown in Figure 7.22, the RIAM conceptual model is based on the technical report from the Electric Power Research Institute (EPRI, 2002). The RIAM method complements the *Nuclear Asset Management (NAM)* approach, which integrates risk management to align business objectives with investment decisions over the long-term lifecycle of assets (EPRI, 2002). The RIAM process incorporates profitability models and performance metrics, such as cost, safety, revenue, and scheduling, to support decision-making. These metrics guide resource allocation and optimization, making RIAM a performance-based framework as well (Liming, 2002; Komljenovic et al., 2005). In essence, the RIAM process provides a structured approach to asset management that balances economic considerations with system reliability and long-term sustainability. It enhances decision-making by integrating risk-based analysis with performance-focused outcomes, offering a valuable tool for complex industries like nuclear power and beyond.

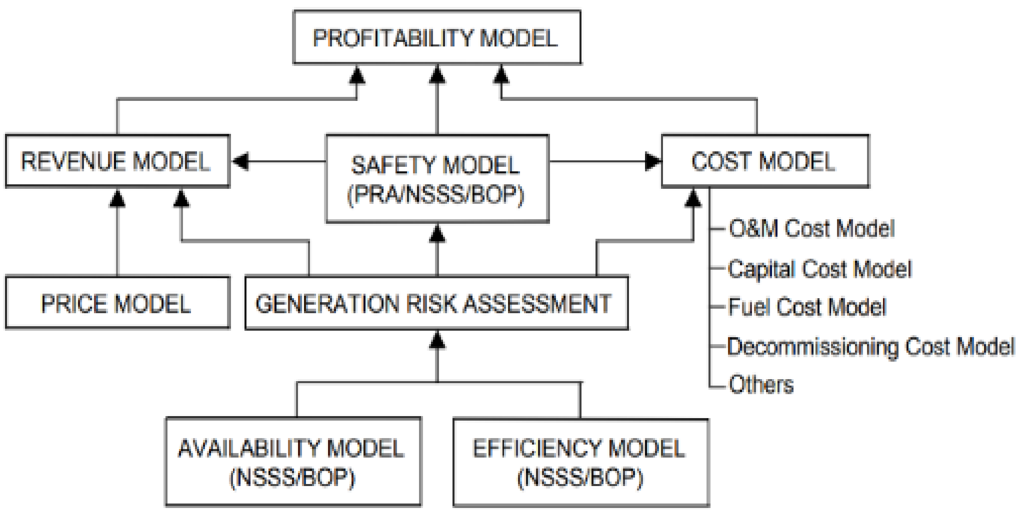

Figure 7.22. Risk-Informed Asset Management process (RIAM)
(Source: EPRI (2002))

7.5 Resilience Engineering

Asset management plays a crucial role in helping organizations navigate external and internal challenges, such as increasing competition, market deregulation, technological innovation, and risks like terrorist attacks, natural disasters, political instability, geomagnetic disturbances, and cyberattacks (Gavrikova et al., 2020).

Figure 7.23 illustrates the hierarchy of these environmental factors. External environments, due to their complexity and profound uncertainty, remain neither fully predictable nor controllable (Komljenovic et al., 2015).

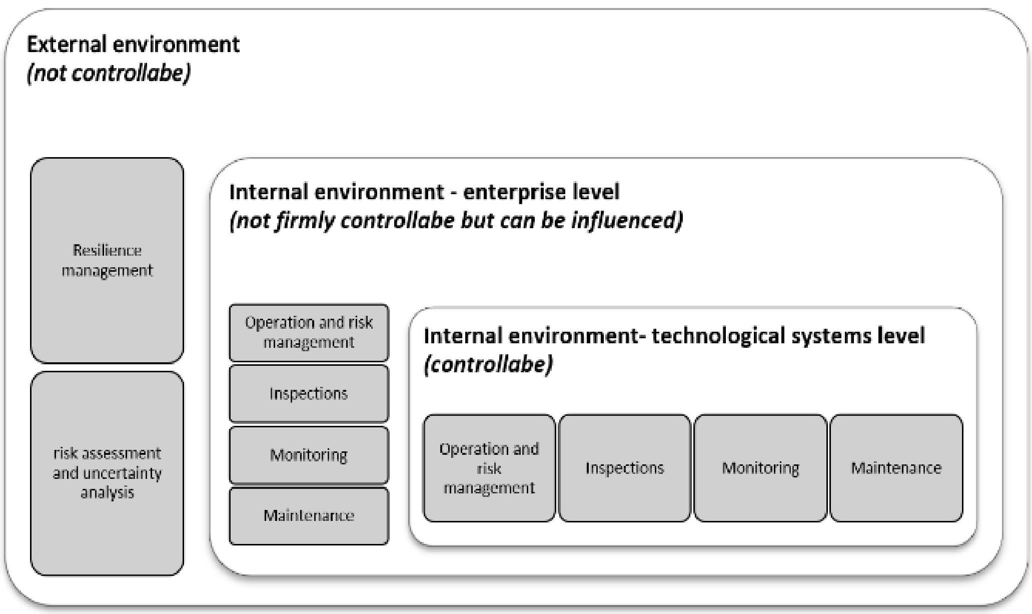

Figure 7.23. Hierarchy of organizational types of ecosystems
(Source: own representation based on Komljenovic et al., (2015))

To address such environments, *resilience management* has emerged as a recognized approach within risk management (RM) and uncertainty analysis. The concept of resilience has been extensively studied, resulting in diverse definitions across scientific literature (Hosseini et al., 2016). Table 7.24 provides a non-exhaustive directory of these definitions, reflecting sector-specific perspectives. This variety can complicate the interpretation and measurement of resilience (Henry et al., 2012). The understanding of resilience varies based on the aspect of a system being studied, whether technical, organizational, social, economic, ecological, or environmental (Lofquist, 2017; Hickford et al., 2018; Vugrin et al., 2010). For instance, *resilience engineering* focuses on the reliability and integrity of physical infrastructure systems, emphasizing safety in complex sociotechnical environments (Hollnagel et al., 2017; Righi et al., 2015); *Socio-ecological resilience*, while sharing common ground with resilience engineering, emphasizes environmental and ecological concerns, disaster response, business continuity, and occupational health and safety (Hickford et al., 2018). Despite these distinctions, four common principles of resilience emerge: (1) surviving disruption by reducing its impact; (2) adapting to change; recovering from adverse events; the speed of recovery as a critical measure of resilience (Hickford et al., 2018).

Resilience, therefore, should be considered a *system-level attribute*, not a component-level characteristic. The general concept of resilience, as depicted in Figure 7.24, involves four phases: *(1) Planning* – anticipating adverse events and preparing responses. *(2) Absorption* – minimizing performance loss during adverse events. *(3) Recovery* – regaining performance after an event, with recovery speed influenced by the magnitude of disruption and resource availability. *(4) Adaptation* – learning from the event to improve future resilience. This framework highlights the importance of continuous improvement and adaptation, as recovery may lead to various post-event performance levels.

Resilience encompasses four main attributes (Hickford et al., 2018; Komljenovic et al., 2020): *(1) Robustness* – the ability to absorb shocks and maintain critical functions. *(2) Redundancy* – ensuring backup systems to mitigate disruptions. *(3) Resourcefulness* - preparing to withstand and address disruptions. *(4) Rapid Recovery* – Quickly restoring functionality after an incident.

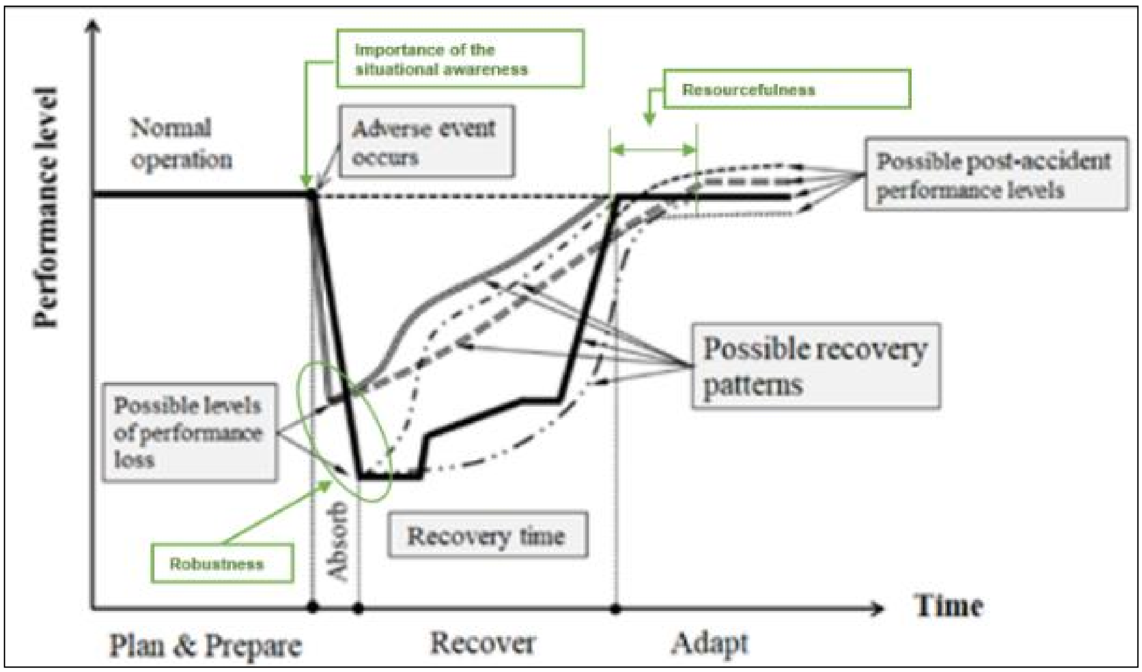

Figure 7.24. General concept of resilience
(Source: Komljenovic et al. (2020))

Table 7.24. Definitions of resilience
(Source: own representation)

Discipline	Authors / Paper	Definition
Resilience engineering	Resilience Engineering Association (2021)/ Resilience Engineering	"Resilience Engineering is a trans-disciplinary perspective that focuses on developing on theories and practices that enable the continuity of operations and societal activities to deliver essential services in the face of ever-growing dynamics and uncertainty. It addresses complexity, non-linearity, inter-dependencies, emergence, formal and informal social structures, threats and opportunities."
	Hollnagel (2013) / Resilience engineering in practice	"The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions".
	Woods (2003) / Creating foresight: how resilience engineering can transform NASA's approach to risky decision making.	"Resilience engineering uses the insights from research on failures in complex systems, including organizational contributors to risk, and the factors that affect human performance to provide systems engineering tools to manage risks proactively"
Resilience in infrastructure systems	Resilience, C. I. (2009) / Final Report and Recommendations.	"The ability to reduce the magnitude, impact, or duration of a disruption".
	Vugrin et al. (2010) / A framework for assessing the resilience of infrastructure and economic systems.	"Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels".
Resilience in organisational systems	ISO-22316 (2017) / Security and resilience, Organizational resilience, Principles and attributes.	"The ability of an organization to absorb and adapt in a changing environment to enable it to deliver its objectives and to survive and prosper".
	Hale et al. (2017) / Defining resilience.	"Resilience describes the characteristic of managing the organisation's activities to anticipate and circumvent threats to its existence and primary goals".
	Denyer (2017) / Organizational resilience: a summary of academic evidence, business insights and new thinking	"The ability of an organisation to anticipate, prepare for, respond, and adapt to incremental change and sudden disruptions in order to survive and prosper".
	Lexicon et al. (2008) / U.S. Department of Homeland Security Risk Steering Committee	"The ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions: (1) ability of systems, infrastructures, government, business, and citizenry to resist, absorb recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance; (2) capacity of an organization to recognize threats and hazards and make adjustments that will improve future protection efforts and risk reduction measures"
	Ortiz-de-Mandojana et al. (2016) / The long-term benefits of organizational resilience through sustainable business practices.	"The ability of organizations to anticipate, avoid, and adjust to shocks in their environment".

Discipline	Authors / Paper	Definition
Resilience in socio-ecological systems	Holling (1973) / Resilience and stability of ecological systems	“A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables”
	Walker et al. (2004) / Resilience, adaptability and transformability in social-ecological systems.	“The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedback.
Resilience in environmental systems	Tierney et al. (2007) / Conceptualizing and Measuring Resilience	“Both the inherent strength and ability to be flexible and adaptable after environmental shocks and disruptive events.”

7.6 Conclusion

Both practitioners and scholars have shown significant interest in asset management (AM) models and tools for developing economic frameworks that optimize a company's value chain. Effective decision-making requires striking a careful balance between competing considerations, such as costs and benefits, as well as opportunities and risks. Therefore, it is essential to thoroughly examine this subject to understand its implications fully and address the strategic demands it presents.

CHAPITRE 8

ARTICLE 2

The Functional Resonance Analysis Method A Performance Appraisal Tool for Risk Assessment and Accident Investigation in Complex and Dynamic Socio-Technical Systems

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Abstract – This article systematically reviews the development and application of the Functional Resonance Analysis Method (FRAM) over the past decade. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was used as a formal standard for data collection and analysis. A total of 47 relevant documents were retrieved from the Scopus database. The findings highlight the need for systemic safety assessment approaches to address performance variability in complex and dynamic sociotechnical systems, particularly in risk assessment and accident investigation. Assessing performance variability is critical in safety appraisals, as unexpected variations can interact in undesirable ways, posing threats to safety and human life. While FRAM offers several advantages, it also has limitations, as discussed in this review. Complementary methods may be required to enhance its effectiveness.

Keywords – Functional Resonance Analysis Method (FRAM), Resilience Engineering, Decision-Making, Strategic Asset Management, Risk Management, Industry 4.0, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

8.1 Introduction

The proper functioning of modern society relies heavily on complex and dynamic sociotechnical systems such as electrical power utilities, nuclear power plants, transportation networks, healthcare systems, railway grids, maritime mining and transportation systems, and oil and gas distribution systems. Traditionally, risk and accident investigations have focused on identifying failures or malfunctions and their propagation within these systems (Hollnagel, 2012; Diop et al., 2021). However, a growing body of research emphasizes studying *"work as done"* (everyday activities executed by practitioners) to understand how safety is achieved in practice, rather than solely relying on *"work as imagined"* by management or regulations (Hollnagel, 2012; de Vries, 2017).

Resilience Engineering (RE) has emerged as a pivotal approach in risk management and uncertainty analysis, focusing on a system's ability to adapt and maintain essential operations under dynamic and uncertain conditions Hollnagel (2013). The latter defines resilience engineering as *"the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions"*. This represents a shift from the traditional *Safety-I* philosophy, which focuses on preventing what goes wrong, to *Safety-II*, which examines why things go right. Understanding how sociotechnical work is achieved daily is critical for ensuring safety in complex environments.

The Functional Resonance Analysis Method (FRAM) was developed to address the limitations of traditional deterministic and probabilistic methods in analyzing complex sociotechnical systems. It aligns with the principles of resilience engineering, emphasizing that safety extends beyond the absence of failures (Hollnagel, 2012). FRAM models the variability of everyday performance, recognizing that such variability can interact and amplify, resulting in *"functional resonance"* – nonlinear effects analogous to stochastic resonance in signal processing (Hollnagel, 2012). Introduced in 2004, FRAM has since evolved as a systemic functional approach for analyzing safety and accidents in complex systems (Hollnagel, 2004; Hollnagel et al., 2008). It models not only why things fail but also why they succeed, offering insights into both retrospective analyses (e.g., accident investigations) and prospective analyses (e.g., risk management scenarios) (Patriarca et al., 2020). Unlike traditional models, FRAM does not make assumptions about system design, potential causes, or causal relationships. Instead, it examines how functions are coupled and how performance variability can propagate and resonate (Hollnagel, 2012; Patriarca et al., 2020).

Today, FRAM is widely applied across high-risk domains such as nuclear power, air traffic management, healthcare, railway systems, and maritime industries (Hollnagel, Woods, & Leveson, 2012; Hollnagel, 2018; Huang et al., 2019; Lee & Chung, 2018). It is supported by collaborative initiatives like the FRAMily network. Despite its growing popularity, there is a lack of systematic reviews examining the development and application of FRAM in complex sociotechnical systems, as noted by Patriarca et al. (2020). This article aims to fill that gap by systematically reviewing publications on FRAM over the past decade. Using the PRISMA guidelines, the study methodically collects and analyzes data to provide a comprehensive overview of FRAM's evolution and applications.

The remainder of the paper is structured as follows: Section II details the methodology of the literature review. Section III summarizes the results of the bibliometric analysis. Section IV discusses the key findings. Finally, Section V concludes the review and outlines future research directions.

8.2 Methodology

A systematic and critical literature search was conducted to map the state of the art on the topic. This review quantified the scientific output and evaluated its quality and impact. A computerized bibliometric analysis[††] was performed on papers published between January 1, 2011, and December 1, 2021, using the Bibliometrix tool to assess both the qualitative and quantitative aspects of research in the field.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were employed as a systematic literature review model to collect and process data (Moher et al., 2009). PRISMA provides a structured checklist to ensure transparency and replicability in the paper selection process. Figure 8.1 illustrates the PRISMA framework applied for this study. Data was systematically retrieved from the Scopus database on December 15, 2021. To ensure comprehensive coverage, a backward analysis was also conducted to evaluate publication trends related to the Functional Resonance Analysis Method (FRAM) in complex and dynamic sociotechnical systems. The query string used for the search was defined as:

[††] 3"Bibliometrics is usually used for the quantitative research assessment of academic output, and it is starting to be used for practice-based research. Concretely, bibliometrics is a set of methods used to study or measure texts and information, especially in big datasets" (Cobo et al., 2011).

Title *("resilience" and "functional resonance analysis method")*
OR
Title *("functional resonance analysis method")*
AND
pub year > 1999
AND
Limit-to *(language, "English")*

This search initially retrieved 47 papers specifically addressing the development and application of FRAM within the last decade.

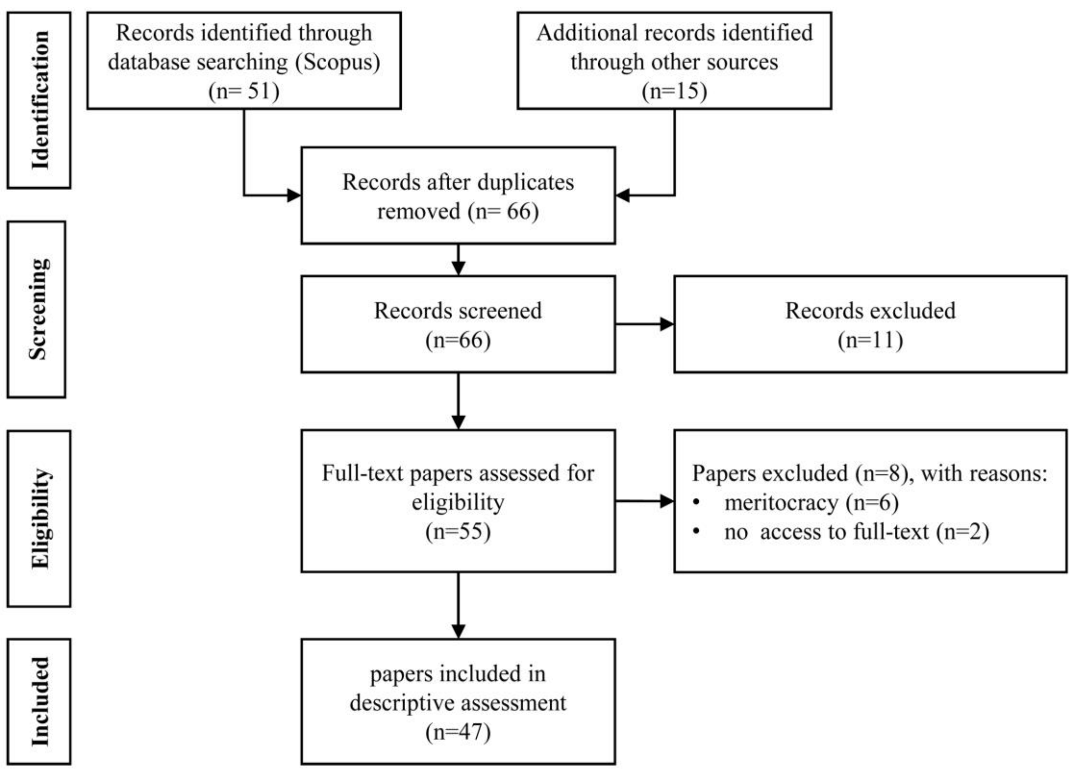


Figure 8.1. PRISMA approach for the literature search
(Source: own representation)

Further analysis was conducted to determine the relevance of each document. The abstract and keywords of each paper were examined to assess its appropriateness. Papers deemed relevant were selected for full reading and detailed investigation. Additionally, a snowball approach was applied by reviewing the references cited in the initially selected papers to identify additional relevant studies. Documents were included in the analysis if they met the following criteria: (1) published as a journal paper, conference paper, or book. (2) written in English. (3) focused on FRAM, as indicated by their abstract. Each document was read in its entirety to confirm its suitability for this review. The selected manuscripts, including their metadata, were exported to the reference management software Endnote and converted into an R data frame using the open-source R package BIBLIOMETRIX (Aria & Cuccurullo, 2017).

To maintain a concise review, not all papers were discussed in detail. Only the most relevant and significant studies were analyzed thoroughly to ensure the review remains focused and within appropriate length.

8.3 Results – Descriptive Analysis

The descriptive analysis outlines the annual research progress, leading authors, influential papers, contributing countries, and the most relevant keywords. This section presents the outcomes of the bibliometric analysis, highlighting research trends and academic collaboration networks. It provides a detailed mapping of annual research growth, topic structure (e.g., co-occurrence networks, thematic maps, social structures), and key metrics, including the most productive authors, impactful papers, prominent countries, frequently recurring keywords, and Keywords Plus[‡‡].

8.3.1 Main Findings about the Collection

Table 8.1 summarizes the key findings related to the collection of studies on the Functional Resonance Analysis Method (FRAM). Figure 8.2 illustrates the annual scientific production in this field, revealing an annual growth rate of 6.5%. A notable decline in publications occurred between 2018 and 2019, followed by a significant peak in 2021. This upward trend underscores the increasing interest in applying the FRAM methodology to assess complex and dynamic sociotechnical systems, particularly those characterized by high mishap hazards. The metrics suggest that the annual number of publications during the survey period remained relatively stable, indicating steady research activity in this area (Afuye et al., 2021; Ellegaard & Wallin, 2015).

[‡‡] "*Keywords*: Author Keywords, those provided by the original authors. *Keywords Plus*: those extracted from the titles of the cited references. *Keywords Plus*, generated by an automatic computer algorithm, are words or phrases that appear frequently in the titles of an article's references and not necessarily in the title of the article or as Author Keywords" (Zhang et al., 2016).

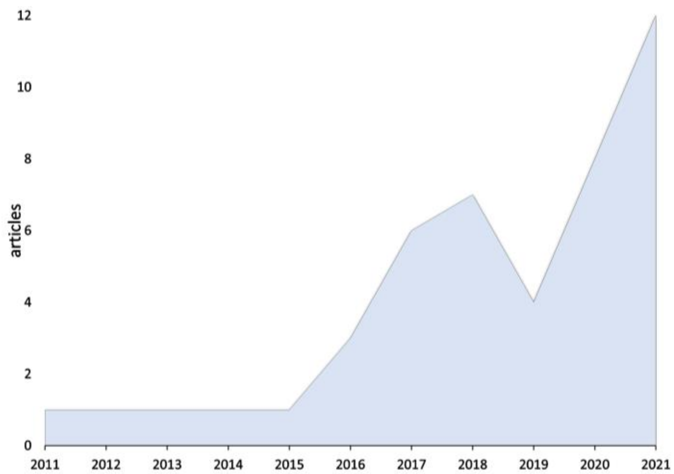


Figure 8.2. Annual scientific production
(Source: own representation)

Table 8.1. Main findings about the collection on FRAM
(Source: own representation)

COLLECTION	
Description	*Results*
Timespan	2011:2022
Sources (journals, books, etc.)	29
Documents	47
Average years from publication	2.43
Average citations per documents	131.4
Average citations per year per doc.	23.01
References	2043

DOCUMENT TYPES	
Description	*Results*
Article	30
Book	1
Book chapter	1
Conference paper	12
Review	3

AUTHORS	
Description	*Results*
Authors	151
Author appearances	179
Authors of single-authored docs.	3
Authors of multi-authored docs.	148

AUTHORS COLLABORATION	
Description	*Results*
Single-authored documents	3
Documents per author	0.311
Authors per document	3.21
Co-authors per documents	3.81
Collaboration index	3.36

DOCUMENT CONTENTS	
Description	*Results*
Keywords Plus (ID)	416
Author’s keywords (DE)	112

Table 8.2 lists the most relevant sources, with Reliability Engineering and System Safety ranking first with 8 publications, followed by Safety Science and Cognition Technology and Work with 6 and 4 publications, respectively. Figure 8.3 illustrates source clustering based on Bradford's law, revealing that a small number of core journals, such as Reliability Engineering and Safety Science, dominate the field by publishing the most relevant articles. This analysis highlights a clear distribution pattern, demonstrating the concentration of knowledge in these key sources.

Table 8.2. Most relevant sources
(Source: own representation)

Sources	Papers	Impact Factor[§§]	H-index[***]	SJR[†††]	SNIP[‡‡‡]
Reliability Engineering and System Safety	8	7.030	146	1.761	2.707
Safety Science	6	4.877	111	1.178	2.473
Cognition Technology and Work	4	2.920	36	0.518	1.430
Applied Ergonomics	2	4.170	98	1.093	2.489
Lecture Notes in Mechanical Engineering	2	0.55	16	0.150	0.287

[§§] *Impact Factor*: "The number of citations of articles published in the source journal in the preceding two years divided by the number of items published in that journal in the previous two years".

[***] The h-index attempts to "*measure both the productivity and impact of the published work of a scientist or scholar*". "*A scientist has index h if h of his or her N_p papers have at least h citations each and the other* (N_p-*h*) *papers have ≤h citations each*" (Hirsch, 2005).

[†††] *SCImago Journal Rank* (*SJR*): "SJR is weighted by the prestige of a journal. Subject field, quality, and reputation of the journal have a direct effect on the value of a citation".

[‡‡‡] *SNIP* (*Source Normalized Impact per Paper*): SNIP measures a source's contextual citation impact by weighting citations based on the total number of citations in a subject field. It helps you make a direct comparison of sources in different subject fields.

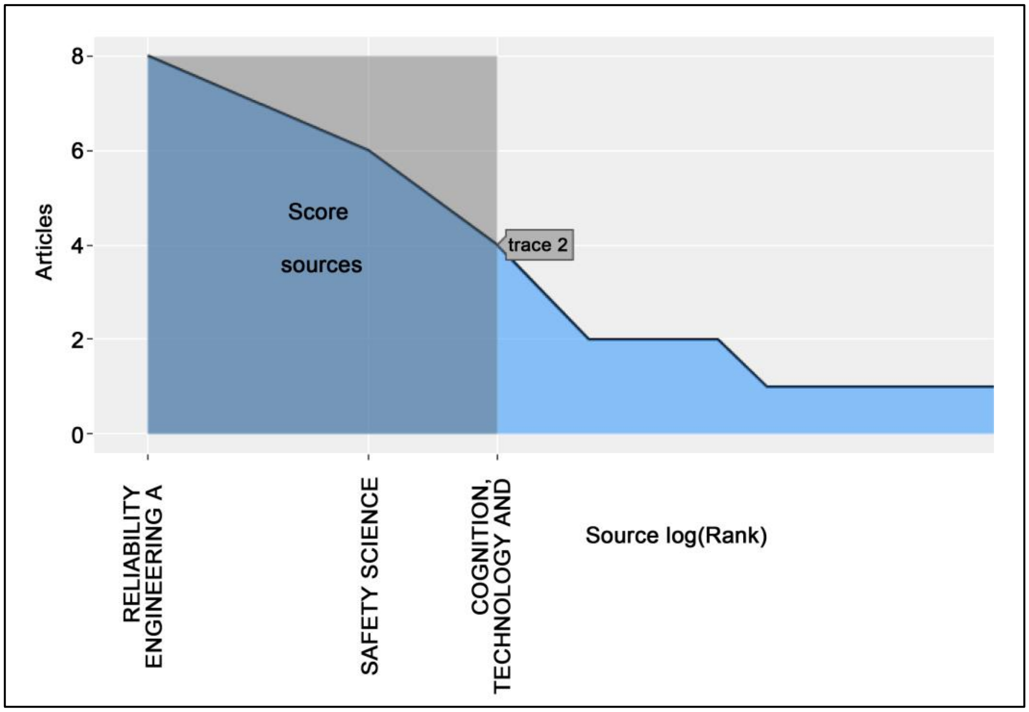


Figure 8.3. Source clustering through Bradford's law
(Source: own representation)

8.3.2 Authors Impact

Table 8.3 presents the most relevant authors, with Costantino F., Di Gravio G., Patriarca R., and Hollnagel E. ranking first, followed by Kaya G.K. and Haddad A.N. Table 8.4 highlights the most cited authors, where Hollnagel E. leads with 608 citations, followed by Costantino F., Di Gravio G., and Patriarca R.

Table 8.3. Most productive authors
(Source: own representation)

Authors	Articles	Total link strength[§§§]	Authors	Articles	Total link strength
Costantino F.	4	156	De Carvalho P.V.R.	2	108
Di Gravio G.	4	156	Haddad A.N.	2	52
Patriarca R.	4	156	Smoczyński P.	2	26
Hollnagel E.	4	82	Bellini E.	2	7
Kaya G.K.	3	47	McCloskey R.	2	28

Table 8.4. Most cited authors
(*Source*: *own representation*)

Authors	Citations	Total link strength	Authors	Citations	Total link strength
Hollnagel E.	608	82	Rosa L.V.	53	52
Costantino F.	181	156	Bellini E.	42	7
Di Gravio G.	181	156	Nesi P.	42	7
Patriarca R.	181	156	Tronci M.	39	34
De Carvalho P.V.R.	163	108	Pardo-Ferreira, M.D.C.	36	62
Haddad A.N.	55	52	Kaya G.K.	20	47

[§§§] "A link is a connection or a relation between two items. Items are the objects of interest, items may for example be publications, researchers, or terms. Each link has a strength, represented by a positive numerical value. The higher this value, the stronger the link" (Van Eck & Waltman, 2013).

Figure 8.4 illustrates the citation network within the collection of papers, showing how authors are interconnected in this specific field of research.

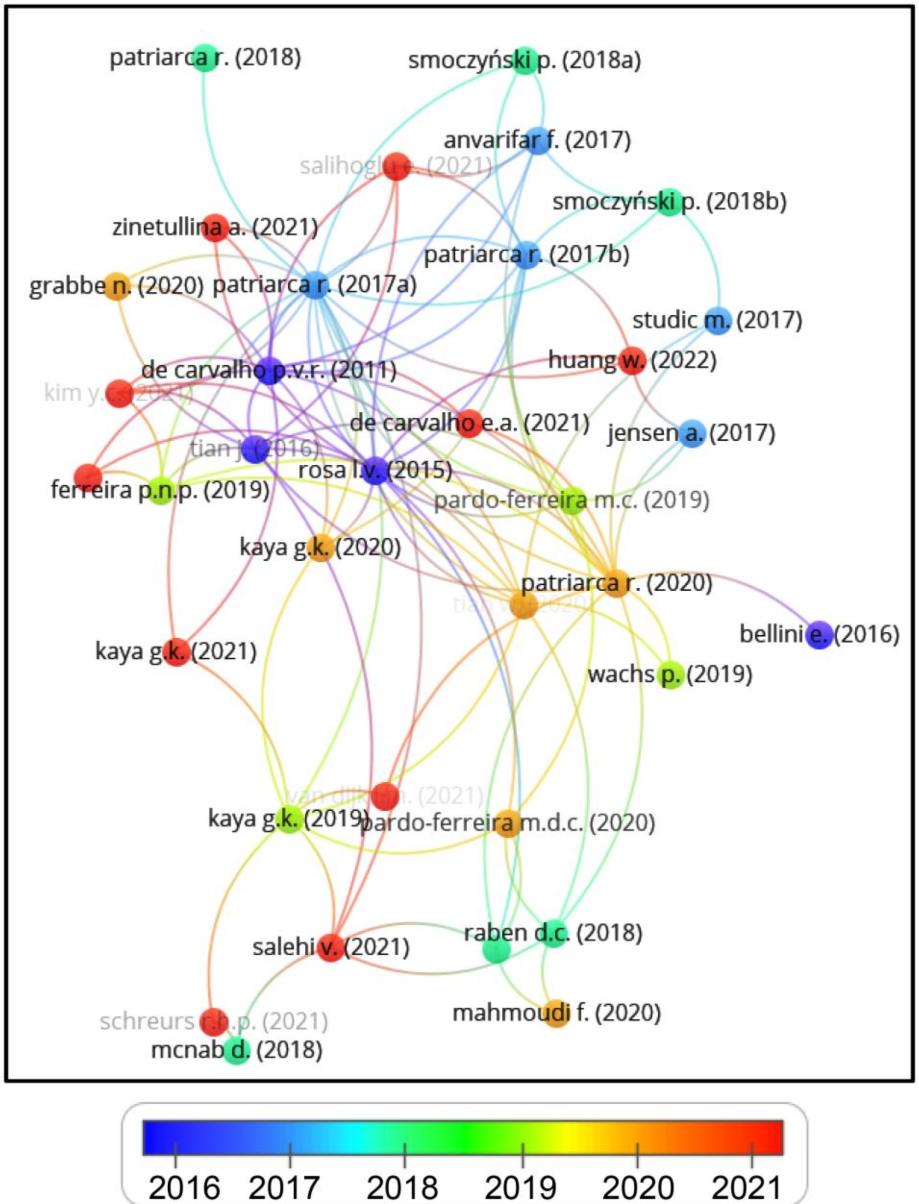


Figure 8.4. Citation network *(Source: own representation)*

Figure 8.5 depicts the top authors' production over time, where each line represents an author's timeline. A bubble on a specific year indicates that the author published at least one paper that year. The bubble size corresponds to the number of papers published, while the color intensity reflects the total number of citations per year for the documents published in that year.

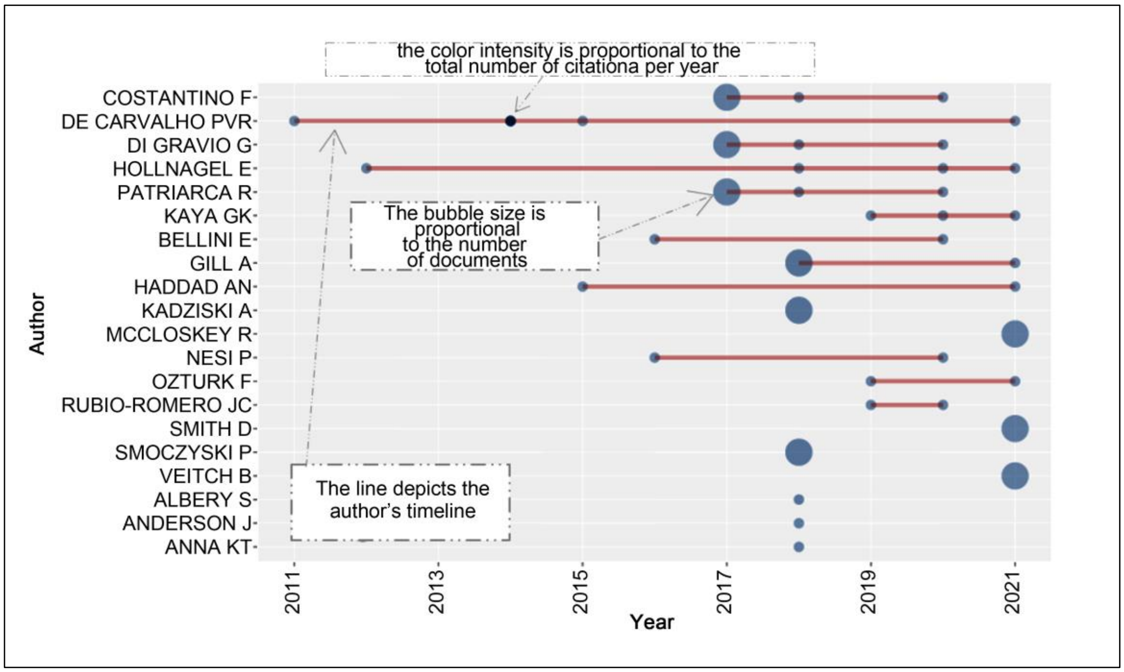
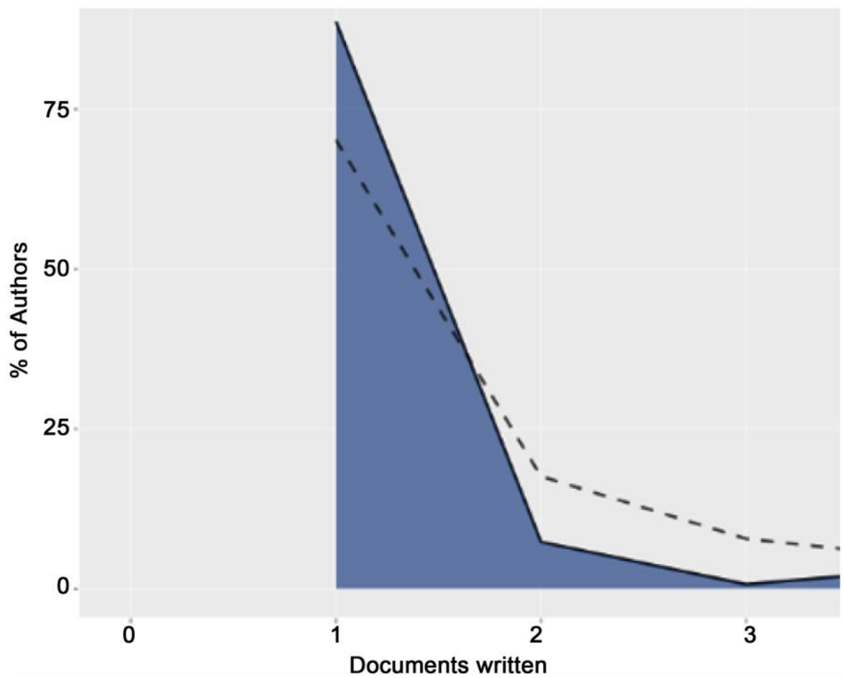


Figure 8.5. Top-authors' production over the time
(Source: own representation)

Figure 8.6 visualizes author productivity using Lotka's law, which describes the frequency of publication by authors in a given field. As the number of publications increases, the number of authors producing that many publications decreases (Lotka, 1926). According to this analysis, only 3.30% of authors have published four papers, while most (88.70%) have authored just one paper. The general formula for Lotka's law is expressed as: $Y = C/X^n$ where X is the number of publications, Y the relative frequency of authors with X publications, and n and C are constants depending on the specific field *(n≈2n)*.



Documents written	N. of authors	Proportion of authors
1	134	0.887
2	11	0.073
3	1	0.007
4	5	0.033

Figure 8.6. Author productivity through Lotka's law
(Source: own representation)

8.3.3 Social Structure – Collaboration Analysis

The collaboration analysis provides insights into how authors and countries interact within a specific research domain. Figure 8.7 illustrates the author collaboration network (co-author network), classified into four clusters[****]. This analysis identifies research groups and pivotal authors. The strength of a link in the network depends on the degree of collaboration between authors; stronger relationships are represented by thicker edges.

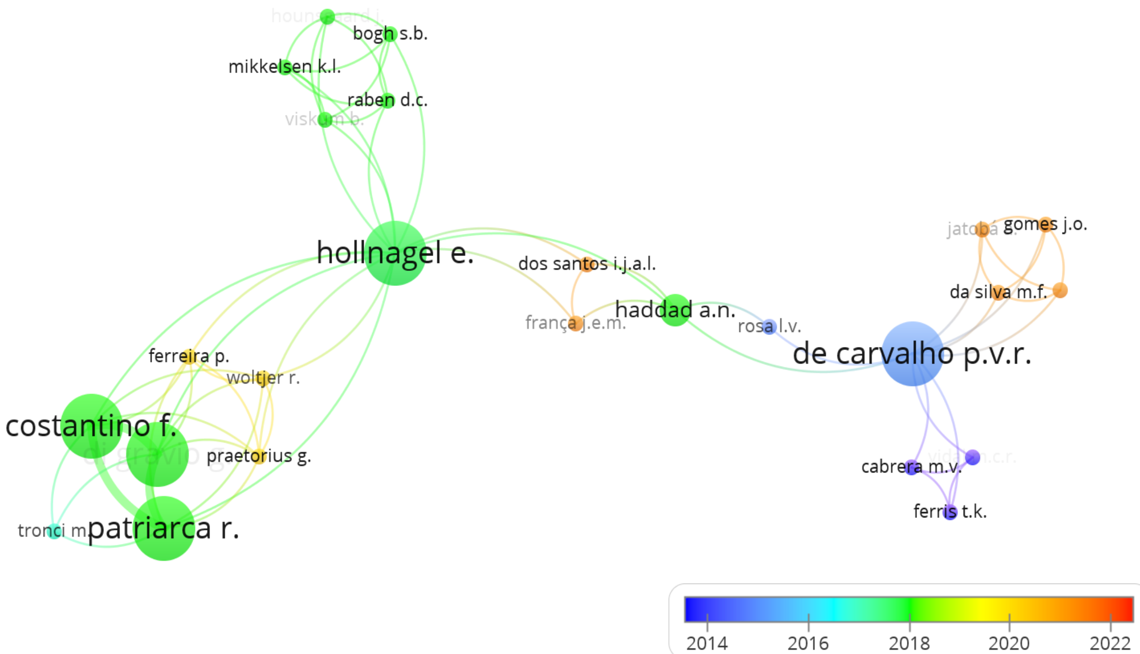


Figure 8.7. Co-authorship analysis (scores: average papers per year)
(Source: own representation)

[****] "The size of the label and the circle of an item is determined by the weight of the item. The higher the weight of an item, the larger the label and the circle of the item. The color of an item is determined by the cluster to which the item belongs. The closer two items are located to each other, the stronger their relatedness" (Lundblad et al., 2008).

Figure 8.8 depicts the authors' bibliographic coupling, also categorized into four clusters. Bibliographic coupling measures the relatedness of authors based on the number of references they share or cite. As Martyn (1964) explains, *"Bibliographic coupling occurs when two works reference a common third work in their bibliographies"*, indicating a potential connection in subject matter.

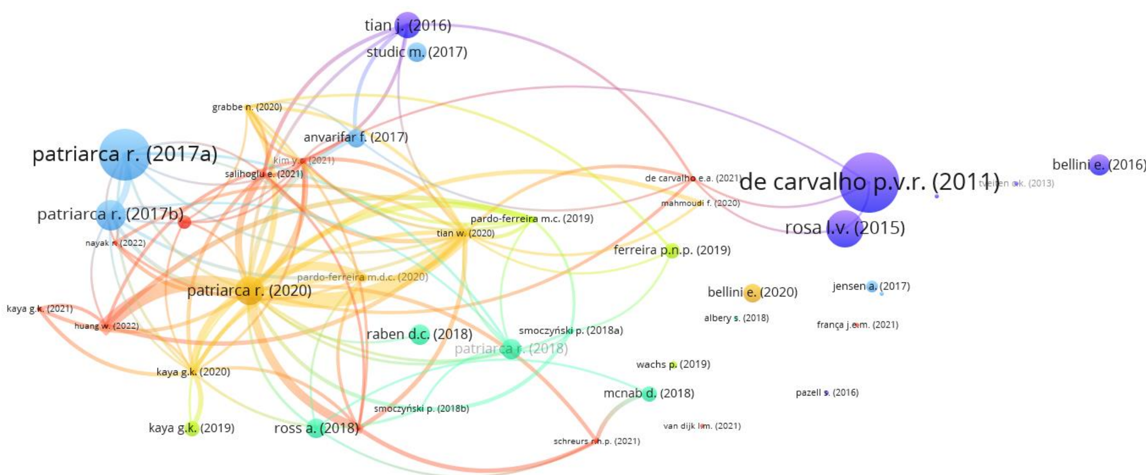


Figure 8.8. Authors bibliographic coupling
(Source: own representation).

Figure 8.9 and Table 8.5 detail the most relevant countries based on the nationalities of corresponding authors. These figures show the number of published papers in Single Country Publications (SCP) and Multiple Country Publications (MCP). Brazil, Italy, and Turkey rank first with the highest number of papers. SCP documents exhibit a higher productivity growth trend. Table 8.6 lists the most cited countries, while Figure 8.10 presents their bibliographic coupling, grouped into three clusters:

- *Cluster 1:* Canada, China, Denmark, Germany, Kazakhstan, Netherlands, Poland, South Korea, Spain, Turkey, United Kingdom.
- *Cluster 2:* Australia, Italy, Norway, Portugal, Sweden.
- *Cluster 3:* Brazil, United States.

The citation analysis explores the structure of the research field through connections between countries, helping to uncover conceptual structures and the evolution of themes over time. Collaboration networks further reveal how countries interact within the research topic, highlighting global partnerships and contributions.

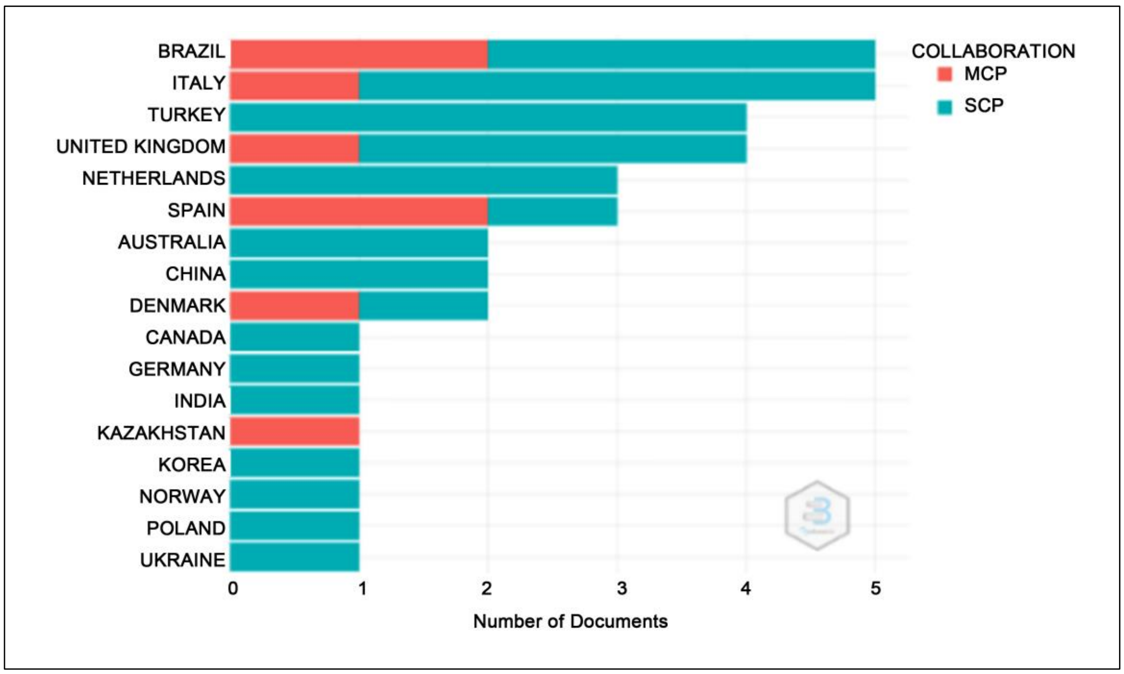


Figure 8.9. Most relevant countries by corresponding author
(SCP: Single Country Publications, MCP: Multiple Country Publications)
(Source: own representation)

Table 8.5. Most relevant countries by corresponding authors

(Source: own representation)

Country	Freq	SCP	MCP	MCP Ratio	Country	Freq	SCP	MCP	MCP Ratio
Brazil	0.1316	3	2	0.40	Ukraine	0.0263	1	0	0.00
Italy	0.1316	4	1	0.20	China	0.0526	2	0	0.00
Turkey	0.1053	4	0	0.00	Denmark	0.0526	1	1	0.50
United Kingdom	0.1053	3	1	0.25	Canada	0.0263	1	0	0.00
Netherlands	0.0789	3	0	0.00	Germany	0.0263	1	0	0.00
Spain	0.0789	1	2	0.67	India	0.0263	1	0	0.00
Australia	0.0526	2	0	0.00	Kazakhstan	0.0263	0	1	1.00
Norway	0.0263	1	0	0.00	Korea	0.0263	1	0	0.00
Poland	0.0263	1	0	0.00	Norway	0.0263	1	0	0.00

Table 8.6. Most cited countries *(Source: own representation)*

Country	Total citations	Documents	Total link strength
Sweden	566	3	17
Denmark	570	2	10
Germany	549	2	3
France	548	1	0
Italy	223	6	54
Brazil	171	6	52
United Kingdom	63	5	26
Australia	62	8	31
Portugal	51	2	25
Norway	48	3	22

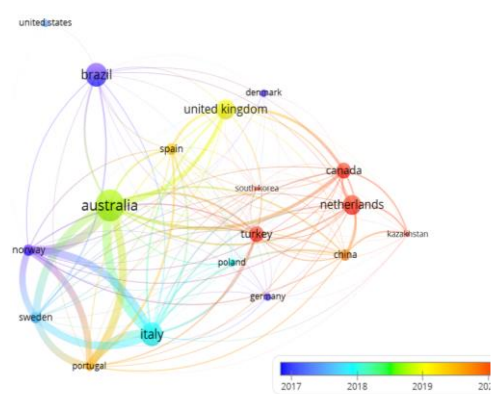


Figure 8.10. Bibliographic coupling of countries *(Source: own representation)*

8.3.4 Conceptual Structure – Co-Word Analysis

This section examines the word treemap and the clusters of the most popular keywords. Figure 8.11 illustrates the co-word network visualization based on the co-occurrence of author keywords. Co-word networks reveal the conceptual structure by mapping relationships between keywords, thereby indicating themes or topics within the document. Each node represents a keyword, and the size of the link reflects the strength of the relationship between them. This analysis helps identify the intellectual domain of FRAM and highlights research hotspots for future studies.

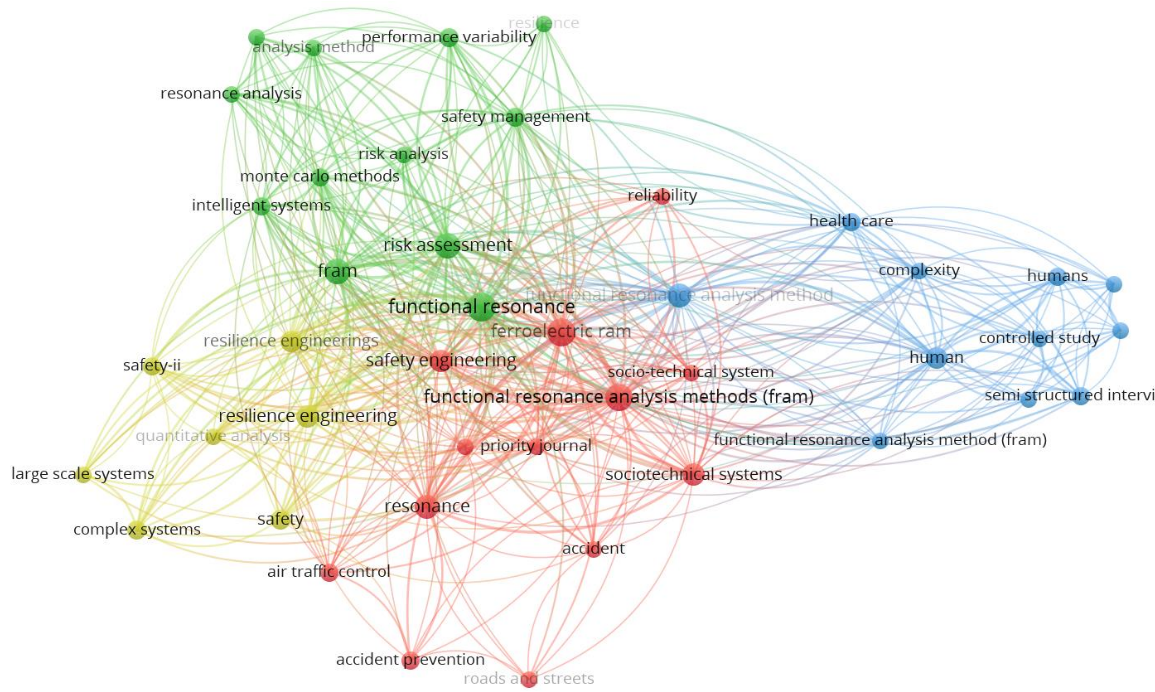


Figure 8.11. Network visualization of the co-word analysis through keyword co-occurrences
(Source: own representation)

Figures 12 and 13 present the treemap visualizations for the most pivotal author keywords (DE) and Keywords Plus (ID) associated with FRAM analyses, respectively. The word treemap outlines prominent themes and dynamic trends, providing insights into key topics and their evolution over time (Cobo et al., 2011). This is essential for identifying hot themes within the research domain.

Figure 8.14 depicts the Three-Fields Plot using three items: Country (AU_CO), Authors (AU), and Author Keywords (DE).

Figure 8.12. Tree-Map (Most relevant words (Author's Keywords))
(Source: own representation)

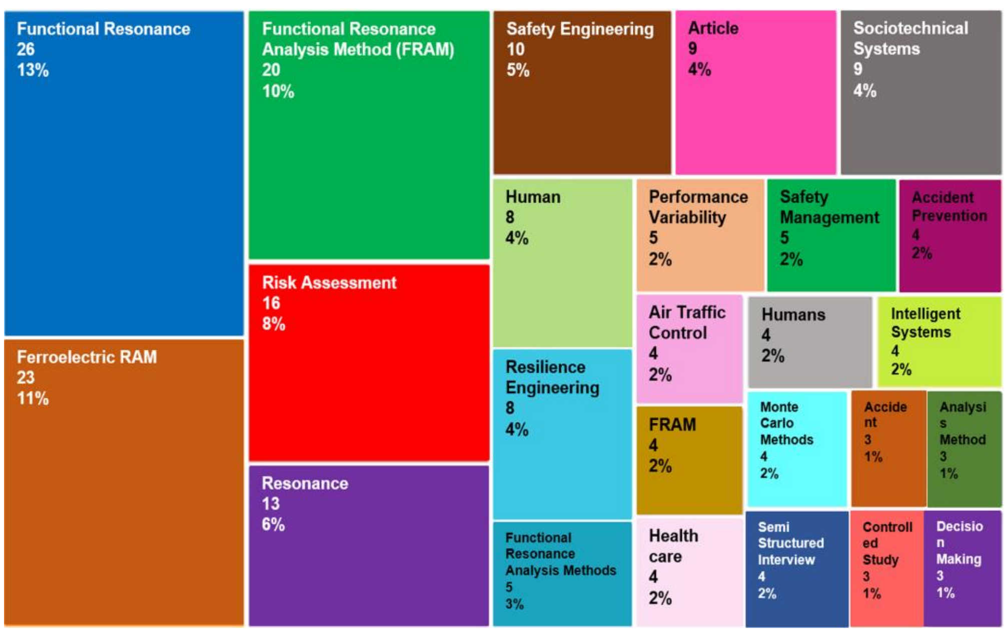


Figure 8.13. Tree-Map (Most relevant words (Keywords Plus)) *(Source: own representation)*

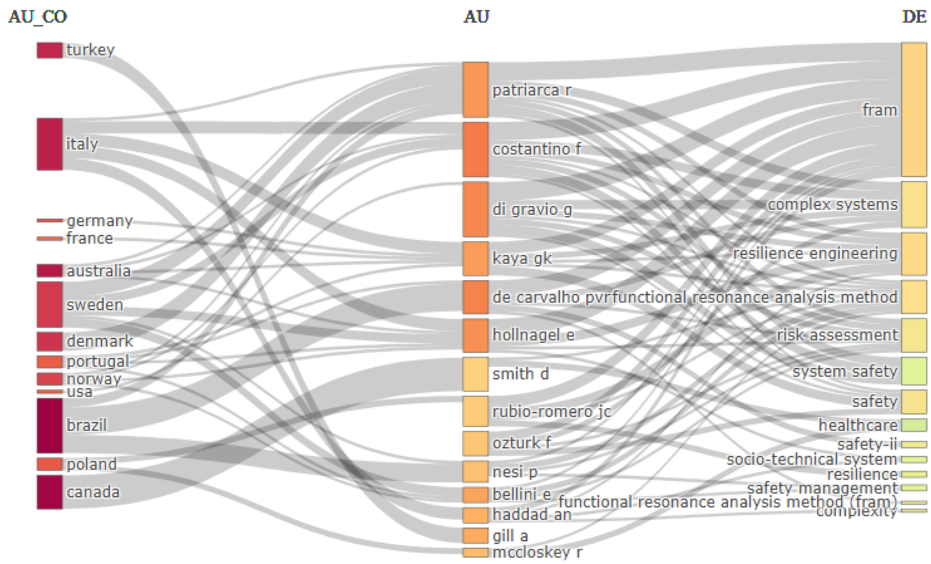


Figure 8.14. Three-Fields Plot: Country (AU_CO), Authors (AU), Keywords (DE)
(Source: own representation)

8.3.5 Thematic Map

Clusters identified through the co-word analysis are categorized as themes based on their density and centrality in a two-dimensional diagram (Cobo et al., 2011; Aria & Cuccurullo, 2017). These themes are analyzed according to the quadrant in which they are positioned. Figure 8.15 illustrates the thematic map with seven clusters derived from the centrality and density[††††] ranking of Keywords Plus.

- The *motor themes* (first quadrant: high centrality and high density) are well-developed and pivotal for shaping the research area. This cluster includes keywords such as human, functional resonance analysis method, health care, delivery of health care, health care personnel, semi-structured interview, and controlled study.
- A cluster bridging *motor themes and basic themes* (good centrality and density) includes highly recurring words such as functional resonance analysis method, ferroelectric RAM, risk assessment, safety engineering, sociotechnical systems, resilience engineering, performance variability, and safety management.
- The *niche themes* (second quadrant: low centrality and high density) are highly specialized but isolated, featuring only the term complex processes, which holds limited relevance to the broader research field.
- The *emerging or declining themes* (third quadrant: low centrality and low density) are weakly studied, with recurring words such as oil spills and urban transportation.
- The *basic and transversal themes* (fourth quadrant: high centrality and low density) span general and diverse research topics. Keywords include accident prevention, accident analysis, aircraft accidents, air traffic control, roads and streets, advanced traffic management systems, air transportation, automation, and behavioral research.
- Lastly, a cluster bridging *motor themes and niche themes* (good centrality and high density) includes the single term uncertainty analysis.

[††††] “The centrality is the degree of interaction of a network cluster in comparison with other clusters and gives information about the importance of a theme. The density measures the internal strength of a cluster network, and it can be assumed as a measure of the theme’s development” (Aria & Cuccurullo, 2017).

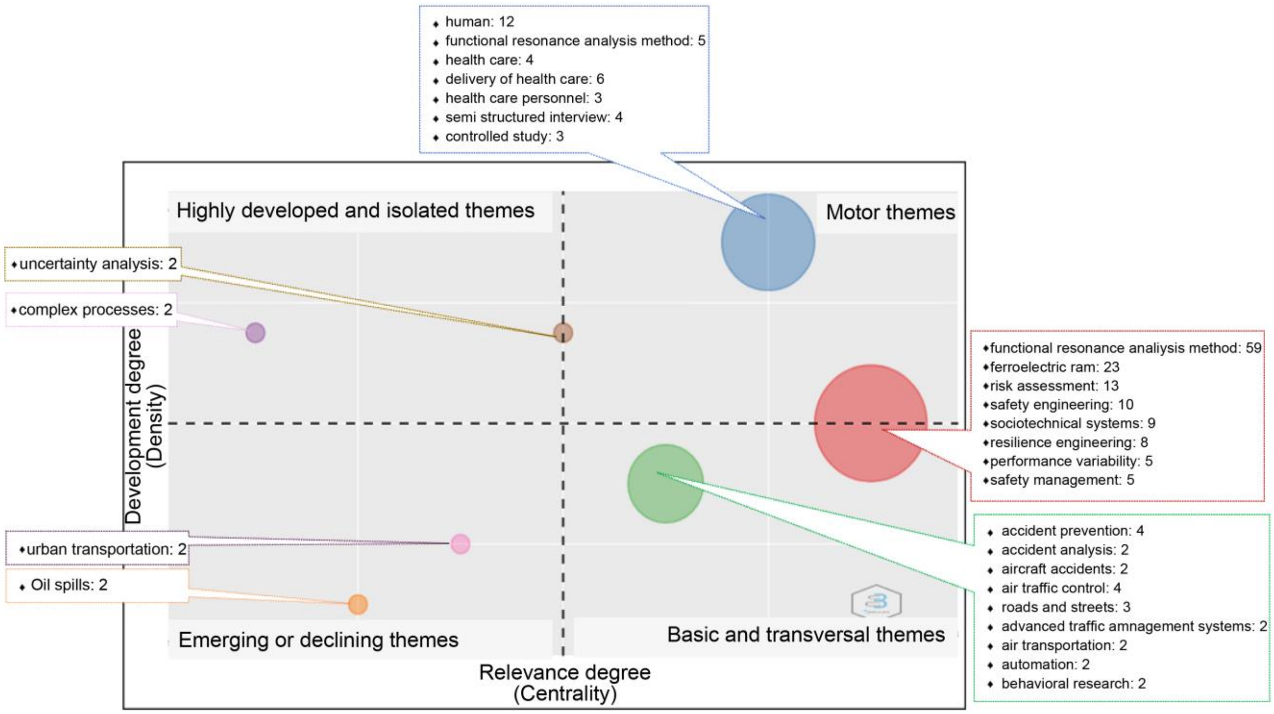


Figure 8.15. Thematic map displaying clusters and Keywords Plus
(Source: own representation)

8.4 Discussion

This study presents a comprehensive bibliometric review of the application of the Functional Resonance Analysis Method (FRAM) for assessing performance variability in complex and dynamic socio-technical systems. The discussion addresses the strengths and limitations of the FRAM approach and compares it with other assessment methods.

8.4.1 The FRAM Approach

The FRAM methodology is increasingly recognized as a valuable tool for analyzing performance variability in high-hazard, complex, and dynamic socio-technical systems (for e.g.: de Vries, 2017; De Carvalho, 2011; Adriaensen et al., 2019; Aguilera et al., 2016; Albery et al., 2016; Anvarifar et al., 2017; Belmonte et al., 2011; Bjerga, et al., 2016; Buikstra et al., 2020; Clay-Williams et al., 2015; Costantino et al., 2018; Duan et al., 2015; Falegnami et al., 2019; Praetorius et al., 2015; Ferreira. & Cañas, 2019; França et al., 2019; Gattola et al., 2018; Smith et al., 2020; Jensen & Aven, 2017; Furniss et al., 2016; Gao et al., 2019). As a performance appraisal tool for risk assessment and accident investigation, FRAM aligns with the principles of Resilience Engineering (RE) and adopts the Safety-II perspective, which focuses on understanding how systems succeed rather than merely analyzing failures (Safety-I). Unlike traditional methods such as Failure Mode and Effects Analysis (FMEA), which emphasize potential failures, FRAM emphasizes identifying essential functions and their interactions to ensure system objectives are met.

FRAM provides a framework for describing socio-technical systems in terms of their functions and the interactions between them. This approach enables the investigation of performance variability to identify potential pathways for functional resonance – where variability propagates and potentially leads to unforeseen and undesirable outcomes. **This focus on variability reflects the core tenet of RE: safety is not merely the absence of failures but the ability of systems to adapt to disturbances while maintaining essential performance** (Hollnagel, 2012; Cabrera et al., 2014).

The primary objectives of FRAM are to understand how functions become coupled and how everyday performance variability resonates across the system. It is not a prescriptive model, but a method rooted in four principles of RE (Hollnagel, 2012): *(1)*

Equivalence of Success and Failure[‡‡‡‡] – success and failure stem from the same underlying processes. *(2) Approximate Adjustments*[§§§§] – systems adapt to external demands, often operating near the limits of performance. *(3) Emergence*[*****] – system behavior results from the interaction of its components, not merely their individual actions.

[‡‡‡‡] *"Equivalence of successes and failures:* Whenever something is done, the intention is always to do something right and never to do something wrong. For each action, the choice of what to do is determined by many different things, including competence, understanding of the situation, experience, habit, demands, available resources, and expectations about how the situation may develop – not least about what others may do. If the expected outcome is obtained, the next action is taken, and so on. But if the outcome is unexpected, then the preceding action is re-evaluated and classified as wrong rather than right, as an error or as a mistake, using the common but fallacious post hoc ergo propter hoc argument. With hindsight, it is pointed out what should have been done, if only people had made the necessary effort at the time. The whole argument is, however, unreasonable because the action was chosen based on the expected rather than the actual outcome. Failures and successes are equivalent in the sense that we can only say whether the preceding action was right or wrong after the outcome is known. That changes the judgement of the action, but not the action itself" (Hollnagel, 2016).

[§§§§] "Approximate adjustments: When working conditions are underspecified or when time or resources are limited, it is necessary to adjust performance to match the conditions. This is a main reason for performance variability. But the very conditions that make performance adjustments necessary also mean that the adjustments will be approximate rather than perfect. The approximations are, however, under most conditions good enough to ensure successful performance" (Hollnagel, 2016).

[*****] Emergence: the meaning of emergence is not that something happened "magically", but simply that it happens in such a way that it cannot be explained using the principles of decomposition and causality (Hollnagel, 2016).

(4) Functional Resonance[†††††] – performance variability can amplify through interactions, leading to unexpected outcomes. These principles guide FRAM's structured methodology, outlined in four core steps (Figure 8.16). Before these steps, *Step 0 (Preliminaries)* is critical for defining the analysis objective, which typically falls into one of two categories: *(i) Risk Assessment* – describing systems to identify potential hazards (e.g., Rosa et al., 2015). *(ii) Accident Investigation* – probing causes and drawing conclusions from past incidents (e.g., De Carvalho, 2011; Herrera & Woltjer, 2010).

FRAM's strengths lie in its ability to model complex interactions and emphasize variability's role in system behavior. However, its application requires expertise and significant effort to map functions and their interactions, which may limit its practical use in certain contexts.

[†††††] "Resonance: In physical systems, classical (or mechanical) resonance refers to the phenomenon that a system can oscillate with larger amplitude at some frequencies than at others. These are known as the system's resonant (or resonance) frequencies. At these frequencies even small external forces that are applied repeatedly can produce large amplitude oscillations, which may seriously damage or even destroy the system. Functional resonance is defined as the detectable signal that emerges from the unintended interaction of the everyday variability of multiple signals. The signals are usually subliminal, both the 'target' signal and the combination of the remaining signals that constitutes the noise. But the variability of the signals is subject to certain regularities that are characteristic for different types of functions, hence not random or stochastic. Since the resonance effects are a consequence of the ways in which the system functions, the phenomenon is called functional resonance rather than stochastic resonance" (Hollnagel, 2016).

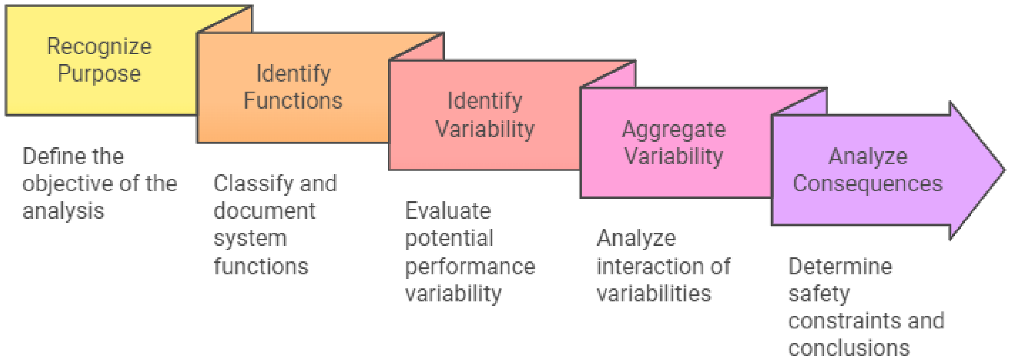


Figure 8.16. Main steps of the FRAM approach
(Source: own representation based on Hollnagel (2012))

8.4.2 Alternative or Complementary Assessment Methods to the FRAM Process

This section evaluates some of the most established methods for risk assessment and management that can serve as alternatives or complements to the FRAM process. These methods include Failure Mode and Effect Analysis (FMEA), AcciMap, Systems-Theoretic Accident Model and Processes (STAMP), Management Oversight and Risk Tree (MORT), Root-Cause Analysis (RCA), and Human Reliability Assessment (HRA). Table 8.7 summarizes these alternative techniques, focusing on their key attributes, such as whether they are qualitative (QL) or quantitative (QT) and whether they adopt a proactive (P) or reactive (R) approach. This comparison provides insights into the suitability of each method for various risk management contexts.

Table 8.7. Alternative risk assessment techniques compared to FRAM
(Source: own representation)
QL: Qualitative approach. QT: Quantitative. P: Proactive approach. R: Reactive approach

Methods	Description	Application	QL/QT	P/R
Functional Resonance Analysis Method (FRAM)	It is used to analyze occupational activities either retrospectively (e.g., accident or event analysis) or prospectively (e.g., current work domains or envisioned scenarios for risk management). It examines how work is performed daily to understand the factors leading to both successes and failures (Hollnagel, 2012; Patriarca et al., 2020). *Strengths:* it is highly effective for modeling and interpreting complex systems. It emphasizes the intricate interplay of functions and the contextual factors that influence system performance, offering a holistic understanding of the system. *Limitations:* it lacks quantitative elements, making it unsuitable for tasks like sensitivity analysis. The method can also be time-consuming, and the couplings between functions may be overly complex to model effectively. *Integration with Other Methods:* in some cases, combining FRAM with complementary approaches, such as Failure Mode and Effects Analysis (FMEA), can enhance its applicability and practical value (Melanson & Nadeau, 2019).	It has been applied across various high-risk fields, including nuclear power, aircraft deicing, air traffic management, safety assessment, healthcare, railway traffic. maritime mining, maritime transportation. Key studies and references supporting its use include Hollnagel (2012, 2018), Hollnagel, Woods, & Leveson (2012), Hollnagel et al. (2014), Hounsgaard (2016), Huang et al. (2019), Lee & Chung (2018), Macchi (2010), Nemeth & Hollnagel (2016), and Slater et al. (2022).	QL	P, R
Systems-Theoretic Accident Model and Processes (STAMP)	It focuses on accidents caused by inadequate control in complex socio-technical systems. It emphasizes interactions, emergent behavior, and system-wide safety constraints, going beyond traditional component-level analyses. *Strengths:* it offers a comprehensive approach by addressing technical, human, and organizational factors. It proactively identifies hazards, captures emergent risks from system interactions, and is adaptable across industries. *Limitations:* it can be complex and resource-intensive, relying on detailed system knowledge and analysts' expertise. It lacks inherent risk quantification, requires significant training, and faces scalability challenges in large systems. *Integration with Other Methods:* it complements traditional safety tools (e.g., FTA, FMEA, Bow-Tie Analysis) by offering a systemic perspective that improves hazard identification and control. It aligns with resilience engineering to enhance adaptability and system management.	It is suited for complex systems like software, aviation, space, human factors, organizational design, medical, defense, and nuclear industries. Key references include Allison et al. (2017), Ferjencik (2011), and Ouyang et al. (2010), which highlight its theoretical framework and practical applications.	QL	P, R

Continued

Methods	Description	Application	QL/QT	P/R
Failure Mode and Effect (Criticality) Analysis (FMEA / FMECA):	FMEA is a systematic approach used to identify potential failure modes in systems, processes, or products, assess their effects, and prioritize mitigation strategies (Dai et al., 2011). When expanded to FMECA, it incorporates criticality analysis to rank failures based on their severity, likelihood, and detectability. *Strengths:* FMEA/FMECA offers several strengths, including its proactive nature, systematic structure, emphasis on cross-functional collaboration, ability to prioritize risks, and contributions to improving safety and reliability. *Limitations:* it also has limitations, such as the subjectivity of scoring, its time-consuming nature, dependency on team expertise, and challenges in managing complex systems or unforeseen failure modes (Patriarca et al., 2020; Das et al., 2018). *Integration with Other Methods:* to address its limitations, FMEA/FMECA is often integrated with other methods (Melanson & Nadeau, 2019; Das et al., 2018; Sujan & Felici, 2012). For example, it can be used in Reliability-Centered Maintenance (RCM) to optimize maintenance tasks or combined with FTA for deeper root cause analysis.	FMEA/FMECA is widely applied across various industries to enhance reliability, safety, and quality. It is extensively used in fields such as manufacturing, military, space applications, healthcare, and the construction industry (Melanson & Nadeau (2019), Das et al. (2018), Sujan & Felici (2012), Rausand & Hoyland (2004), Chiozza & Ponzetti (2009), and Abdelgawad & Fayek (2010)).	QL, QT	P
Root-Cause Analysis (RCA)	RCA is a systematic method for identifying the underlying causes of problems to address them at their source rather than treating symptoms (Rasmussen et al.,1994; Johnson, 1973). *Strengths:* its strengths lie in its structured approach, prevention-oriented focus, adaptability, and promotion of continuous improvement and collaboration. *Limitations:* it can be time-consuming, requires expertise, and depends heavily on data quality, with a risk of overlooking secondary factors. In contrast to the FRAM, RCA does not provide a deeper understanding of the complexity of processes or the couplings within work settings. Additionally, there may be more than one root cause for a malfunction (Patriarca et al., 2020; Alm & Woltjer, 2010; Nakajima, 2017). *Integration with Other Methods:* RCA often integrates with other methods like FMEA, RCM, Six Sigma, and Lean practices, as well as tools like Ishikawa diagrams, the 5 Whys technique, and fault tree analysis, enhancing its effectiveness in solving complex problems and improving systems.	RCA is particularly valuable in fields such as risk management in the nuclear industry, IT, industrial process control, accident analysis, and telecommunications, as documented in studies by Appicharla (2011), Alm and Woltjer (2010), and Nakajima (2017).	QL	P
Fault Tree Analysis (FTA)	FTA is a deductive top-down method used to identify and visualize how component failures contribute to a system-level failure, known as the top event. By using logic gates (AND, OR), it traces failure paths, offering a structured approach for safety and reliability analysis in various industries (Dai et al., 2011). *Strengths:* the method's strengths include its systematic approach, ability to perform both qualitative and quantitative analyses, and its focus on identifying critical failure points. It offers predictive capabilities and is widely applicable in complex systems. *Limitations:* however, FTA has limitations, such as being time-consuming, requiring accurate failure data, and its static nature, which does not account for dynamic interactions (Patriarca et al., 2020; Toroody et al., 2016; Praetorius & Kataria, 2016). It also relies heavily on the analyst's expertise, which can introduce subjectivity. *Integration with Other Methods:* FTA is often integrated with other methods to enhance its utility (Toroody et al., 2016). For example, it can complement FMEA or ETA to provide a more comprehensive view of risks.	It is widely used in high-hazard industries like nuclear power, aerospace, petrochemical, chemical processing, software engineering, and pharmaceuticals (Toroody et al. (2016), Praetorius & Kataria (2016), Goldberg et al. (1994), the Center for Chemical Process Safety (1999, 2008), the U.S. Department of Labor Occupational Safety and Health Administration (1994), and Lacey (2011)).	QL, QT	P

Continued

Methods	Description	Application	QL/QT	P/R
Human Reliability Assessment (HRA)	The first generation of HRA methodologies, including Human Cognitive Reliability Correlation (HCR) and the Technique for Human Error-Rate Prediction (THERP), focuses on evaluating the probability of human errors during task execution. *Strengths:* the strengths of HRA include its ability to proactively identify risks, adapt to various contexts, support decision-making, enhance safety culture, and integrate seamlessly into broader risk analysis frameworks. *Limitations:* it has limitations such as reliance on subjective judgments, data dependency, implementation complexity, challenges in addressing dynamic situations, and a narrow focus on individual errors over systemic factors. *Integration with Other Methods:* HRA integrates effectively with other methods, such as PRA, FTA, ETA, ergonomic studies, simulation testing, and organizational safety evaluations.	HRA is widely used across high-risk industries to assess and mitigate risks from human actions, improving safety, efficiency, and operational reliability. It reduces risks in complex systems across sectors such as nuclear power, aviation, healthcare, railways, and oil and gas (Kirwan, 2017; Embrey, 2011; Hollnagel, 2005; Swain & Guttmann, 1983).	QL QT	P, R
A Technique for Human Event Analysis (ATHENA)	A second-generation HRA methodology, it evaluates the likelihood of human error during specific tasks by analyzing human interactions and decision-making in complex, high-risk environments. *Strengths:* it identifies and mitigates human errors by examining cognitive and contextual factors. *Limitations:* it is resource-intensive, requires significant expertise and data, and does not address Human Error Probability (HEP), numerical modeling, or predictive outputs, making it less suitable for sensitivity analysis. *Integration with Other Methods:* while effective, ATHENA is often paired with other methodologies, like HEART, THERP, FTA and FMEA, to enhance its comprehensiveness in risk assessments.	ATHENA is widely used in high-risk industries, such as nuclear power, aviation, healthcare, process industries, and defense, to analyze human reliability and decision-making.	QL	R
The Cognitive Reliability and Error Analysis Method (CREAM)	The second-generation HRA method, CREAM, analyzes human performance in complex systems by examining cognitive errors and contextual factors. It integrates individual, technological, and organizational elements into an error taxonomy based on cognitive engineering principles (Hollnagel, 1998). *Strengths:* its strengths include a holistic approach, predictive capabilities, flexibility, and a structured framework. *Limitations:* it has limitations like complexity, subjectivity, limited quantification, and data dependency. *Integration with Other Methods:* to enhance its effectiveness, CREAM is often integrated with methods like THERP, FTA, HEART, PSA, and Bowtie Analysis, combining qualitative insights with quantitative reliability for comprehensive risk assessments.	CREAM is widely applied in high-risk industries, including nuclear power, aviation, healthcare, process industries, and transportation, to assess human reliability and analyze cognitive errors (Hollnagel, 1998).	QL	P

Continued

Methods	Description	Application	QL/QT	P/R
The AcciMap approach	It is a systems-based method for accident analysis that identifies causal factors across multiple levels of a socio-technical system, including organizational, regulatory, technical, and human factors. Developed by Rasmussen (1997), it provides a holistic understanding of accident causation and emphasizes systemic interactions. *Strengths:* its strengths include its ability to capture complex relationships, offer intuitive visual representations, and focus on systemic weaknesses for preventative measures. *Limitations:* it can be resource-intensive, complex, and subjective, with a lack of quantitative analysis. *Integration with Other Methods:* to enhance its effectiveness, AcciMap is often integrated with methods like Bowtie Analysis, FTA, STPA, and HRA, enabling a comprehensive approach to accident prevention and risk management (Yousefi et al., 2019).	It is used in high-risk industries like aviation, healthcare, nuclear power, transportation, and process industries to analyze accidents by uncovering systemic causes across organizational, regulatory, technical, and human factors.	QL	R
Human Factors Analysis and Classification System (HFACS)	It is a taxonomy-based method for analyzing aviation accidents, designed to identify the human causes of accidents (Salmon et al., 2012). Rooted in Reason's (1990) Swiss Cheese model of human error, HFACS provides a structured framework for categorizing and understanding the human errors that contribute to accidents. *Strengths:* it analyzes accident causation through four levels of human failure: unsafe acts, preconditions, unsafe supervision, and organizational influences. *Limitations:* its effectiveness heavily depends on the expertise of the analysts involved and is time-intensive, subjective, and primarily retrospective, focusing on past events. *Integration with Other Methods:* to enhance its utility, HFACS is often integrated with methods like Bowtie Analysis, FTA, STPA, and HRA, enabling more robust accident analysis and safety management.	It is widely applied in industries like aviation, healthcare, and the military, offering a structured approach to identifying systemic weaknesses and guiding safety improvements.	QL	R

8.5 Conclusion and Future Research

The Functional Resonance Analysis Method (FRAM) has emerged as a valuable tool for understanding performance variability in socio-technical systems, with applications across sectors such as supply chain sustainability, healthcare, aviation, and energy utilities. While FRAM offers significant benefits for systemic safety assessment, further refinement and the exploration of complementary approaches are essential to address strategic demands and enhance resilience in complex systems. Integrating comprehensive frameworks to strengthen decision-making processes and risk management strategies can significantly improve organizational adaptability and safety outcomes in dynamic environments. Future research should focus on advancing these methodologies to ensure their broader applicability and effectiveness in mitigating emerging challenges.

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Conflicts of Interest – The authors declare no conflicts of interest regarding the publication of this paper.

CHAPITRE 9

ARTICLE 3

A High-Level Risk Management Framework as Part of An Overall Asset Management Process for The Assessment of Industry 4.0 Related New Emerging Technological Risks

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Abstract – Long-established businesses face evolving challenges, particularly in Industry 4.0, where conventional risk management methods often prove inefficient and fail to address emerging systemic and organizational risks. These limitations, compounded by cognitive and motivational biases, necessitate comprehensive asset management and decision-support approaches that integrate conventional and emerging safety risks. Innovative methods capable of addressing the complexity of socio-technical systems are critical to supporting practitioners in managing these threats. This paper explores risk management strategies for addressing emerging safety risks in Industry 4.0, including technology-related risks, rare and extreme disruptive events, and uncertainties arising from global crises such as the Covid-19 pandemic and armed conflicts. We focus on system theory-based approaches, specifically the Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP), and the risk-informed decision-making (RIDM) framework, as suitable methodologies for addressing these challenges. The benefits of these methods are discussed, along with their potential integration into a high-level risk management and decision-making framework.

Keywords – Enterprise Risk Management, Occupational Safety and Health, Resilience, Industry 4.0, Risk-Informed Decision-Making, Functional Resonance Analysis Method, System-Theoretic Accident Model and Processes.

9.1 Introduction

The escalating complexity of socio-technical systems, coupled with emerging technology-related risks, poses significant challenges to conventional system safety approaches (Leveson, 2016). This growing complexity inherently leads to new and unknown risks that must be addressed within asset management, considering the organization's external and internal contexts, including human performance, socio-economic factors, and socio-cultural influences. Figure 9.1 illustrates the characteristics of an organization's environment, distinguishing between the external environment, internal enterprise-level environment, and technological system-level environment.

At the internal level, technological systems allow for control and prediction of random uncertainties, while the enterprise level involves managing workforce and physical assets efficiently. However, tight control over organizational structures, processes, and ways of doing business remains challenging. The external environment, characterized by aleatory and epistemic uncertainties, is influenced by factors such as cultural, political, economic, and technological contexts, making it unpredictable, uncontrollable, and resistant to influence.

Traditional safety risk analysis techniques, such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Hazard and Operability Analysis (HAZOP), and Bowtie Analysis, struggle to address the complexity of modern socio-technical systems. These methods, rooted in linear accident causation models like Reason's Swiss Cheese Model (Reason, 1997) and Heinrich's domino theory (Heinrich et al., 1980), often fail to account for systemic interactions and emergent risks resulting from design deficiencies or interactions among non-failing components. Introduced before the 1980s, these techniques are increasingly limited in addressing the rapid technological advancements and heightened complexity of Industry 4.0 systems. Conventional methods, while effective for analyzing mechanical elements or hardware, are insufficient for addressing human, organizational, software, and social dimensions. Attempting to impose modern technology and contemporary degrees of complexity into obsolete methods might not be successful. New tools are required for the new problems. Nonetheless, it is worth emphasizing that traditional analysis techniques of safety risks should not be discredited but should be extended and enhanced. They perform best on mechanical elements or hardware. Though, they have serious limitations on for e.g., human operators, organizational and social considerations, software program-related aspects, etc. (Leveson, 2016).

The need for advanced approaches has led to the adoption of system theory-based methods, such as the Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP), and Risk-Informed Decision-Making (RIDM). These methods offer a holistic view of system safety and risk management by focusing on performance variability, systemic interactions, and informed decision-making (Gaha et al., 2021; Patriarca et al., 2020; Leveson, 2016; Komljenovic et al., 2016; Zio et al., 2012; Dezfuli et al., 2010c).

This paper proposes a high-level risk management and decision-making framework that combines FRAM, STAMP, and RIDM processes within an overall asset management strategy. The framework aims to address emerging and unknown technology-related risks while fostering resilience against extreme, rare, and disruptive events that could severely impact organizational performance. It also aligns with Enterprise Risk Management (ERM) and Occupational Safety and Health (OS&H) requirements, providing a robust approach for organizations transitioning toward digital technologies and facing increasingly complex environments.

The remainder of this paper is structured as follows: Section 2 reviews the literature on asset management, resilience, and uncertainty, particularly during the Covid-19 pandemic, global inflation, and other extreme events. It also explores Industry 4.0/5.0, risk management, FRAM, STAMP, and RIDM. Section 3 introduces the proposed high-level risk management framework. Section 4 discusses key findings, while Section 5 concludes the study, highlights research gaps, and suggests future research directions.

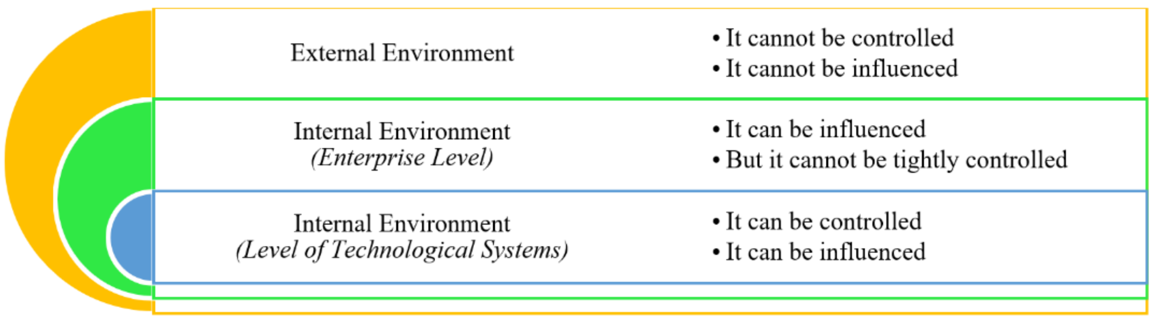

Figure 9.1. Depiction of the external and internal environment of an organization
(Source: own representation)

9.2 Literature review

This literature review covers various domains of knowledge, including asset management, Industry 4.0, Industry 5.0, risks and risk management, RIDM, FRAM, and STAMP. It offers readers an overview of essential background information on the subject.

9.2.1 Asset Management

This section summarizes the literature review on physical asset management (AM), defined as the *"coordinated activity of an organization to realize value from assets" (ISO, 2014)*. It focuses on the components of AM models and the challenges organizations face in implementing them.

- *Asset Management Models*

An effective asset management strategy involves a range of interconnected and interdependent activities across various organizational levels, such as strategic, organizational, project, product, and process levels. These activities should be closely aligned with the organization's strategic planning (IAM, 2015; ISO, 2014). Both practitioners and scholars are required to manage complex sociotechnical systems and navigate decision-making processes at all levels of organizational strategy, including corporate, business, and functional levels. These systems are often characterized by unpredictability, impacting various dimensions of resilience, such as organizational, technological, operational, social, economic, financial, reputational, and business models (Roshani et al., 2014; Woods, 2015).

Complex sociotechnical systems are composed of numerous uncertain and interdependent technological elements, including capital investments, requirement definitions, acquisitions, installations, commissioning, decommissioning, operations and maintenance (O&M), shutdown strategies, and lifecycle value realization. Additionally, aging assets introduce dependability challenges such as reliability, availability, and maintainability. These challenges are further compounded by Occupational Safety and Health (OS&H) constraints, Enterprise Risk Management (ERM) requirements, and increasing expectations for maintenance performance (Komljenovic et al., 2016 Baglee et al., 2016; Brown et al., 2014). For instance, power utilities face the challenge of replacing large portions of their aging assets that are becoming obsolete due to technological advancements or transitioning to more efficient, carbon-free alternatives (Komljenovic, 2018).

Over the past decades, numerous economic models have been developed to support AM decision-makers and practitioners across various sectors. Those leading models relevant to this subject matter of interest are enumerated below (see Table 9.1). Among the most prominent are the models established by the Institute of Asset Management (IAM, 2015), which conceptualize AM into six thematic groups: (1) strategy and planning, (2) asset management decision-making, (3) lifecycle delivery, (4) asset information, (5) organization and people, and (6) risk and review (see Figure 9.2).

These themes, developed by the Global Forum on Maintenance and Asset Management (GFMAM), are detailed in IAM's Asset Management - An Anatomy, a framework comprising 39 subjects that align with the ISO-55000 (2024, 2014) series of standards for assessing asset management maturity (GFMAM, 2014; IAM, 2015).

For those unfamiliar with these models, further details can be found in Diop et al. (2021) and their referenced bibliographies. This foundational knowledge serves to guide asset management practitioners in addressing challenges associated with aging assets, technological change, and resilience-building in socio-technical systems.

Table 9.1 Relevant Asset Management Models
(Source: own representation)

Model	Designation	Source
PAS 55	Publicly Available Specification for the optimal management of physical assets	British Standard Institute (BSI, 2013, 2008)
ISO 55000	Asset management – Overview, principles and terminology	International Organization for Standardization (ISO, 2014)
ISO 55001	Asset management – Management systems - Requirements	International Organization for Standardization (ISO, 2014)
ISO 55002	Asset management – Management systems - Guidelines for the application of ISO 55001	International Organization for Standardization (ISO, 2018)
ISO 55010	Guidance on the alignment of financial and non-financial functions in asset management	International Organization for Standardization (ISO, 2019)
GFMAM	The Global Forum on Maintenance & Asset Management, GFMAM Landscape of subjects	The Global Forum on Maintenance & Asset Management (GFMAM, 2014)
IAM	The IAM Asset Management – An Anatomy	The Institute of Asset Management (IAM, 2015)
CIGRE	International Council on Large Electric Systems (Conseil international des grands réseaux électriques, CIGRÉ) decision making decision making processus	International Council on Large Electric Systems (CIGRÉ, 1921)
AMBoK	Asset Management Body of Knowledge (AMBoK)	Australian Asset Management Council (AM-Council, 2014)
EFNMS-Bok	European Federation of National Maintenance Societies (EFNMS) Conceptual Model	The European Asset Management Committee (EAMC, 2018)
RIDM	The Risk-Informed Decision-Making (RIDM) process	The National Aeronautics and Space Administration , NASA and the US Nuclear Regulatory Commission (NASA, 2010)
RIAM / NAM	Risk-Informed Asset Management process (RIAM) Nuclear Asset Management process (NAM)	Electric Power Research Institute (EPRI, 2002)

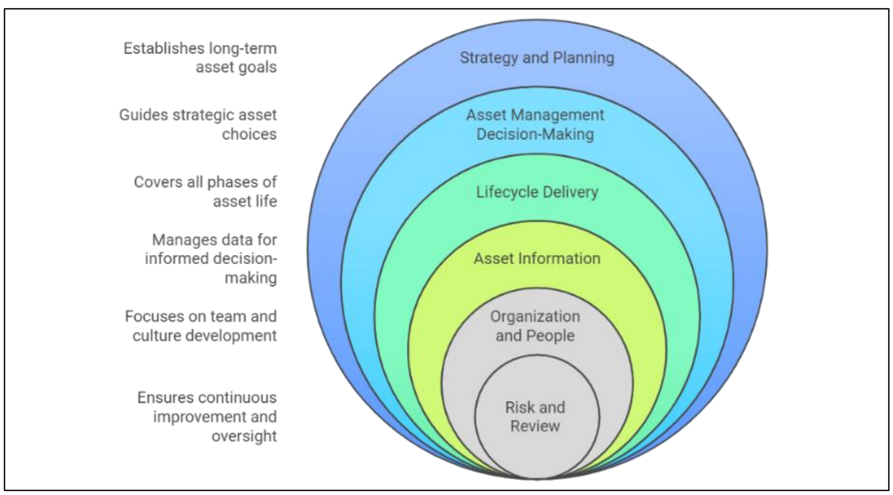

Figure 9.2. Conceptual Framework for Asset Management
(Source: own representation based on IAM (2015) & GFMAM (2014))

- *Resilience and Asset Management Amid Complexity and Global Disruptions*

The complexity of socio-technical systems stems from the interplay of new technologies, strategic planning, operational excellence, supply chain management, regulatory compliance, financial management, and health and safety requirements. This complexity generates uncertainty and non-linearity, which pose challenges for resilience engineering. Resilience engineering ensures continuity of operations and business stability despite increasing uncertainty, interdependencies, and disruptive events.

In industries such as electrical and nuclear power, where design and operation involve critical processes like power generation, transmission, and distribution, asset and risk management are pivotal for ensuring performance. These industries, managing capital-intensive assets and operating as Complex Adaptive Systems (CAS), must prepare for rising technology-related risks and the increasing frequency and severity of extreme, rare, and disruptive events that threaten organizational performance (Checkland, 1981; Farmer, 2012).

Organizations face significant challenges due to global economic volatility, heightened political insecurity, and crises like the Covid-19 pandemic. These factors compel asset decision-makers to revise economic models to address uncertainties that affect investment decisions, operational costs, and overall business performance. Furthermore, risks such as cyber threats, climate change, natural disasters, and economic inflation exemplify *"known-unknown"* and *"unknown-unknown"* risks, creating conditions for disruptive events that impact technical systems, human operators, and organizational objectives.

In this complex environment, scientists recommend studying modern organizations as CAS[‡‡‡‡‡] using complexity theory to address system challenges (Keating et al., 2022; Katina et al., 2021). The concept of Complex System Governance (CSG) offers a framework for enhancing system performance through design, execution, and adaptation of essential metasystem functions (Keating et al., 2022; Katina et al., 2021). This approach is critical for developing holistic asset management (AM) strategies that address complexity and emerging risks while incorporating Enterprise Risk Management (ERM) and Occupational Safety and Health (OS&H) requirements. One example is Hydro-Québec, which manages a significant portfolio of assets (Komljenovic, 2018). The utility must ensure asset reliability, availability, and maintainability while minimizing service interruptions and maximizing productivity. Abdul-Nour et al. (2021) propose a decision-making framework for managing risks, uncertainties, and resilience in complex socio-technical systems, as illustrated in Figure 9.3. This framework evaluates uncertainties by categorizing them into three levels (minor, moderate, and significant) and adapts management strategies accordingly: traditional risk management, management under uncertainty, or resilience-based management. The process concludes with a comprehensive review and informed decision-making, emphasizing the importance of

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[‡‡‡‡‡] “*A Complex Adaptive System* is a system that is complex in that it is a dynamic network of interactions, but the behavior of the ensemble may not be predictable according to the behavior of the components. It is *adaptive* in that the individual and collective behavior mutate and self-organize corresponding to the change-initiating micro-event or collection of events” (Anish et al., 2010; Mitleton-Kelly, 2003; Wikipedia, 2024).

differentiated approaches to enhance safety and resilience, particularly in contexts where performance variability is critical.

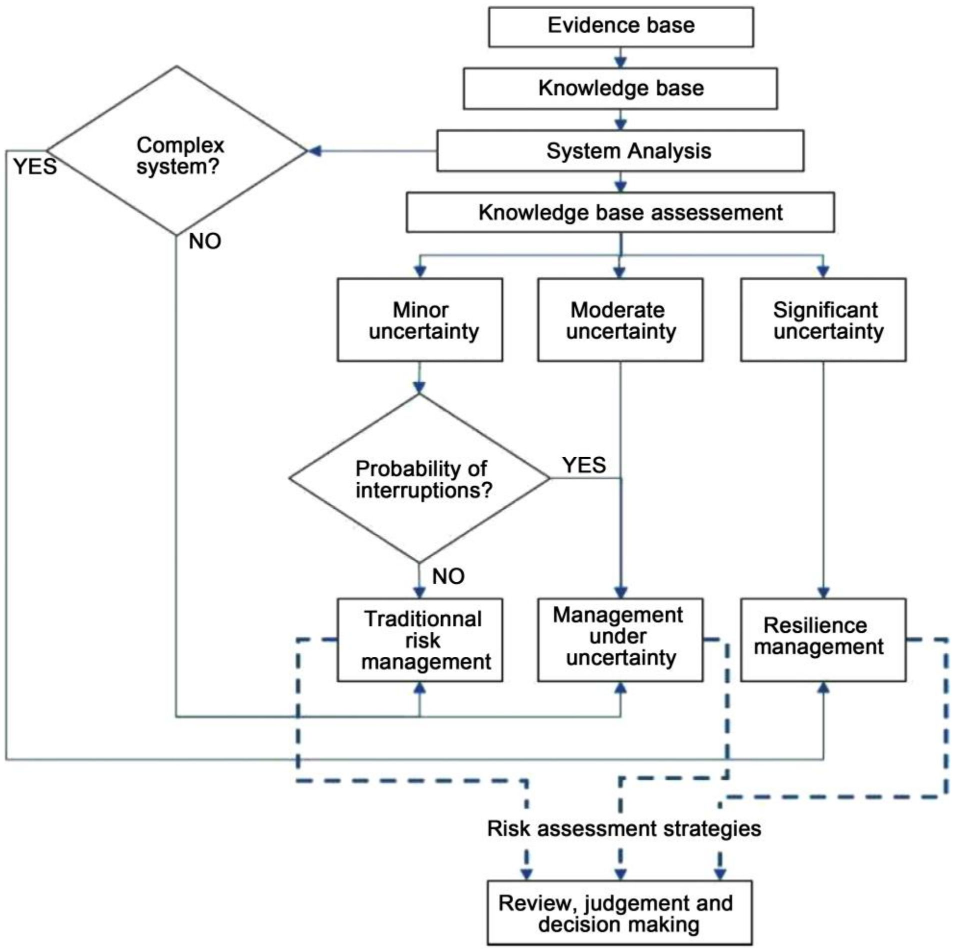

Figure 9.3. Decision-Making Framework for Managing Risks, Uncertainties, and Resilience in Complex Systems
(Source: Abdul-Nour et al. (2021))

Resilience, a key approach for managing risks and uncertainties, is defined as the ability of a system to adapt and maintain operations under both expected and unexpected conditions (Hollnagel, 2013). Resilience involves four stages: *(1) Planning*, which anticipates undesirable events; *(2) Absorption*, which limits damage during adverse events; *(3) Recovery,* which restores performance post-event; and *(4) Adaptation,* which improves resilience over time through continuous learning and adjustment. These stages rely on core properties like robustness, redundancy, resourcefulness, and rapid recovery (Komljenovic, 2019; Hickford et al., 2018). Figure 9.4 illustrates the general concept of resilience.

In conclusion, asset management strategies must integrate resilience concepts and leverage advanced frameworks like CAS and CSG to address the challenges posed by modern socio-technical systems. Improving situational awareness, preparedness, and adaptive capacity is essential to navigating uncertainty and ensuring organizational stability in the face of emerging risks.

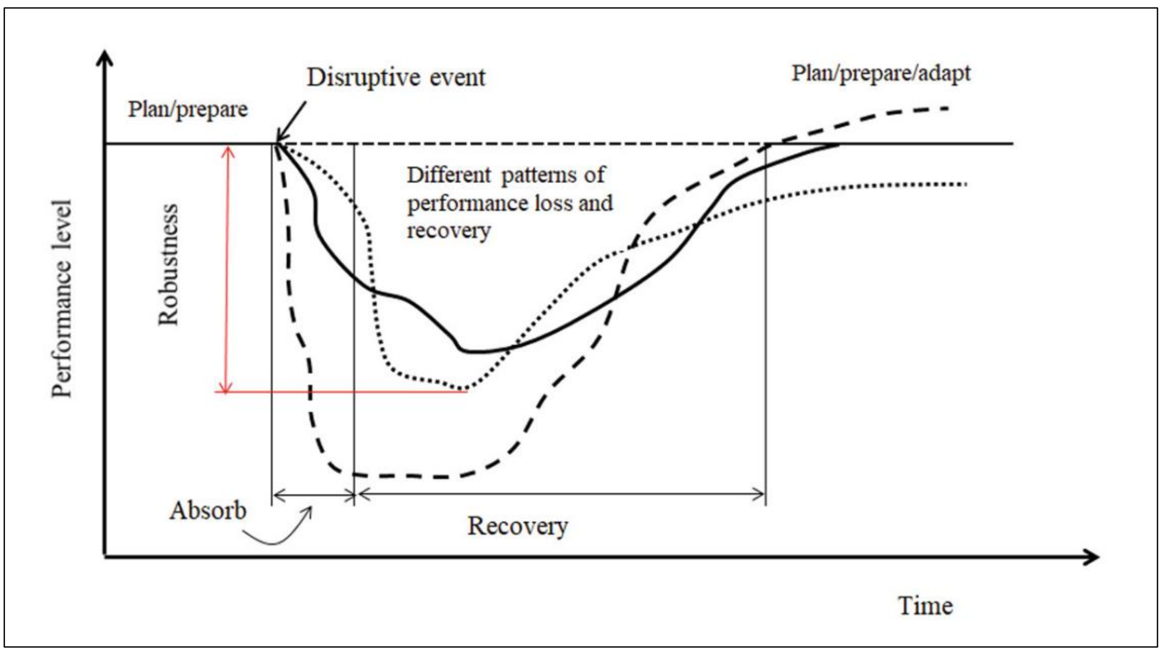

Figure 9.4. The General Concept of Resilience and its Key Components
(Source: Komljenovic (2019))

9.2.2 Industry 4.0 / 5.0 Challenges

The fourth industrial revolution, also known as Industry 4.0 or the *"industry of the future"*, is an initiative launched by the German government to enhance the competitiveness and productivity of the manufacturing sector (Blanchet, 2014). The concept was introduced in 2006 during the Hanover Fair, the world's largest industrial technology event, as part of Germany's *"High-Tech Strategy"*. It marked the first association of Industry 4.0 with the onset of an industrial revolution. In 2011, at the same event, three experts – Dr. Kagermann, Dr. Wolfgang Wahlster (German Research Center for Artificial Intelligence), and Dr. Wolf-Dieter Lukas (Federal Ministry of Research and Education) – outlined how a paradigm shift driven by cyber-physical systems (CPS) and new business models would transform industrial manufacturing in the coming decades (Kagermann et al., 2011). Their work identified three core features of future industrial manufacturing: (i) high product customization with flexible production, (ii) customer and business partner involvement in design and value creation, and (iii) integration of production and quality services to create hybrid products.

Industry 4.0 has become a globally adopted framework in advanced countries, revolutionizing industrial value chains through intelligent networking and automation. It integrates virtual and physical systems using technologies like IoT, CPS, cloud computing, cognitive computing, and big data, giving rise to the Smart Factory with interconnected smart machines (Boston-Consulting-Group, 2020; European-Asset-Management-Committee, 2017; Erboz, 2017). Unlike previous industrial revolutions, which were defined by singular technological breakthroughs, Industry 4.0 is marked by the convergence of advanced technologies. It builds on the earlier revolutions: mechanization with steam engines in the 18th century, mass production with electricity in the 19th century, and automation through electronics and IT in the 20th century.

While Industry 4.0 offers immense opportunities for digital transformation, it also introduces new challenges and risks, particularly in Occupational Safety and Health (OS&H), Enterprise Risk Management (ERM), cybersecurity, system interconnectivity, process standardization, data governance, and workforce acquisition and retention. Decision-makers who understand and harness these technologies will be better positioned to address these challenges. Companies must adapt their economic models to align with the evolving digital landscape rather than reinventing their strategies entirely.

The fifth industrial revolution, (a.k.a. Industry 5.0), is an initiative launched by the European Commission (EC), the executive branch of the European Union (De Nul et al., 2021). Announced on the tenth anniversary of Industry 4.0, Industry 5.0 complements its predecessor by emphasizing a sustainable, human-centric, and resilient approach to manufacturing. It aims to enhance Industry 4.0 technologies while prioritizing environmentally friendly processes and placing employee well-being at the core of the production chain. This vision extends beyond jobs and growth to achieve societal objectives, social fairness, and resilience within the boundaries of the planet (De Nul et al., 2021).

Industry 5.0 introduces a value-driven paradigm, contrasting with Industry 4.0’s technology-driven focus (Xu et al., 2021). Its core principles (human-centricity, sustainability, and resilience) shift the emphasis from shareholder value to stakeholder value, reinforcing the industry's responsibility to society. Figure 9.5 illustrates these foundational values. Additionally, the EC has identified six enabling technologies for Industry 5.0, as detailed in Table 9.2 (Müller, 2020).

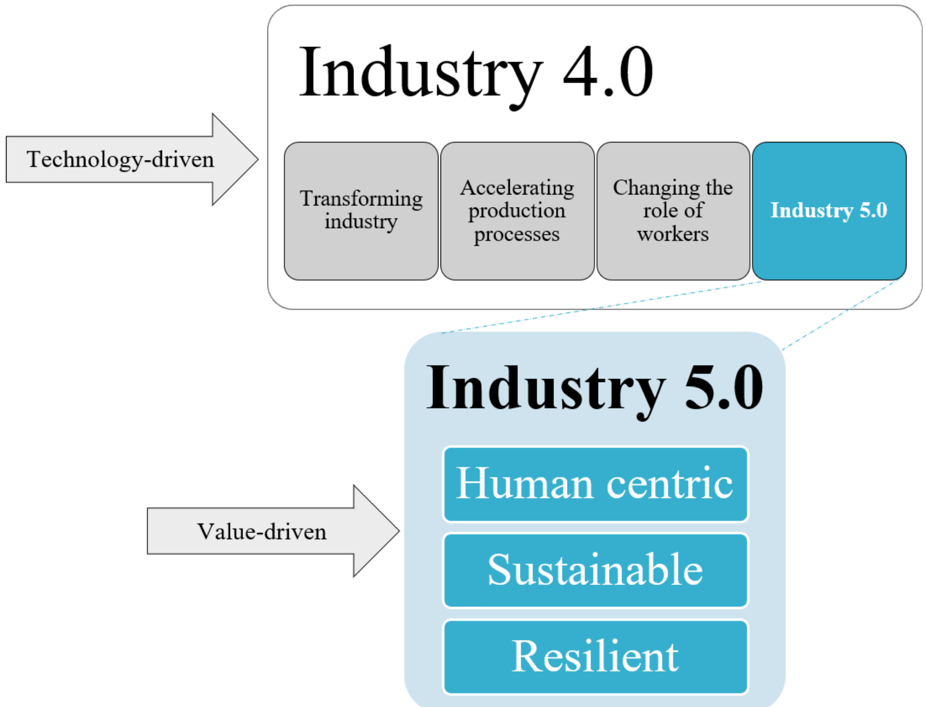

Figure 9.5. Core values of industry 5.0 complementing industry 4.0
(Source: own representation)

Table 9.2 Industry 5.0 six enabling technologies
(Source: own representation based on the EC)

Enabling technologies	Attributes	Technologies properties
Individualized human-machine interaction	• Prioritizing a human-centric approach by empowering operators, enhancing skills, and improving working conditions. • Bridging human innovation with technology and enabling knowledge transfer to robots. • Adapting robotic behavior to align with workers' needs.	For example, the following tools can assist humans in physical and cognitive tasks: • Multi-lingual speech and gesture recognition. • Tracking technologies to monitor mental health and anxiety levels of workers. • Collaborative robots designed to assist humans. • Augmented reality technologies. • Virtual reality technologies, primarily for training purposes. • Exoskeletons for physical support. • Advanced safety equipment. • Artificial intelligence to aid decision-making and enhance cognitive processes.
Bio-inspired technologies and smart materials	• Drawing inspiration from biological transformation concepts. • Embedding sensors into materials. • Enhancing material properties. • Promoting material recycling.	For example: • Self-healing or self-repairing materials. • Lightweight and recyclable materials. • Generating raw materials from waste. • Incorporating living materials. • Embedding sensor technologies and biosensors. • Adaptive ergonomics and responsive surface properties. Materials with intrinsic traceability.
Digital Twins and simulation	• Modeling entire systems. • Optimizing production processes. • Inspecting and evaluating products. • Testing and validating processes. • Identifying potential hazards and assessing risks.	For example: • Digital twins for products and processes. • Virtual simulation and testing for human-centricity, operational safety, and product/process validation. • Multi-scale dynamic modeling and simulation. • Assessing environmental and social impacts through simulation and measurement. • Cyber-physical systems and digital twins for entire systems. • Scheduled and planned maintenance.
Data transmission, storage, and analysis technologies	• Securely processing data, including acquisition, transmission, storage, and analysis. • Implementing energy-efficient solutions. • Ensuring interoperability across systems.	For example: • Networked sensors. • Interoperability of data and systems. • Scalable, multi-level cybersecurity. • Secure cloud IT infrastructure for cybersecurity. • Big data management and analysis. • Traceability, including data origin and specification compliance. • Data processing to support learning processes. • Edge computing for decentralized data processing.

Continued

Enabling technologies	Attributes	Technologies properties
Artificial Intelligence	• Equipping machines with intelligence through machine learning, deep learning, and similar technologies. • Enabling advanced analysis and problem-solving in complex and dynamic systems.	For example: • Causality-based artificial intelligence, going beyond mere correlations. • Identifying relationships and network effects outside standard correlations. • Autonomous response to new or unexpected conditions without human intervention. • Swarm intelligence for collective decision-making. • Brain-machine interfaces enabling direct communication between humans and machines. • Individualized, person-centric artificial intelligence. • Informed deep learning, combining expert knowledge with AI capabilities. • Skill matching between humans and tasks for optimized performance.
Technologies for energy efficiency, renewables, storage and autonomy	• Implementing energy-efficient solutions. • Achieving emission neutrality. • Facilitating the transition to a circular economy.	For example: • Integrating renewable energy sources. • Supporting hydrogen and Power-to-X technologies. • Utilizing smart glasses and energy-autonomous sensors. • Enabling low-energy data transmission and analysis.

9.2.3 Defining Risk and Risk Management Process

- *Overview*

This section outlines the key concepts of risk and the risk management (RM) process within asset management (AM) across all organizational levels.

According to ISO-31000 (2018, 2009), RM refers to *"coordinated activities to direct and control an organization with regard to risk"*. Its primary objectives include achieving organizational goals, creating and protecting value, enhancing performance, and fostering innovation. Risk is defined as *"an effect of uncertainty on objectives"*. This effect can be positive, negative, or both and can address or result in opportunities and threats. Objectives may vary (e.g., financial, health and safety, environmental) and apply at different levels (strategic, organization-wide, project, or process). Uncertainty is described as a state of incomplete knowledge regarding an event, its consequences, or likelihood (ISO-31000, 2018, 2009). Additionally, NASA's procedural requirement (NPR 8000.4) defines risk as a triplet: scenarios, likelihoods, and consequences (Dezfuli et al., 2010c). This enables differentiation between low-impact high-probability outcomes (LIHP) and high-impact low-frequency outcomes (HILF), supporting proactive RM approaches.

- *Risk Management Framework*

Managing risk involves three key elements: (1) principles, (2) framework, and (3) process.

(1) Principles: The principles establish the foundation for RM by ensuring it is effective and aligned with organizational objectives. The key attributes are outlined in Figure 9.6.

- *Value Creation and Protection:* RM should enhance value in areas like occupational safety, legal compliance, financial performance, environmental protection, and business continuity management (BCM).
- *Integrated:* RM should be embedded into all organizational processes and decision-making activities.
- *Structured and Comprehensive:* RM must provide consistent and comparable outcomes.
- *Customized:* RM should be tailored to the organization’s specific context and objectives.
- *Inclusive:* Stakeholders at all levels should be actively involved to maintain relevance.
- *Dynamic:* RM should adapt to changes in the external and internal context.
- *Best Available Information:* Decisions should rely on accurate and up-to-date data from reliable sources.
- *Human and Cultural Factors:* RM must account for the impact of human behavior and organizational culture.
- *Continual Improvement:* RM should evolve through learning and skill development.

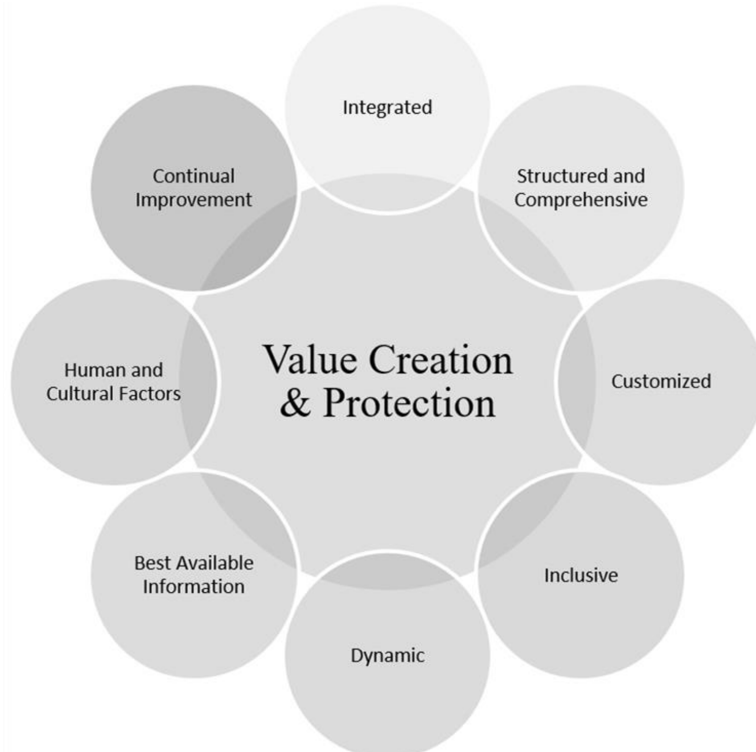

Figure 9.6. Key principles of risk management
(Source: own representation based on ISO-31000 (2018))

(2) Framework: The RM framework supports governance by integrating RM into major activities and functions of the organization. Figure 9.7 illustrates its five components.

- *Integration:* RM should align with the organization's strategy, culture, and complexity.
- *Design:* Involves understanding the organizational context, assigning responsibilities, allocating resources, and establishing communication channels.
- *Implementation:* Includes planning, revising decision-making processes, and adapting to contextual changes.
- *Evaluation:* Requires measuring the RM framework's performance using key indicators and assessing its relevance.
- *Improvement:* Involves continuously updating and enhancing the framework to increase organizational value.

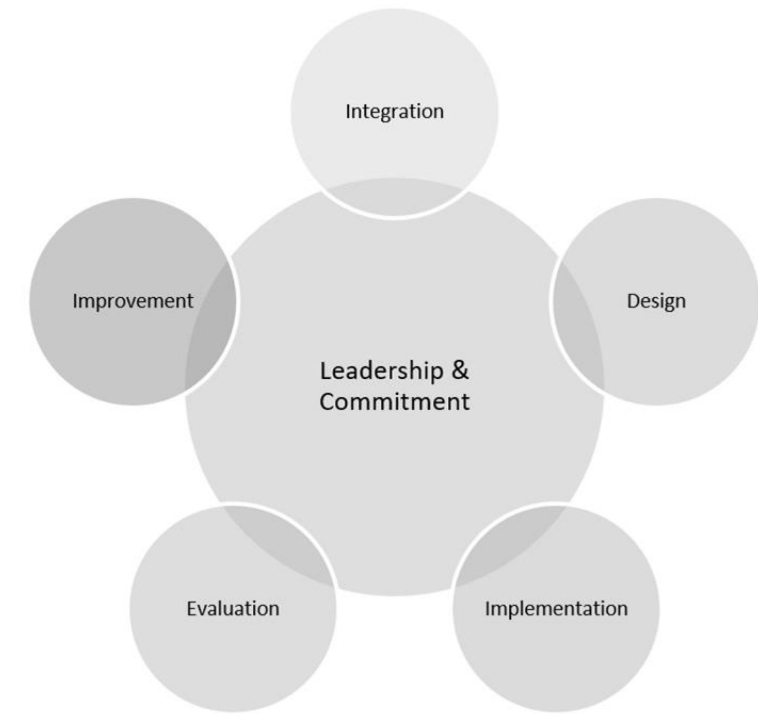

Figure 9.7. Five components of the risk management framework
(Source: own representation based on ISO-31000 (2018))

(3) *Process:* The RM process is a systematic application of guidelines, procedures, and practices within the organization. It encompasses the following steps, as depicted in Figure 9.8.

- *Communication and Consultation:* Engaging stakeholders throughout the RM process.
- *Establishing Scope, Context, and Criteria:* Defining the boundaries and objectives of RM activities.
- *Risk Assessment:* Identification (recognizing potential risks), Analysis (understanding the nature of risks), Evaluation (prioritizing risks based on their likelihood and impact).
- *Risk Treatment:* Developing and implementing mitigation strategies.
- *Monitoring and Review:* Continuously assessing the effectiveness of RM activities.
- *Recording and Reporting:* Documenting and sharing RM outcomes.

- *Emerging Risks and Resilience*

Emerging risks, such as those related to new technologies, present unique challenges to business continuity and resilience. ISO-31050 (2023) and CEN (2013) provide guidance on addressing *"known-unknown"* and *"unknown-unknown"* risks, emphasizing the need to manage these alongside established risks (ISO-31000, 2018, 2009) for comprehensive enterprise risk management (ERM).

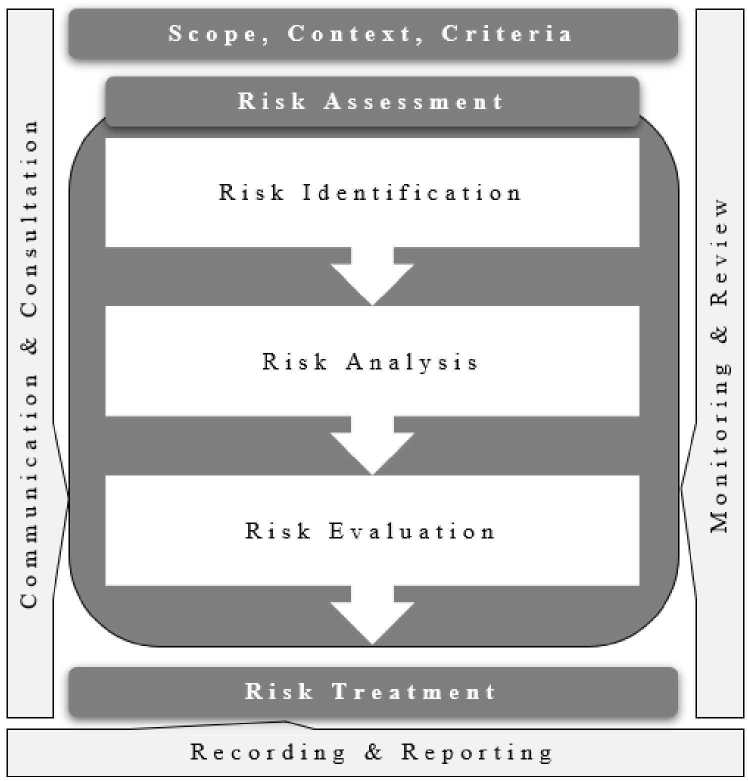

Figure 9.8. Risk management process
(Source: own representation based on ISO-31000 (2018))

9.2.4 Application of FRAM, STAMP, and RIDM in Risk Management

This section explores the Functional Resonance Analysis Method (FRAM), the System-Theoretic Accident Model and Processes (STAMP), and the Risk-Informed Decision-Making (RIDM) process. These methodologies provide comprehensive approaches for characterizing system safety risks in Asset Management (AM).

- *The FRAM Approach*

FRAM is a modern performance assessment method developed for accident investigation and risk assessment. It aligns with the Safety II concept, focusing on identifying mandatory functions for a system's success rather than analyzing failures (Hollnagel, 2012, 2014). Unlike traditional methods like FMEA or HAZOP, FRAM emphasizes the variability of everyday performance and its impact on overall system behavior (Sun et al., 2022; Hollnagel, 2012). The HAZOP studied risks from the point of view of design and operation deviations. The FMEA method identifies probable failure modes and effects, establishes the potential causes of each failure, then recommends actions to eliminate the hazards (Sun et al., 2022).

The FRAM concept was established for the benefit of “going behind human error and beyond the failure concept” by modelling the required functions for everyday performance to be successful. At the early stages in 2004, the FRAM idea was motivated by the limitations of deterministic and probabilistic approaches to understand complex systems’ comportment, based on the Stochastic Resonance Theory in Physics (Hollnagel, 2004). The pioneers have implemented the FRAM process as a systemic functional approach for accident investigation and safety assessment in complex socio-technical systems (Hollnagel, 2004; Hollnagel et al., 2008a; Hollnagel et al., 2008b). These days, the FRAM is adopted to model complex and dynamic socio-technical systems to capture not only why things sometimes end up going wrong but also succeed (Hollnagel, 2012). Hence, the FRAM method supports decision-makers to assess activities in complex and dynamic socio-technical systems in term of the system's functions as well as complex dependencies and interactions among functions. Therefore, the system's functions and performance can be studied to understand where performance variability might arise before spreading all over the system. Sun et al. (2022) state that the socio-technical system must have appropriate resilience to withstand the disturbance and absorb the performance variability of its sub-systems and procedures.

The key principles of FRAM are: *(1) Equivalence of Success and Failure* – both success and failure stem from the same processes. *(2) Approximate Adjustments* – everyday activities adjust to changing circumstances, causing variability. *(3) Emergence* – outcomes are emergent properties of the entire system's behavior. *(4) Functional Resonance* – variability in coupled functions may amplify, causing resonance and leading to accidents.

Since the FRAM was developed in 2004, there is a growing appeal in using the FRAM approach for the assessment of activities in complex and dynamic socio-technical systems, in other words Complex Adaptive Systems (CAS). The method is used in numerous high-risk domains such Maritime Transportation, Air Traffic Management Safety Assessment, Maritime Mining, Nuclear Power, Aircraft De-icing, Health Care, Railway Traffic, etc. (for Example: Slater et al. (2022); Gao et al. (2019); França et al. (2019); Hollnagel (2018); Costantino et al. (2018); Anvarifar et al. (2017); Hounsgaard (2016); Aguilera et al. (2016); Rosa et al. (2015); Hollnagel et al. (2014); Hollnagel (2012); De Carvalho (2011); Herrera et al. (2010)).

The FRAM process involves four main steps: *Define the Purpose (step 0)* – determine whether the focus is prospective (risk assessment) or retrospective (accident investigation). *Identify Functions (step 1)* – characterize system functions using six aspects: input (I), output (O), preconditions (P), resources (R), time (T), and control (C). *Identify Variability (Step 2)* – *a*ssess how variability in one function affects others through upstream and downstream coupling. *Aggregate Variability (Step 3)* – analyze functional resonance and its impact on system performance. *Determine Outcomes (Step 4)* – develop safety constraints and strategies to manage performance variability.

Figure 9.8 depicts the representation of a function in FRAM. The primary purpose of the FRAM concept is to figure out the function resonance sources through the analysis of these aspects of a function with respect to the coupling among the functions (Hollnagel, 2012; Sun et al., 2022). As a result, activities are identified, explained, and categorized in term of how they are achieved daily rather than how they are imagined. This enables decision-makers to further improve insight into how variability might arise and spread all over the functions. The latter are regarded as either (i) "*foreground"*, that is functions whose variability could affect the outcome of the appraisal, or (ii) "*background"*, that is functions that are quite stable and have less impact on the outcome of the appraisal. The coupling among functional modules is described as the interaction and dependencies among functional modules. On the one hand, functional module that arises before another one is called an *"upstream functional module"*. On the other hand, a function that arises after another one is called a *"downstream functional module"*. The potential variability assessment facilitates to understand how *"upstream functional module"* variations affect *"downstream functional modules"* by up-down coupling.

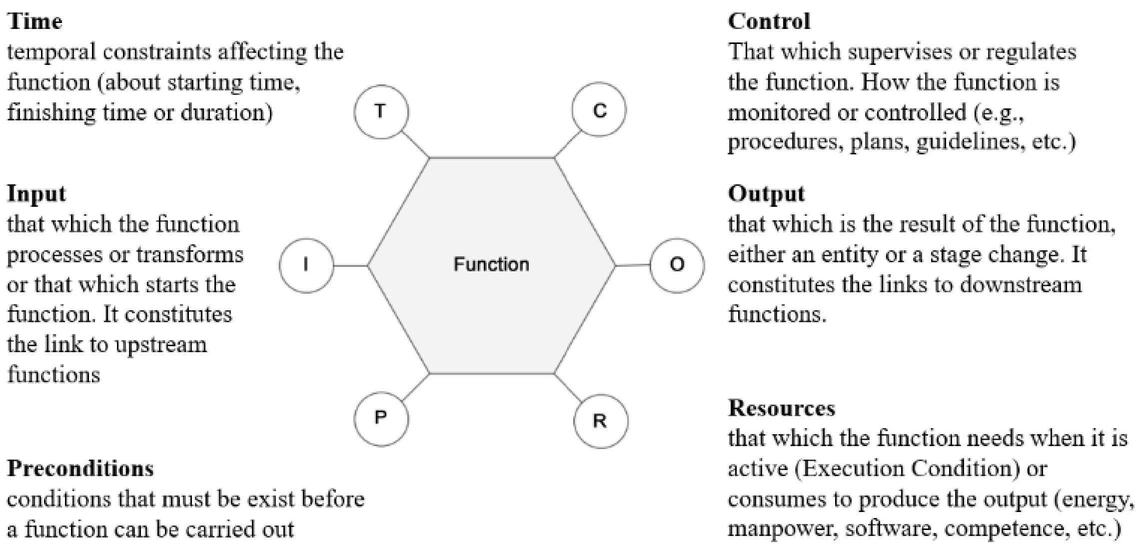

Figure 9.9. Depiction of a function in FRAM.
(Source: own representation based on Hollnagel (2012))

- *The STAMP Approach*

Traditional causality models often attribute accidents to component failures or random concurrent events without thoroughly explaining the root causes. These models assume a linear *"chain-of-failure"* causality, where one failure directly triggers the next in a sequence. However, such models focus narrowly on failures, neglecting unsafe interactions between system components and latent factors like human performance, organizational behaviors, technology, and deficiencies in processes (e.g., maintenance, design, fabrication, or installation).

As systems become more complex with Industry 4.0 advancements, cyber threats, climate change, natural disasters, and economic inflation, traditional models are increasingly inadequate for analyzing socio-technical systems. Nancy Leveson (2016) introduced STAMP, a systems-thinking approach that provides a comprehensive framework for understanding accidents in complex socio-technical systems. It considers human operators, organizational factors, technical aspects (e.g., software and hardware), and their interactions. Unlike traditional models, STAMP addresses safety and security as *dynamic control problems* rather than merely preventing failures or improving reliability. STAMP emphasizes the identification and enforcement of safety constraints across the system to prevent unsafe interactions and component failures.

The STAMP process incorporates System-Theoretic Process Analysis (STPA), a hazard assessment method based on control theory rather than traditional reliability theory. STPA focuses on defining safety objectives, addressing stakeholder needs, and developing a Hierarchical Safety Control Structure (HSCS) to identify Unsafe Control Actions (UCAs) within control and feedback mechanisms. By examining component failures, hazardous interactions, human errors, software behavior, and design flaws, STPA generates comprehensive accident causation scenarios.

The STPA process follows a structured approach to ensure a thorough safety assessment. It begins by defining the purpose of the analysis, establishing specific goals and the scope of the assessment, with an emphasis on safety objectives and stakeholder requirements. A detailed HSCS is then developed to represent the system's control and feedback mechanisms, forming a foundation for analyzing interactions and dependencies. The process further examines these mechanisms to identify UCAs (actions or omissions that could lead to unsafe system behavior). Finally, loss scenarios are created to demonstrate how these UCAs, in combination with factors such as design flaws, human errors, or hazardous interactions, could result in system failures or losses. This approach ensures a comprehensive evaluation of safety by addressing dynamic interactions and control processes within the system.

Figure 9.10 illustrates the dynamic control process, showcasing the interaction between the controller, the controlled process, and the feedback and control actions that connect them (Leveson, 2018, 2016). Figure 9.11 depicts an example of a HSCS. Figure 9.12 illustrates the tools available within the STAMP framework, including STPA and its extensions, such as CAST for causal analysis, STPA-sec for security analysis, and STECA for early concept analysis (Leveson, 2016).

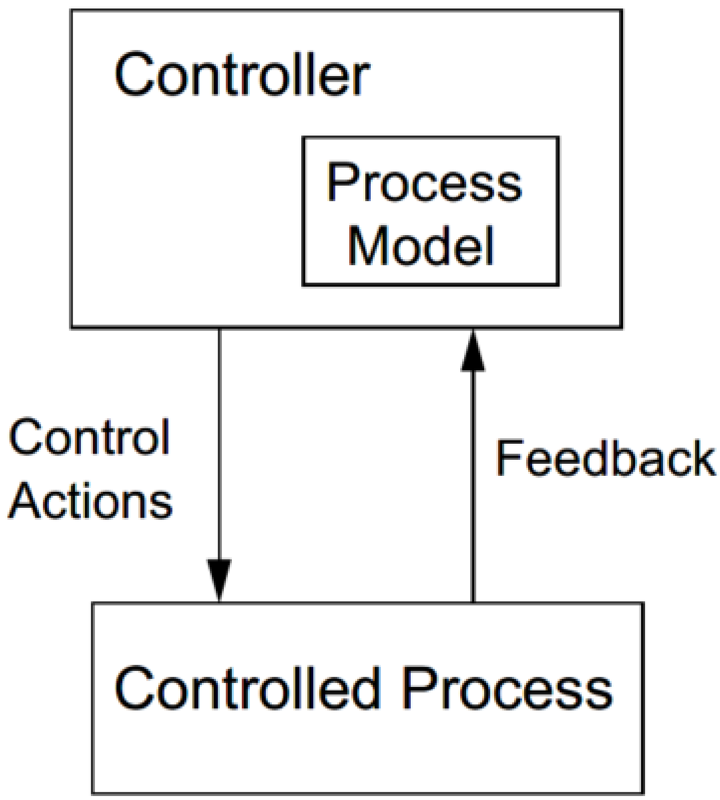

Figure 9.10. Depiction of the dynamic of the process control
(Source: (Leveson, 2018, 2016))

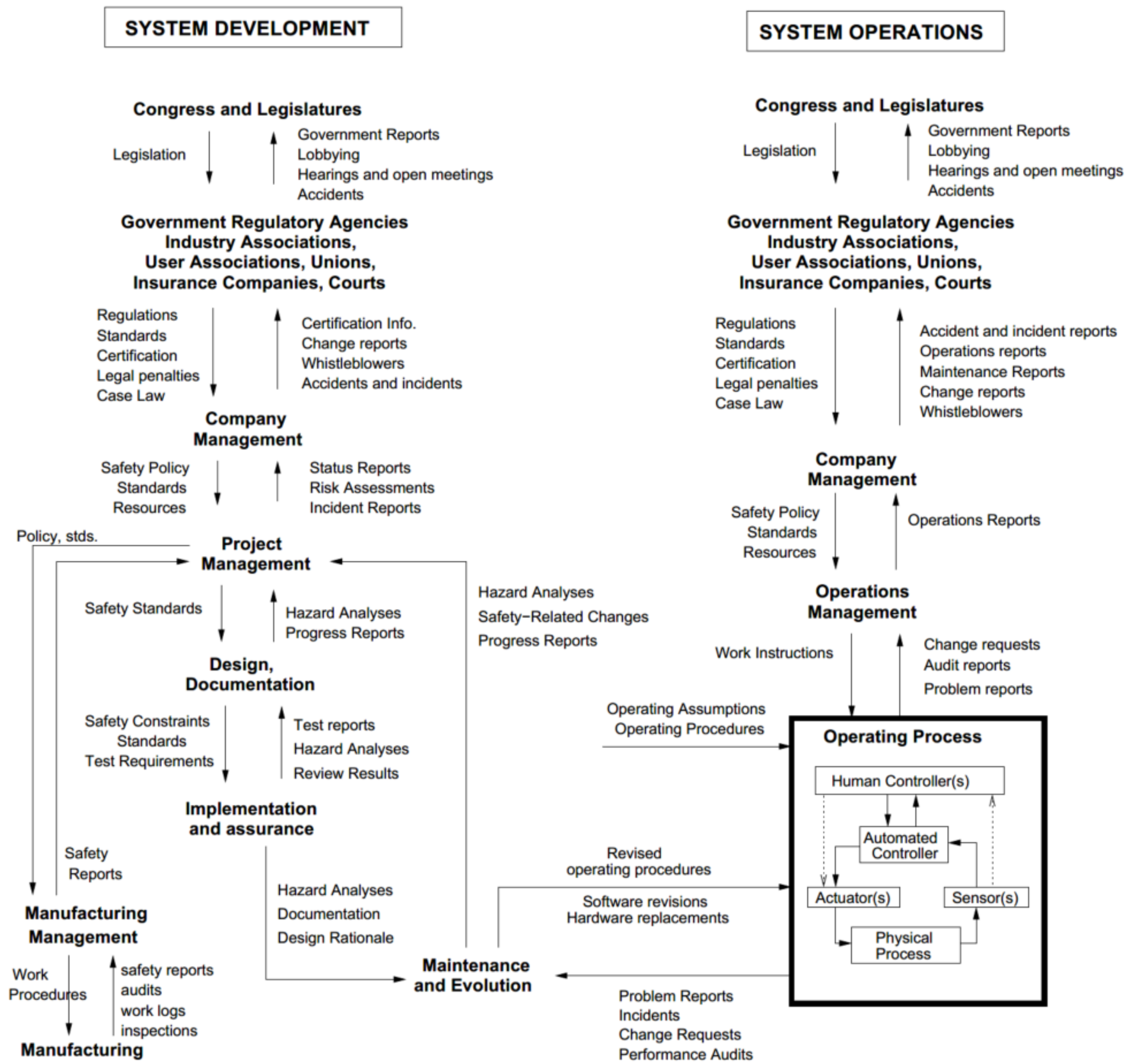

Figure 9.11. Depiction of an example of hierarchical safety control structure (HSCS)
(Source: Leveson (2016))

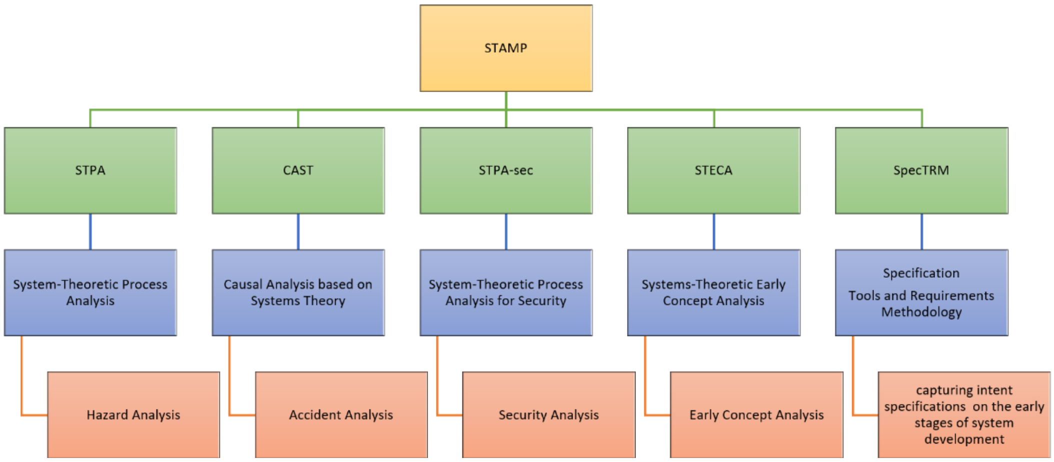

Figure 9.12. Depiction of the various tools available in the STAMP process.
(Source: own representation based on Leveson (2016))

- *The Risk-Informed Decision-Making*

Initially developed in the 1990s by the US Nuclear Regulatory Commission (USNRC) and NASA, the risk-informed decision-making (RIDM) was designed to address safety concerns in the nuclear power and aerospace industries (Travers, 1999). The International Atomic Energy Agency (IAEA) later introduced a generic framework for integrated RIDM (Lyubarskiy et al., 2011). As described by Zio et al. (2012), RIDM involves *"structured processes that assist decision-makers when faced with high-impact, complex decisions involving multiple objectives and uncertainty"*. The objective is to ensure that decisions among alternatives are made with a comprehensive understanding of the associated risks in an integrated manner. Scientific literature highlights a variety of definitions for RIDM, reflecting its complexity and multidisciplinary nature. Bujor et al. (2010) describe RIDM as a discipline that incorporates a range of inputs and insights, including traditional engineering analyses, deterministic and probabilistic risk analyses, operational experience, cost-benefit evaluations, regulatory requirements, and other relevant quantitative, qualitative, and intangible factors.

For this study, the definition proposed by Komljenovic et al. (2016) is adopted, which aligns with the Candu Owners Group (COG) and is technology-neutral. It defines RIDM as: *"Decision-making in which the decision-maker considers all pertinent factors, including uncertainties that may impact the resolution of the issue. These factors include both quantitative and qualitative inputs weighted according to the decision-maker's judgment and experience. The risk component is one of many inputs and is weighted appropriately depending on the situation, contrasting with a risk-based approach that relies solely on numerical risk assessments".*

Today, RIDM is applied in various industries, including aerospace and infrastructure safety (e.g., dams and aviation), providing practical decision-making support for decision-makers, management, and stakeholders (Dezfuli et al., 2010a, 2010b, 2010c). However, it is not typically suitable for everyday decision-making processes. Figure 9.13 depicts the fundamental principles and components of the RIDM process, highlighting the integration of safety analyses, risk assessments, operational experience, regulatory requirements, and socio-economic considerations.

Figure 9.13. Depiction of principles of RIDM
(Source: own representation based on US Nuclear Regulatory Commission. (2002)

9.3 The Proposed Framework for System Safety Risk Characterization in AM

To address emerging safety risks in socio-technical systems, a high-level risk management framework is proposed, built on system theories and integrating three techniques: FRAM, STAMP-STPA, and RIDM (see Figure 9.14). FRAM models functional dependencies and variabilities by analyzing interactions and dependencies among functional modules. It assesses risks by identifying performance variability and functional resonance, revealing potential non-linear effects, such as extreme or rare events. STAMP-STPA is used to enforce safety requirements and constraints by controlling the behavior of system components and the system as a whole, mitigating risks through dynamic safety analysis. RIDM integrates the outcomes of FRAM and STAMP-STPA into a holistic decision-making framework. It enhances long-term performance and sustainability by addressing uncertainties, rare events, and complex risks in asset management strategies. This three-fold approach ensures a comprehensive understanding and management of risks in dynamic and complex systems.

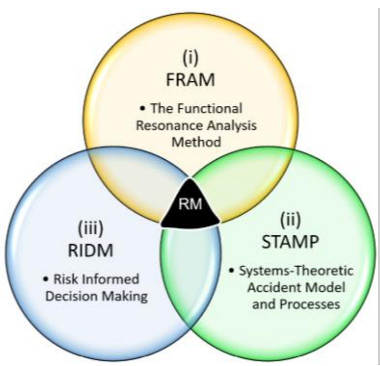

Figure 9.14. High-Level Risk Management Framework with FRAM, STAMP-STPA, and RIDM
(Source: own representation)

The RIDM process is a novel decision-making methodology suited for large projects and long-term sustainability. Figure 9.15 depicts the three steps of the RIDM process. Step 1 establish a decision-making framework by defining the context, objectives, and options to be analyzed. This phase includes selecting scientific and technical assessment techniques and tools. Step 2 conduct detailed qualitative and quantitative analyses, such as engineering, risk, and economic appraisals, performed by subject matter experts. The results provide evidence-based insights for decision-makers. Step 3 deliberate and make the final decision through collaboration between decision-makers, stakeholders, and experts.

Figure 9.16 outlines the seven sub-models within Step 2 of the RIDM process. These sub-models encompass key areas of AM, including strategy and planning, decision-making, lifecycle delivery, asset information, organizational factors, and risk review. This framework aligns with the Global Forum on Maintenance and Asset Management guidelines (GFMAM, 2014; IAM, 2015) and integrates ISO-31000 (2018, 2009) methodologies for risk assessment. Figure 9.17 illustrates the Global Risk-Informed Decision-Making Model in AM, aligned with the ISO 31000 standard.

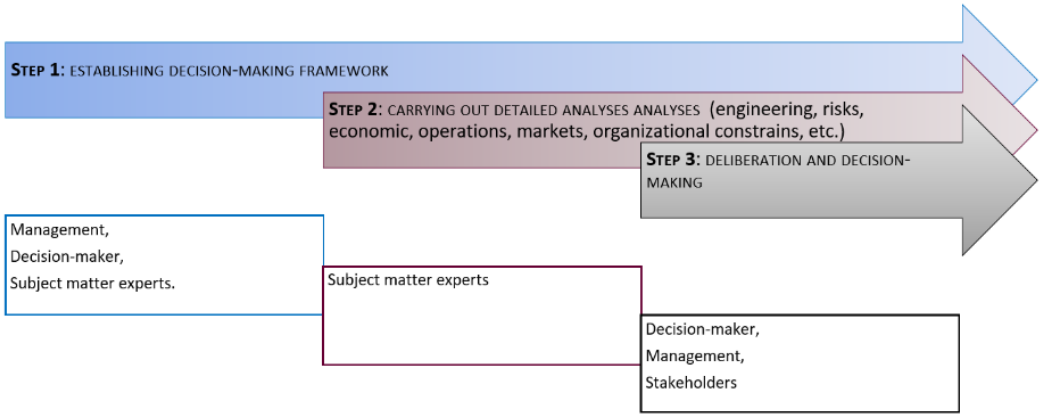

Figure 9.15. Depiction of Global RIDM process in AM
(Source: own representation)

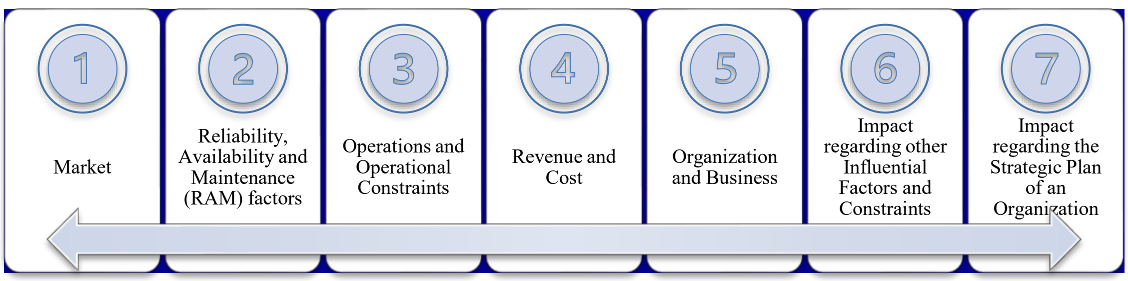

Figure 9.16. Aspects of Step 2 in the Global RIDM Process for AM
(Source: own representation)

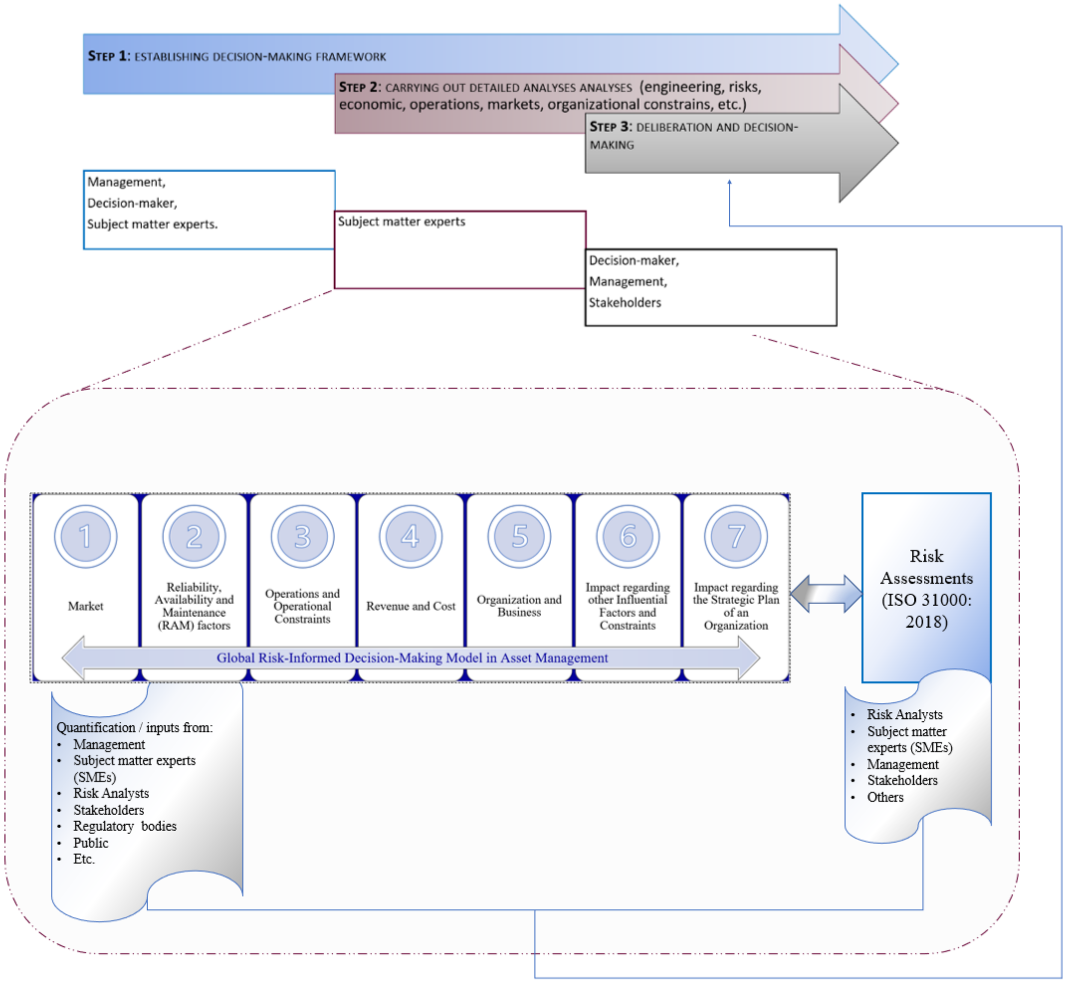

Figure 9.17. Global RIDM in Asset Management Aligned with ISO 31000
(Source: own representation)

The sub-models of the Global RIDM framework in AM, primarily inspired by Komljenovic et al. (2016), are defined 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

Figure 9.18. Market sub-model

(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)

Figure 9.19. Depiction of the sub-model of reliability, availability, and maintenance (RAM) factors

(3) Sub-model of operations and operational constraints

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

Figure 9.20. Depiction of the sub-model of operations and operational constraints

(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

Figure 9.21. Depiction of the revenue and cost sub-model

(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

Figure 9.22. Depiction of the organizational and business sub-model

(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.

Figure 9.23. Depiction of the sub-model of impact regarding other influential factors and constraints

(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

Figure 9.24. Depiction of the sub-model of impact regarding the strategic plan of an organization

9.4 Conclusion

This research introduces a high-level risk management and decision-making framework integrating FRAM, STAMP-STPA, and RIDM to address emerging and disruptive risks in socio-technical systems. The framework aims to enhance asset management by providing a dynamic approach to managing extreme events and uncertainties, outperforming traditional methods. Future case studies will assess its effectiveness in mitigating industry 4.0 safety risks, handling rare and disruptive events, and ensuring organizational resilience.

CHAPITRE 10

ARTICLE 4

A Comprehensive Decision-Making Approach: Evaluating and Managing Risks Associated with Emerging Technologies – A LineDrone Technology Case Study

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Abstract – The primary objective of this paper is to conduct an exploratory, qualitative study in Industrial Asset Management, focusing on the development of an Integrated Decision-Making Framework. This framework is designed to evaluate performance variability caused by emerging technology risks and extreme, rare, and disruptive events. To achieve this, we integrate two robust decision-support tools: the Functional Resonance Analysis Method (FRAM) and the System-Theoretic Process Analysis (STPA). FRAM provides a comprehensive analysis of sociotechnical system functions, highlighting their interconnections and dependencies. In contrast, STPA, based on the System-Theoretic Accident Model and Processes (STAMP), takes a top-down approach to hazard assessment. The integration of FRAM and STPA aims to create a powerful decision-support framework. A case study on the LineDrone, which inspects high-voltage transmission lines without direct human interaction, demonstrates the framework's effectiveness in managing performance variability within complex sociotechnical environments.

Keywords **–** Asset Management Strategy, Emerging Risks, Extreme-Rare-and-Disruptive-Events, Industry 4.0, Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP), System-Theoretic Process Analysis (STPA).

10.1 Introduction

Industry 4.0 has ushered in a plethora of cutting-edge technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and Cyber-Physical Systems (CPS). These advancements facilitate automation, data-driven decision-making, and seamless integration of system components. Though these technologies offer considerable advantages, they also introduce unique risks that traditional analysis methods may not fully comprehend. Keating et al. (2022) and Katina et al. (2021) have identified these challenges for complex system governance.

The dynamic and interconnected nature of Industry 4.0 systems demands more advanced and comprehensive approaches to assess safety risks and ensure system resilience. Scientists need to improve existing approaches or develop new ones. In response to these challenges, innovative methodologies have emerged. These include system dynamics modeling, resilience engineering (Hickford et al., 2018; Woods, 2015) and systemic risk analysis, and managing emerging risks (ISO, 2023, 2019). In the same vein, the FRAM approach (Diop et al., 2022b; Hollnagel, 2018) and the STAMP approach (Leveson, 2023; Allison et al., 2017), as well as the Risk-Informed Decision Making (RIDM) approach (Gaha et al., 2021; Komljenovic et al., 2016) have emerged to better analyze complex systems, understand their behavior, and manage performance variability and safety risks. The efficacy of these tools lies in their ability to comprehensively address the interdependencies and interactions between diverse system components, encompassing both technological and human elements. Moreover, these tools must account for the potential cascading effects and emerging risks that can arise within complex socio-technical systems.

Given the complexity of modern power systems, entities like Hydro-Québec (HQ) [§§§§§] face significant challenges in asset management. HQ's operations involve managing a vast portfolio of assets, ensuring the efficient performance and longevity of its infrastructure. To effectively operate and maintain their infrastructure, HQ needs to have detailed information about the condition, location, and availability of these assets throughout the entire operation chain. This information is crucial for optimizing productivity, minimizing service interruptions, and ensuring the safety of operations and end-users. By having accurate and up-to-date knowledge about their assets, HQ can make informed decisions regarding maintenance schedules, asset replacements, and resource allocation. This enables them to enhance the efficiency and reliability of their operations, ultimately leading to improved service delivery to customers. Furthermore, having a comprehensive understanding of asset condition and availability allows HQ to proactively identify potential issues or risks that may impact the system's performance.

This paper presents an exploratory, qualitative study aimed at developing an Integrated Decision-Making Framework to assess performance variability caused by emerging technology

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[§§§§§] Hydro-Québec is a leading electricity utility in North America, specializing in the generation, transmission, and distribution of electricity across Canada. With a focus on hydroelectric power, the company leverages the region's abundant water resources to deliver reliable and sustainable electricity to residential, commercial, and industrial customers.

risks and disruptive events. The framework combines FRAM and STPA, two methodologies designed to address the complexities of modern sociotechnical systems. A case study on the LineDrone, an Unmanned Aerial Vehicle (UAV) used by Hydro-Québec for inspecting high-voltage transmission lines, is conducted to validate the framework's effectiveness in managing performance variability in real-world applications.

The remainder of the manuscript is organized as follows: section 2 provides an overview of the FRAM method, while section 3 introduces the STAMP-STPA control theory. In section 4, the case-study is conducted, followed by final thoughts of the outcomes in section 5. Finally, in section 6, we conclude the study and outline potential avenues for future research.

10.2 FRAM Method

Introduced by Hollnagel in 2004 and further developed in 2012, the FRAM method aims to identify and assess performance variability in sociotechnical systems (Hollnagel, 2012, 2004). Essentially, it analyzes and understands the dynamic behavior of complex systems, focusing on how functions and their variabilities impact system performance. Performance variability, a key aspect in FRAM, reflects the dynamic nature of complex systems. FRAM acknowledges that variability, an inherent aspect of systems, does not invariably result in failure but is a part of normal functioning. Unlike conventional approaches that simplify or linearize system relationships, the FRAM method adopts a systemic perspective, embracing complexity and nonlinearity without reducing the sociotechnical system to its individual components. In the FRAM approach, the focus is on understanding how activities are performed in practice (referred to as *"work as done"*) rather than how they are ideally or conceptually supposed to be performed (referred to as *"work as imagined"*) *(Sun et al., 2022, Hollnagel, 2012;)*. This perspective allows for a more realistic and accurate assessment of the system's behavior, considering the variability and adaptations that occur in real-world operational contexts (the way activities are carried out), influenced by factors such as human factors, organizational factors, and contextual factors. By studying the *"work as done",* it becomes possible to identify the actual strategies, actions, and interactions that take place in the system. This understanding is crucial for assessing both performance variability and resilience, reflecting the real-world functioning of complex sociotechnical systems. This approach helps bridge the gap between the intended design of the system and its actual functioning. The FRAM structure is fundamentally a five-step process, summarized in Figure 10.1.

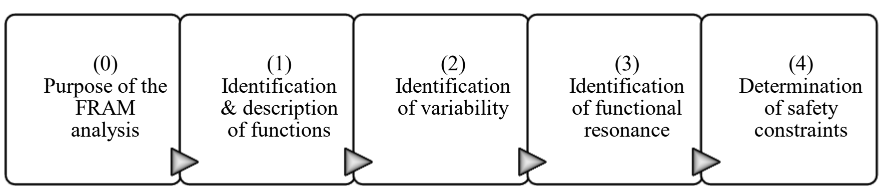


Figure 10.1. Depiction of the Main Steps of the FRAM Method

- *Step 0: Purpose of the FRAM Analysis*

This step highlights the objective of the analysis, which can be either to understand events that have occurred in the past (retrospective events such as accident investigation) or to anticipate events in the future (prospective events such as risk assessment). Accident analysis focuses on examining past incidents to understand what went wrong and why, with the goal of preventing similar occurrences in the future. Conversely, safety assessment involves anticipating potential risks and implementing preventive measures before any accidents occur.

- *Step 1: Identification and Description of Functions*

This step focuses on identifying, describing, and classifying essential functions or activities[******] for the system's accurate operation. These functions can be carried out by humans, machines, or a collaborative effort between humans and machines. Each function is symbolized by a hexagon encompassing six aspects: Input (I), Output (O), Preconditions (P), Resources (R), Time (T), and Control (C). These aspects are characterized as follows (Hollnagel, 2004):

(1) Input: information, materials, or elements processed or transformed by the function, or that initiate its operation.

(2) Output: the outcome of a function, which may be a tangible product or a state change.

(3) Preconditions: the prerequisites or conditions that must be fulfilled before a function can be executed.

(4) Resources: the requirements necessary for the function's execution (execution condition) or the resources consumed in generating the output.

(5) Time: the temporal limitations that impact the function, encompassing factors such as initiation time, completion time, or duration.

(6) Control: the methods and mechanisms in place for monitoring and regulating the behavior and execution of a function.

These aspects represent the five types of incoming instances that are linked to the function from other functions *(referred to as upstream functions)*. Each aspect indicates a specific type of input or influence that is received by the function from other interconnected functions within the

[******] In the context of FRAM, a function refers to the means or activities required to achieve a specific goal (Hollnagel, 2016). It represents the actions or processes that must be executed to attain a desired outcome or objective within a system.

system. These incoming instances (or influences) play a role in shaping the behavior and operation of the function under consideration. The output of a function refers to the result or outcome that is produced by the function and is subsequently linked to one or more aspects of other functions *(referred to as downstream functions)*. The output of a function serves as an incoming instance (or influence) for other interconnected functions within the system, impacting their behavior and operation.

Figure 10.2 provides a graphical depiction of functions and their interactions *(Upstream-downstream coupling)*, visually outlining the structure and components of each function within the system, including the hexagonal symbol and its associated aspects *(Input, Output, Preconditions, Resources, Control, and Time)*.

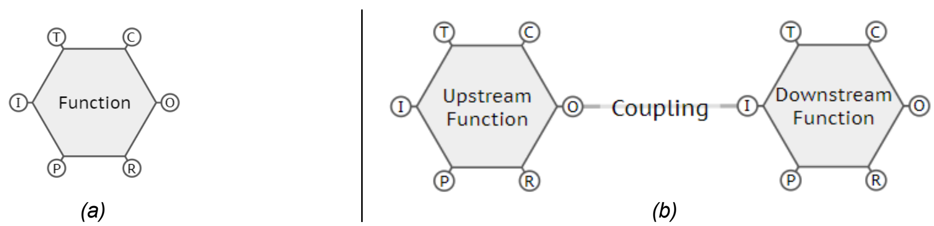
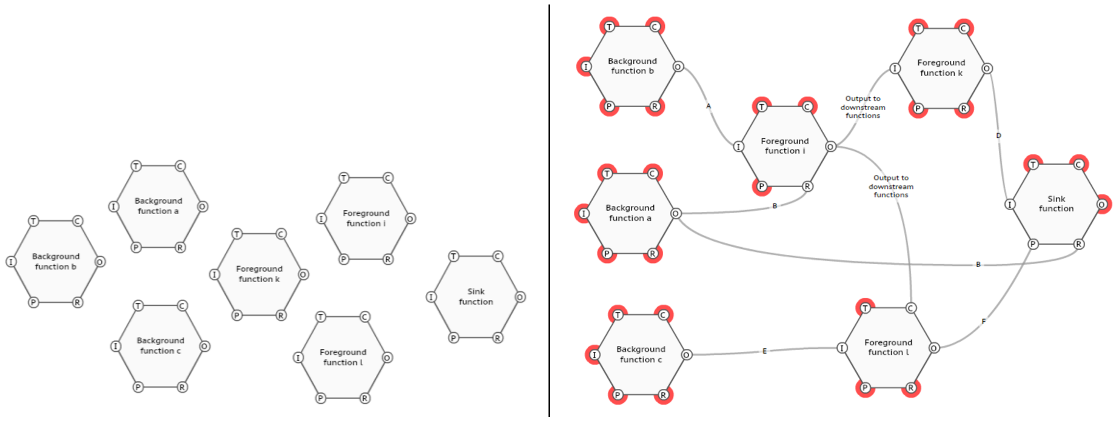


Figure 10.2. Depiction of a Function (a) and Upstream–Downstream Coupling (b) in FRAM

After completing the initial steps (zero and one), the FRAM model is considered complete. Figure 10.3 depicts a graphical representation of *(a) the FRAM model*, visually illustrating the various functions within the system, and *(b) an instantiation of the model*, showcasing the functional structure and interrelationships. In this representation, functions are interconnected, highlighting their relationships and interactions. In other words, the couplings express how these functions rely on and interact with one another for the system to operate effectively and achieve the overall system objectives.

Macchi (2010) outlines a three-step process for identifying and categorizing functions in system analysis. (1) The first step is to identify the foreground of the safety assessment, focusing on the key functions essential to achieving the desired outcomes. (2) Next, the system boundaries are defined based on functional relationships rather than physical objects, allowing for a more flexible and dynamic analysis that considers the interactions and ripple effects between functions. (3) Lastly, the appropriate level of granularity is determined, ensuring a balance between providing sufficient detail and avoiding unnecessary complexity, tailored to the objectives of the study.



(a) (b)

Figure 10.3. Depiction of a FRAM Model (a) and a FRAM Instantiation (b) of the Model

- *Step 2: Identification of Variability*

FRAM emphasizes the critical role of performance variability, acknowledging the dynamic nature of complex systems. From this perspective, variability is not merely a pathway to failure but a fundamental characteristic of regular system operations (Hollnagel, 2012). The model facilitates the generation of diverse potential instantiations, delineating specific analysis scenarios within the sociotechnical system. An instantiation captures the specific couplings and interactions between upstream and downstream functions at a particular time or under certain conditions. It provides a snapshot of the system's behavior and dynamics in a specific context. In the original version of the method, potential variability was estimated by evaluating a set of *Common Performance Conditions (CPCs)*, as detailed in Table 10.1. These CPCs assess the likelihood of performance variability for each function, based on their type and nature (Macchi, 2010; Hollnagel, 2004).

Table 10.1. Likely Performance Variability Based on CPCs (Source: Adapted from Macchi, 2010; Hollnagel, 2004)

H: Human, T: Technological, O: Organization

Common Performance Conditions (CPC)	*Affected Functions*			*Impact of each CPC*		
	H	*T*	*O*	*Adequate*	*Inadequate*	*Unpredictable*
Availability of resources	*	*		Small	Noticeable	High
Training and experience (competence)	*			Small	High	High
Quality of communication	*	*		Small	Noticeable	High
HMI and operational support		*		Small	Noticeable	High
Availability of procedures and plans	*			Small	Noticeable	High
Conditions of work		*	*	Small	Noticeable	High
Number of goals and conflict resolution	*		*	Small	High	High
Available time and time pressure	*			Small	High	Very high
Circadian rhythm, stress	*			Small	Noticeable	High
Team collaboration quality	*			Small	Noticeable	High
Quality and support of the organization			*	Small	Noticeable	High

Due to certain limitations, the CPCs-based performance variability assessment approach has some drawbacks. Consequently, Hollnagel (2012) proposes an alternative methodology to accurately estimate normal performance variability. The author identifies two factors that can contribute to variability in the output of a function, namely: *Internal Variability* (IV) and *External Variability* (EV). In essence, the model helps determine how each individual functional output within the system can be influenced by IV (endogenous variability) or EV (exogenous variability). A clear distinction needs to be made between EV, which is introduced from external sources, depicted through the impact of both functional couplings and performance conditions; and IV, originating from within the function itself. In other words, IV encompasses the intrinsic attributes influenced by the prevailing performance conditions during execution. This includes technological aspects, organizational environment, potential variability in human-based functions, such as inherent possibility of human error, emotional states, circadian rhythm, human factors, ergonomics (including psychological and physiological aspects), social pressures, decision-making processes, and other relevant considerations. Table 10.2 outlines these two factors that can contribute to variability, along with their potential sources and the likelihood of performance variability for each type of function.

Extending the range of performance conditions to incorporate external factors, including environmental circumstances and the risks associated with extreme, rare, and disruptive events in asset management, is a viable option. The extent to which this extension is applied would hinge on the specific context of the analysis.

Table 10.2. Internal and External Variabilities
(Source: Adapted from Hollnagel, 2012)

H: Human, T: Technological, O: Organization, IV: Internal variabilities, EV: External variabilities

Variability Type	Function Type	Possible Sources of Performance Variability	Likelihood of Performance Variability
IV	T	Few → *(Well known)*	Low
	H	Very many → *(Physiological and Psychological)*	High Frequency Large Amplitude
	O	Many → *(Function Specific and/or relating to "Culture")*	Low Frequency Large Amplitude
EV	T	Maintenance → *(Mis(use))*	Low
	H	Very many → *(Social and Organizational)*	High Frequency Large Amplitude
	O	Many → *(Instrumental or "Culture")*	Low Frequency Large Amplitude

(1) *Technological Functions (T)* are accomplished through various types of technology. The FRAM concept assumes that technological functions are generally predictable and reliable, hence considered stable. In the current analysis, the outputs of these functions are not expected to vary significantly. Nonetheless, it is important to note that the performance of technology-based functions can still undergo changes. This variability may arise due to factors such as inadequate maintenance, unfavorable operating conditions, gradual wear and degradation, and other similar influences.

(2) *Human functions (H)* are performed either individually or collectively by human operators. These functions are recognized as variable and prone to instability due to the inherent possibility of human error. The potential variability in human-based functions can be attributed to factors such as circadian rhythm, human factors, ergonomics (including psychological and physiological aspects), social pressures, decision-making processes, and other relevant considerations.

(3) *Organizational functions (O)* are carried out by groups of individuals within an organization and are described at the organizational level, distinguishing them from individual human-based functions. The variability in organizational functions is often characterized by a low frequency, meaning that they change slowly over time. Yet, when it occurs, it tends to have a significant impact with high amplitude. Factors contributing to variability in organizational functions include unpredictable events, unsuccessful communication, conflicting or ambiguous priorities, and lack of coordination, among other organizational dynamics.

Table 10.3 provides a summary of the potential variability in output Timing and Precision. It highlights possible variations in the *timing* of the output, indicating whether it can be early, delayed, or occur at unpredictable intervals. Additionally, it describes the *precision* of the output, specifying whether it can be exact, approximate, or vary within a certain range. Understanding these attributes is crucial for assessing potential impacts on downstream functions and identifying areas for improvement in the system.

Table 10.3. Potential Output Variability with Respect to Time and Precision
(Adapted from Hollnagel, 2012)

Temporal Variability of Response				
Function type	*Too early*	*On time*	*Too late*	*Not at all*
Technological	Unlikely	Normal, expected	Unlikely, but possible if software is involved	Very unlikely (only in case of complete breakdown)
Human	Possible, serendipity	Possible, should be typical	Possible, more likely than too early	Possible, to a lesser degree
Organization	Unlikely	Likely	Possible	Possible

Variability in Precision of Response			
Function type	*Precise*	*Acceptable*	*Imprecise*
Technological	Normal, expected	Unlikely	Unlikely
Human	Possible, but unlikely	Typical	Possible, likely
Organization	Unlikely	Possible	Likely

- *Step 3: Identification of Functional Resonance*

This step delves into the aggregating variability by characterizing the functional resonance sources via the study of the functional aspects. Functional resonance, in the FRAM context, signifies the amplification or spread of performance variability from one function to others within a system. It results from variability in upstream functions affecting downstream functions, which can amplify or accumulate variability. This phenomenon intensifies when propagated through the system, potentially elevating the risk of accidents or undesired outcomes. Should functional resonance exceed a critical tolerance threshold, it heightens the system's accident or incident risk. Understanding functional resonance offers insights into the system's cascading effects and dependencies, providing a comprehensive view of how variability is propagated and managed.

Managing *output quality* is crucial for optimizing system performance and minimizing risks. *Output quality*, reflecting both Precision and Timing, directly influences downstream function variability (Macchi, 2010). The *quality (q)* of output affects the performance variability of downstream functions: higher quality reduces variability, while lower quality increases it. Degraded quality necessitates more local adjustments in downstream functions to maintain system functionality.

Table 10.4 illustrates potential output qualities, their ranges, and their impact on downstream functions' performance variability. To estimate a function's likely performance variability, it is crucial to aggregate the quality weights of all related aspects. This process involves establishing specific hypotheses about how these qualities influence performance variability, rated on a scale from positive (+1 to +3) for dampening variability to negative (-1 to -3) for increasing it. The aggregated output quality of a function, representing its overall score, is then determined by taking the *median* of these aspect qualities.

Table 10.4. Output Quality with respect to Time and Precision
(Source: own representation)

Precision range of variability of output		Temporal range of variability of response		
		Too early	***On time***	***Too late***
	Precise	$q = Ia$ Although the output to downstream functions is accurate, it is generated too early. → (This suggests a moderate potential for reducing variability, contributing to variability dampening) → Rate: (+2)	$q = II$ The output to downstream functions is accurate and delivered with optimal timing. → This indicates a strong potential for reducing variability (dampening) → Rate: (+3)	$q = IIIa$ The output to downstream functions is accurate, but the delay reduces the available time. → (This suggests a low potential for reducing variability (dampening)) → Rate: (+1)
	Acceptable	$q = IIIb$ The output to downstream functions is appropriate, but it is generated prematurely. → (This suggests a low potential for reducing variability (dampening)) → Rate: (+1)	$q = Ib$ The output to downstream functions is appropriate and delivered with correct timing. → (This suggests a moderate potential for reducing variability, contributing to variability dampening) → Rate: (+2)	$q = IVa$ The output to downstream functions is appropriate, but the delay reduces the available time. → (This suggests a low potential for increased variability) → Rate: (-1)
	Imprecise	$q = IVb$ The output to downstream functions is both inaccurate and generated prematurely. → (This suggests a low potential for increased variability) → Rate: (-1)	$q = V$ The output to downstream functions is delivered on time but lacks accuracy. → (This suggests a moderate potential for increased variability) → Rate: (-2)	$q = VI$ The output to downstream functions is both inaccurate and delayed. → (This suggests a high potential for increased variability) → Rate: (-3)

To illustrate the process of assessing performance variability, consider Figure 10.4, adapted from Macchi (2010). This figure presents a hypothetical Function Z connected to four preceding functions, receiving two Inputs, one Control, and one Precondition. Each of these elements contributes differently to the performance of Function Z:

(1) Inputs are assessed with a quality rating of $q = IVa$, indicating they are of *acceptable quality* but arrive *too late*, resulting in a value rating of (-1).

(2) Control is assessed with a quality rating of $q = Ia$, representing *precise control* that arrives too early, leading to a positive value rating of (+2).

(3) Precondition is assessed with a quality rating of $q = VI$, signifying it is *imprecise* and arrives *too late*, which corresponds to a value rating of (-3).

To determine the likely performance variability of Function Z, it is essential to assess the cumulative impact of the contributing aspects. This is done by calculating the median of the aspect qualities, which in this case is (-1), based on the individual ratings of (-3, -1, +2). Thus, the median quality of the aspects becomes the quality of Function Z's output. In this example, the median value[††††††] is (-1), corresponding to an output quality level of $q = IVa$ or $q = IVb$.

This methodological approach allows for a systematic assessment of how various input qualities contribute to the overall performance variability of a function, providing a clear, aggregated view of output quality based on aspect ratings.

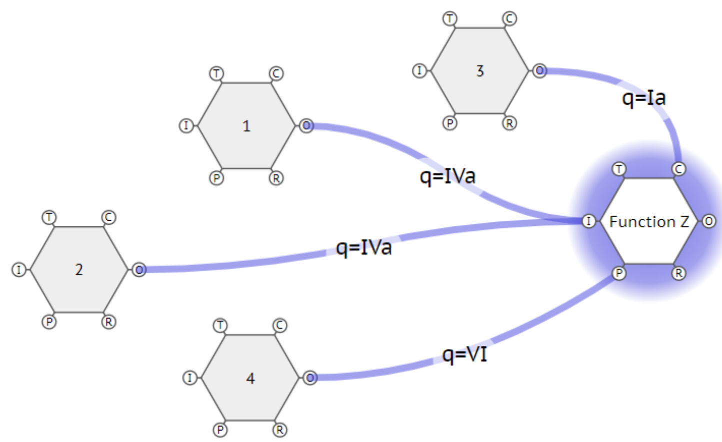


Figure 10.4. Illustration of Deriving the Overall Score for a Function by Employing the Median of Its Aspect Qualities
(Source: own representation based on Macchi, 2010)

Given the variability in the output of a function, five specific linkages between upstream and downstream couplings play a crucial role in the propagation of effects within a system (Hollnagel et al., 2014). These linkages include the interrelations of Output with Input, Output with Time, Output with Resources, Output with Control, and Output with Preconditions. Each linkage has a distinct impact on the variability of downstream functions, which can be understood through the following symbols, as illustrated in Table 10.5:

[††††††] Let's sort those values in ascending order: (-3), (-1), (+2). Now, the median is the middle value, which is (-1) in this case.

(1) V↑: Indicates a strong likelihood of increased variability, such as when the output of an upstream function is delayed, affecting the timing of downstream inputs.

(2) V↓: Indicates a strong likelihood of reduced variability, which might occur when precise control from an upstream function enhances the stability of downstream processes.

(3) V↔: Indicates a strong likelihood that the variability will remain unchanged, for example, when the output quality consistently meets the requirements of downstream functions, neither improving nor worsening their performance variability."

Table 10.5. Potential Effects of Output Variability in an Upstream Function on Downstream Functions
(Source: own representation based on Hollnagel et al., 2014)

			Potential effects through various aspects of downstream functions				
			Effects on Input	Effects on Time	Effects on Resources	Effects on Control	Effects on Preconditions
Variability in the Output of an Upstream Function	Timing	*Too early*	V↑ or V↓	V↑	V↔ or V↓	V↑	V↑
		On time	V↓	V↓	V↓	V↓	V↓
		Too late	V↑	V↑	V↑	V↑	V↑
	Precision	*Imprecise*	V↑	V↑	V↑	V↑	V↑
		Acceptable	V↔	V↔	V↔	V↔	V↔
		Precise	V↓	V↓	V↓	V↓	V↓

Let's take a quick look at brief descriptions for each of these connections:

(1) *Coupling between Output and Input* – The relationship between output and input, or coupling, is critical. The input acts as both the initiator of a function and the data that the function processes or modifies. Variability in upstream output can cause the function to start either too early or too late. For example, optimizing a function for time savings might mitigate delays, but it could also increase variability in the output, especially in terms of precision. When the input is processed by the function, precision variability becomes more important than timing. An imprecise input can lead to delays and result in incorrect outputs.

(2) *Coupling between Output and Time* – In a nutshell, the relationship between output and time is crucial for understanding how a function is executed. Time factors, such as availability, synchronization, and duration, play a key role in determining a function's performance. Insufficient time can negatively affect performance, whether due to delays, premature termination, or extended durations.

(3) *Coupling between Output and Resources* – To perform a function effectively, adequate resources and proper execution conditions are essential. Resources are consumed during the process and must be replenished by an upstream function. A lack of resources or improper conditions may lead to searching for alternatives, causing unexpected delays in function output. If alternatives are not fully compatible, this can increase variability, whereas abundant resources and ideal conditions can help reduce it.

(4) Coupling between Output and Control – The relationship between output and control is key to understanding how a function operates, as control guides execution. Standardized control can be seen as the output of a background function, while more dynamic control represents the output of a foreground function. The timing of control, such as its availability, is especially important when dealing with verbal instructions. Insufficient or imprecise control may require additional resources, particularly time, to confirm or gather more information.

(5) Coupling between Output and Preconditions – Output and Preconditions are closely linked within a system. Preconditions, which define the necessary conditions for a function, are derived from the output of preceding (upstream) functions. When a function relies on specific Preconditions, it often begins by verifying them. Variability in the output of Preconditions introduces variability in downstream functions, potentially causing delays, resource inefficiencies, or even the premature initiation of functions before Preconditions are fully confirmed, often driven by demands from other functions.

- *Step 4: Determination of Safety Constraints*

This step focuses on addressing safety concerns by analyzing variability and its consequences to develop strategies that mitigate risks and enhance system resilience. It emphasizes adjusting performance variability to promote positive outcomes, in line with the FRAM principles[‡‡‡‡‡‡]. Solutions may include eliminating risks, implementing safeguards, redundancy, training, feedback mechanisms, and other control measures to mitigate the negative effects (dampening the variability) or enhance the positive effects of variability and improve the system's resilience. Additionally, changes in processes, technology, or organizational factors can help manage variability more effectively.

In conclusion, while a FRAM model is useful for identifying safety constraints, this aspect extends beyond FRAM's fundamental principles (Hollnagel, 2018a). FRAM is ideal for conducting a *macro-level analysis*, providing a broad perspective on system functioning and dynamics. To address more specific safety concerns, we incorporate the STAMP methodology, as suggested by Hollnagel (2018a) and Leveson (2023, 2012). STAMP allows for a more detailed, *micro-level analysis*, focusing on the interactions and relationships between individual system components (Diop et al., 2022a, 2022b). By combining FRAM and STAMP, we gain a comprehensive understanding of both the system's overall dynamics and its detailed elements.

[‡‡‡‡‡‡] Four key principles of FRAM: 1) equivalence of success and failures; 2) approximate adjustments; 3) emergence; and 4) functional resonance.

10.3 STAMP-STPA Control Theory

Leveson's pioneering work in *"Engineering a Safer World"* introduces a systems paradigm to safety engineering called the System-Theoretic Accident Model and Processes (STAMP) (Leveson, 2023, 2016). This approach offers a more effective way to analyze complex systems than traditional safety methods, focusing on the dynamic interactions between system components. STAMP treats systems as interconnected components regulated through feedback control loops, differing from linear models of causality. It considers human, organizational, and technical factors, viewing safety and security as emergent properties arising from system interactions. STAMP approaches system safety and security as a *"Dynamic Control Problem"* moving away from the traditional approach of focusing solely on failure prevention or reliability. This perspective enables the monitoring of both system components and the system as a whole to ensure that safety requirements and constraints are effectively addressed during system operation.

The STAMP process includes System-Theoretic Process Analysis (STPA), a hazard assessment method based on control theory rather than traditional reliability theory. Its goal is to identify safety objectives, stakeholder needs, and create a Hierarchical Safety Control Structure (HSCS) to detect Unsafe Control Actions (UCAs) in control and feedback mechanisms. This approach helps generate accident causation scenarios by considering factors like component failures, hazardous interactions, human errors, software behavior, and design flaws. Figure 10.5 illustrates the key steps involved in the STPA process.

- *Step 1: Define the Purpose of the Analysis*

The initial step of the analysis process involves defining the analysis purpose, which includes identifying the safety needs and objectives of the stakeholders. During this phase, system boundaries are established, and system hazards and losses that need to be considered in the study are identified. Safety constraints are then determined based on the system's hazards and losses, establishing the desired safety level for the system.

- *Step 2: Model the Control Structure*

Systems theory views systems as Hierarchical Safety Control Structures (HSCS), which consist of feedback control loops operating at different levels, encompassing various system activities and behaviors. In the context of STPA, feedback control loops are fundamental. Figure 10.6 (a) illustrates a feedback control loop, highlighting interactions between the Controlled Process and the Controller, involving a bidirectional flow of information. Downward arrows depict control relationships that enforce safety constraints through Control Actions (CAs), regulating and influencing system components. Upward arrows represent feedback from the Controlled Process to the Controller, providing information on the system's state to enable necessary adjustments.

In this model, the top level corresponds to the Controller responsible for decision-making and control, while the bottom level represents the Controlled Process, which is regulated and monitored by the Controller. The STPA model, also referred to as the HSCS, captures these control and feedback mechanisms between Controllers and Controlled Processes. The core principle of the HSCS model is that systems are made up of interdependent components that maintain dynamic equilibrium through control loops and information flow (Leveson, 2004). The control loop helps address two major challenges in modern safety engineering: (i) interactions between human operators and the system, and (ii) the complex behavior of software. Figure 10.6 (b) illustrates an HSCS model composed of multiple interconnected control loops.

(1) *The Control Algorithm*[§§§§§§] represents the decision-making process used by the Controller. It plays a crucial role in determining the appropriate Control Actions (CAs) to be executed. Controllers rely on a Process Model (PM), previous control inputs and outputs, and other factors to guide their decision-making and determine the specific CAs (commands) to be carried out.

(2) *Process Models (PMs)* [*******] represent the controller's internal beliefs, which the control algorithm relies on to make decisions. When these beliefs do not align with reality, PM flaws occur. Leveson & Thomas (2018) suggest that these PM flaws may arise from: (i) the controller receiving incorrect feedback or information, (ii) the controller receiving correct feedback or information but misinterpreting or ignoring it, (iii) the controller not receiving feedback or information when needed (either delayed or not received at all), or (iv) the necessary feedback or information being unavailable.

[§§§§§§] For human controllers, Decision-Making or Operating Procedures is the equivalent of a control algorithm and can be influenced by factors like procedures, prior experience, etc.

[*******] When it comes to Human Controllers, we call the PM the Mental Model (MM). The latter influences human Controller decision-making (control algorithm) and CAs (commands).

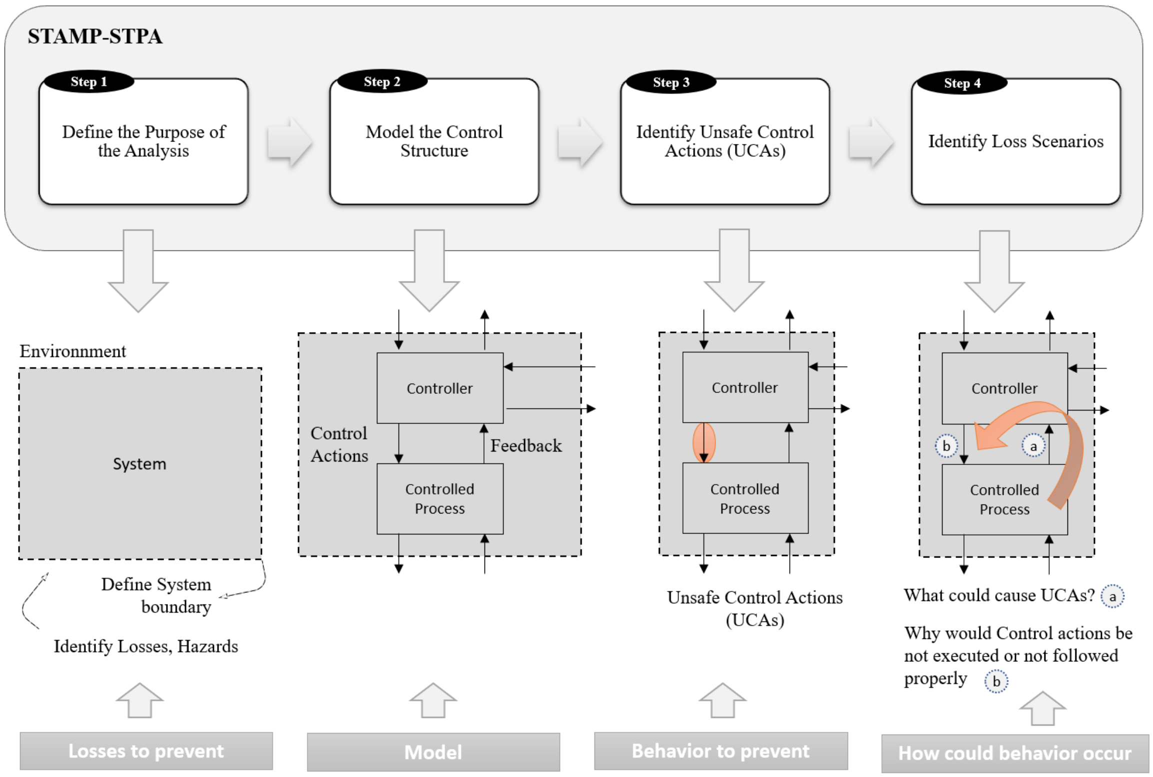


Figure 10.5. Depiction of the Key Steps Involved in the STAMP-STPA Process
(Source: Adapted from Leveson & Thomas 2018)

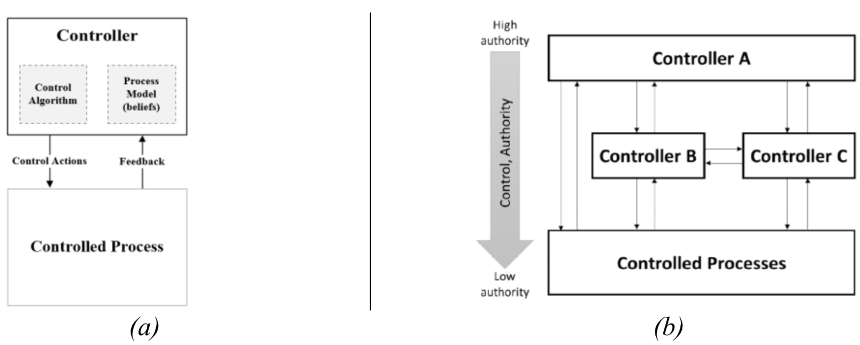


Figure 10.6. Depiction of a Control Loop (a) and a Generic HSCS(b)
(Source: Leveson & Thomas 2018)

- *Step 3: Identify Potential Unsafe Control Actions*

This phase of analysis focuses on identifying Unsafe Control Actions (UCAs), which are actions or behaviors that must be prevented to mitigate hazards and avoid system losses. The process involves reviewing each Control Action (CA) and determining the associated UCAs that could lead to undesirable outcomes. By identifying these UCAs, strategies can be developed to prevent or mitigate them, improving system safety and reliability. Losses occur when safety constraints are not correctly enforced or are missing, such as when the Process Model (PM) does not match the state of the Controlled Process, leading to unsafe commands from the Controller. Accidents arise when the Hierarchical Safety Control Structure (HSCS) fails to manage system interactions, violating safety constraints.

The STPA methodology addresses both systemic interactions and individual component failures to provide a comprehensive analysis of factors contributing to accidents in complex systems. By considering both, STPA offers a holistic approach to system safety. Leveson (2004) highlights various forms of control that influence system behavior, including managerial, organizational, physical, operational, and manufacturing-based controls. These controls regulate system behavior and ensure safety not just through engineering or operator intervention, but also through policies, procedures, shared values, and organizational culture, which ultimately affect system safety and performance. Four distinct types of UCAs have been identified (Leveson, 2023, 2016):

(1) *Not Providing Causes Hazard* – This UCA occurs when necessary CAs are not provided, leading to hazardous conditions. It highlights the importance of ensuring that all required CAs are fulfilled to prevent potential hazards.

(2) *Providing Causes Hazard* – This UCA arises when the execution of the CAs themselves creates hazardous conditions, emphasizing the need to carefully evaluate CAs to ensure they do not inadvertently contribute to system hazards.

(3) *Too Soon, Too Late, Out of Order* – This UCA involves situations where CAs are performed either too early, too late, or out of sequence. Improper timing or sequencing of CAs can introduce risks and potentially lead to hazards.

(4) *Stopped Too Soon, Applied Too Long* – This UCA refers to cases where CAs are prematurely stopped or extended beyond their intended duration. Deviations in the timing or duration of CAs can negatively affect system safety and performance.

- *Step 4: Identify Loss Scenarios*

In the final step of the analysis, the focus shifts to understanding how each UCA identified in Step 3 can occur and propagate, leading to system losses. A loss scenario describes the causal factors that lead to UCAs and associated hazards. Two categories of loss scenarios must be considered (Leveson & Thomas, 2018):

(1) Reasons for the occurrence of UCAs – *Why would UCAs occur?*

(2) Reasons for the improper execution or non-execution of CAs – *Why would CAs be improperly executed or not executed), resulting in hazards?* (see Figure 10.7).

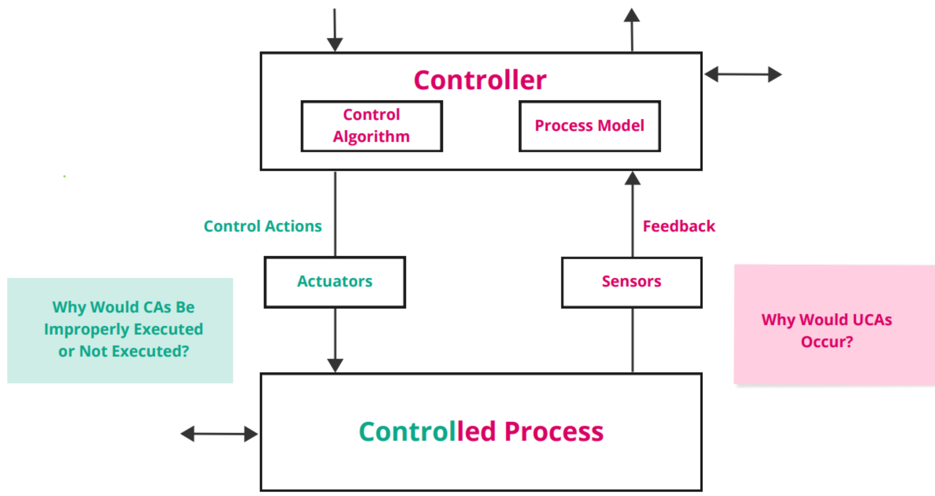


Figure 10.7. Two Types of Scenarios that Must Be Considered
(Source: own representation based on Leveson & Thomas, 2018)

10.4 Case study

Power systems require substantial capital investment and face numerous challenges, including growing demand, aging assets, and various operational constraints. To address these challenges, Asset Management (AM) is recognized as a critical approach for decision-making in the power industry. AM plays a pivotal role in optimizing the performance of power systems and ensuring efficient resource allocation (Diop et al., 2023, 2021; Khuntia et al., 2016). Asset managers at Hydro-Québec (HQ) face the complex task of preparing for a wide range of threats and uncertainties related to emerging risks in their operations. To enhance their AM practices, the Hydro-Québec Research Institute (IREQ) has developed innovative robotic tools and strategies. These technological advancements enable HQ to proactively address asset-related challenges, ensuring the long-term reliability and efficiency of their power systems.

The LineDrone is one of the Hydro-Quebec's Unmanned Aerial Vehicles (UAVs), which is featured in Figure 10.8, representing the system under study. Technical specifications provided by its manufacturer, Drone-Volt, are detailed in Appendix 1 (Drone-Volt, 2024). This advanced drone can land on energized high-power transmission lines. Once in contact with the line, the propellers deactivate, and motorized wheels specifically designed for the task allow the drone to traverse the entire line span. This capability enables valuable inspection and maintenance activities to be performed using customized payloads. The LineDrone's operation is seamless for the network owner, eliminating the need for tower climbing, preventing linemen’s exposure to energized components, and requiring no outages or non-reclosing authorizations. With its industrialization by DroneVolt, the LineDrone has become an integral part of Hydro-Québec's routine operations.

This case study employs two safety assessment methods: FRAM and STAMP-STPA. FRAM is first used to analyze the system's functional aspects and interdependencies, identifying performance variations. STAMP-STPA is then applied for a deeper safety assessment, considering sociotechnical elements like human factors, organizational components, and system constraints to identify hazards, control flaws, and potential causes of safety incidents or performance deviations.

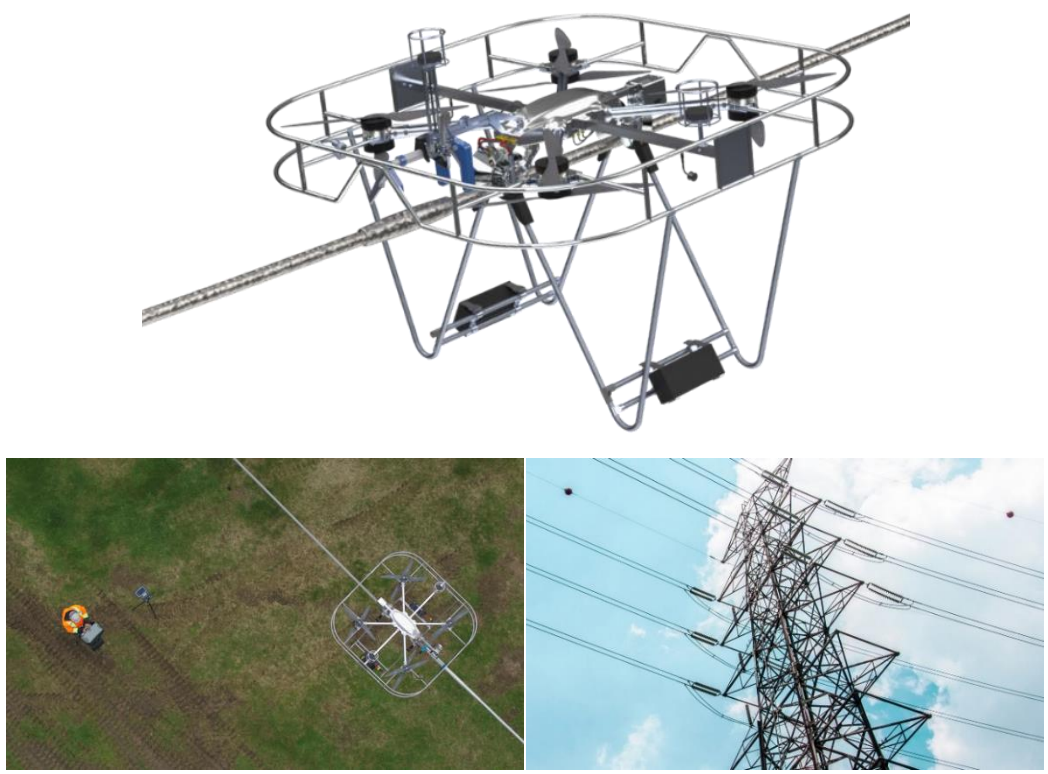


Figure 10.8. Hydro-Quebec LINEDRONE (UAV for Power Lines Inspection)
(Source: Hydro-Presse (2024))

10.4.1 FRAM model development and analysis

- Purpose of the FRAM Analysis

The FRAM Analysis aims to comprehensively assess functional variability in the LineDrone system during operational activities. The LineDrone, equipped with advanced control and intelligent algorithms, conducts detailed inspections to identify issues on power lines. The inspection procedure covers preparation, equipment checks, communication protocols, deployment (including flight planning and data collection), and safety considerations. The collected data helps analyze transmission line health, assisting maintenance teams and asset managers in making informed decisions on repairs or replacements.

- Identifying and Describing the Functions

The essential functions[†††††††] required for the system's accurate operation have been identified and categorized (see Table 10.6 to 10.10). These functions form the set of activities analyzed and can be performed by humans, machines, or through human-machine collaboration. In total, we identified eleven foreground functions, consisting of four technological, two organizational, and five human functions.

Foreground functions refer to the primary operational functions within a sociotechnical system that directly contribute to its intended purpose and outcomes. **These functions are the focus of analysis, as they play a critical role in achieving the system's objectives.** Unlike background functions, which provide foundational support and serve as inputs for the foreground functions, foreground functions encompass the core activities, tasks, and processes that drive the system's performance and functionality. In this analysis, the system’s foreground primarily consists of LineDrone activities, which are the central focus of the model.

The boundaries within which the foreground functions operate are defined by the outputs of the background function, which is considered constant and not subject to variability (Hollnagel, 2012; Macchi, 2010). As a result, all outputs of the background function are assumed to be flawless and of high quality. These background functions often serve as the backbone of the system, ensuring its smooth operation and supporting the execution of foreground functions. For example,

[†††††††] The color scheme used is as follows: *organizational* functions in green color; *technological* functions in golden color; *human* functions in blue color; *background* functions in purple color, finally *sink* function in red color. By color-coding the functions in the FRAM model, one can easily identify and distinguish the different types of functions, aiding in the analysis and understanding of the system's dynamics and interactions.

if a function requires a specific procedure as a Precondition (P) for its execution, this procedure must be generated as the Output (O) of a background function.

Foreground functions within a sociotechnical system can be categorized into three main groups: (1) organizational, (2) human, and (3) technical. Additionally, there is the (4) sink function, which represents the system's ultimate goal. In the following paragraphs, we will describe each group in detail, offering insights into their roles and contributions within the system:

(1) *Organizational functions* refer to the set of activities and processes responsible for managing and coordinating resources, people, and tasks within an organization or system. These functions encompass a wide range of activities, including, but not limited to, planning, scheduling, communication coordination, task assignment, resource allocation, decision-making, performance monitoring, and collaboration facilitation. They provide the structure and framework within which the LineDrone operates, enabling smooth operations and effective decision-making.

(2) *Human functions* refer to the actions, tasks, and responsibilities performed by human operators within a sociotechnical system. These functions involve the cognitive and physical activities required for operating, monitoring, and controlling the LineDrone during its operational tasks. Understanding and analyzing these functions is essential for assessing the performance, capabilities, and limitations of human operators within the sociotechnical system.

(3) *Technological functions* refer to the activities and operations carried out by the technological components or systems within a sociotechnical system. These functions specifically relate to the technological aspects of the LineDrone and its supporting systems. They encompass the use of various technological components and capabilities that enable the LineDrone to effectively perform its intended tasks and operations.

(4) *Sink function* refers to the ultimate goal or desired outcome of a sociotechnical system. In the case of the LineDrone, the sink function represents the overall objective or desired outcome of its inspection activities.

Table 10.6. Identification of Organizational Functions (Foreground Functions)
O: Output. I: Input. P: Preconditions. R: Resources. T: Time. C: Control

Function	*O*	*I*	*P*	*R*	*T*	*C*
Planning Inspections, Resource Allocation and Management	1) Inspections Plan 2) Operation Plan → location, airspace, deployment method, risk analysis, emergency plan, etc. 3) Resource Allocation	Work Order → Distinguish between annual planning and the planning done by an installer / technician to identify the location of assets, access methods, etc.	1) Comprehensive Asset Inventory 2) Defined Inspection Objectives 3) Clear Communication Channels 4) Regulatory compliance confirmed	1) Decision-Making Supports → Tools, Software, etc. 2) Trained Personnels → Pilot, Copilot, Lineman 3) Necessary Equipments → Drones, Tools for Deployment, etc.	Sufficient Time for thorough Planning and Resource Allocation → TBD	1) Predefined Procedures → guidelines, and instructions to perform inspection tasks 2) Emergency Response Plans 3) Risk Management Protocols and Safety Standards

Planning LineDrone inspections involves setting objectives, allocating resources, and assessing risks.
Efficient resource management focuses on scheduling, route assignment, and optimizing productivity.

Table (6 continued)

Function	*O*	*I*	*P*	*R*	*T*	*C*
Training Operators (Pilot, Copilot, Lineman)	Trained Personnels → Pilot, Copilot, Lineman → Operators Adhering to Best Practices and Complying with Drone Regulations → Operators with skills and knowledge required to operate the LineDrone safely and effectively	Training Programs and Development Plans	1) Drone Pilot Certificate → Drone pilot certificate - Advanced operations 2) Transportation Means → Heavy Truck and an ATV (All-Terrain Vehicle) → At least one team member must be qualified to operate a heavy truck and an ATV (All-Terrain Vehicle)	1) LineDrone Manufacturer's Training Program → DroneVolt → Nucleom 2) HQ Internal Complementary Training Program for LineDrone 3) HQ Internal Procedures for Operating LineDrone on Live Lines 4) Best Practices → for training operators to enhance efficiency and safety	Adequate Time Allocation → for both theoretical and practical training components → TBD	1) Predefined Procedures → guidelines, and instructions to perform inspection tasks 2) Support and Supervision for Initial Worksites → having someone on-site to ensure everything is going well

Operator training is essential for the safe and effective operation of the LineDrone.
Drone pilots must hold a valid Drone Pilot Certificate (Advanced Operations) from Transport Canada.
The training includes theoretical and practical components, covering drone regulations, safety protocols, operational procedures, and emergency procedures (see Getting a drone pilot certificate, Transport Canada).
A drone pilot can become a LineDrone pilot after completing training provided by DroneVolt, the manufacturer, and joining Hydro-Québec's internal team.
Furthermore, at least one team member must be trained to operate a heavy truck and ATV (all-terrain vehicle) for transporting the LineDrone.

Table 10.7. Identification of Human Functions (Foreground Functions)
Ø: Not Described Initially. O: Output. I: Input. P: Preconditions. R: Resources. T: Time. C: Control

Function	*O*	*I*	*P*	*R*	*T*	*C*
Supervising Operation	Supervised Operation	1) Operational Plans 2) Inspection Plan 3) Defined Inspection Objectives 3) Meteorological Data	1) Work Order 2) Clear Communication Channels	1) Communication Tools 2 Telemetry Systems 3) LineDrone Equipment 4) Trained Personnels → Pilot, Copilot, Lineman	Throughout the Operation →TBD	Real-Time Monitoring and Adjustments

Effective communication and timely decision-making are essential for addressing concerns and mitigating risks.

- → The pilot is responsible for preparing the flight operation by providing a flight plan, including the operation plan, risk analysis, safety measures, and emergency procedures, as well as deploying the LineDrone (including takeoff and landing on power lines).
- → The copilot assists the pilot by providing information, monitoring telemetry before and during the flight, and operating the LineDrone along the line. He/she is responsible for transmitting measurements to the maintenance manager.
- → The lineman requests operational authorization, verifies the feasibility of the operation (such as distances between phases), and facilitates site access.

Table 7 (continued)

Function	*O*	*I*	*P*	*R*	*T*	*C*
LineDrone System Inspection[‡‡‡‡‡‡‡]	Inspected LineDrone System	1) Inspection Checklists 2) Operational Guidelines	1) Availability of Inspection Tools and Equipments 2) Trained Personnel: → Pilot, → Copilot, → Lineman	1) Operators Adhering to Best Practices 2) Inspection Tools & Field Equipment Box 3) Transportation Means → Heavy Truck and an ATV (All-Terrain Vehicle) → At least one team member must be qualified to operate a heavy truck and an ATV (All-Terrain Vehicle)	1) Before Departure for the Inspection 2) On-Site after Transport for Deployment 3) Upon Return to the Warehouse	1) Inspection Protocols 2) Predefined Procedures: → guidelines, and instructions to perform inspection tasks

The LineDrone must be inspected:
→ Before departure for the inspection,
→ On-site after transport for deployment,
→ Upon return to the warehouse.

Table (7 continued)

Function	*O*	*I*	*P*	*R*	*T*	*C*
System Maintenance and Calibration	LineDrone Ready for the Mission	1) Inspections Plan 2) Inspected LineDrone System	1) Availability of Maintenance and Calibration Tools and Equipments 2) Trained Personnels	1) Operators Adhering to Best Practices 2) Manufacturers Inputs → DroneVolt → Nucleom 3) Transportation Means → Heavy Truck and an ATV (All-Terrain Vehicle) → At least one team member must be qualified to operate a heavy truck and an ATV (All-Terrain Vehicle)	Ø *(TBD)*	System Maintenance and Calibration Protocols

Regular maintenance and calibration are essential for the LineDrone's performance and reliability.
→ Maintenance includes cleaning, repairing mechanical, electrical, and electronic parts, and updating software.
→ Calibration ensures accurate data collection by adjusting sensors, cameras, and measurement devices.

[‡‡‡‡‡‡‡] This refers to the inspection of the LineDrone itself, not the inspection it performs on power lines.

Table (7 continued)

Function	O	I	P	R	T	C
Data Analysis and Interpretation	Analyzed Data	Collected Data	Ø	Ø	Ø	Predefined Procedures → guidelines, and instructions to perform inspection tasks

Data analysis and interpretation in LineDrone inspections involve processing collected data to assess asset conditions, identify issues, and support decision-making. This helps prioritize repairs, optimize operations, and guide maintenance activities.

Table (7 continued)

Function	O	I	P	R	T	C
Reporting	Inspection Report	Analyzed Data	Ø	Ø	Ø	Predefined Procedures → guidelines, and instructions to perform inspection tasks

After analyzing LineDrone inspection data, findings should be communicated through detailed reports that outline inspection outcomes, identified issues, and provide recommendations.

Table 10.8. Identification of Technological Functions (Foreground Functions)

O: Output. I: Input. P: Preconditions. R: Resources. T: Time. C: Control.

Function	O	I	P	R	T	C
Providing Meteorological Data	Meteorological Data Provided	1) Work Order 2) Inspections Plan 2) Operation Plan → location, airspace, deployment method, risk analysis, emergency plan, etc.	Inspections Plan	1) Meteorological Websites 2) KP Index Data Sources	1) 48h Prior to Inspection Operations 2) 24h Prior to Inspection Operations 3) On-Site	On-Site / Visually → Weather conditions: Daytime flights in fine weather only; No precipitation or fog. → Operating temperature -10°C to + 40°C (14°F to 104°F) → Wind resistance: 25 km/h (15,5 mph) and up to 40 km/h (25 mph) wind gusts.

Key data such as wind speed, temperature, precipitation, and visibility help assess environmental conditions, identify hazards, and make informed Go/No-Go decisions to ensure safe and efficient missions.
The KP index, which measures geomagnetic activity, can also be significant for drone operations as it affects communication and navigation systems.

Table (8 continued)

Function	O	I	P	R	T	C
Task Execution (Flying, landing, and rolling on energized power lines to collect data)	Collected Data	1) Operation Plan 2) Defined Inspection Objectives 3) Resource Allocation 4) Predefined Procedures → guidelines, and instructions to perform inspection tasks	1) Operation Authorized by Network Operators → Intervention Mode 2) Regulatory compliance confirmed 3) Meteorological Data Provided 4) LineDrone Ready for the Mission	1) Trained Personnels → Pilot, Copilot, Lineman 2) LineDrone authorized for operation → Necessary Equipments → Drones, Tools for Deployment, etc.	Approximately 1 minute to take off from the ground and land on a conductor. Total flight time before a battery switch is needed: 12 minutes.	Effective Control and Maneuvering of the LineDrone during Inspections Utilizing Various Sensors

Task execution for the LineDrone involves flying, landing, and rolling on energized power lines to capture data using dedicated payloads.
The drone relies on sensors and algorithms to ensure precise movement, stability, and navigation throughout operations.

Table (8 continued)

Function	*O*	*I*	*P*	*R*	*T*	*C*
Data Storage and Management (LineSpector / PRIAD)	Decision-Making Support	Inspection Report	Ø	Information Exchanged	Ø	Predefined Procedures
Data from LineDrone inspections is securely stored and managed using the LineSpector and PRIAD systems, aiding decision-making. Currently, data is sent to LineSpector, with studies planned to explore its integration with PRIAD. PRIAD provides tools for analysis, visualization, and interpretation, supporting maintenance teams in trend analysis, performance evaluation, and risk identification to meet safety and performance goals.						

Table (8 continued)

Function	*O*	*I*	*P*	*R*	*T*	*C*
Communication Infrastructure	Information Exchanged	**1) Ground Control Station / In-Air Antenna** → Serial and Ethernet Data → Telemetry → Camera → sensor data → LineDrone displacement commands for probe positioning **2) RC Transmitter / RC Receiver** → Drone control **3) Audio** → Pilot/co-pilot – field communication **4) VHF Radio**	Ø	Ø	Ø	Ø
A robust communication infrastructure is essential for the effective operation of the LineDrone system. It enables the exchange of information between the LineDrone, the Ground Control Station / In-Air Antenna, the RC Transmitter / RC Receiver, and the operators.						

Table 10.9. Identification of Background Functions

Ø: Not Described Initially. O: Output. I: Input. P: Preconditions. R: Resources. T: Time. C: Control

Function	*O*	*I*	*P*	*R*	*T*	*C*
Regulatory Compliance Check	Regulatory compliance confirmed → LineDrone authorized for operation → LineDrone Ready for the Mission → Operators Adhering to Best Practices and Complying with Drone Regulations	Ø *(Background function)*	Ø *(Background function)*	Ø *(Background function)*	Ø *(Background function)*	Ø *(Background function)*
This function ensures the Hydro-Quebec LineDrone meets regulatory requirements and holds necessary certificates, verifying adherence to legal and safety standards for smooth and compliant operations.						

Table (9 continued)

Function	***O***	***I***	***P***	***R***	***T***	***C***
Stakeholders	1) Predefined Procedures → guidelines, and instructions to perform inspection tasks 2) Defined Inspection Objectives 3) Inspections Plan 4) Work Order 5) Training Programs and Development Plans	Ø *(Background function)*	Ø *(Background function)*	Ø *(Background function)*	Ø *(Background function)*	Ø *(Background function)*
Stakeholders are integral to the broader system, with their interactions, expectations, and contributions playing a key role in understanding how the system functions effectively. The stakeholders include Hydro-Québec's Robotization and Drone & Health and Safety Group, Asset Manager, Scheduler, Maintenance Manager, and Network Operator.						

Table 10.10. Identification of the Sink Function

O: Output. I: Input. P: Preconditions. R: Resources. T: Time. C: Control

Function	***O***	***I***	***P***	***R***	***T***	***C***
Successful Completion of Inspection Tasks	N/A *(Sink function)*	Inspection Report	N/A *(Sink function)*	N/A *(Sink function)*	N/A *(Sink function)*	N/A *(Sink function)*
The successful execution of inspection tasks ensures efficient resource use, minimizes downtime, and enhances safety by identifying potential hazards in transmission lines. This reduces the risk of accidents and service disruptions.						

Once the functions have been identified, they are characterized using the six key aspects (see Figure 10.9), namely, Input (I), Output (O), Control (C), Preconditions (P), Resources (R), and Time (T).

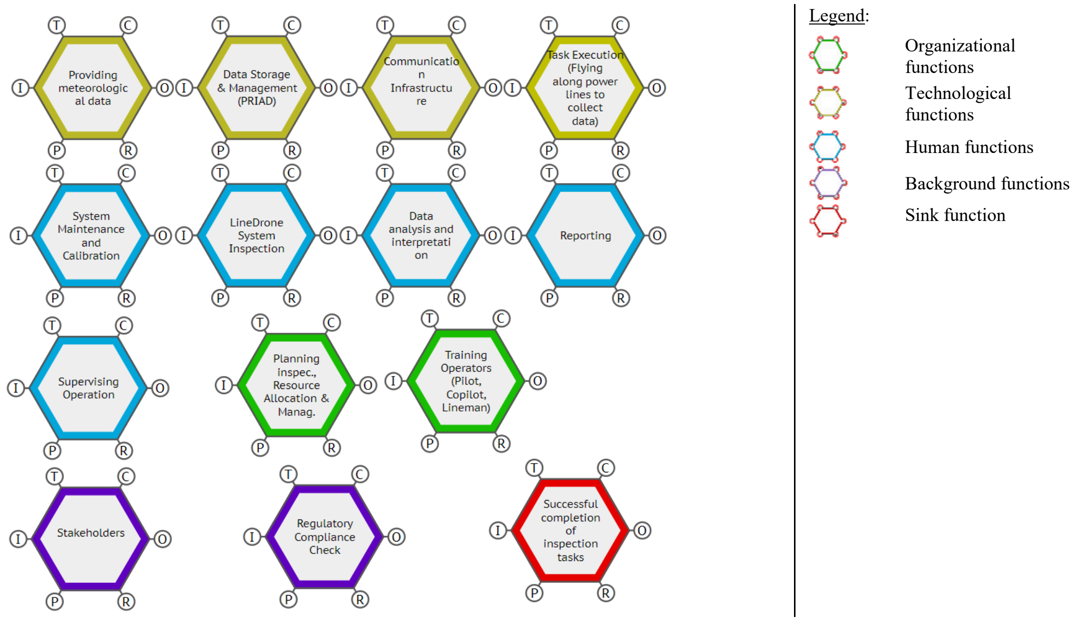


Figure 10.9. FRAM Model of the Sociotechnical System

- Identifying Variability and Functional Resonance

Performance variability is a key aspect in FRAM, reflecting the dynamic nature of complex systems. FRAM recognizes that variability is inherent and does not always lead to failure (it is just part of the system's normal functioning) (Hollnagel, 2012).

Two contributing factors to variability in a function's output have been recognized, namely: Internal Variability (IV) and External Variability (EV). In essence, the model helps comprehend the impact of IV, which arises from within the system (a.k.a. *endogenous variability*), and EV, which originates from external sources (a.k.a. *exogenous variability*), on each function within the system.

When assessing variability in a function's output, two key factors (Time and Precision) must be considered. Variability in these areas can impact the system's efficiency, effectiveness, and overall reliability. **In this study, for the sake of simplification, we focus on EV, specifically related to Time and Precision**.

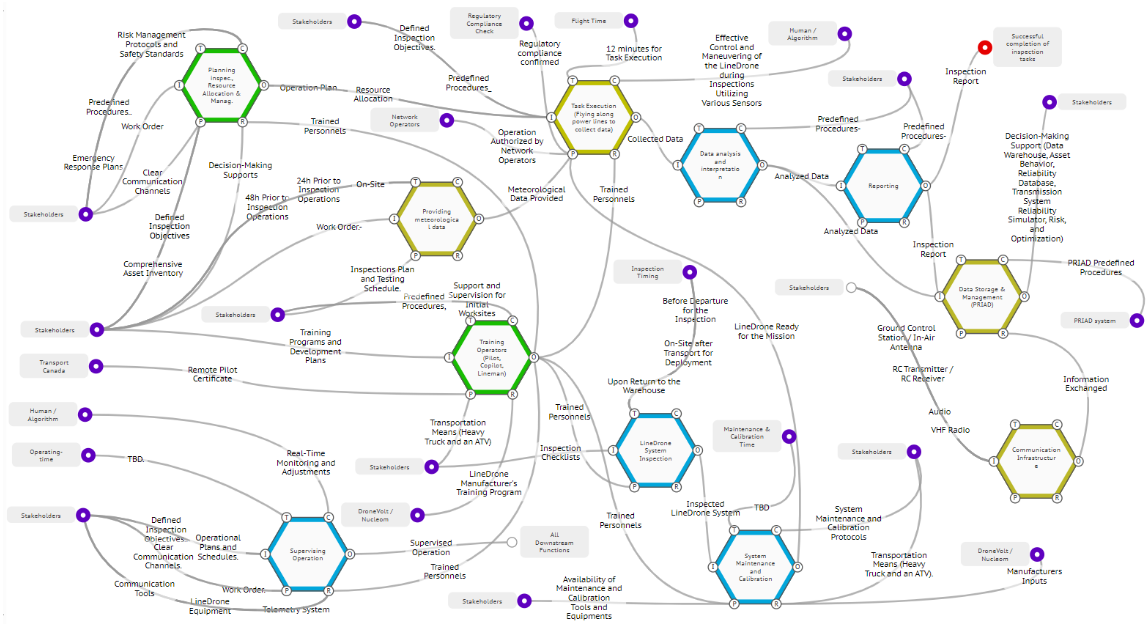
(1) Variability related to Time refers to the system's timeliness or responsiveness in delivering outputs. This includes factors such as delays, latencies, and variations in the speed or efficiency of output generation.
(2) Variability related to Precision pertains to the accuracy, correctness, or level of detail in the system's outputs. It involves considerations such as errors, inaccuracies, inconsistencies, or variations in the quality or specificity of the output information.

In the following section, we will present three specific instantiations: *(A) the first instantiation of the ideal scenario (work-as-imagined)*, *(B) the second instantiation (variability within an organizational function)*, and *(C) the third instantiation (variability within a human function)*. These examples illustrate how variabilities in the output of one function can influence other functions, leading to their own variabilities.

It is worth noting that we have not examined an instantiation of a Technological Function. The FRAM concept assumes that Technological Functions are generally predictable and reliable, suggesting stability. However, it is important to acknowledge that even technology-based functions can experience variability. Such deviations may arise from factors like insufficient maintenance, adverse operating conditions, gradual wear and degradation, among others. Human performance is the primary source of variability in socio-technical systems. Typically, technology performs reliably, with failures being infrequent, but when they do occur, humans must adapt to degraded conditions. Therefore, understanding performance variability primarily involves describing human performance in such scenarios.

(A) First Instantiation of the Ideal Scenario (Work-As-Imagined)

As previously mentioned, the operational boundaries of the foreground functions are determined by the outputs of the background functions, which are regarded as constant and immune to variability. Therefore, all outputs of the background functions are presumed to be impeccable, characterized by a high level of quality. The analysis primarily focusses on the foreground functions, which are subject to potential variability in their outputs. However, if all incoming aspects from background functions were flawless, the corresponding outputs would also be flawless and devoid of variability. Thus, the model's *Ideal State* illustrates a scenario (normal scenario) in which all outputs are flawless, and no variability is present (all outputs meet the desired criteria). Naturally, this idealized condition is not realistic in real-world situations. Although this ideal scenario may not be attainable in practical applications, it serves as a reference point for understanding the expected performance and goals of the system. This state reflects the concept of ***"work-as-imagined"***, as outlined in predefined procedures, guidelines, instructions, etc. Figure 10.10 illustrates this scenario[§§§§§§§].



Legend:					
	Organizational function	Technological function	Human function	Background function	Sink function

Figure 10.10. First Instantiation of the FRAM Model (Ideal Scenario or Work-As-Imagined)

[§§§§§§§] It is important to note that not all aspects need to be completed for each function. Only those aspects that are directly relevant to the respective function should be filled in. For more detailed information on each function, please refer to its corresponding table below rather than the graphic.

Table 10.11 illustrates the potential variabilities in outputs with respect to Time and Precision within an *Ideal Scenario*. As previously mentioned, the process of attaining a comprehensive assessment of the probable performance variability of a function involves consolidating the *quality weights* of all linked aspects. This entails the formulation of specific assumptions. The scale for evaluating the potential to mitigate performance variability (*dampening performance variability*) spans from (+1) to (+3), while the scale for evaluating the potential to amplify performance variability (*increasing performance variability*) ranges from (-1) to (-3). The overall score of a specific function can be determined by taking the *median* of its *aspect qualities*, which represents the aggregated *output quality* of the function[********].

Table 10.11. Potential Performance Variabilities[††††††††] in Output Concerning Time and Precision: Ideal Scenario (Work-As-Imagined) for Organizational Functions

I: Input, C: Control, T: Time, P: Preconditions, R: Resources.

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Planning Inspections, Resource Allocation and Management	1) Inspections Plan 2) Operation Plan → location, → airspace, → Deployment method, → risk analysis, → emergency plan, etc. 3) Resource Allocation	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the Planning Inspections, Resource Allocation, and Management function of LineDrone ensures meticulous planning (precise) and timely execution of inspection plans, and resource allocation.
This reduces variability and ensures accuracy and punctuality in delivering plans and data.
High-quality outputs (On time and Precise, as indicated in Table 4) from this function are essential for downstream processes, such as Task Execution and Meteorological Data Provision, which depend on precise and timely information.

******** It is worth noting that FRAM is primarily *a qualitative analysis method* that aims to understand the behaviour and dynamics of a system rather than providing precise *numerical metrics.* It focuses on capturing the complex interactions and dependencies among functions that contribute to its resilience and performance rather than providing quantitative metrics.

†††††††† In this study, for the sake of simplification, we focus on EV (variability pertaining to Time and Precision).

Table (11 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Training Operators (Pilot, Copilot, Lineman)	Trained Personnels → Pilot, Copilot, Lineman → Operators Adhering to Best Practices and Complying with Drone Regulations → Operators with skills and knowledge required to operate the LineDrone safely and effectively	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Training Operators* function ensures that Pilots, Copilots, and Linemen are thoroughly trained, significantly reducing variability and promoting safe, *precise* and *timely* LineDrone operations.
A valid Drone Pilot Certificate (Advanced Operations) from Transport Canada is mandatory, and at least one team member must be trained to operate a heavy truck and ATV for transporting the LineDrone.
This rigorous training process minimizes variability and ensures the accuracy and punctuality of plans and data delivery.
High-quality outputs (*On time* and *Precise*, as outlined in Table 4) from this function are crucial for downstream processes, such as *Inspection Planning*, *Task Execution*, and *System Maintenance*, all of which rely on *precise* and *timely* information.
The ideal outcome is a *Precise/On time* output with a quality rating of (+3), which is preferred over alternatives like *Precise/Too early* or *Acceptable/On time* outputs with a quality rating of (+2), or *Precise/Too late* or *Acceptable/Too early* outputs with a quality rating of (+1).
By focusing on precise timing and comprehensive instruction, the *Training Operators* function demonstrates a strong potential for minimizing variability. Adherence to best practices ensures that only skilled and knowledgeable operators handle the LineDrone, maintaining accuracy and punctuality in all operations.

Table (11 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Supervising Operation	Supervised Operation	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Supervising Operation* function is critical for LineDrone operations, as it ensures that *precise* and *timely* information is provided to minimize uncertainties and reduce variability (dampening). Effective communication and prompt decision-making are vital for addressing concerns and mitigating risks. When the pilot, copilot, and lineman adhere to best practices with optimal timing, the potential for minimizing variability is significant. The pilot deploys the LineDrone, the copilot assists by providing information, monitoring telemetry, and operating the drone, while the lineman requests authorization, verifies operational feasibility, and facilitates site access.
This function guarantees that only skilled and knowledgeable operators (pilot, copilot, lineman) manage the LineDrone, thereby maintaining safety, accuracy, and punctuality in operations.
High-quality outputs (*On time* and *Precise*, as outlined in Table 10.4) are essential for downstream processes, including *Planning Inspections*, *Resource Allocation and Management*, *Training Operators*, *Providing Meteorological Data*, *LineDrone System Inspection*, *System Maintenance and Calibration*, *Task Execution*, *Data Analysis and Interpretation*, *Reporting*, *Data Storage and Management (PRIAD)*, *Communication Infrastructure*, and *Regulatory Compliance Check*, all of which depend on precise information.

Table 10.12. Potential Performance Variabilities in Output Concerning Time and Precision: Ideal Scenario (Work-As-Imagined) for Human Function
I: Input, C: Control, T: Time, P: Preconditions, R: Resources

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function		Median value
				Precision	Timing	
LineDrone System Inspection	Inspected LineDrone System	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *LineDrone System Inspection* function is critical for ensuring *precise* and *timely* inspections, which are essential for minimizing uncertainties and reducing variability.
The LineDrone undergoes inspections at three key stages: before departure for the inspection, on-site after transport for deployment, and upon return to the warehouse.
High-quality outputs, characterized by being *On-time* and *Precise* (as per Table 4), are vital for downstream processes such as *System Maintenance and Calibration*, *Task Execution*, *Communication Infrastructure*, and *Regulatory Compliance Check*, all of which rely on precise information.

Table (12 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function		Median value
				Precision	Timing	
System Maintenance and Calibration	LineDrone Ready for the Mission	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *System Maintenance and Calibration* function, characterized by *precision* and *timely* execution, is vital for minimizing variability (dampening) and ensuring the LineDrone is mission-ready.
Strict adherence to best practices by operators further increases the chances of reducing variability.
Managing the *System Maintenance and Calibration* function involves recognizing and mitigating potential risks.
The ideal outcome is a *Precise*/*On time* output, which produces a quality rating of (+3). This is more desirable than other outcomes, such as a *Precise*/*Too early* or *Acceptable*/*On time* output with a quality rating of (+2), or a *Precise*/*Too late* or *Acceptable*/*Too early* output, which receive a quality rating of (+1).

Table (12 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function		Median value
				Precision	Timing	
Data Analysis and Interpretation	Analyzed Data	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Data Analysis and Interpretation* function, characterized by its *precision* and *timeliness*, is crucial for subsequent functions like Reporting and Data Storage and Management (PRIAD).
This ensures accurate data analysis, interpretation, and timing, which significantly reduces variability.
In LineDrone inspections, data analysis and interpretation involve processing the collected data to evaluate asset conditions, identify issues, and inform decision-making, aiding in the prioritization of repairs, optimization of operations, and guidance of maintenance activities.

Table (12 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Reporting	Inspection Report	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Reporting* function, characterized by the inspection report's *precision* and *timely* delivery, underscores its potential to minimize variability.
Following the analysis of LineDrone data, findings should be communicated through detailed reports that outline outcomes, identify issues, and provide recommendations.

Table 10.13. Potential Performance Variabilities in Output Concerning Time and Precision: Ideal Scenario (Work-As-Imagined) for Technological Function
I: Input, C: Control, T: Time, P: Preconditions, R: Resources

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Providing Meteorological Data	Meteorological Data Provided	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Providing Meteorological Data* function is crucial for LineDrone operations, as *precise* and *timely* weather information helps minimize uncertainties and reduce variability, particularly in the energy and infrastructure sectors.
High-quality outputs (*On time* and *Precise*, as per Table 10.4) are essential for downstream processes like *Task Execution*, *Supervising Operation*, and *Communication Infrastructure*, all of which depend on precise data.
Accurate weather data, including wind speed, temperature, precipitation, and visibility, improves operational efficiency, optimizes schedules, and ensures flight safety.
Additionally, the KP index, which measures geomagnetic activity, is vital for drone operations, as it affects navigation systems.

Table (13 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Task Execution **(Flying, landing, and rolling on energized power lines to collect data)**	Collected Data	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Task Execution (Flying, landing, and rolling on energized power lines to collect data)* function involves precise navigation along power lines to capture accurate data, using sensors and algorithms to maintain stability.
The operation is highly efficient, with a 12-minute flight time, and focuses on *timely* and *precise* data collection to minimize variability.
Success depends on key inputs, preconditions, and resources, such as trained personnel and mission-ready equipment, while effective control ensures accuracy throughout the inspection process.

Table (13 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Data Storage and Management (LineSpector /PRIAD)	Decision-Making Support → Data Warehouse, Asset Behavior, Reliability Database, Transmission System Reliability Simulator, Risk, and Optimization	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The Data Storage and Management function in LineDrone operations is essential for precise decision-making and reducing variability. Inspection data is securely stored and efficiently managed using the LineSpector and PRIAD systems, ensuring both safe storage and effective utilization.

Table (13 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Communication Infrastructure	Information Exchanged	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The Communication Infrastructure function ensures accurate and timely information exchange between the LineDrone, ground systems, and operators, reducing variability in inspections

Table 10.14. Potential Performance Variabilities in Output Concerning Time and Precision: Ideal Scenario (Work-As-Imagined) for Background Function
I: Input, C: Control, T: Time, P: Preconditions, R: Resources.

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function: Precision	Potential impact on downstream function: Timing	Median value
Stakeholders	1) Predefined Procedures → guidelines, and instructions to perform inspection tasks 2) Defined Inspection Objectives 3) Inspections Plan 4) Work Order 5) Training Programs and Development Plans	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Stakeholders* function, regarded as a background function, is assumed to be flawless and of high quality, thereby influencing system behavior.
Stakeholders play a critical role in shaping the context within which activities and functions occur.
Essential components for sustaining a dynamic and adaptive system include Predefined Procedures (guidelines and instructions for inspection tasks), Defined Inspection Objectives, Inspection Plans, Work Orders, and Training Programs and Development Plans.
The Stakeholders' *precise* and *timely* output is vital for safety and the successful execution of LineDrone operations.

Table (14 continued)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function		Median value
				Precision	Timing	
Regulatory Compliance Check	Regulatory compliance confirmed → LineDrone authorized for operation → LineDrone Ready for the Mission → Operators Adhering to Best Practices and Complying with Drone Regulations	I: II	3	V↓	V↓	3
		C: II	3	V↓	V↓	
		T: II	3	V↓	V↓	
		P: II	3	V↓	V↓	
		R: II	3	V↓	V↓	

The output from the *Regulatory Compliance Check* function is seen as flawless, ensuring high-quality outcomes that influence overall system behavior.
This function ensures that LineDrone operations meet legal standards, confirming that the drone is mission-ready and that operators adhere to best practices.
The *precise* and *timely* output of the *Regulatory Compliance Check* is crucial for maintaining safety, avoiding legal risks, and ensuring the smooth execution of the mission, directly contributing to the overall success of LineDrone operations.

(B) Second Instantiation: Variability Within an Organizational Function

In this iteration, we examine how the variability of output within the *Training Operators* function (an organizational function) impacts downstream functions (refer to Figure 10.11 and Table 10.15). We hypothesize that the source of this variability lies in operators lacking sufficient training (i.e., lacking the necessary skills and knowledge to operate the LineDrone safely and effectively) or not adhering to best practices and complying with drone regulations. This variability in the output of the *Training Operators* function creates a ripple effect on various downstream functions, such as *Planning Inspections*, *Resource Allocation and Management*, *Supervising Operation*, *LineDrone System Inspection*, *System Maintenance and Calibration*, and *Task Execution* (Flying along power lines to collect data), thereby propagating variability throughout the system.

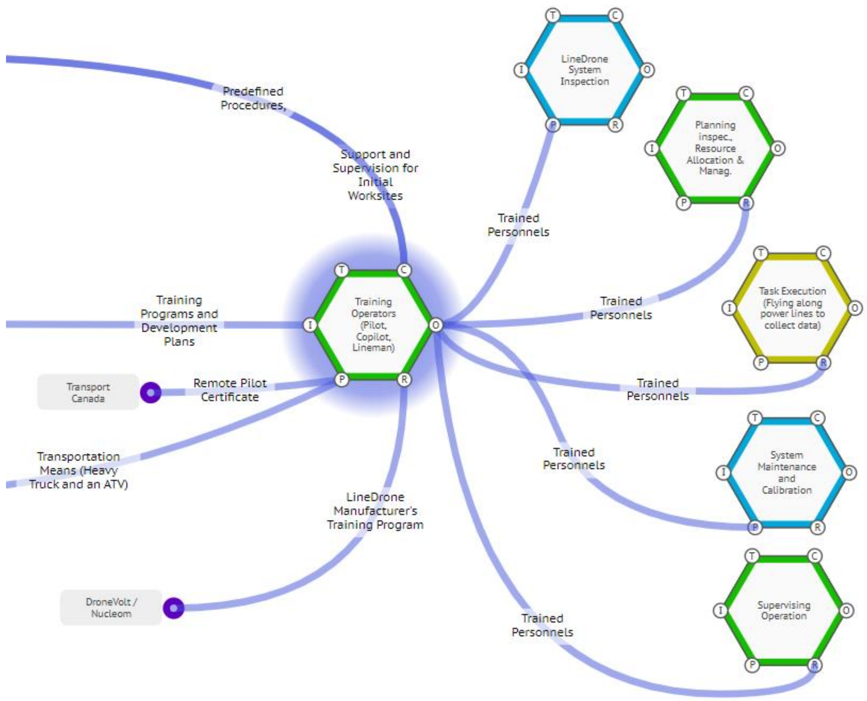


Figure 10.11. Second Instantiation of the FRAM Model

Table 10.15. Variability Within The "Training Operators" Function (An Organizational Function)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function		Median value
				Precision	Timing	
Training Operators (Pilot, Copilot, Lineman)	Trained Personnels → Pilot, Copilot, Lineman → Operators lacking the skills and knowledge necessary to operate the LineDrone safely and effectively (Operators deviating from best practices)	I: II	-3	V↑	V↑	-3
		C: II	-3	V↑	V↑	
		T: II	-3	V↑	V↑	
		P: II	-3	V↑	V↑	
		R: II	-3	V↑	V↑	

The least desirable outcome[‡‡‡‡‡‡‡‡] is an *Imprecise/Too late* output with a quality rating of (-3), which is less preferable than alternatives such as an *Imprecise/On time* output with a quality rating of (-2) or an *Imprecise/Too late* or *Imprecise/Too early* output with a quality rating of (-1).

[‡‡‡‡‡‡‡‡] We did not suggest any predetermined levels of acceptability for the combination of variability.

This example highlights the emergence of risks from the combination of performance variability across various functions, in alignment with Safety II principles [§§§§§§§§].

It is important to note that the degradation and associated risk do not stem from a direct cause-and-effect relationship between the *Training Operators* function and upstream functions. Instead, these issues arise from the complex socio-technical system, where functions, even if not directly connected, can influence one another. This observation reinforces the idea that variability is inherent in the system and does not necessarily lead to failure; rather, it is a component of the system's regular operation. FRAM offers a different perspective by recognizing that risks are not solely about things going wrong but also about the variability in everyday performance. Traditional methods might overlook these nuances because they often focus on binary outcomes – either things are working correctly, or they are not.

In the context of the *Training Operators* function, FRAM views variability as a double-edged factor. On one hand, variability in training conditions and adaptive training programs can enhance efficiency by exposing operators to diverse scenarios and promoting adaptive skills. On the other hand, if not carefully managed, this variability can pose safety risks, potentially leading to unexpected combinations or misunderstandings that could compromise safety. FRAM emphasizes the importance of detailed analysis to understand how variability within the training process impacts overall system performance.

(C) Third Instantiation: Variability Within a Human Function

In this iteration, we explore the ramifications of **insufficient system maintenance and inadequate calibration**, specifically focusing on the variability in output within the human-performed *System Maintenance and Calibration* function (refer to Figure 10.12 and Table 10.16). *Inaccuracies* and *delays* in this process significantly compromise the ability to minimize variability, posing a threat to the LineDrone's mission readiness.

[§§§§§§§§] Safety II is a concept that emerged as a complement to Safety-I in the realm of safety management. Safety-I typically focuses on preventing accidents and minimizing risks by identifying and controlling hazards. In contrast, Safety II looks at how systems succeed under varying conditions and aims to understand why things go right rather than just why they go wrong. It emphasizes learning from everyday work, resilience, adaptive capacity, distributed decision-making, taking a holistic perspective, and continuous improvement (Hollnagel, 2018b).

Additionally, operator non-compliance with best practices further reduces the likelihood of controlling variability. Regular maintenance and calibration are essential for the LineDrone's performance and reliability. Maintenance includes cleaning, repairing mechanical, electrical, and electronic parts, and updating software, while calibration ensures accurate data collection by adjusting sensors, cameras, and measurement devices.

Variability within the *System Maintenance and Calibration* function can ripple through downstream functions like *Task Execution (Flying along power lines to collect data)*, perpetuating variability across the entire system.

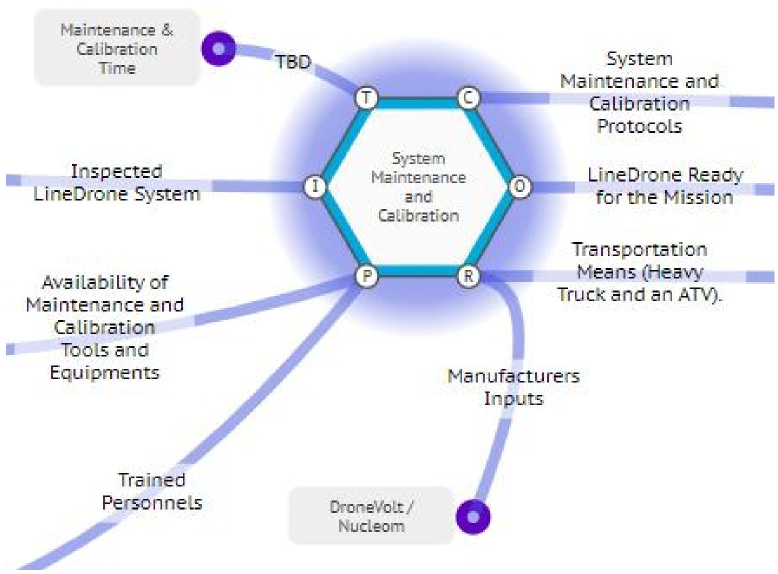


Figure 10.12. Third Instantiation of the FRAM Model

Table 10.16. Variability Within The "System Maintenance and Calibration" Function (A Human Function)

Function	Output of the Function	Quality	Quality Value	Potential impact on downstream function		Median value
				Precision	Timing	
System Maintenance and Calibration	LineDrone not ready for the mission	I: II	-3	V↑	V↑	-3
		C: II	-3	V↑	V↑	
		T: II	-3	V↑	V↑	
		P: II	-3	V↑	V↑	
		R: II	-3	V↑	V↑	

Analyzing the System Maintenance and Calibration function reveals potential risks, with the least favorable outcome[*********] being an Imprecise/Too late output with a quality rating of (-3), which is less preferable than alternatives such as an Imprecise/On time output with a quality rating of (-2) or an Imprecise/Too late or Imprecise/Too early output with a quality rating of (-1).

Given that this function relies on human performance, it is prone to a high degree of variability. The observed variations may result from insufficient Maintenance and Calibration Time allocated to the *System Maintenance and Calibration* function. Alternatively, variability could stem from inadequate control, as indicated by the lack of well-defined System Maintenance and Calibration Protocols, and instructions for conducting inspection tasks. Additionally, insufficient resources, such as operators not adhering to best practices, and the unavailability of necessary Maintenance and Calibration Tools and Equipment, may also contribute to this variability. These factors highlight a significant potential for increased variability.

Risks and degradation in a socio-technical system arise from complex interactions, not just direct cause-and-effect relationships. FRAM highlights that risks can come from everyday variability in system performance, not just from failures, emphasizing the need to understand the dynamic nature of systems and the potential hazards in even seemingly correct operations.

The *System Maintenance and Calibration* function demonstrates how adaptability to different conditions and the ability to respond to variability enhance overall system efficiency. Variability in equipment conditions, maintenance schedules, and human factors allows the system to adjust and optimize its processes. FRAM views this variability not as a hindrance but as an opportunity for the system to adapt and improve its performance in changing circumstances.

[*********] We did not suggest any predetermined levels of acceptability for the combination of variability.

- Determining Safety Constraints

The goal is to develop strategies that mitigate identified risks and enhance system robustness. Although the FRAM model is useful for macro-level analysis, it does not fully encompass the identification of safety constraints. Instead, the STPA process is preferred for determining safety constraints, as it offers detailed micro-level examination and analysis of system components.

10.4.2 STPA Model Development and Analysis

In this case study section, the goal is to assess how well STPA enhances the understanding of LineDrone's operational activities when combined with insights from the FRAM model. STPA proves valuable by offering a detailed micro-level examination of the system's components, providing a thorough analysis of the process.

- Defining the Purpose of the Analysis

To perform an STPA hazard analysis, it is essential to meticulously define the scope of the problem. We engaged Hydro-Quebec domain experts and university subject matter experts in the collaborative process of generating these insights. The initial step of STPA involves identifying Hazards ($H-i$) and Safety Constraints ($SC-j$) based on the identified losses ($L-k$) within the system (refer to Table 10.17). We have generated five potential hazards associated with these losses through brainstorming. The safety constraints aim to ensure the safe operation of the LineDrone, mitigate risks, and promote a culture of safety throughout its lifecycle. Table 18 provides a summary of the identified hazards and their respective safety constraints.

Table 10.17. Identified Losses (L-k)

L-k	*Losses*
L-1	Loss of life or serious injury to personnel involved in the operation or bystanders.
L-2	Mission loss (e.g., loss of the LineDrone, damage to the LineDrone or equipment damage, loss of power generation).
L-3	Damage to structures that impact transmission lines or other infrastructure owned by Hydro-Quebec.

Table 10.18. Identified Hazards (H-i) and Safety Constraints (SC-j)

Hazards (H-i)	*Relationship to Losses L-k*	*Safety Constraints (SC-j)*
H-1 Failure in the Autopilot	**L-1, L-2, L-3**	**SC-1-1** Establish procedures and use technological tools to prevent public collisions, focusing on sensors, real-time monitoring, and operator training. **SC-1-2** Regularly perform maintenance and diagnostics on the autopilot system to detect potential issues before they lead to failure. **SC-1-3** Design the autopilot system with fail-safe modes that allow the drone to safely perform a controlled landing in case of failure. → *The autopilot system is responsible for recognizing the drone's state, responding to commands, and controlling the motors in flight.* → *A failure in this system can lead to loss of control, unresponsive behavior, or erratic movement of the drone.*
H-2 Failure in the Tool board *(LineOhm, LineCore, Motorized Rolling Mechanism)*	**L-2, L-3**	**SC-2-1** Establish a maintenance schedule for regular inspection and testing of the LineOhm, LineCore, and Motorized Rolling Mechanism. **SC-2-2:** Develop protocols for the drone to safely disengage from the transmission line and return to base if critical tool board components fail. → *The tool board transmits data from the LineOhm for non-destructive electrical resistance assessment and from the LineCore for corrosion detection. It also controls the probe deployment motors and the motorized rolling mechanism, enabling smooth movement along transmission lines. When the pilot arms the LineDrone for takeoff, it automatically triggers certain safety mechanisms (e.g., opening LineCore doors, stopping motorized wheels, etc.).* → *Failure of the tool board compromises the drone's ability to perform inspection tasks accurately and safely.*
H-3 Failure in the LIDAR (Light Detection and Ranging) Sensors	**L-1, L-2, L-3**	**SC-3-1** Conduct routine maintenance of the LIDAR sensors to prevent drift and degradation in performance. → *The integration of LIDAR sensors enhances system stability and ease of operation, particularly during landing and take-off. These sensors assist pilots by displaying precise landing information on the copilot's screen.* → *A failure in these sensors can result in inaccurate landing data, leading to potential collisions or unsafe landings.*
H-4 Deficiency in Operations Management[†††††††††]	**L-1, L-2, L-3**	**SC-4-1** Implement comprehensive operations management training to ensure that all personnel understand and execute operational procedures effectively. **SC-4-2** Regularly review and update operational procedures to address any identified deficiencies and align with best practices.

[†††††††††] Operations management optimizes the inspection process for safety, efficiency, and reliability, covering everything from planning to data handling.

Hazards (H-i)	*Relationship to Losses L-k*	*Safety Constraints (SC-j)*
H-5 Deficiency in LineDrone Operations Team	**L-1, L-2, L-3**	**SC-5-1** Ensure that all members of the LineDrone Operations Team (pilot, copilot, lineman) are thoroughly trained and certified. **SC-5-2** Develop clear communication protocols to ensure that all team members are aligned and informed during operations.

- Modeling the Control Structure

This step involves creating a Hierarchical Safety Control Structure (HSCS) to visually represent the control and feedback mechanisms that ensure safety and compliance (see Figure 10.13). The model guides the analysis and management of safety concerns in complex industrial settings, with a specific focus on a drone system comprising various critical components, such as the RC Controller, Ground Control Station, Power Distribution, Autopilot, Sensors, and other essential equipment.

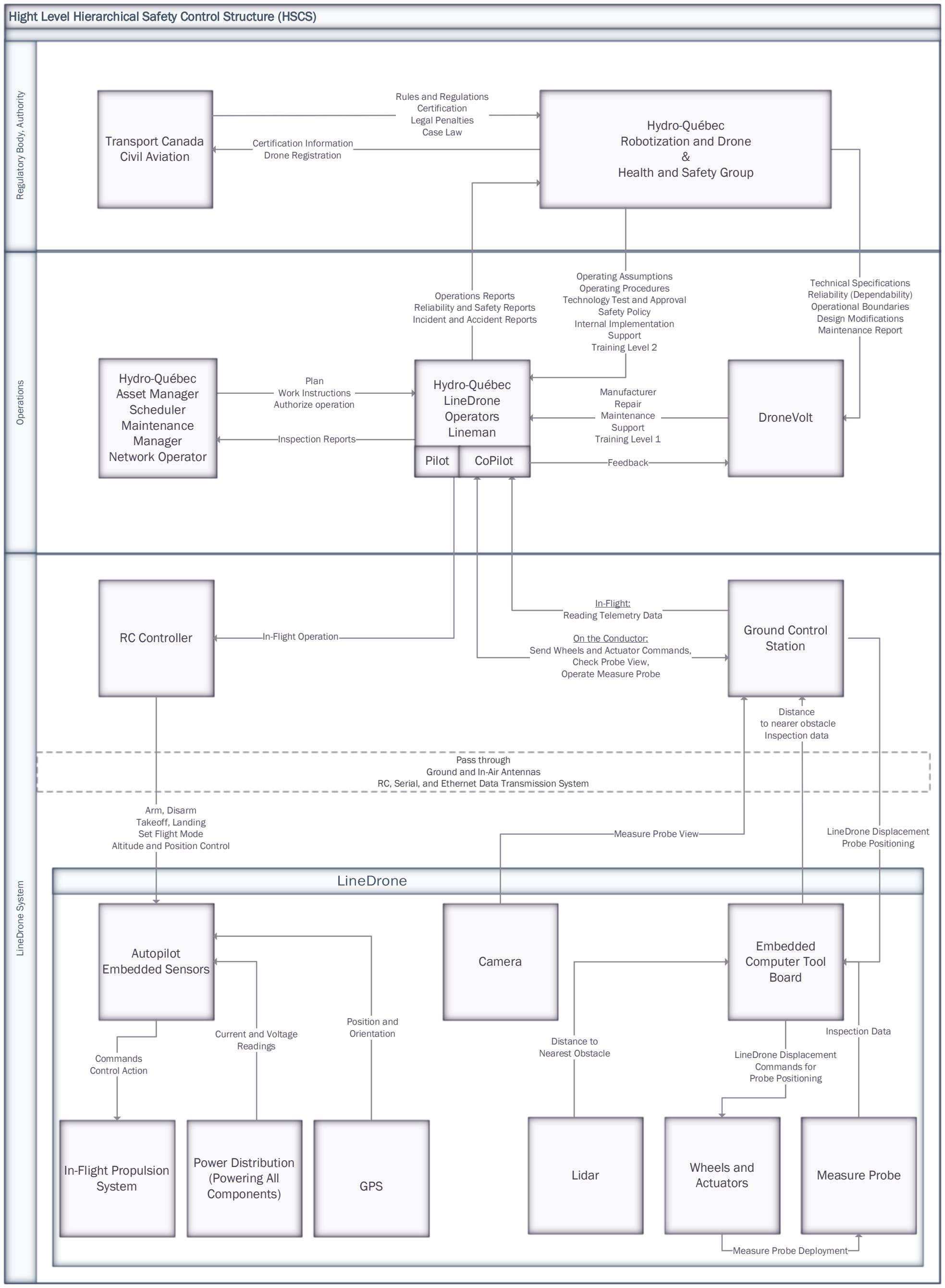


Figure 10.13. *HSCS for the LineDrone System (Source: own representation)*

- Identify Potential Unsafe Control Actions (UCAs)

Once the Hierarchical Safety Control Structure (HSCS) is established, the analysis phase can begin. In the initial step of the analysis, we identify Unsafe Control Actions (UCAs). These are control actions (CAs) that, under specific conditions and in a worst-case scenario, may result in a hazard. For each CA assigned to every controller, four potential categories of UCAs have been identified:

(1) Not providing causes a hazard.
(2) Providing causes a hazard.
(3) Too early, too late, or out of order.
(4) Stopped too soon or applied too long.

Tables 10.19 to 10.37 present the identified CAs and their corresponding potential UCAs[‡‡‡‡‡‡‡‡‡]. CAs can manifest in various forms, including physical devices, rules, procedures, standards, and other similar mechanisms. By identifying and categorizing these UCAs, stakeholders can gain a better understanding of the specific ways in which CAs can contribute to system hazards. This knowledge is valuable for designing effective control strategies and implementing appropriate mitigations to minimize the occurrence of these UCAs and ensure the overall safety of the system.

[‡‡‡‡‡‡‡‡‡] In order to keep the paper within a manageable length and improve the readability of the table on a letter-sized format, we opted not to conduct a comprehensive examination of all CAs associated with LineDrone's operation. Instead, our focus centered on specific examples of CAs for the analysis.

Table 10.19. Identified CAs and Potential UCAs (Technological Controller) – Drone State Recognition

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Autopilot System	**CA-01 Recognizing the drone's state** *(using sensors)*	**UCA-01-1** The autopilot fails to stabilize the LineDrone, causing it to become uncontrollable and leading to a crash **(H-1)**.	**UCA-01-2** The autopilot system receives incorrect sensor information **(H-1)**. False positives, which indicate a problem where none exists, could cause unnecessary landings **(H-1)**. Conversely, false negatives, which fail to detect actual issues, could result in continued operation under unsafe conditions **(H-1)**.	**UCA-01-3** Too late: The autopilot system conducts health monitoring too late, potentially missing critical issues as they develop **(H-1)**.	**UCA-01-4** Stopped too soon: The autopilot system's incomplete monitoring may miss emerging issues, leaving the drone vulnerable to sudden failures during operation **(H-1)**.	Comment: → The autopilot system is responsible for recognizing the drone's state. → A failure in this system can lead to a loss of control, unresponsive behavior (failure to respond to emergencies), erratic movement of the drone, or flyaway, thereby increasing the risk of collisions or crashes. Mitigation: → Before each takeoff, key parameters need to be checked via telemetry. After the drone is transported to the inspection site, the pilot must execute basic in-flight maneuvers on the first takeoff to ensure the autopilot is functioning correctly. → In case of complete control loss, the pilot can activate the emergency motor shutdown. → The LineDrone must never be operated over individuals. → The autopilot system must undergo regular and thorough pre-flight inspections to ensure it is in airworthy condition. → Regularly perform maintenance and diagnostics on the autopilot system to detect potential issues before they lead to failure. → Develop protocols for the drone to safely disengage from the transmission line and return to base if critical components fail.
Potential impacts						
	Safety	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Environment	1	1	1	1	Low impact
	Operation	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	3	3	3	3	Very serious impact, though not threatening the inspection activities
[§§§§§§§§§] Total score: 52						

[§§§§§§§§§] For more details on the ratings, refer to the Risk Matrix and Impact Matrix in **Appendix 2**.

Table 10.20. Identified CAs and Potential UCAs (Technological Controller) – Response to Commands

Controller & Control Actions		Unsafe Control Actions / Hazards				
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	*Safety Constraints*
Autopilot System	**CA-02 Responding to the Commands**	**UCA-02-1** The autopilot system fails to properly receive commands, potentially leading to a collision or crash **(H-1)**.	**UCA-02-2** The autopilot system responds to commands incorrectly, such as interpreting a minor adjustment as a major maneuver. This can lead to hazardous situations, including sudden altitude changes or unintended flight paths **(H-1).**	**UCA-02-3** Too late: The autopilot system responds to commands too late, resulting in missed opportunities to correct the drone's path or stabilize it. This delay can lead to accidents or deviations from the intended flight plan **(H-1)**.	**UCA-02-4** Stopped too soon / Applied too long: The autopilot system stops responding to commands too soon or continues to apply a command for too long causing control issues **(H-1)**.	Comment: → The autopilot system is responsible for responding to commands. → Its failure can lead to loss of control, unresponsive behavior, or erratic movement due to communication loss. Mitigation: → In the event of a communication loss, the autopilot may initiate an emergency landing of the LineDrone, potentially leading to a collision or crash if the drone is above an obstacle. → The autopilot system must undergo regular and thorough pre-flight inspections to ensure it is in airworthy condition. → Regularly perform maintenance and diagnostics on the autopilot system to detect potential issues before they lead to failure. → Develop protocols for the drone to safely disengage from the transmission line and return to base if critical components fail.
Potential impacts						
	Safety	2	2	2	2	Significant impact causing harm to the inspection activities
	Environment	1	1	1	1	Low impact
	Operation	2	2	2	2	Significant impact causing harm to the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	3	3	3	3	Very serious impact, though not threatening the inspection activities
Total score:24						

Table 10.21. Identified CAs and Potential UCAs (Technological Controller) – Motor Control During Flight

Controller & Control Actions		Unsafe Control Actions / Hazards				
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	*Safety Constraints*
Autopilot System	**CA-03 Controlling the motors in flight**	**UCA-03-1** The autopilot system fails to control the motors, causing instability and increasing the risk of crashes. **(H-1)**	**UCA-03-2** The autopilot system incorrectly adjusts motor speeds, causing the drone to become unbalanced and potentially leading to loss of control or crashes **(H-1)**. Alternatively, the autopilot may overpower or underpower the motors, resulting in rapid ascent, descent, or failure to maintain altitude **(H-1)**.	**UCA-03-3** Too early: The autopilot system performs premature adjustments to motor speeds that do not align with actual flight needs, causing instability or unnecessary maneuvers **(H-1)** Too late: The autopilot system makes motor control adjustments too late, resulting in missed opportunities to correct the drone's path or stabilize it. This delay can lead to accidents or deviations from the intended flight plan **(H-1)**.	**UCA-03-4** Stopped too soon: The autopilot system stops motor control adjustments too soon, potentially leading to failures that could have been prevented by continuing the adjustments longer **(H-1)**.	Comment: → The autopilot system is responsible for controlling the motors in flight. → A failure in this system can result in loss of control, unresponsive behavior, or erratic movement of the drone. Mitigation: → If a motor fails, the LineDrone can continue flying. → In the event of total control loss, the pilot can activate the emergency motor shutdown. → The LineDrone must never be operated over individuals. → The autopilot system must undergo regular and thorough pre-flight inspections to ensure it is in airworthy condition. → Regularly perform maintenance and diagnostics on the autopilot system to detect potential issues before they lead to failure. → Develop protocols for the drone to safely disengage from the transmission line and return to base if critical components fail.
Potential impacts						
	Safety	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Environment	1	1	1	1	Low impact
	Operation	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	3	3	3	3	Very serious impact, though not threatening the inspection activities
Total score: 52						

Table 10.22. Identified CAs and Potential UCAs (Technological Controller) – LineOhm Deployment

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Tool Board System	**CA-04** **Deploying the LineOhm** *(On-board sensors for non-destructive assessment of electrical resistance.)* *1) Deploying the LineOhm (for taking measurements)* *2) Transmitting the data to the operator (copilot)*	**UCA-04-1** The tool board system fails to deploy the LineOhm, preventing necessary measurements and leaving electrical resistance issues undetected, which could lead to failures in the electricity transmission system **(H-2)** The tool board system fails to transmit data to the copilot, leading to inaccurate analysis and decision-making **(H-2).**	**UCA-04-2** The tool board system incorrectly deploys the LineOhm, potentially damaging it and resulting in inaccurate measurements **(H-2)**.	**UCA-04-3** Too early /Too late: The tool board system deploys the LineOhm at the wrong time, either too early or too late, causing measurements to be taken in the wrong location and resulting in inaccurate data **(H-2).**	**UCA-04-4** Stopped too soon: The tool board system stops the LineOhm deployment too soon, resulting in incomplete data collection and insufficient information for accurate assessment **(H-2)**. Stopped too soon: The tool board system prematurely terminates data transmission, resulting in incomplete information reaching the operator (copilot), which leads to insufficient data for accurate analysis and decision-making **(H-2)**.	Comment: → See **Appendix 1** for Technical Specifications. → The LineOhm, equipped with sensors manufacture by Nucleom and Hydro-Québec, performs non-destructive inspections. It assesses electrical resistance in compressed joint sleeves on conductors, offering high-quality measurements for evaluating equipment integrity and lifespan. → Failure in of this component can compromise the drone's ability to perform its inspection tasks accurately and safely. Mitigation: ® Measurements are taken three consecutive times, each following a slight movement, and they must be identical. → Establish a maintenance schedule for regular inspection and testing of the LineOhm. → Develop protocols for the drone to safely disengage from the transmission line and return to base if critical components fail.
Potential impacts						
	Safety	n/a	n/a	n/a	n/a	n/a
	Environment	n/a	n/a	n/a	n/a	n/a
	Operation	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	n/a	n/a	n/a	n/a	n/a
Total score: 20						

Figure 10.14 shows the LineOhm system, an on-board sensor system designed for the non-destructive assessment of electrical resistance. It facilitates measurement and transmits the collected data to the operator, including the Ground Control Station and copilot.

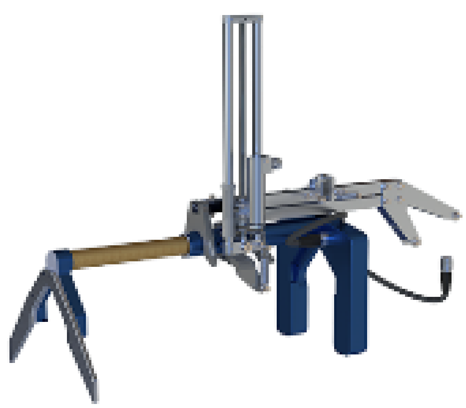


Figure 10.14. LineOhm System (Source: Hydro-Presse (2024))

Table 10.23. Identified CAs and Potential UCAs (Technological Controller) – LineCore Deployment

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Tool Board System	**CA-05 Deploying the LineCore** *(On-board Sensors for Corrosion Detection)* *1) Deploying the LineCore (for security)* *2) Transmitting the data to the operator (copilot)*	**UCA-05-1** The tool board system fails to transmit LineCore data, leading to undetected corrosion that may cause catastrophic infrastructure failures, endangering lives and resulting in significant economic losses from unplanned downtime and costly repairs **(H-2)**.	**UCA-05-2** The tool board system incorrectly deploys the LineCore, potentially damaging it and resulting in inaccurate measurements **(H-2).** The tool board system transmits corrupted data to the copilot, leading to inaccurate analysis and decision-making **(H-2).**	**UCA-05-3** Too early /Too late: The tool board system deploys the LineCore at the wrong time, either too early or too late, causing measurements to be taken in the wrong location and resulting in inaccurate data **(H-2).**	**UCA-05-4** Stopped too soon: The tool board system prematurely terminates data transmission, resulting in incomplete information reaching the operator (copilot), which leads to insufficient data for accurate analysis and decision-making **(H-2).**	Comment: → See **Appendix 1** for Technical Specifications. → Developed by Nucleom and Hydro-Québec, the LineCore provides a non-destructive method for assessing under-voltage corrosion and early detection of zinc layer degradation. The sensor measures the thickness of residual galvanic protection. → Failure in this component can compromise the drone's ability to perform its inspection tasks accurately and safely. Mitigation: → Establish a maintenance schedule for regular inspection and testing of the LineCore. → Develop protocols for the drone to safely disengage from the transmission line and return to base if critical components fail.
Potential impacts						
	Safety	n/a	n/a	n/a	n/a	n/a
	Environment	n/a	n/a	n/a	n/a	n/a
	Operation	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	n/a	n/a	n/a	n/a	n/a
Total score: 20						

Figure 10.15 shows the LineCore system, an on-board sensor designed for corrosion detection. It also assists in securing the LineDrone on the powerline for safety. The system facilitates measurement and transmits the collected data to the operator, including the Ground Control Station and copilot.

Figure 10.15. LineCore System (Source: Hydro-Presse (2024))

Table 10.24. Identified CAs and Potential UCAs (Technological Controller) – Motorized Rolling Mechanism Activation

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Tool Board System	**CA-06 Activating the Motorized Rolling Mechanism** *(for Seamless Movement along Transmission Lines)*	**UCA-06-1** The tool board system fails to activate the Motorized Rolling Mechanism (for seamless movement along transmission lines). As a result, the LineDrone is unable to move along the transmission lines, leading to incomplete inspections tasks. This inability to reach critical sections could potentially cause issues to be missed, which may lead to failures or outages **(H-2).**	**UCA-06-2** The tool board system incorrectly deploys the Motorized Rolling Mechanism, leading to unexpected or uncontrolled displacement along the transmission line. This can potentially cause collisions and derailments from the transmission line **(H-2).**	**UCA-06-3** Too early/Too late: The tool board system activates the Motorized Rolling Mechanism either too early or too late, before proper setup, resulting in improper positioning and potentially leading to ineffective or hazardous movements **(H-2).**	**UCA-06-4** Stopped too soon: The tool board system prematurely stops the deployment of the Motorized Rolling Mechanism, leaving sections of the transmission line uninspected, potentially missing critical issues **(H-2).** Applied too long: The tool board system fails to stop the Motorized Rolling Mechanism at the appropriate time, causing it to operate beyond the intended section of the transmission line. This extended operation may lead to collisions with other components or obstacles, potentially causing derailments or damage to the transmission line **(H-2).**	Comment: → The tool board includes the Motorized Rolling Mechanism for seamless movement along transmission lines. → Failure in this component can compromise the drone's ability to perform its inspection tasks accurately and safely. Mitigation: → Establish a maintenance schedule for regular inspection and testing of the Motorized Rolling Mechanism. → Develop protocols for the drone to safely disengage from the transmission line and return to base if critical components fail.
Potential impacts						
	Safety	n/a	n/a	n/a	n/a	n/a
	Environment	n/a	n/a	n/a	n/a	n/a
	Operation	4	4	4	4	Extremely serious impact, threatening the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	n/a	n/a	n/a	n/a	n/a
Total score: 20						

Table 10.25. Identified CAs and Potential UCAs (Technological Controller) – Pilot Assistance System Activation

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LIDAR (Light Detection and Ranging) Sensors	**CA-07 Activating the Pilot Assistance System** *(Value displayed on the copilot's screen to aid in precise conductor landings)*	**UCA-07-1** The LIDAR system fails to activate the Pilot Assistance System. As a result, without LIDAR sensor data, the copilot lacks precise distance and positioning information, leading to an increased risk of inaccurate landings, which could potentially cause a collision or crash **(H-3)**.	**UCA-07-2** The LIDAR system incorrectly deploys the Pilot Assistance System. Sensor malfunctions can result in erroneous data being displayed, leading to incorrect decisions and hazardous maneuvers by the copilot, potentially causing a collision or crash **(H-3)**.	**UCA-07-3** Too Late: The LIDAR system activates the Pilot Assistance System too late, causing the copilot to miss essential information required for precise landing or take-off. This delay increases the risk of misjudgment and unsafe operations **(H-3).**	**UCA-07-4** Stopped too soon: The LIDAR system prematurely stops the deployment of the Pilot Assistance System, resulting in the copilot missing crucial information necessary for precise landing or take-off, thereby increasing the risk of misjudgment and unsafe operations **(H-3).**	Comment: → LIDAR sensors and software enhance stability during landing and take-off, but if they fail, inaccurate data could lead to unsafe landings. → The copilot verifies the accuracy of the Lidar value before takeoff and, when possible, compares it with the LineDrone's altitude. Mitigation: → Conduct routine maintenance of the LIDAR sensors to prevent drift and degradation in performance.
Potential impacts						
	Safety	1	1	1	1	Low impact
	Environment	1	1	1	1	Low impact
	Operation	2	2	2	2	Significant impact causing harm to the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	1	1	1	1	Low impact
Total score: 24						

Table 10.26. Identified CAs and Potential UCAs (Organizational Controller) – Inspection Preparation (Pilot)

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Operations Management Team	**CA-08** **Preparing Inspection** **1) <u>Pilot</u>**: The pilot is responsible for preparing the flight operation *(Providing a Flight Plan, operation plan, risk analysis, safety measures, emergency procedure)*	**UCA-08-1** The Operations Management Team fails to provide the necessary preparations for the flight, including the flight plan, risk analysis, and safety measures, resulting in the pilot, the copilot and the lineman being unprepared for the operation. This lack of preparation increases the likelihood of unforeseen issues during the flight, potentially leading to accidents **(H-4).**	**UCA-08-2** The Operations Management Team incorrectly or poorly prepares the flight plan and risk analysis, increasing the risk of accidents due to inadequate decision-making and handling of hazards and emergencies **(H-4).**	**UCA-08-3** <u>Too Early</u>: The Operations Management team begins preparing inspections too early, leading to outdated information and incorrect planning decisions **(H-4).** <u>Too Late</u>: The Operations Management Team delays preparing inspections, resulting in rushed decisions and increased operational risks **(H-4).**	**UCA-08-4** <u>Stopped too soon</u>: The Operations Management Team prematurely stops preparation, resulting in an incomplete flight plan and risk analysis, increasing the chances of unexpected events during the flight. **(H-4)**.	<u>Comment:</u> → Effective Operations Management is vital in ensuring that all essential flight preparations are completed thoroughly. This involves delivering a comprehensive and accurate flight plan, conducting a detailed risk analysis, and implementing all necessary safety measures and emergency procedures. <u>Mitigation:</u> → To address safety concerns, once on site for the inspection, the pilot must evaluate the situation and adjust or cancel the operation if needed. → Implement standardized procedures for flight plan preparation to ensure consistency and thoroughness. → Ensure all relevant information is current and accurately reflects the conditions at the time of operation. → Develop contingency plans that can be quickly executed in case of delays or issues during the preparation process, reducing the impact on operations.
Potential impacts						
Safety		2	2	2	2	Significant impact causing harm to the inspection activities
Environment		1	1	1	1	Low impact
Operation		3	3	3	3	Very serious impact, though not threatening the inspection activities
Financial		1	1	1	1	Low impact
Compliance		2	2	2	2	Significant impact causing harm to the inspection activities
Reputation		1	1	1	1	Low impact
Total score: 40						

Table 10.27. Identified CAs and Potential UCAs (Organizational Controller) – Inspection Preparation (Copilot)

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Operations Management Team	**CA-09** **During the Inspection** **2) Copilot:** The copilot assists the pilot by providing information, monitoring telemetry before and during the flight, and operating the LineDrone along the line.	**UCA-09-1** The Operations Management Team fails to ensure that the copilot is properly trained and equipped with the necessary tools and information. This lack of preparation can result in ineffective assistance to the pilot, increasing the risk of flight errors and safety hazards **(H-4).**	**UCA-09-2** The Operations Management Team provides incorrect or incomplete information to the copilot regarding inspection procedures or LineDrone operation. This incorrect guidance can lead to errors in monitoring, miscommunication with the pilot, and potential safety risks during flight **(H-4).**	**UCA-09-3** <u>Out of Order</u>: The copilot performs tasks out of sequence, such as attempting to operate the LineDrone along the line before verifying telemetry data or without ensuring that all necessary information has been provided to the pilot, leading to increased risks **(H-4)**.	**UCA-09-4** <u>Stopped too Soon</u>: The copilot prematurely stops monitoring telemetry or ceases providing information before the flight is safely completed, leading to missed critical data or unsafe operations **(H-4).**	<u>Comment</u>: → Effective communication between the pilot and copilot is essential for aligning tasks with operational needs. <u>Mitigation</u>: → Implement comprehensive operations management training to ensure that all personnel understand and execute operational procedures effectively. → Ensure that the copilot receives comprehensive training on telemetry monitoring, LineDrone operations, and the specific inspection protocols required.
Potential impacts						
Safety		2	2	2	2	Significant impact causing harm to the inspection activities
Environment		1	1	1	1	Low impact
Operation		2	2	2	2	Significant impact causing harm to the inspection activities
Financial		1	1	1	1	Low impact
Compliance		2	2	2	2	Significant impact causing harm to the inspection activities
Reputation		1	1	1	1	Low impact
Total score: 36						

Table 10.28. Identified CAs and Potential UCAs (Organizational Controller) – Inspection Preparation (Lineman)

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
Operations Management Team	**CA-10** **Preparing Inspection** **3) Lineman:** The lineman is responsible for requesting operational authorization, verifying the feasibility of the operation (such as distances between phases), and facilitating site access. The role of the Lineman can be assumed by the pilot or copilot if one of them is a Lineman.	**UCA-10-1** The Operations Management Team fails to request authorization or verify feasibility, leading to unsafe conditions and an increased risk of accidents **(H-4).**	**UCA-10-2** The Operations Management Team requests incorrect authorizations or conducts improper verification, leading to operations in unsafe conditions and increasing potential hazards **(H-4).**	**UCA-10-3** Out of order: The Operations Management Team misorders actions, like starting operations before obtaining authorization, leading to regulatory violations and unsafe practices **(H-4).**	**UCA-10-4** N/A	Comment: → The Lineman is essential in ensuring operations are authorized and feasible by securing proper site access and clearances. Mismanagement in this role can lead to significant safety risks. Mitigation: → Implement a review process to confirm that all necessary checks are completed before operations begin.
Potential impacts						
	Safety	1	1	1	n/a	Low impact
	Environment	1	1	1	n/a	Low impact
	Operation	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Financial	1	1	1	n/a	Low impact
	Compliance	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Reputation	2	2	2	n/a	Low impact
Total score: 27						

Table 10.29. Identified CAs and Potential UCAs (Human Controller) – Validation of Wind, Weather, and Solar Activity

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, CoPilot, Lineman)	**CA-11 Validating Wind, weather, and Solar Activity**	**UCA-11-1** The LineDrone Operations Team fails to validate environmental conditions, leading to potential loss of control, inaccurate flight paths, and increased risk of crashes or operational failure due to unsafe weather or solar interference **(H-5).**	**UCA-11-2** The LineDrone Operations Team provides incorrect environmental data, leading to unsafe flight conditions, including unstable flight, exposure to severe weather, and GPS or communication issues, increasing the risk of hazards **(H-5).**	**UCA-11-3** Too early:The LineDrone Operations Team validates wind, weather, and solar activity too early, resulting in decisions based on outdated data and increasing the risk of the drone encountering unexpected conditions during the mission **(H-5).**	**UCA-11-4** N/A	Comment: → Validating environmental conditions is crucial for preventing hazards like loss of control and communication failures during drone operations. Mitigation: → Validate conditions just before the flight, set safety protocols, train the team, and monitor conditions in real time during the operation.
Potential impacts						
	Safety	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Environment	1	1	1	n/a	Low impact
	Operation	3	3	3	n/a	Very serious impact, though not threatening the inspection activities
	Financial	1	1	1	n/a	Low impact
	Compliance	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Reputation	1	1	1	n/a	Low impact
Total score: 30						

Table 10.30. Identified CAs and Potential UCAs (Human Controller) – Issuing an Insurance Certificate

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, CoPilot, Lineman)	**CA-12 Providing an Insurance Certificate**	**UCA-12-1** The LineDrone Operations Team fails to provide the insurance certificate, exposing the organization to financial and legal risks, and regulatory non-compliance **(H-5).**	**UCA-12-2** N/A *(as long as the certificate is valid and applicable)* .	**UCA-12-3** Too late: The LineDrone Operations Team provides the certificate too late, causing delays in the operation, impacting the mission's timeline, and leading to operational inefficiencies, particularly if the certificate is needed for authorization or compliance checks **(H-5).**	**UCA-12-4** N/A	Comment: → A valid and timely insurance certificate is essential to protect the organization from liabilities and avoid legal issues or disruptions. Mitigation: → Ensure the insurance certificate is valid and timely and train the team on the importance of proper documentation.
Potential impacts						
	Safety	n/a	n/a	n/a	n/a	n/a
	Environment	n/a	n/a	n/a	n/a	n/a
	Operation	n/a	n/a	n/a	n/a	n/a
	Financial	2	2	2	n/a	Low impact
	Compliance	3	3	3	n/a	Low impact
	Reputation	2	2	2	n/a	Low impact
Total score: 21						

Table 10.31. Identified CAs and Potential UCAs (Human Controller) – Verifying and Charging VHF Radios and Other Communication Devices

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, CoPilot, Lineman)	**CA-13 Verifying and Charging VHF Radios and Other Communication Means**	**UCA-13-1** The LineDrone Operations Team fails to verify and charge communication devices, increasing the risk of communication loss and potential hazards during flight **(H-5)**.	**UCA-13-2** The LineDrone Operations Team improperly verifies and charges communication devices, causing malfunctions, communication failures during critical moments, and operational errors **(H-5).**	**UCA-13-3** Too early: The LineDrone Operations Team charges communication devices too early, causing charge loss and risking communication failure during critical moments of the flight **(H-5).** Too late: The LineDrone Operations Team charges devices too late, leaving them not fully charged for the operation, which may lead to communication failures during the flight **(H-5).**	**UCA-13-4** Stopped too soon: The LineDrone Operations Team stops charging communication devices too soon, leading to incomplete charging, undetected low battery levels, and potential failures during the mission **(H-5).** Applied too long: The LineDrone Operations Team spends too much time on the charging process, risking overcharging, overheating, reduced battery life, or fire hazards **(H-5).**	Comment: → Properly charging VHF radios and other communication devices is crucial for reliable communication. → Charging issues can lead to communication breakdowns, raising the risk of operational failures and accidents. Mitigation: → Establish clear protocols for charging radios and other communication devices, including checking charge levels before the flight and using correct equipment and methods. → Implement routine checks to ensure radios are fully charged and operational before each flight. → Consider using backup communication systems to ensure continuous communication in case of VHF radio failure.
Potential impacts						
	Safety:	2	2	2	2	Significant impact causing harm to the the inspection activities
	Environment	1	1	1	1	Low impact
	Operation	2	2	2	2	Significant impact causing harm to the the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	2	2	2	2	Significant impact causing harm to the the inspection activities
	Reputation	1	1	1	1	Low impact
Total score: 36						

Table 10.32. Identified CAs and Potential UCAs (Human Controller) – Providing Personal Protective Equipment (PPE)

Controller & Control Actions		Unsafe Control Actions / Hazards				
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	*Safety Constraints*
LineDrone Operations Team (Pilot, CoPilot, Lineman)	**CA-14 Providing Personal Protective Equipment (PPE)**	**UCA-14-1** The LineDrone Operations Team fails to provide PPE, putting team members at risk of serious injuries or fatalities in high-risk environments **(H-5).**	**UCA-14-2** The LineDrone Operations Team provides inadequate PPE, increasing the risk of injuries due to insufficient protection and a false sense of security **(H-5).**	**UCA-14-3** Too late: The LineDrone Operations Team provides PPE too late, causing team members to start operations without necessary protection and exposing them to hazards **(H-5).**	**UCA-14-4** N/A	Comment: → Proper PPE provision and inspection are essential to protect the LineDrone Operations Team from hazards. Mitigation: → Establish strict protocols for providing and inspecting PPE before operations. → Train team members on the importance of PPE and proper usage.
Potential impacts						
	Safety	3	3	3	n/a	Very serious impact, though not threatening the inspection activities
	Environment	n/a	n/a	n/a	n/a	n/a
	Operation	n/a	n/a	n/a	n/a	n/a
	Financial	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Compliance	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Reputation	1	1	1	n/a	Low impact
Total score: 24						

Table 10.33. Identified CAs and Potential UCAs (Human Controller) – Proper Configuration of Integrated Safety Systems

Controller & Control Actions		Unsafe Control Actions / Hazards				
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	*Safety Constraints*
LineDrone Operations Team (Pilot, CoPilot, Lineman)	**CA-15 Configuring Correctly Integrated Safety Systems**	**UCA-15-1** The LineDrone Operations Team fails to configure safety systems properly, raising the risk of accidents due to the drone's inability to handle emergencies **(H-5).**	**UCA-15-2** The LineDrone Operations team incorrectly configures safety systems, leading to unintended activations, unnecessary evasive maneuvers, or accidents due to system conflicts **(H-5).**	**UCA-15-3** Too late: The LineDrone Operations team configures safety systems too late, resulting in the systems not being ready in time for the flight, which leaves the drone without proper safety measures **(H-5).**	**UCA-15-4** Stopped too soon: The LineDrone Operations team incompletely configures safety systems, leading to safety risks and leaving the drone without proper safety measures **(H-5).**	Comment: → Proper and thorough configuration of the drone's safety systems is essential to prevent accidents and ensure control during unexpected situations. Mitigation: → Establish standardized procedures to ensure safety system configurations align with the flight plan and conditions.
Potential impacts						
	Safety	2	2	2	2	Significant impact causing harm to the inspection activities
	Environment	1	1	1	1	Low impact
	Operation	3	3	3	3	Very serious impact, though not threatening the inspection activities
	Financial	1	1	1	1	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	1	1	1	1	Low impact
Total score: 32						

Table 10.34. Identified CAs and Potential UCAs (Human Controller) – Securing Equipment Fastening During Transport

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, Copilot, Lineman)	**CA-16** **Securing fastening of equipment during transport** (to prevent damage to drone components)	**UCA-16-1** The LineDrone Operations Team fails to secure the equipment properly during transport, resulting in potential damage to the LineDrone components and increasing the risk of malfunction during operation **(H-5).**	**UCA-16-2** The LineDrone Operations Team secures the equipment incorrectly (e.g., improper placement), leading to damage of critical components and resulting in operational problems or failures **(H-5).**	**UCA-16-3** N/A	**UCA-16-4** N/A	Comment: → Ensuring that equipment is properly secured during transport is essential to prevent damage to the LineDrone components, which could affect its operational performance and safety. Mitigation: → Establish a verification process to ensure that all equipment is secured properly before the vehicle departs for transport.
Potential impacts						
	Safety	2	2	n/a	n/a	Low impact
	Environment	n/a	n/a	n/a	n/a	n/a
	Operation	4	4	n/a	n/a	Significant impact causing harm to the the inspection activities
	Financial	n/a	n/a	n/a	n/a	n/a
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	n/a	n/a	n/a	n/a	n/a
Total score: 12						

Table 10.35. Identified CAs and Potential UCAs (Human Controller) – Measuring Distance Between Phases

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, CoPilot, Lineman)	**CA-17** **Measuring the distance between electrical conductors (distances between phases), the height of the conductors, and any obstacles** **Lineman:** The lineman is responsible for requesting operational authorization, verifying the feasibility of the operation (such as distances between phases), and facilitating site access. The role of the Lineman can be assumed by the pilot or copilot if one of them is a Lineman.	**UCA-17-1** The LineDrone Operations Team fails to measure the distances between phases, the height of the conductors, and obstacles before the flight. This could lead to the drone encountering obstacles or coming too close to conductors, increasing the risk of collisions, or short circuits **(H-5).**	**UCA-17-2** The LineDrone Operations Team provides incorrect or inaccurate measurements of distances between phases and obstacles, leading to incorrect flight path adjustments and potential safety hazards such as collisions or short circuit **(H-5).**	**UCA-17-3** N/A	**UCA-17-4** N/A	Comment: → The most critical task is measuring the distance between phases to prevent issues such as magnetic interference or short circuits during operations. → This helps the pilot avoid obstacles and ensures a safe flight path. Mitigation: → It is recommended (though not mandatory) to measure the distance between phases, the height of the conductors, and any obstacles using a Wrench before the flight.
Potential impacts						
	Safety	2	2	n/a	n/a	Low impact
	Environment	1	1	n/a	n/a	Low impact
	Operation	2	2	n/a	n/a	Low impact
	Financial	1	1	n/a	n/a	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	n/a	n/a	n/a	n/a	n/a
Total score: 12						

Table 10.36. Identified CAs and Potential UCAs (Human Controller) – LineDrone Deployment (Pilot)

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, Copilot, Lineman)	**CA-18 Deploying the LineDrone** __**Pilot**__: Responsible for deploying the LineDrone (including Takeoff and Landing on power lines)	**UCA-18-1** The LineDrone Operations Team (pilot) fails to deploy the LineDrone, resulting in the inability to perform takeoff or landing on power lines. This failure increases the risk of unforeseen issues during the operation, potentially leading to unsafe conditions or incidents **(H-5).**	**UCA-18-2** The LineDrone is deployed under unsafe conditions, such as during adverse weather or in unsecured areas, leading to an increased risk of accidents, equipment damage, or harm to infrastructure **(H-5).**	**UCA-18-3** __Too Early__: The LineDrone is deployed prematurely, before completing all necessary safety checks and preparations, potentially creating hazardous conditions **(H-5).** __Out of order__: The LineDrone is deployed out of sequence, such as before obtaining the required permissions or clearances, potentially leading to regulatory violations or unsafe operational conditions **(H-5).**	**UCA-18-4** N/A	__Comment:__ → Effective operations management ensures thorough and safe flight deployments by adhering to safety protocols and considering environmental conditions. __Mitigation:__ → Deploy the LineDrone only after completing all safety checks and confirming safe conditions. → Follow clear protocols for deployment timing to avoid premature or delayed deployment. → Obtain all necessary permissions and clearances before deployment to prevent regulatory violations. → Regularly train the LineDrone Operations Team on updated safety procedures to maintain high operational safety standards.
Potential impacts						
	Safety	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Environment	1	1	1	n/a	Low impact
	Operation	4	4	4	n/a	Very serious impact, though not threatening the inspection activities
	Financial	1	1	1	n/a	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	1	1	1	n/a	Low impact
Total score: 27						

Table 10.37. Identified CAs and Potential UCAs (Human Controller) – LineDrone Deployment (copilot)

Controller & Control Actions		Unsafe Control Actions / Hazards				Safety Constraints
Controller	*Control Actions*	*Not providing causes hazard*	*Providing causes hazard*	*Too early/ too late/ out of order*	*Stopped too soon/ applied too long*	
LineDrone Operations Team (Pilot, Copilot, Lineman)	**CA-19 Deploying the LineDrone** **Copilot:** Responsible for assisting the pilot and managing Inspection Data by providing information (checks telemetry and approves takeoff or landing), monitoring telemetry before and during the flight, and operating the LineDrone along the line. The copilot is responsible for transmitting measurements to the maintenance manager.	**UCA-19-1** The copilot fails to assist the pilot and manage inspection data by neglecting key tasks such as checking telemetry, approving takeoff/landing, monitoring telemetry during the flight, and properly operating the LineDrone along the line. This failure increases the risk of incorrect flight operations, inaccurate data collection, and potential safety hazards, potentially compromising the overall mission and safety of the operation **(H-5).** The LineDrone Operations Team (copilot) fails to transmit measurements to the maintenance manager, increasing the risk of operational errors, data loss, or miscommunication. This failure could potentially lead to unsafe conditions or missed maintenance opportunities **(H-5).**	**UCA-19-2** The copilot provides incorrect assistance, including inaccurate telemetry checks, improper approval of takeoff or landing, inadequate monitoring of telemetry during the flight, or incorrect operation of the LineDrone along the line. This failure leads to risks in flight operations, data inaccuracies, and potential safety hazards **(H-5)**. The LineDrone Operations Team (copilot) provides incorrect or corrupted data, which could mislead maintenance decisions and potentially lead to inappropriate or insufficient maintenance actions, thereby increasing the risk of system failures **(H-5).**	**UCA-19-3** Too early: The copilot approves takeoff/landing too early, before necessary checks are completed. This premature approval could lead to incorrect flight operations, increasing the risk of safety hazards **(H-5).** Too early: The copilot transmits inspection data too early, before necessary checks are completed, or accurate measurements are collected. This premature action could result in data inaccuracies and inappropriate maintenance decisions, thereby increasing the risk of safety hazards **(H-5)**.	**UCA-19-4** N/A	Comment: → Effective coordination between the copilot and other team members is critical to ensuring safe flight operations and accurate data management. → Data storage and management are essential in LineDrone inspections, with the PRIAD system providing secure storage, analysis, and informed decision-making. It facilitates trend analysis, performance evaluation, and risk identification, enhancing safety and performance assessments. Mitigation: → Implement strict protocols to ensure the copilot performs necessary checks and monitors telemetry before and during the flight. → Ensure that data transmitted to the maintenance manager is accurate and timely, avoiding premature or incorrect data transmission.
Potential impacts						
	Safety	2	2	2	n/a	Significant impact causing harm to the inspection activities
	Environment	1	1	1	n/a	Low impact
	Operation	3	3	3	n/a	Very serious impact, though not threatening the inspection activities
	Financial	1	1	1	n/a	Low impact
	Compliance	n/a	n/a	n/a	n/a	n/a
	Reputation	1	1	1	n/a	Low impact
Total score: 24						

- Identifying Loss Scenarios

A loss scenario outlines the causal factors leading to Unsafe Control Actions (UCAs) and associated hazards. It is essential to consider two types of loss scenarios: **(1) reasons for the occurrence of UCAs** *(Why would UCAs occur?)*, **(2) reasons for the improper execution or non-execution of Control Actions (CAs)**, leading to hazards *(Why would CAs be improperly executed or not executed, leading to hazards?)* as shown previously in Figure 10.7.

(1) Scenarios that lead to UCAs (Why would UCAs occur?)

To identify scenarios involving UCAs, we need to consider the elements outlined in Figure 10.16, specifically: (A) Unsafe Controller Behavior and (B) Inadequate Feedback and Other Inputs.

(A) Unsafe Controller Behavior (root cause of the UCA): Several factors can lead to loss scenarios related to *Unsafe Controller Behavior* (root cause of the UCA), explaining why a controller might produce a UCA. These factors (i.e., failure modes) include: (i) physical failures of the controller; (ii) deficient control algorithms, such as flawed or incorrect implementations; (iii) unsafe control inputs caused by failures from another controller; and (iv) inadequate process models (PM) due to feedback issues. Table 10.38 provides examples of loss scenarios for the control action *CA-03 (controlling the motors in flight)*[**********], illustrating how the UCA *(UCA-03-1 – the autopilot system fails to control the motors, causing instability and increasing the risk of crashes)* could manifest during LineDrone operations[††††††††††].

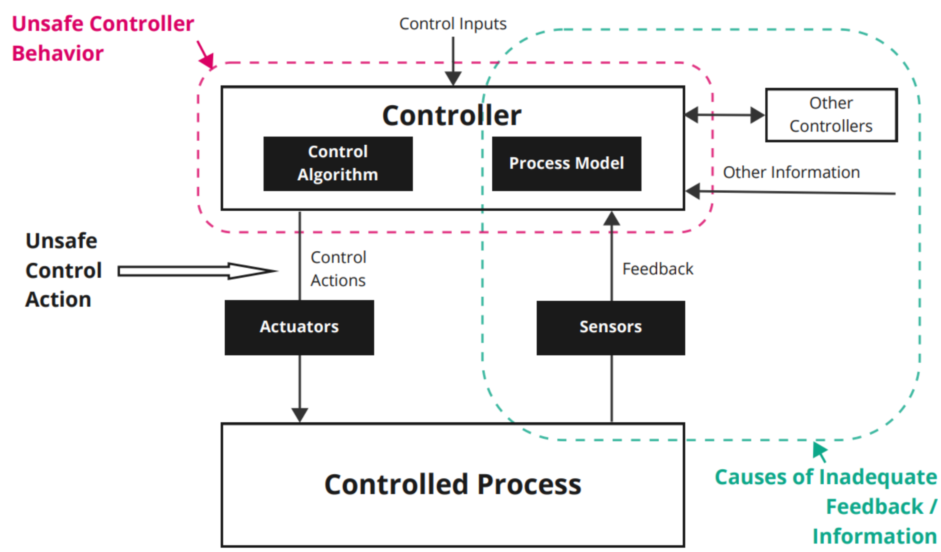


Figure 10.16. Why would UCAs occur?
(Source: own representation based on Leveson & Thomas, 2018)

[**********] We selected control action CA-03 to illustrate the identified loss scenarios, as it has the highest potential impact score of 52 (see Table 10.21)

[††††††††††] To maintain a manageable paper length, we opted not to conduct an exhaustive examination of all UCA-related scenarios in LineDrone operations. Instead, we focused on specific UCA examples for analysis.

Table 10.38. Examples of Loss Scenarios Related to Unsafe Controller Behavior

Unsafe Control Action (UCA)	*Unsafe Controller Behavior*	*Loss Scenarios*
	Physical Controller Failures	A hardware malfunction causes the autopilot system to stop sending appropriate signals to the motor controllers (UCA-03-1), leading to uncontrolled direction, resulting in a crash (H-1).
	Deficient Control Algorithms	Errors in the drone's control algorithms (software bugs) in the autopilot system cause it to send incorrect commands to the motors, such as sudden speed incorrect directional adjustments (UCA-03-1), leading to a loss of control over the drone's trajectory (H-1).
	Insafe Control Inputs Resulting from another Controller's Failure	Environmental factors, such as severe weather conditions (e.g., strong winds), cause the autopilot system to misinterpret sensor data (UCA-03-1), leading to incorrect motor adjustments that destabilize the LineDrone (H-1). If the drone's sensors (e.g., GPS) provide incorrect data, the autopilot system could receive misleading information (UCA-03-1), causing unsafe motor control decisions (H-1). For example, if GPS data is inaccurate, the drone might move into an unsafe zone, causing collision risks or unintentional disruption to the power grid.
UCA-03-1 – The autopilot system fails to control the motors, causing instability and increasing the risk of crashes (H-1)	**Inadequate Process Models (a.k.a. Belief) due to Feedback issues**	Faulty or delayed feedback from sensors (e.g., altitude or speed sensors) may cause the autopilot system to believe (or misinterpret) that the LineDrone is in a safe state when it is actually deviating from its intended flight path (UCA-03-1). The system may fail to make the necessary motor adjustments in time, leading to loss of control (H-1).

(B) Causes of Inadequate Feedback and other Inputs: Feedback is usually provided by sensors, while additional information may come from other processes, controllers, or sources within the system. Leveson and Thomas (2018) describe two scenarios of inadequate feedback and inputs: *(1) feedback is not received* due to issues like sensor failure or absence in the control structure, and *(2) inadequate feedback is received*, where sensors either respond incorrectly or are not designed to provide the necessary feedback. As an example, let us analyze the scenario for UCA-03-1, where the autopilot system fails to control the motors, causing instability and increasing the risk of crashes (see Table 39)[‡‡‡‡‡‡‡‡‡‡].

[‡‡‡‡‡‡‡‡‡‡] We focused on specific causes for analysis to keep the paper concise, rather than covering all potential causes of unsuccessful feedback and inputs.

Table 10.39. Examples of Loss Scenarios Related to Causes of Inadequate Feedback and other Inputs

True State from UCA Context	*Information Received*	*How Might This Circumstance Occur Considering the Actual Situation*	*Loss Scenario*
The autopilot system fails to know (or determine) the position and altitude of the LineDrone due to a GPS malfunction, making it uncontrollable.	The GPS sensor either provides inaccurate location data or does not provide feedback at all during critical phases of flight, like navigation or landing, leading to loss of positional awareness.	– The GPS sensor experiences a technical failure, preventing accurate feedback. Either the feedback is not received or applied to the sensor, or the sensor responds inadequately to the received feedback. – The sensor correctly receives and sends feedback, but it fails to reach the controller. Although the sensor provides accurate feedback, the controller receives it improperly.	– If GPS feedback is inaccurate or missing, the autopilot system cannot correctly position or navigate the LineDrone, increasing the risk of deviating from the flight path or making unsafe landings (H-2). – In the absence of GPS feedback, the drone may miscalculate its speed and altitude, causing operational failures, and increasing the likelihood of an unsafe descent or crash (H-2). – Without reliable GPS data, the autopilot system may struggle to maintain control, leading to instability during flight or failure to land within safe parameters, resulting in potential damage to the drone and infrastructure (H-2).

(2) Scenarios in which CAs are improperly executed or not executed (Why would CAs be improperly executed or not executed, leading to hazards?)

Hazards can arise from UCAs, as previously studied, but they can also occur without UCAs if Control Actions (CAs) are improperly executed or not executed at all. Creating these scenarios requires analyzing factors that affect both the (C) Control Path and the (D) Controlled Process. Figure 10.17 outlines the generic control loop, illustrating both the control path and additional factors, such as external elements, environmental conditions, and the potential risks posed by extreme, rare, and disruptive events that may impact the Controlled Process.

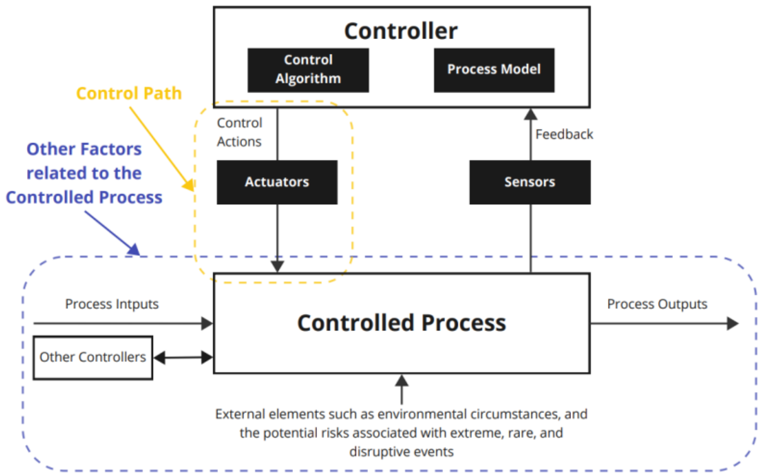


Figure 10.17. Why would CAs be improperly executed or not executed, leading to hazards?
(Source: own representation based on Leveson & Thomas, 2018)

(C) Scenarios Involving the Control Path: The control path delivers CAs to the controlled process, and its complexity can vary from a single actuator to a network of components. Identifying potential issues along this path is crucial, as they may lead to improper or missed execution of CAs, impacting the controlled process. Scenarios involving the control path may include: *(i) CAs not executed* due to failures in transmission or actuator response, or *(ii) CAs improperly executed* due to miscommunication or inadequate actuator response. To explore scenarios related to the control path, let's consider the following example in Table 40.

Table 10.40. Examples of Loss Scenarios Involving the Control Path

Control Action (CA):	*Scenarios*	*Loss Scenarios*
The autopilot **sends a command (control action)** to control the motors in flight	– CA not executed due to failures in transmission or actuator response.	– The autopilot system **sends a command** to control the motors in flight, but due to an actuator failure, the system **does not execute the control action** (H-1). This results in an inability to adjust speed or direction, leading to a loss of navigation control and potential collisions. o The actuator responsible for executing the CA fails to operate, preventing the autopilot's command from being applied. o Bugs in the autopilot's software prevent proper command execution or cause the actuator to misinterpret the command.
	– CA improperly executed due to miscommunicatio n or inadequate actuator response.	– The autopilot system **sends the correct command** to control the motors, but **miscommunication or inadequate actuator response** results in the motors operating at the wrong speed or direction (H-1). This improper execution could cause unstable flight, potential damage to the motors, and increased risk of collision or system failure. o Bugs in the autopilot's software prevent proper command execution or cause the actuator to misinterpret the command. o Environmental conditions, such as extreme weather or electromagnetic interference, disrupt the communication or operation of the control system.

(A) Scenarios related to the Controlled Process: Control Actions (CAs) applied to the controlled process may be ineffective or influenced by actions from other controllers. Scenarios related to the controlled process may involve: *(i) CA not executed*, where the controlled process does not respond, and *(ii) CA improperly executed*, where the controlled process responds incorrectly. To explore scenarios related to the controlled process, let's consider the following example in Table 10.41.

Table 10.41. Examples of Loss Scenarios Involving the Controlled Process

Control Action (CA):	*Scenarios*	*Loss Scenarios*
The autopilot **sends a command (control action)** to control the motors in flight	– CA not executed	– The command to control the motors is sent but not applied by the controlled process (H-1), leading to an inability to adjust speed or direction during flight. This results in the potential for loss of control, instability, or even a crash. o The actuator responsible for implementing the CA does not function properly, leading to failure in adjusting motor speed or direction. o The system fails to detect the appropriate conditions for motor control due to a faulty sensor, resulting in the command not being executed.
	– CA improperly executed	– The command **is applied, but the controlled process responds incorrectly**, such as adjusting the motors to the wrong speed or direction. This improper response can result in unstable flight, damage to the motors, or collision due to improper navigation. o The autopilot's control algorithm may contain software issues that prevent proper execution of the command. o External disturbances, such as extreme weather conditions, could interfere with the sensor or actuator performance, causing the motors to respond incorrectly.

10.5 Final Thought

The shift towards a systemic perspective in safety management is transformative and a game-changer. Viewing performance as a complex and emergent phenomenon acknowledges the interconnectedness of various factors. Safety is not merely about addressing individual errors but about understanding the entire system and its dynamics. Traditional safety management approaches often focused on investigating accidents by identifying immediate causes, such as human errors or equipment failures, and resolving these specific issues to prevent similar incidents. These methods, known as *root cause analysis*, assume a *linear cause-and-effect relationship* and tend to focus on finding and fixing isolated failures.

In contrast, the systemic perspective recognizes that modern systems are complex and interconnected, involving numerous components, interactions, and feedback loops. From this viewpoint, safety is seen as an *emergent property* of the entire system, rather than a feature attributable to isolated events. This approach acknowledges that accidents result from the interaction of multiple factors, including organizational culture, management practices, technology, and human behavior.

Resilience engineering challenges conventional views that link performance solely to failures and errors. Instead, it emphasizes the necessity of variability for effective and adaptive functioning in dynamic environments.

FRAM and STPA are complementary system analysis methodologies, each with unique strengths. FRAM focuses on functional flexibility, allowing system modifications without complete remodeling, and provides a broader understanding of system behavior under different conditions. It contrasts with traditional models by incorporating verbal descriptions and avoiding fixed cause-effect relationships. STPA, based on the STAMP model, views safety as a control issue, analyzing hazards through Unsafe Control Actions (UCAs) and interactions even without component failures. Together, FRAM and STPA offer a comprehensive approach for analyzing complex systems, leveraging their combined strengths as decision-support tools.

Table 10.42 presents a concise analysis of the pros and cons of both FRAM and STAMP-STPA. While FRAM offers several strengths, it is important to acknowledge that the methodology may not adequately account for technological failures. Even in a more mature version, FRAM should be considered a complement to reliability analysis methods rather than a standalone solution. This distinction highlights the need for a comprehensive approach that integrates the insights provided by FRAM with the strengths of STAMP and the analytical rigor of traditional reliability analysis methods, ensuring a more thorough understanding of system safety.

Table 10.42. A brief analysis outlining the advantages and limitations of FRAM and STAMP-STPA.

	FRAM	STAMP-STPA
Pros	- Can be applied to various domains and effectively analyzes complex systems. - Provides a holistic view by emphasizing the functions performed by the system. - Handles system changes and dynamic situations well. - Suitable for real-time analysis in dynamic and evolving systems.	- Flexible and applicable across various domains and industries. - Considers system interactions and dependencies, providing a more comprehensive safety analysis. - Emphasizes identifying and addressing root causes of hazards, supporting a proactive approach to safety. - Can be implemented early in the design phase, allowing safety considerations to be integrated from the start.
Cons	- Relies on expert judgment, making interpretation potentially subjective. - May involve a learning curve, especially for those unfamiliar with the method. - Better at explaining what happened than offering specific improvement solutions.	- The analysis may be subjective, with different analysts potentially reaching different conclusions. - Requires significant time, expertise, and a deep understanding of the system. - Analyzing intricate system interconnections can be challenging.

10.6 Conclusion

The paper presents an innovative Integrated Decision-Making Framework that combines FRAM and STAMP to address emerging safety risks in complex socio-technical systems. A key distinction of this framework is its alignment with Safety II principles, which promote a proactive approach to safety management. Safety II complements Safety-I by shifting the focus from merely preventing accidents and controlling hazards to understanding how systems succeed under various conditions. It emphasizes learning from everyday operations, resilience, adaptive capacity, distributed decision-making, and taking a holistic approach for continuous improvement. Rather than focusing solely on failures, Safety II seeks to understand why things go right and how systems adapt effectively to challenges. The application to a real case study demonstrates the framework's feasibility and effectiveness, providing valuable insights. However, the study faces limitations, such as potential data quality issues. Future research should validate the framework across industries, improve data quality, incorporate human factors, and explore additional dimensions to enhance its applicability in diverse organizational contexts.

Appendices

- *Appendix 1: Technical Specifications for The LineDrone*

Table 10.43 provides technical specifications from Drone-Volt, the manufacturer of the LineDrone, offering insights into the drone's capabilities, such as its design features, operational range, payload capacity, and other performance characteristics.

Table 10.43. Technical specifications for the LineDrone
(Source: Drone-Volt (2024))

TECHNICAL SPECIFICATIONS			
FLIGHT SPECIFICATIONS		SENSORS DESCRIPTION	
Flight time	12 minutes	Travel speed on conductor	0,6m/s (20ft/s)
Weight with batteries	20 kg (44.1 lbs)	Travelling distance on conductor	>1km
Max Take-off weight	22 kg (48.5 lbs)	Data positioning accuracy	+/- 1 cm (0.4 inch)
Power	Batteries 44,4 V 22000 mah	Voltage resistance	Up to 315 kV
Max payload weight	2 kg (4.4 lbs)	Electrical resistance	Up to 2000A
Dimensions (Length x Width x Height)	135 cm x 135 cm x 93 cm (103 cm with the LineOhm mounted)	Diameter of the element on which the LineDrone rolls	10 mm à 70 mm (0.4 inch to 2.7 inch)
Electromagnetic Immunity (EMC)	Immunised for lines from 120 to 315Kv. Maximum 2000 A	Max. crossable sleeve diameter	70 mm (2.7 inch)
Max. roll/pitch during take-off from the line	+/- 35°	Conductor tilt	15° max.
GNSS Positioning accuracy	+/- 4 cm	Maximum drone roll after landing	+/- 5
Weather conditions	Daytime flights in fine weather only. No precipitation or fog.		
Operating temperature	-10°C to + 40°C (14°F to 104°F)		
Wind resistance	25 km/h (15,5mph) and up to 40 km/h (25mph) wind gusts.		
RC transmission distance	1 km (1.24 mi)		
Wireless drone/ground IP transmission distance	1 km (0.62 mi), encrypted, 25MBit/s.		
On-board camera(s)	Sensor position validation camera (resolution 720p min.)		
Flight Software(s)	LineDroneStation (Compatible with Android and Windows)		
SPECIFICATIONS ON CONDUCTOR			
LineOhm Manufactured by Nucleom, the LineOhm sensor enables the non-destructive evaluation of the electrical resistance of junction sleeves compressed onto electrical conductors.		**LineCore** Manufactured by Nucleom, the LineCore sensor enables, on energised or de-energised lines, the assessment of residual galvanic protection on the steel core of aluminium conductors, reinforced with steel conductor (ACSR).	
Operating temperature	from 5°C to 30°C	Operating temperature	From 5°C to 30°C
Conductor temperature	Tested up to 100°C	Conductor temperature	Tested up to 100°C
Conductor diameter	From 15 to 45 mm	Data acquisition speed	Up to 1,0 m/s
Sleeve diameter	From 15 to 70 mm	Resolution	1pt/mm max
Adjustable length	From 19 to 33 cm	Adjustable length	From 15 to 36,5 cm
Line voltage	Up to 735 kV	Line voltage	Up to 735 kV
Current	From 2.5 A to 3000 A	Current	Tested up to 500 A

- **Appendix 2: Risk Matrix and Impact Matrix**

Tables 44 and 45 present the risk and impact matrices. The risk matrix evaluates the severity of risks in six categories: safety, environment, operation, financial, compliance, and reputation, using a color-coded scale from severe (red) to minor (green). The impact matrix categorizes impact levels using a scoring system, with low scores indicating minimal harm and higher scores representing increasingly severe impacts, up to threatening the viability of inspection activities. Together, these matrices help prioritize risks based on their severity.

Table 10.44. Risk Matrix

Rating	Business Values					
	Safety	*Environment*	*Operation*	*Financial*	*Compliance*	*Reputation*
Severe	4	4	4	4	4	4
Major	3	3	3	3	3	3
Moderate	2	2	2	2	2	2
Minor	1	1	1	1	1	1

Table 10.45. Impact Matrix

Score	*Impact*
]0; 4]	Low impact
]4; 8]	Significant impact causing harm to the inspection activities
]8; 12]	Very serious impact, though not threatening the inspection activities
]12; 16]	Extremely serious impact, threatening the inspection activities

Acknowledgements – The authors acknowledge the anonymous reviewers, whose critiques and suggestions improved the quality of this manuscript. Likewise, the authors express gratitude to Hydro-Quebec Research Institute (IREQ) in Canada and Rees Hill (the developer of the FRAM Model Visualizer software), as well as the Department of Industrial Engineering, University of Quebec in Trois-Rivieres (UQTR).

Disclosure statement – The authors declare no conflicts of interest regarding the publication of this paper.

Data availability statement – Due to the commercial nature of this research, supporting data is not available.

CONCLUSION ET RECOMMANDATIONS

10.7 Synthèse et discussion générale

Cette recherche propose un cadre novateur et efficace pour la prise de décision en matière de gestion des risques, incluant ceux relativement nouveaux ou émergents qui étaient peu connus il y a encore quelques années.

Ce cadre s'appuie sur deux outils avancés d'évaluation: (1) la méthode FRAM (Functional Resonance Analysis Method), qui analyse la variabilité des performances et les interconnexions des systèmes, et (2) la méthode STPA (System-Theoretic Process Analysis), issue du paradigme STAMP (System-Theoretic Accident Model and Processes), qui identifie les dangers et évalue les contraintes de sécurité. Ces techniques se révèlent bien plus puissantes et efficaces que les approches traditionnelles pour examiner les systèmes sociotechniques complexes.

Le cadre a été appliqué à un cas pratique réel, le LineDrone, une technologie de drone autonome développée par Hydro-Québec pour inspecter les lignes de transmission haute tension sans intervention humaine directe. À travers une consultation consensuelle impliquant des chercheurs et des gestionnaires d'actifs industriels via la méthode Delphi (processus d'élicitation d'experts), cette étude a permis de structurer et d'orienter l'évaluation des risques liés au LineDrone. Les résultats démontrent la capacité du cadre à réduire la variabilité des performances, à renforcer la résilience des systèmes, et à optimiser la sécurité, confirmant ainsi son potentiel pour répondre aux défis des systèmes complexes modernes.

10.8 Limites méthodologiques

La transition vers une perspective systémique dans la gestion des risques constitue une transformation majeure et un véritable changement de paradigme. Envisager la performance comme un phénomène complexe et émergent met en évidence l'interconnexion de multiples facteurs. La gestion des risques ne se limite plus à traiter des erreurs individuelles, mais s'attache désormais à comprendre l'ensemble du système et ses dynamiques.

Les approches traditionnelles de gestion des risques se concentraient principalement sur l'investigation des accidents, en identifiant les causes immédiates, telles que les erreurs humaines ou les défaillances d'équipements, et en corrigeant ces problèmes spécifiques pour éviter des incidents similaires. Ces méthodes, souvent désignées sous le terme d'analyse des causes profondes (ou causes racines), reposent sur une relation linéaire de cause à effet, privilégiant la résolution de défaillances isolées.

À l'inverse, la perspective systémique reconnaît que les systèmes modernes sont complexes et interconnectés, intégrant de nombreux composants, interactions et boucles de rétroaction. Dans cette optique, le risque est perçu comme une propriété émergente de l'ensemble du système, plutôt qu'une caractéristique attribuée à des événements isolés. Cette approche considère que les accidents résultent de l'interaction de multiples facteurs, notamment la culture organisationnelle, les pratiques de gestion, les technologies et les comportements humains.

L'ingénierie de la résilience remet en question les approches conventionnelles qui associent la performance uniquement aux défaillances et aux erreurs. Elle met en avant la nécessité de la variabilité pour garantir un fonctionnement efficace et adaptatif dans des environnements dynamiques.

Les méthodologies systémiques telles que FRAM et STPA sont complémentaires et possèdent des forces distinctes. FRAM met l'accent sur la flexibilité fonctionnelle, permettant d'apporter des modifications au système sans en nécessiter une refonte complète. Il offre une compréhension élargie du comportement des systèmes dans diverses conditions, tout en évitant les relations fixes de cause à effet grâce à l'utilisation de descriptions verbales. De même, STPA, basé sur le modèle STAMP, considère le risque comme une problématique de contrôle, en analysant les dangers à travers les actions de contrôle dangereuses *(UCAs : Unsafe Control Actions)* et leurs interactions, même en l'absence de défaillances des composants. Ensemble, FRAM et STPA offrent une approche globale pour analyser des systèmes complexes, en combinant leurs forces pour servir d'outils d'aide à la décision.

Cependant, bien que FRAM présente de nombreux atouts, il est important de noter que cette méthodologie peut ne pas traiter de manière adéquate les défaillances technologiques. Même dans une version plus avancée, FRAM doit être considéré comme un complément aux méthodes traditionnelles d'analyse de la fiabilité plutôt qu'une solution autonome. Cela souligne la nécessité d'une approche intégrée qui combine les perspectives apportées par FRAM avec les forces de STAMP et la rigueur analytique des méthodes classiques, pour garantir une compréhension plus complète de la sécurité des systèmes.

10.9 Opportunités de recherche future

Les recherches futures devraient approfondir l'analyse des limites des méthodes FRAM et STAMP, en particulier concernant leur capacité à intégrer les défaillances technologiques et la variabilité des jugements d'experts. Il serait également pertinent de développer des outils pédagogiques et de formation pour faciliter l'apprentissage et la diffusion de ces méthodes dans les milieux industriels. Une intégration plus poussée des facteurs humains et organisationnels dans les analyses permettrait de mieux comprendre leur rôle dans la variabilité des performances et les actions de contrôle dangereuses.

En ce qui concerne le développement et l'intégration du processus RIDM au cadre, il serait opportun d'évaluer comment ce processus peut être enrichi par des outils d'intelligence artificielle et des approches prédictive basées sur les données (par exemple Maintenance 4.0, Jumeaux numériques) afin d'améliorer la prise de décision en temps réel. Comparer l'efficacité du RIDM et du cadre proposé avec les approches traditionnelles dans divers contextes de gestion des actifs contribuerait également à mieux valider son impact.

La validation du cadre devrait être renforcée par des études de cas supplémentaires appliquées à des technologies complexes. Ces expérimentations pourraient être étendues à différents secteurs, tels que l'énergie, la santé et les transports, afin de démontrer la polyvalence, l'universalité et la transférabilité des résultats. Impliquer un panel diversifié d'experts, comprenant des universitaires, des industriels et des gestionnaires d'actifs, permettrait également d'enrichir les analyses et de recueillir des retours d'expérience pertinents.

L'utilisation de la méthode Delphi pourrait faciliter l'identification de stratégies de prévention et d'atténuation des risques, notamment face aux événements extrêmes, rares et perturbateurs. Une exploration approfondie de cette thématique, intégrée à des analyses pratiques, contribuerait à une meilleure compréhension des stratégies de résilience.

Enfin, il est essentiel de résoudre les défis liés à l'accès aux données et à la connaissance des systèmes analysés, comme cela a été observé lors de l'étude de cas chez Hydro-Québec. Cela pourrait être accompli par des partenariats avec les parties prenantes de l'industrie, ainsi que par le développement d'outils adaptés à la collecte et à la structuration des données propres aux systèmes sociotechniques complexes. L'intégration d'un processus d'amélioration continue, basé sur les retours d'expérience internes et externes (audits, événements passés, etc.), renforcerait également la robustesse, la résilience et l'efficacité du cadre proposé. Ces retours pourraient en outre informer les politiques et pratiques de gestion des actifs à long terme.

Ces recommandations ouvrent la voie à un renforcement significatif des approches modernes en gestion des actifs physiques industriels (GDA-PI), en combinant robustesse théorique et applicabilité pratique. Les recherches futures contribueraient à améliorer la résilience des systèmes sociotechniques complexes, à relever les défis des environnements dynamiques et des risques émergents, et à faciliter la transition vers des stratégies innovantes et durables de gestion des actifs dans un monde en constante évolution.

ANNEXE I CHAPITRE DE LIVRE

A Framework for Assessing Emerging Technology Risks in Industrial Asset

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Abstract – The management of risks in Industry 4.0 faces significant challenges due to the limitations of traditional methods, which often fail to account for the complexities of modern sociotechnical systems. This can lead to an underestimation or misperception of risks in critical domains. To address these challenges, there is a pressing need for comprehensive Asset Management and Decision Support approaches that integrate both conventional and emerging risk management strategies. Such approaches should provide innovative tools to help practitioners navigate the complexities of these environments. This study focuses on identifying and analyzing the components of risk management, with a particular emphasis on emerging safety risks in the context of Industry 4.0. It also examines the implications of extreme, rare, and disruptive events, which can significantly impact organizational performance. To address these issues, the research employs modern system-based methods, including the Functional Resonance Analysis Method (FRAM) and the System-Theoretic Accident Model and Processes (STAMP). These methodologies are considered highly suitable for achieving the research objectives. Future work will involve validating these methods through case studies, aiming to generate actionable insights and demonstrate their applicability in real-world scenarios.

Keywords – Asset Management Strategy, Emerging Risks, Extreme-Rare-and-Disruptive-Events, Resilience, Industry 4.0 / 5.0, Risk-Informed Decision-Making Approach (RIDM), Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP).

ANNEXE II CHAPITRE DE LIVRE

Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks.

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Diop, I., Abdul-Nour, G., & Komljenovic, D. (2024). Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks. In 17th WCEAM Proceedings. Cham: The Springer eBook series is indexed by Scopus and Ei. Series: Lecture Notes in Mechanical Engineering. Ho Chi Minh City, Vietnam, 18-20 October 2023.

Abstract – The growing complexity and uncertainty of modern systems in the digital era pose significant challenges to traditional methods of assessing and managing safety risks. These methods often fall short in addressing the multifaceted nature of sociotechnical system safety, particularly in the face of emerging risks. Consequently, there is a pressing need for innovative tools and comprehensive decision-support methodologies to tackle the unique challenges of Industry 4.0. These challenges include natural disasters, organizational risks, and cognitive biases. This paper proposes an Integrated Decision-Making Framework for Industrial Asset Management to assess and manage emerging technological risks and extreme, rare, and disruptive events. The framework incorporates both traditional and modern safety management approaches, leveraging the Functional Resonance Analysis Method (FRAM) and the System-Theoretic Accident Model and Processes (STAMP). These methods are highly effective in addressing the complexities and uncertainties of contemporary sociotechnical systems. To demonstrate the practical application of this framework, future research will focus on a case study involving LineDrone – a robotic platform developed by Hydro-Québec for inspecting and maintaining energized transmission lines. This case study will validate the framework's utility in managing risks within a complex socio-technological context.

Keywords – Functional Resonance Analysis Method (FRAM). System-Theoretic Accident Model and Processes (STAMP). System-Theoretic Process Analysis (STPA), Emerging Risks, Extreme-Rare-and-Disruptive-Events, Industry 4.0.

ANNEXE III ARTICLE DE COMPTE-RENDU DE CONFÉRENCE

Assessing and Managing Risks Linked to Emerging Technologies

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Abstract – This paper explores industrial asset management by proposing an integrated decision-making framework to evaluate performance amidst emerging technological risks. The framework combines the Functional Resonance Analysis Method (FRAM) for analyzing system functions and the System-Theoretic Process Analysis (STPA) for hazard assessment, providing robust decision support for managing industrial assets effectively. To validate the framework, a case study will utilize the LineDrone, an advanced Unmanned Aerial Vehicle (UAV) developed by Hydro-Québec and manufactured by DroneVolt. Designed for the inspection of high-voltage transmission lines without direct human interaction, the LineDrone exemplifies a complex sociotechnical system. This case study will demonstrate the framework's practical value in assessing and managing performance variability in such contexts.

Keywords – Emerging Risks, Industry 4.0, Functional Resonance Analysis Method (FRAM), System-Theoretic Process Analysis (STPA).

ANNEXE IV ARTICLE DE COMPTE-RENDU DE CONFÉRENCE

Assessment of Performance Variability in Complex Sociotechnical Systems. A Case Study Using FRAM and STPA

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Abstract – Complexity is the primary source of nonlinearity and uncertainty in modern sociotechnical systems. These challenges arise from the interactions of new technologies introduced by Industry 4.0, uncertainties associated with future natural disasters and exceptional events, as well as contemporary organizational threats and cognitive biases. This paper develops an Integrated Decision-Making Framework to assess performance variability resulting from emerging technological risks and extreme, rare, and disruptive events. The framework employs a combination of the Functional Resonance Analysis Method (FRAM) and the System-Theoretic Process Analysis (STPA), a top-down hazard assessment method derived from the System-Theoretic Accident Model and Processes (STAMP). These tools offer a more comprehensive approach compared to traditional practices, effectively addressing complexity and nonlinearity in sociotechnical systems. To validate the framework, a case study examines its application in assessing and managing performance variability in a complex and uncertain sociotechnical system. The subject of the study is the LineDrone, a Hydro-Québec Unmanned Aerial Vehicle (UAV) designed for non-contact inspection and maintenance of high-voltage transmission lines.

Keywords – Asset Management Strategy, Emerging Risks, Extreme-Rare-and-Disruptive-Events, Industry 4.0, Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP), System-Theoretic Process Analysis (STPA).

ANNEXE V ARTICLE DE COMPTE-RENDU DE CONFÉRENCE

STPA, an Innovative Top-Down Hazard Assessment Method based on STAMP. A Bibliometric Review

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Diop, I., Abdul-Nour, G., & Komljenovic, D. (2024). System-Theoretic Process Analysis (STPA): An Innovative Top-Down Hazard Assessment Method Based on the System-Theoretic Accident Model and Processes (STAMP) – A bibliometric Review. Proceedings of the American Society of Mechanical Engineers (ASME 2024): Asset Integrity Management – Critical Infrastructure Conference (AIM-CI). Delta Marriott Orlando Celebration on February 5-6, 2024, Orlando, FL, USA. AIM-CI2024-110532.

Abstract – This paper presents a systematic review of publications on the development and application of the System-Theoretic Accident Model and Processes (STAMP) and System-Theoretic Process Analysis (STPA) over the past decade. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, a widely recognized standard for systematic literature reviews. A total of nineteen papers were systematically retrieved from the Scopus database for analysis. The findings highlight the need to integrate STAMP/STPA with other systemic safety assessment approaches to develop a comprehensive Integrated Decision-Making Framework for Industrial Asset Management. Such a framework would enhance the assessment and management of emerging technological risks, as well as address extreme, rare, and disruptive events. Future research will focus on validating the framework's efficiency and practicality through case studies to generate more accurate data and insights.

Keywords – System-Theoretic Process Analysis (STPA), System-Theoretic Accident Model and Processes (STAMP), Systemic Safety Assessment Approaches, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

ANNEXE VI ARTICLE DE COMPTE-RENDU DE CONFÉRENCE

Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks

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Abstract – The growing complexity and uncertainty of modern systems in the digital era have exposed significant limitations in traditional methods for assessing and managing safety risks. These methods often fail to address all factors influencing sociotechnical system safety, particularly in the context of emerging risks. As a result, new tools and comprehensive decision-support methodologies are needed to address the challenges of Industry 4.0, including the inherent complexity of emerging technologies, the uncertainty of natural disasters, organizational risks, and biases in human logic. This paper proposes an Integrated Decision-Making Framework for Industrial Asset Management to assess and manage emerging technological risks, as well as extreme, rare, and disruptive events. The framework integrates two advanced approaches: the Functional Resonance Analysis Method (FRAM) and the System-Theoretic Accident Model and Processes (STAMP), which are more effective than traditional methods in addressing the complexity and uncertainty of modern sociotechnical systems. To validate the framework, future research will focus on a case study involving LineDrone, a robotic platform developed by Hydro-Québec for inspecting and maintaining energized transmission lines. This study aims to demonstrate the framework's practical value in managing industrial asset risks in complex sociotechnical contexts.

Keywords – Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP), System-Theoretic Process Analysis (STPA), Emerging Risks, Extreme-Rare-and-Disruptive-Events, Industry 4.0.

ANNEXE VII ARTICLE DE COMPTE-RENDU DE CONFÉRENCE

Asset and Risk Management Approach in the Context of Complexity in Industry 4.0/5.0 Systems

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Abstract – The management of risks in Industry 4.0 and Industry 5.0, faces significant challenges due to the lack of accurate and efficient systematic approaches and tools. This gap often leads to an unrealistic understanding of risks in critical domains. Traditional methods, while valuable, have inherent limitations and may fail to capture all factors influencing system safety. The integration of conventional industry challenges with emerging risks, systemic and organizational threats, and cognitive biases necessitates the development of comprehensive Asset Management (AM) and Decision Support approaches. This paper aims to address these challenges by identifying and analyzing risk management components, particularly for emerging safety risks within Industry 4.0. It also considers the increasing impact of extreme, rare, and disruptive events that can severely affect organizational performance. The research employs innovative, system-based methodologies, including the Functional Resonance Analysis Method (FRAM), the System-Theoretic Accident Model and Processes (STAMP), and the Risk-Informed Decision-Making (RIDM) approach. These methods provide a holistic perspective to help AM practitioners navigate the complexities of sociotechnical systems effectively. Future research will validate the efficiency and practicality of these methods through case studies to gather precise data and actionable insights.

Keywords – Emerging Risks, Extreme-Rare-and-Disruptive-Events, Resilience, Industry 4.0 / 5.0, Risk-Informed Decision-Making Approach (RIDM), Functional Resonance Analysis Method (FRAM), System-Theoretic Accident Model and Processes (STAMP).

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