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Overview of Strategic Approach to Asset Management and Decision-Making

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***Abstract*—This article focuses on identifying and analyzing elements of strategic asset management (SAM). It reviews physical asset management (AM) models defined as the coordinated activity of an organization to realize value from assets, along with SAM which focuses on aligning AM strategies with various levels of organizational strategy (corporate, business, and functional-level strategy). The analysis of recent scientific papers devoted to AM with a special emphasis on SAM aspects and decision-making models as well as risk management help provide a starting point for new research directions specifically the influence of risk-informed decision-making (RIDM) process and emerging industry 4.0 technologies, as well as resilience engineering on SAM. For instance, applying Maintenance 4.0 using technological solutions such as industrial internet of things (IIOT), cloud computing, cyber-physical systems (CPS), and big data analytics could decrease the challenges encountered by top management such as managerial, technological, and methodological challenges. The outcomes will contribute to position and validate the link between SAM and RIDM, as well as Maintenance 4.0 and resilience engineering inside the vast discipline of AM and the alignment with various levels of organizational strategy.**

Keywords—Asset management strategy; risk management; resilience engineering; maintenance 4.0; industry 4.0; decision-making.

I. INTRODUCTION

ISO 55000 standard defines Asset Management (AM) as "*the coordinated activity of an organization to realize value from assets*" [1]. AM strategies should align with various levels of organizational strategy (corporate, business, and functional-level strategy). Managing assets has become more complex and demanding due to harsh international competition, unpredictability, volatility, as well as insecurity. These businesses face significant uncertainties and dreaded risks of all kinds. These include the strategic, operational, organizational, and financial, as well as technological and technical concerns that seriously influence all the company's business processes. Hence, organizations have serious demands to reduce harmful and unexpected equipment failures inducing high degree expectations from maintenance [2]. They are increasingly thriving to foresee all potential futures in the challenging and dynamic market characterized by escalating resource shortage, environment impairment liability, climate change, etc. [3]. For instance, Komljenovic [4] point out that power utilities *"should manage the replacement of huge parts of their assets as they reach the end of their lifecycle, become obsolete due to technological changes or because of transition to more efficient and carbon-free power alternatives"*.

AM is not a novelty; in practice, asset-intensive businesses such as aviation and electrical power compagnies have been managing assets since the dawn of time [5]. Both AM decision makers and stakeholders in various industries are frequently obliged to make more at lower price. Asset management system (AMS) must establish clear and effective connectivity of the strategic asset management plan (SAMP) and the activities of the various departments and stakeholders of the organization (human resources, operations, maintenance, engineering, etc.) [6]. AM supports business leaders in understanding the value of assets and their role in achieving organizational goals [1].

This review contributes to the current literature on physical asset management and decision-making by attempting through a holistic approach to bring together information about strategic approach to AM and decision-making models with special emphasis on risk management. A focus is given on risk management approach to improving implementation and governance of AM with respect to risk identification and characterization, as well as risk treatment of extreme and rare events which are research components of major interest in the scientific community.

The remainder of this paper is structured as follows: PART 2 presents the methodology of the review to identify papers relevant for this topic. PART 3 conveys a comprehensive review on the theoretical background of the range of decision-making models and techniques used in AM with respect to their usefulness and contribution to the harmonisation and coordination, as well as alignment with various levels of organizational strategy. PART 4 provides a broad overview of emerging aspects of SAM and maintenance 4.0. Finally, PART 5 concludes the review and highlights gaps and provides new research directions in the existing literature as a starting point for future targets for this research.

II. METHODOLOGY FOR THE SYSTEMATIC LITERATURE REVIEW

To have a mapping of the state of the art relevant to this topic, a systematic and critical literature search has been conducted to quantify the scientific production and measure its quality and impact. The search methodology used entailed the following steps: (i) identifying appropriate and relevant keywords employed in the search of databases, (ii) searching the online database Scopus, then (iii) gathering relevant articles, (iv) identifying whether the paper is relevant or not, (v) performing snowball approach to identify more relevant papers, (vi) performing inverse search with the help of the Web of Science (WoS) core collection and Google scholars. The subsequent paragraphs described each step.

A. Keywords definition, online database search and paper selection

First and foremost, keywords relevant to the subject matter were defined as follows:

(a) "strategic asset management" or "strategic approach to asset management" or "asset management strategy" or "asset management model" or "physical assets management model" or "physical assets management framework",
(b) "risk-informed decision-making" or "risk-informed asset management",
(c) "industry 4.0" and maintenance or "intelligent maintenance" or "predictive maintenance" or "condition-based maintenance",
(d) "resilience engineering" or "system resilience" or "resilience modeling"
To retrieve further relevant papers, keywords were generated by combining keywords from (a), (b), (c) and (d). Then the combined keywords were used to investigate the databases. The online database Scopus was used to systematically retrieve recent scientific analysis of studies that included either (a), (b), (c), or (d) in the article title and published between 2010 and 2021.

Moreover, further analysis was needed to identify whether the paper is relevant or not. Therefore, each article thus found was subjected to a further investigation of their title, abstract, keywords and, if it appeared to be pertinent, the article was selected to be entirely read and analyze.

Furthermore, snowball approach was conducted by verifying the bibliographies of the previously selected articles to mine more data for this review to be analyzed. Finally, an inverse search was performed with the help of the online databases WoS and Google scholars to gather scholarly relevant research papers which cited the selected articles.

The initial search retrieves 96 bibliographic references for the string (a), 103 for (b), 122 for (c), 650 for (d). In the subsequent section, we performes the bibliometrix analysis of the research field, its structure and evolution as well as its dynamical aspects. This analysis gives a mapping of the field growth, the leading productive authors, papers, countries and most relevant keywords.

B. Results

1) Descriptive Analysis and conceptual structure for (a) keywords

The following figures provide a visualization of the scientific landscape of the subject-matter using the (a) keywords in the search of databases: *"Strategic asset management" or "strategic approach to asset management" or "asset management strategy" or "asset management model" or "physical assets management model" or "physical assets management framework".*

Information in Table 1 beolow shows that most of the publications was issued as conference paper (51.50%), journal article (39.00%) and book chapter (3.90%).

Table 1 Document Type for string (a)

Rank	Document Type	# Documents ~ %
1	Article	49~51.00%
2	Conference Paper	41~42.70%
3	Book	2~2.10%
4	Review	2~2.10%
5	Review	8~2.0%
6	Book Chapter	1~1.00%
8	Note	1~1.00%

Figure 1 depicts the the annual total references published between 2010 and 2021 and the annual growth of publications.The number of references decreased in significantly in 2012 then fluctuated from 2013 to 2019 before a high peak was observed in 2020 followed by a decline in 2021. These metrics imply that the annual amount of references published during the survey period was meaningfully erratic. This signals that this research area was unstable in the matter of amount of publications [7, 8].

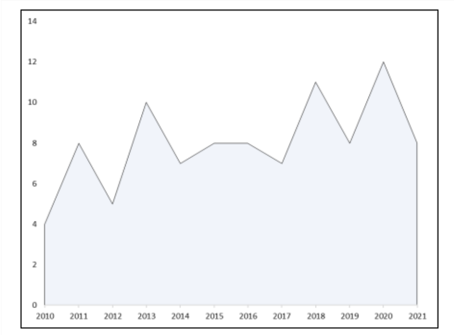

Table 2 Co-word Analysis through Keyword co-occurrences for string (a)

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

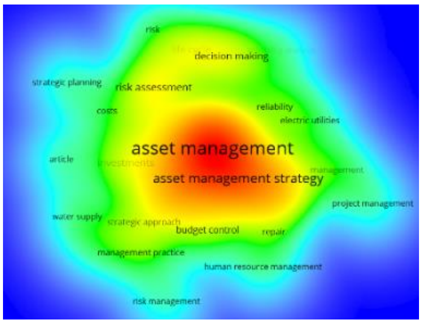

Figure 1 the number of annual references for string (a)

Information in the chart (Table 2) depicts the most frequent and relevant keyword co-occurrences on the intellectual domain and as well provide hotspots in the field of asset management. The value of author’s keyword co-occurrences, and their usefulness within a particular area of research were shown in prior investigations [8-10].

The co-word analysis through keyword co-occurrences point out clusters of keywords. For more details on co-word analysis, the reader is referred to the paper by Cobo [11] and their bibliographic references. Five clusters was found, clustered into four areas of research as shown in Table 3.

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Table 3 Top Keyword clustered into 4 areas of research for string (a)

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

Table 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 [13]	42
2	Vlok, P.J.	3	Roshani [14]	28
3	Brito , R.S.	2	Caradot [15]	22
4	Brown, K .	2	Joseph [23]	21
5	Dray, A.	2	Morrison [26]	13
6	Hamilto n, M.	2	Ten Veldhuis [27]	13
7	Keast, R.	2	Alegre [16]	13
8	Laue, M .	2	Vreeburg [28]	9
9	Mahmood, M.N .	2	Haynes [30]	8
10	Rødseth, H.	2	Clements [33]	7

Table 4 depicts the most productive-authors as well as the most cited-author references. Afuye [8] remark that the number of papers published in a research area is typically deemed an valuable system of measurement to quantify the impact of an author in a specific area of research. In the same vein, Wang [12] mentioned that the volume of papers published by an author reveals his influence as well as the usefulness of his research. Alegre H. and Vlok, P.J. ranked first in term of amount of publications with 3 papers. In term of amount of citations, Velasquez-Contreras [13] ranked first with 42 citations followed by Roshani [14] ranking second (28 citations) and Caradot [15] (22 citations).

The citation analysis depicts the structure of the field through the linkages between nodes Co-citation network illustrates interactions among cited-reference works, cited-journals. Aria [34] indicates that *"the useful dimensions to comment the co-citation networks are: (i) centrality and peripherality of nodes, (ii) their proximity and distance, (iii) strength of ties, (iv) clusters, (iiv) bridging contributions"*. Information in Table 5 illustrates the top 10 countries list from the perspective of amount of papers published and amount of citations per country. Within the survey period, the United states ranked first with the largest document number followed by the United kingdom, then Australia. The country collaboration networks depicts how a country interact to others in a particular area of study.

Information Table 6 shows the performance in international collaboration between countries clustered into 5 research groups. The density visualization map shows regular research groups in this area of research and their relations [11].

2) Descriptive Analysis and conceptual structure for (b) keywords

The following figures provide a visualization of the scientific landscape of the subject-matter using the (b) keywords in the search of databases: *"Risk-informed decision-making" or "risk-informed asset management".*

Information in Table 7 shows that most of the manuscripts was published as conference paper (69.90%) and journal article (26.20%). Figure 2 depicts the the annual total references

Table 5 Top 10 Most Productive Country for string (a)

Rank	Country	Documents	Citations
1	United states	23	22
2	United 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 6 Country collaborations clustered into 5 research groups for string (a)

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

published between 2010 and 2021 and the annual growth of publications. The number of references decreased drastically arount 2013 and 2014 before a high peak was observed in 2019. These metrics infer that the annual amount of references published during the survey period was significantly unstable. This indicates that this research area was unsteady in the matter of amount of publications [7, 8].

Table 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%

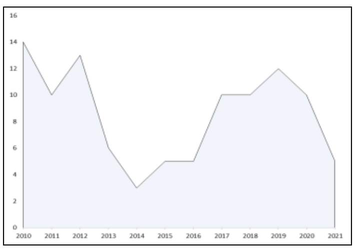

Figure 2 the number of annual references for string (b)

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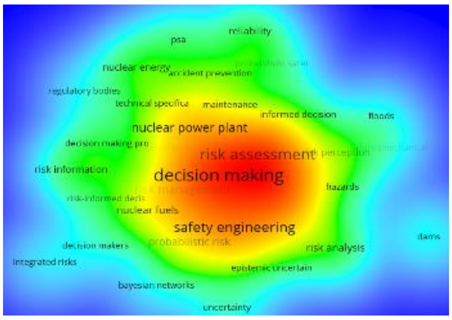
Table 8 Co-word Analysis through Keyword co-occurrences for string (b)

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



Information in Table 8 illustrates the most frequent and relevant keyword co-occurrences on the intellectual domain and as well provide hotspots in this subject-matter. The reader is referred to Zhang [9], Chen [10] and Afuye [8] and their cited references for more details on the value of author's keyword co-occurrences, and their usefulness within a particular area of research.

The co-word analysis through keyword co-occurrences point out clusters of keywords. Five clusters was found, clustered into five areas of research as shown in Table 9.

Table 9 Top Keyword clustered into 5 areas of research for string (b)

Cluseter 1 (9 items)	Cluseter 2 (9 items)	Cluseter 3 (6 items)
Dams	Accident prevention	Bayesian network
Failure (mechanical)	Decision making	Maintenance
Hazards	Decision making process	Nuclear industry
Risk analysis	Nuclear energy	Risk-informed decision making
Risk assessment	Nuclear power plants	Technical specifications
Risk perception	Probabilistic safety assessment	Uncertainty
Risk-informed decision making	PSA	
Safety engineering	Regulatory bodies	
Uncertainty analysis	Risk management	

Cluseter 4 (5 items)	Cluseter 5 (3 items)
Decision makers	Epistemic uncertainties
Integrated risks	Informed decision
Nuclear fuels	Reliability
Probabilistic risk assessment	
Risk information	

Table 10 Top 10 Authors for string (b)

	Most Productive-Authors		Most Cited-Author References	
Rank	Author	Documents	Author	Citations
1	Narumiya y.	7	Dubois [35]	45
2	Parry g.	6	Vaurio [36]	41
3	Ferrante f.	5	Volkanovski [37]	27
4	Cho n.	4	Ham [54]	20
5	Dube d.	4	Talarico [55]	16
6	Jang d.	4	Aven [56]	13
7	Lewis s .	4	Fumagalli [58]	11
8	Yamaguchi a.	4	Morales-Torres [62]	8
9	Bujor a .	3	Alipour [66]	8
10	Carlos, S.	3	Gjorgiev [69]	8

Table 11 Top 10 Most Productive Country for string (b)

Rank	Country	Documents	Citations
1	United states	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

Table 10 shows the most productive-authors as well as the most cited-author references. Narumiya y. ranked first in term of amount of publications with 7 papers, followed by Parry g. ranking second with 6 papers. However, Dubois [35] ranked first in term of amount of citations with 45 citations, followed by Vaurio [36] with 41 citations and Volkanovski [37] with 27 citations.

Information in the Table 11 illustrates the most productive countries from the perspective of amount of papers published and amount of citations per country. Within the survey period, the United states ranked first with the largest document number and citations, followed by Canada, then Japan.

3) Descriptive Analysis and conceptual structure for (c) keywords

The following figures provide a visualization of the scientific landscape of the subject-matter using the (c) keywords in the search of databases: *"Industry 4.0" and maintenance or "intelligent maintenance" or "predictive maintenance" or "condition-based maintenance".*

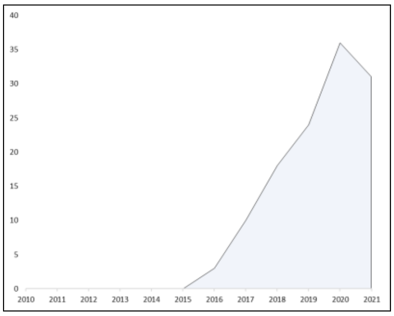
Information in Table 12 shows that most of the documents was published as conference paper (55.20%), journal article (35.10%) and book chapter (3.7%).

Table 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 3 illustrates the the annual total references published between 2010 and 2021 and the annual growth of publications. The number of references increased considerably. These metrics infer that the annual amount of references published during the survey period was significantly high and stable. This implies that this research area was steady in the matter of amount of publications [7, 8].

Figure 3 the number of annual references for string (c)



Information in Table 13 illustrates the most frequent and relevant keyword co-occurrences on the intellectual domain and as well provide hotspots in this subject-matter.

Four clusters was found, clustered into four areas of research as shown in Table 14.

Table 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

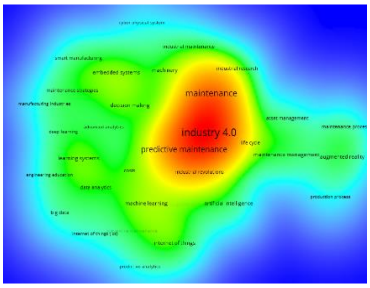


Table 14 Top keyword clustered into 4 areas of research for string (c)

Cluseter 1 (11 items)	Cluseter 2 (8 items)	Cluseter 3 (7 items)	Cluseter 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 15 shows the most productive-authors as well as the most cited-author references. El-Thalji, I. and Mentzas, G. ranked first in term of amount of publications with 4 articles. However, Yan [70] ranked first in term of amount of citations with 155 citations, followed by Masoni [71] with 101 citations and Sahal [72] with 84 citations.

Table 15 Top 10 Authors for string (c)

Most Productive-Authors			Most Cited-Author References	
Rank	Author	Documents	Author	Citations
1	El-Thalji, I.	4	Yan [70]	155
2	Mentzas, G.	4	Masoni [71]	101
3	Bousdekis, A.	3	Sahal [72]	84
4	Fiorentino, M.	3	Li [84]	79
5	Frontoni, E.	3	Ceruti [88]	76
6	Gattullo, M.	3	Franciosi [89]	46
7	Nordal, H.	3	Scurati [83]	42
8	Paolanti, M.	3	Sipsas [90]	40
9	Uva, A.E.	3	Zonta [91]	39
10	Apostolou, D.	2	Alqahtani [92]	39

Information in the Table 16 shows the most productive countries from the perspective of amount of papers published and amount of citations per country. Within the survey period, Italy ranked first with the largest document number and citations, followed by Germany, then Greece.

Table 16 Top 10 Most Productive Country for string (c)

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 Kingdom	8	115
7	Spain	7	68
8	France	6	91
9	India	6	20
10	United States	6	113

Information in Table 17 shows the performance in international collaboration between countries clustered into 4 research groups.

Table 17 Country collaborations clustered into 4 research groups for string (c)

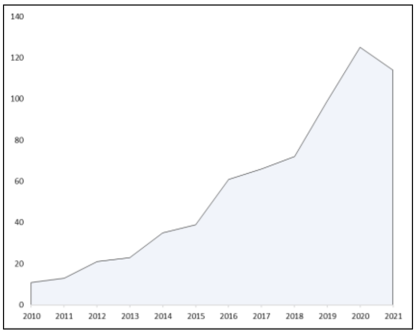
Cluseter 1 (3 countries)	Cluseter 2 (3 countries)	Cluseter 3 (3 countries)	Cluseter 4 (2 countries)
Germany	India	France	Brazil
Greece	Norway	Spain	United states
Poland	United kingdom	Italy	

4) Descriptive analysis and conceptual structure for (d) keywords

Table 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 4 the number of annual references for string (d)



The following figures provide a visualization of the scientific landscape of the subject-matter using the (d) keywords in the search of databases: *"resilience engineering" or "system resilience" or "resilience modeling"*.

Information in Table 18 shows that most of the manuscripts was published as journal article (50.00%), conference paper (33.30%) and book chapter (6.70%).

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Table 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

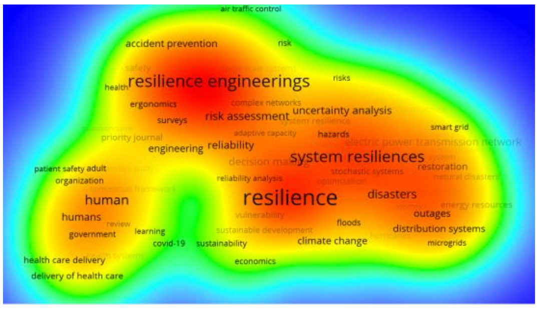

Figure 4 describes the the annual total references published between 2010 and 2021 and the annual growth of publications. The number of references increased considerably. These metrics infer that the annual amount of references published during the survey period was significantly high and stable. A high peak was observed in 2021 with a total of 114 references published. This indicates that this research area was steady in the matter of amount of publications.

Information in Table 19 illustrates the most frequent and relevant keyword co-occurrences on the intellectual domain and as well provide hotspots in this subject-matter. Five clusters was found, clustered into five areas of research as shown in Table 20.

Table 21 shows the most productive-authors as well as the most cited-author references. Azadeh [93] ranked first in term of amount of publications with 22 articles published followed by Hollnagel [94] with 12 articles published . In term of amount of citations, Hollnagel [94] ranked first with 1395 citations, followed by Hosseini [95] with 682 citations.

Information in the Table 22 shows the most productive countries from the perspective of amount of papers published and amount of citations per country. Within the survey period, the United States ranked first with the largest document number (212) and the largest references cited (5825) , followed by the United Kingdom with 65 references cited 1691 times.

Information in Table 23 shows the performance in international collaboration between countries clustered into 6 research groups.

Table 20 Top keyword clustered into 5 areas of research for string (d)

Clusteter 1 (25 items)	Clusteter 2 (23 items)	Clusteter 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	Adaptive 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		

Clusteter 4 (11 items)	Clusteter 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 1 Top 10 Authors for string (d)

Most Productive-Authors			Most Cited-Author References	
Rank	Author	Documents	Author	Citations
1	Azadeh [93]	22	Hollnagel [94]	1395
2	Hollnagel [94]	12	Hosseini [95]	682
3	Azadeh [93]	12	Henry [96]	456
4	Righi [97]	11	Woods [98]	310
5	Bie [99]	7	Panteli [100]	309
6	Panteli [100]	7	Ayyub [101]	289
7	Ranasinghe [102]	7	Hollnagel [103]	289
8	Woods [98]	7	Li [104]	251
9	Patriarca [105]	6	Bie [99]	231
10	Azadeh [106]	5	Farzin [107]	224

Table 22 Top 10 Most Productive Country for string (d)

Rank	Country	Documents	Citations
1	United States	212	5825
2	United Kingdom	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

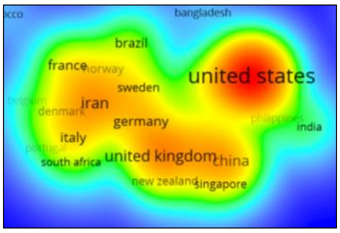

Table 23 Country collaborations clustered into 6 research groups for string (d)

Cluseter 1 (8 countries)	Cluseter 2 (8 countries)	Cluseter 3 (5 countries)	Cluseter 4 (3 countries)	Cluseter 5 (3 countries)	Cluseter 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				

It was then necessary to select according to the relevance of the content of the paper in relation to the research. Precisely, papers were integrated in the analysis if they were written in English, they were a journal or conference papers or written by a subject matter expert and their summary specified that the document focuses broadly on strategic approach to asset management and/or decision making. Further analysis was done to identify whether the paper is appropriate or not. Each article content was read to identify whether its subject matter is relevant to our review or not. The selected documents were then exported to the reference management software Endnote. However, all articles were not discussed in depth to keep the length of this paper within acceptable boundaries. Only those articles that are most appropriate and relevant to the review were discussed in detail.

III. Asset Management Models

The new normal of the environment of industrial systems characterized by complexity as well as the wide range of industrial automation applications compel organizations to optimize their strategic management economic models for physical assets management. AM decision makers and practitioners have developed numerous tactics and processes to support their competitiveness at the worldwide market. For instance, Baglee [2] points out that a "*system-wide communication approach*" is essential to accurately manage the complexity from data gathering, analysis, visualisation and sharing to sustain the development of useful maintenance strategy. These days, executives rely on the explosion of industry 4.0 tools such as IIoT, AI, CPS and Cloud Computing to manage data and make optimal decisions.

AM plays a determining role allowing assets a long-term survival to cope with factors such as the escalating competition, and markets deregulation, as well as technological innovation and risks from other events such as terrorist attacks, natural disasters, major geomagnetic disturbances and cyberattacks [108, 109]. Likewise, a rapid move has been noticed on the range of this research area from managing unfussy repair operations to optimising multiple units which are more complex systems leading to the rise of the concept of *"multi-unit system"* [110]. The reader is referred is referred to Petchrompo [110] and their bibliographic references for more details on the insights into the recent trends in multi-asset maintenance. The purpose of this review section is to provide the reader with an overview of key relevant AM models. The leading models of AM lying in the field of interest are summarized in Table 24.

A. The ISO range of standards

The ISO range of standards (55000, 55001 & 55002) builds the basic concepts of a holistic approach to AM with all its implications and purpose. The family of standards in question and the manual for international infrastructure management succeed the PAS 55 guide. Thusly, even if the PAS 55 has become obsolete as a formal specification of the British Standard Institute (BSI) since 2015, organizations may note the existence of a value of this guide as educational material. ISO 55000 standard provides an overview, principles and terminology of AM and Asset Management System and the context for the ISO 5500x series[1]. ISO 55001 specifies requirements for an Asset Management System (AMS) within the context of the organization. It identifies the requirements for the establishment, implementation, maintenance and improvement of AMS [114]. Guidelines relating to the requirements for the application of ISO 55001 are formulated in the ISO 55002 standard [115, 116].

B. The GFMAM: Asset Management Landscape Subjects

The GFMAM: Asset Management Landscape Subjects: In 2011 a gathering of various experts, academics, and other professionals in the field of AM and Maintenance founded the Global Forum on Maintenance and Asset Management (GFMAM). This landscape contrasts from ISO's themes. The latter do not cover the entire scope of AM knowledge as GFMAM does [117]. The GFMAM published a document bringing together 39 subjects of AM in 6 groupings (themes) describing a section of the body of knowledge which are detailed in the following paragraphs [118]:

1) Strategy and planning theme

Strategy and planning theme seeks to align AM activities with the organization's mission and organizational goals. It deals with: (i) the development of a policy framing the practice of AM within the organization, (ii) the translation of the expectations of the various stakeholders into AM objectives and strategies, (iii) as well as the planning to coordinate activities throughout the asset lifecycle. The "Strategy and Planning" theme is made up of five subjects (see Table 25):

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Table 24 summary of relevant models developed in physical asset management
(Source: Own representation)

Acronym	Designation	Main goal	Source
PAS 55	Publicly Available Specification for the optimal management of physical assets	explicitly focussed on the optimal management of physical assets	British Standard Institute (BSI) (2002, 2004, 2008)
ISO 55000	Asset management - Overview, principles and terminology	specifies basic concepts of a holistic approach to AM	International Organization for Standardization, ISO (2014)
ISO 55001	Asset management - Management systems - Requirements	is a standard for ANY asset type; it defines the requirements for an asset management system within the context of the organization	International Organization for Standardization, ISO (2014)
ISO 55002	Asset management - Management systems - Guidelines for the application of ISO 55001	provides interpretation and implementation guidance for such a management system.	International Organization for Standardization, ISO (2018)
ISO 55010	Guidance on the alignment of financial and non-financial functions in asset management	enables better understanding why and how alignment between financial and non-financial functions is crucial in realizing value from assets.	International Organization for Standardization, ISO (2019)
The GFMAM Asset Management Landscape	The Global Forum on Maintenance & Asset Management, GFMAM Landscape of subjects	promote a common global approach to Asset Management and Maintenance professions by collaborating on knowledge, standards and practices. 39 AM Subjects and Principles and a framework for describing best practices, maturity and standards	The Global Forum on Maintenance & Asset Management, GFMAM (2011)
The IAM Conceptual AM model	The IAM Asset Management - An Anatomy	is a framework for assessing maturity in AM. This framework is aligned with the principles of ISO 55000 series of standards. It is made up of 39 topics that detail the AM activities within an organization.	The Institute of Asset Management (IAM) (2015)
CIGRE conceptual decision-making process for AM	International Council on Large Electric Systems (Conseil international des grands réseaux électriques, CIGRÉ) decision making decision making processus	is "the Asset Management of Transmission and Distribution business operating in an electricity market involves the central key decision making for the network business to maximize long term profits, whilst delivering high service levels to customers, with acceptable and manageable risks" **[111, 112]**.	International Council on Large Electric Systems (Conseil international des grands réseaux électriques, CIGRÉ) (1921)
AMBoK	Asset Management Body of Knowledge (AMBoK)	provides a collection of models (strategic, operational, tactical, maturity) and definitions forming a comprehensive framework of AM practices	Australian Asset Management Council (AM-Council) (2014)
EFNMS-Bok	European Federation of National Maintenance Societies (EFNMS) Conceptual Model	is a conceptual model of AM based on continuous improvement approach PDCA (Plan Do Check Act); it provide the body of knowledge (Bok) describing the maintenance landscape and the knowledge required	The European Asset Management Committee, EAMC (2018)
RIDM	The Risk-Informed Decision-Making (RIDM) process	"These are structured processes which assist decision-makers when faced with high impact, complex decisions involving multiple objectives and the presence of uncertainty. They aim to ensure that decisions between competing alternatives are taken with an awareness of the risks associated with each option, and that all attributes of a decision are considered in an integrated manner" **[113]**.	The National Aeronautics and Space Administration , NASA and the US Nuclear Regulatory Commission (2008, (2010)

Table 25 Strategy and planning

Strategy and planning				
Asset Management Policy	Asset Management Strategy and Objectives	Demand Analysis	Strategic Planning	Asset Management Planning

Asset Management Policy subject analyzes the principles and requirements that flow from the Strategic Asset Management Plan (SAMP) and that guide the organization's AM activities. This topic analyzes the organization's AM policy, which ensures management commitment and provides a framework for the development and implementation of AM objectives and strategies. Politics is a key component of the AM approach. It serves as a catalyst for a change in culture and in the way of doing things and as a starting point to lead the development of the AM strategy. If the policy is not communicated or understood throughout the organization, it is difficult to align asset management activities with organizational objectives and to achieve the expected results of the process.

Asset Management Strategy and Objectives subject deals with the SAMP which directs the organization's AM activities and describes the long-term planning approach that will be taken. It analyzes current and future AM capabilities and supports the alignment between organizational goals and AM objectives and describes the processes and strategies to be adopted to achieve them.

Demand Analysis subject analyzes the procedures used to assess the demand for assets and the organization level of service. This subject looks at the historical and future demand for the service as well as its evolution over time. It analyzes demand requirements and their impact on the asset portfolio and its capacity.

Strategic Planning subject discusses the procedures used by the organization to implement the SAMP. It assesses the development of a strategic planning framework and process that describes how demand analysis and required service

Table 26 Asset management decision-making

Asset management decision-making				
Capital Investment Decision Making	Operation and Maintenance Decision Making	Lifecycle Value Realisation	Resourcing Strategy	Shutdowns and Outage Strategy

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levels are factored into and modeled in business development.

Asset Management Planning subject assesses activities aimed at developing Asset Management Plans (AMPs) that describe the condition of assets and specify the tasks, timelines, responsibilities, and resources required to achieve AM objectives. It also examines the financial strategy and the lifecycle management strategy as well as the risks associated with the planning and implementation of activities.

2) Asset management decision-making theme

Asset management decision-making theme helps identify processes for informed decision making that maximize value in different phases of the asset lifecycle. It examines the processes that assess the impact and criticality of the various choices of acquisition, operation, maintenance, and disposal of assets in terms of performance, risks, and associated costs. This theme involves five subjects as shown in Table 26.

Capital Investment Decision Making subject deals with the procedures and decisions to assess and analyze the organization's capital investment scenarios. These procedures and decisions may relate to new assets acquisition or replacements of end-of-life assets.

Operation and Maintenance Decision Making subject covers the management activities and procedures that go into determining the requirements for operation and maintenance decision-making to support AM objectives. This subject assesses the various maintenance strategies (predictive, preventive, corrective, etc.) and their correlation with the level of criticality of the assets and analyzes the alignment of these strategies with the optimal delivery of the service. It would be relevant to align O&M decision making with the objectives of AM. Maintenance strategies should be reviewed considering their impact on service delivery.

Lifecycle Value Realisation subject focuses on the activities performed by an organization to assess the various intervention options required to upgrade assets during their lifecycle (maintenance, replacement, decommissioning, etc.). This subject analyzes assessment models that are based on a comparison of the cost and benefit ratio of options and a comparison of the total lifecycle value.

Resourcing Strategy subject examines the processes and activities that an organization must implement to optimize the use of human resources, facilities, tools, and materials to achieve AM goals. It analyzes the strategy for acquiring resources and their integration across the organization to implement Asset Management Plans (AMP).

Shutdowns and Outage Strategy subject assesses activities carried out by the organization to develop a strategy to manage breakdowns and various types of asset shutdowns (for e.g.: periodic maintenance shutdowns). It involves procedures and requirements needed to ensure a robust agreement between all concerned players. This allows to reduce the impact on the service level of the organization (reduce wasted time, downtime, etc.).

3) Lifecycle Delivery theme

Lifecycle Delivery theme characterizes how the organization carries out the selected projects, operates and maintains the assets to ensure the production of an expected level of service. It first establishes the strategies developed and AMP and then frames the activities and risks associated with the asset lifecycle (acquisition, operation, maintenance, and disposal). Lifecycle Delivery theme consists of 11 subjects as shown in Table 27.

Technical Standards and Legislation subject encompasses the procedures used in an organization to ensure that its AM activities comply with applicable legislation and technical standards.

Table 27 Lifecycle Delivery

Lifecycle Delivery										
Technical Standards and Legislation	Asset Creation and Acquisition	Systems Engineering	Configuration Management	Maintenance Delivery	Reliability Engineering	Asset Operations	Resource Management	Shutdown and Outage Management	Fault and Incident Response	Asset Decommissio-ning and Disposal

Asset Creation and Acquisition subject assesses the organizational processes that frame the first phase of the life cycle, that is, the definition of requirements, acquisition, installation, and commissioning of assets. It ensures that the choices and selection of new options for operability, maintainability and resource sustainability are based on the value of the entire life cycle of the asset.

Systems Engineering subject analyzes engineering processes so that they follow an interdisciplinary and collaborative approach to analyze needs, design, and evaluate assets. It refers to the policies and procedures for requirements analysis, design, and assessment of assets.

Configuration Management subject covers configuration management procedures and asset functionality review and monitoring processes. It examines how to adapt equipment to achieve better functional consistency and optimal performance throughout the life cycle.

Maintenance Delivery subject deals with the management of AM activities including methodologies for managing inspections and preventive and corrective maintenance carried out on assets.

Reliability Engineering subject frames studies to ensure that an asset will operate in accordance with a specified standard, for a given duration and in a defined environment. It investigates the organization's reliability plans and requirements and performance requirement compliance processes.

Asset Operations subject describes the procedures an organization uses to leverage its assets to achieve business objectives. It ensures that operator instructions are in accordance with defined parameters for design, maintenance, and operation.

Resource Management subject assesses the implementation of organizational strategies aimed at managing the use of funds, labor, facilities, tools, and materials in the performance of AM activities. It also covers the efficiency of the resource management process, its coordination and integration within the organization.

Shutdown and Outage Management subject deals with the application of the processes that an organization uses to

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identify, plan, schedule, execute and control work related to the different types of asset shutdowns.

Fault and Incident Response subject analyzes the systematic response to failures and incidents including incident detection and identification, failure analysis, temporary and permanent repairs, etc.

Asset Decommissioning and Disposal subject discusses the procedures an organization uses to decommission and retire assets due to aging or changes in performance and capacity requirements. It ensures that asset retirement is planned as part of the life cycle.

4) Asset Information theme

Asset Information theme aims to develop an in-depth knowledge of the asset portfolio (condition, criticality, capacity, etc.) which serves as an input and a key element in various AM processes. It studies the availability, reliability, and accessibility of relevant information on which the quality of decisions in operation, maintenance, financing, and risk management is based. The theme consists of 4 subjects as shown in Table 28.

Table 28 Asset Information:

Asset Information			
Asset Information Strategy	Asset Information Standards	Asset Information Systems	Data and Information Management

Asset Information Strategy subject deals with the necessary strategic approach to defining, collecting, managing, communicating and general governance of asset information to support the implementation of the objectives and the AM strategy. It checks the alignment of the information management strategy with the Strategic Asset Management Plan (SAMP) and analyzes the information needs and requirements related to assets.

Asset Information Standards subject assesses the establishment of a coherent structure and format intended to collect and store information relating to assets and report on its quality and accuracy. It examines the standards developed to adopt an approach to recording and classifying information aligned with the asset reporting strategy.

Asset Information Systems subject focuses on the information systems an organization puts in place to support AM activities and decision-making processes in accordance with the asset information strategy. It validates whether the architecture in place processes and supports information relating to the life cycle of assets and whether it ensures the centralization of data and its accessibility to the various stakeholders.

Data and Information Management subject analyzes data and information held by an organization within asset information systems and the management and governance procedures. It examines the various processes and plans that frame the management and coordination of the information lifecycle.

5) Organization and People theme

Organization and People theme looks at the organizational structure and culture, roles, responsibilities, and key skills related to AM. It examines the adoption of AM thinking among senior management and employees, as well as the alignment of their efforts and behaviors with best practices. *Organization and People theme* consists of five *subjects* as shown in Table 29.

Table 29 Organization and People

Organization and People				
Procurement and Supply Chain Management	Asset Management Leadership	Organizational Structure	Organizational Culture	Competence Management

Procurement and Supply Chain Management subject deals with the procedures used by an organization to ensure that all outsourced AM activities are aligned with AM objectives and to monitor the results of these activities. It reviews the activities required to create, manage, and maintain relationships with service providers, suppliers, and contractors.

Asset Management Leadership subject assesses the leadership required in an organization to promote a lifecycle approach to AM with the goal of maximizing value and serving the purpose of the organization.

Organizational Structure subject verifies whether the organizational structure promotes the achievement of the organization's mission and AM objectives, within the framework of a multidisciplinary collaborative approach. It analyzes the roles and responsibilities, interdependencies and information flows between different departments and functions.

Organizational Culture subject discusses the culture of an organization in relation to its ability to achieve organizational goals. It assesses the values shared in the organization, behaviors, perceptions, rules, and societal influences.

Competence Management subject discusses the processes an organization uses to consistently develop and maintain a skilled workforce and board of directors who are motivated to achieve AM goals to meet current and future needs. This subject assesses training and evaluation programs for operational skills, thinking and analysis skills, programs for developing knowledge in AM and understanding of the activities to be carried out through the. life cycle.

6) Risk and Review theme

Risk and Review theme is an important influencer of themes that cover strategic planning and decision making in AM. It deals with the organization's sensitivity to asset failures and the level of resilience of the various business sectors associated with them. It addresses several basic activities including the identification of risk management, determination of effective feedback and review mechanisms to provide assurance that objectives are achieved, knowledge of the physical condition and performance of assets, continuous improvement of AM activities. Furthermore, this theme covers the performance and reliability of the Asset Management System (AMS) ensured by the feedback and monitoring processes. The Risk and Review theme consists of nine subjects as shown in Table 30.

Table 30 Risk and Review

Risk and Review								
Risk Assessment and Management	Contingency Planning and Resilience Analysis	Sustainable Development	Management of Change	Assets Performance and Health Monitoring	Asset Management System Monitoring	Management Review Audit and Assurance	Asset Costing and Valuation	Stakeholder Engagement

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Risk Assessment and Management subject covers the policies and procedures for identifying, quantifying, and mitigating risks and exploiting opportunities. *Risk Assessment and Management* is common to all the themes of the AM conceptual model. This subject validates its integration in strategy, in AM Planning as well as in the implementation of the various phases of the life cycle.

Contingency Planning and Resilience Analysis subject assesses the procedures and systems put in place by an organization to ensure, in the event of unforeseen events, the continuity of operation of assets to provide the required level of service. It validates whether in critical moments the organization is prepared to respond well and make appropriate decisions based on contingency plans and proven scenarios.

Sustainable Development subject analyzes the multidisciplinary and collaborative processes that an organization uses to ensure a sustainable and balanced approach to its economic activity, its environmental responsibility, and its social progress, with a view to ensuring that all its activities are sustainable in the long run.

Management of Change subject deals with an organization's procedures for identifying, evaluating, implementing, and communicating changes affecting people, processes, and assets. It addresses the management of risks and opportunities associated with changes that may affect the achievement of AM objectives and measures to mitigate their impact.

Assets Performance and Health Monitoring subject inspects the processes and metrics an organization uses to measure the condition and performance of its assets. It analyzes the compliance of asset lifecycle assessment and monitoring programs against performance goals.

Asset Management System Monitoring subject covers the procedures and measures an organization uses to assess the performance of its AMS. It analyzes the monitoring program of this system and evaluates its performance.

Management Review, Audit and Assurance subject discusses an organization's processes that review and audit the effectiveness of its procedures and AMS. It examines the internal audit, control policies and plans as well as the reports of non-conformities and the resulting corrective measures.

Asset Costing and Valuation subject covers the processes used to define and capture the costs of building, maintaining, and renewing assets. Also included are the methods used to assess the value and depreciation of assets. This topic analyzes the framework that defines the composition of all costs associated with managing the lifecycle of assets and estimating and forecasting their value, considering changes in costs over their useful life.

Stakeholder Engagement subject assesses the methods an organization uses to foster stakeholder engagement in AM. It reviews policies and procedures for mapping stakeholders and their expectations as well as communicating and interacting with them.

C. The IAM Conceptual AM model

The institute of asset management (IAM) has developed a conceptual model for AM including the six groups of themes covering the 39 above-mentioned themes of AM initially published by the GFMAM [6, 118]. The IAM *Asset Management - An Anatomy* is a framework for assessing maturity in AM. This framework is aligned with the principles of ISO 55000 series of standards. It is made up of 39 topics that detail the AM activities within an organization. These 39 *subjects* are grouped into 6 *themes*. This demonstrates the scope of AM, the interrelationship between multiple activities and the need to integrate them, as well as the importance of alignment with the objectives and strategy of the organization. Figure 5 depicts the IAM model for the management of physical asset including the 6 subjects' groups.

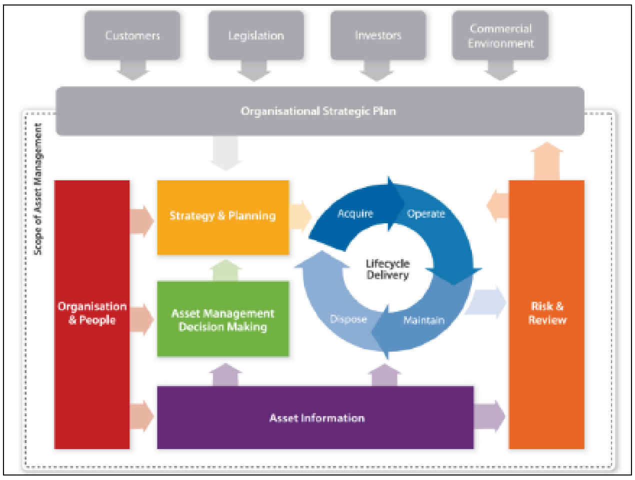

Figure 5 Conceptual AM model [6]

The maturity levels used to qualify the organization's level of progress in the management of physical assets are based on definitions adopted by IAM. Figure 6 shows the path through excellent AM practices. The maturity rating is measured on a scale of 0 to 5, whereby level 3 corresponds to the qualified degree of "*Competence*". The latter corresponds to the certification requirements of the ISO 55001 standard [114]. This level means that processes are in place for AM activities, that they are well documented, communicated and controlled across the organization, and that they are delivering the expected results.

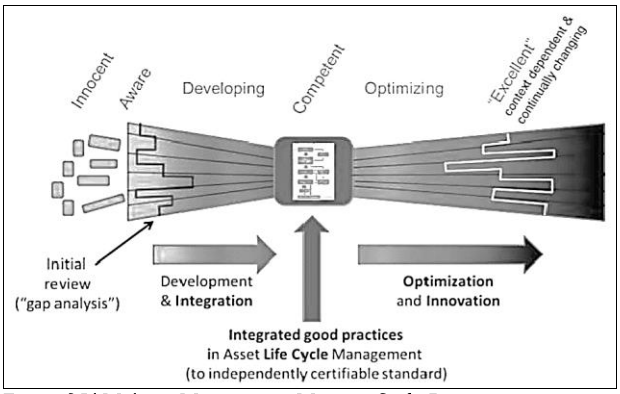

Figure 6 IAM Asset Management Maturity Scale 5
(Source: The Institute of Asset Management (IAM))

It is common to observe a level of maturity of "*Awareness*" among organizations that perform an initial assessment of their AM practices. This step is often a starting point on the organization's journey towards best AM practices, which is a continuous and evolving process based on continuous improvement.

D. Asset Management Body of Knowledge (AMBoK)

In 2014, the australian asset management council (AM-Council) developed a compilation of best practices known by the acronym AMBoK constituting a comprehensive AM framework [119]. AMBoK provides a collection of models (strategic, operational, tactical, maturity) and definitions forming a comprehensive framework of AM practices. Figure 7 illustrates the different models developed and their levels of involvement in AM.

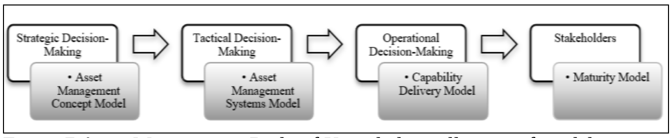

Figure 7 Asset Management Body of Knowledge collection of models (AMBoK)
(Source: Own representation based on Asset Management Council [119])

CIGRE conceptual decision-making process for AM

The international council on large electric systems, CIGRÉ (Conseil international des grands réseaux électriques, CIGRÉ) is a world-wide nonprofit professional organization in the field of high voltage electricity initiated in 1921 in France. Thusly, in Electrical Utilities, CIGRE characterize AM as follows: *"The Asset Management of Transmission and Distribution business operating in an electricity market involves the central key decision making for the network business to maximize long term profits, whilst delivering high service levels to customers, with acceptable and manageable risks"* [111, 112].

CIGRÉ has developed a conceptual model of decision-making for AM *(Asset Management Decision Process)* comprising three levels of information requirements: Corporate Level, Network Level, and Component Level. Figure 8 illustrates the conceptual decision-making process for AM in the power sector according to CIGRE [120, 121]. Indeed, the process shows the different levels of information requirements for decision making in a Risk Management Regime.

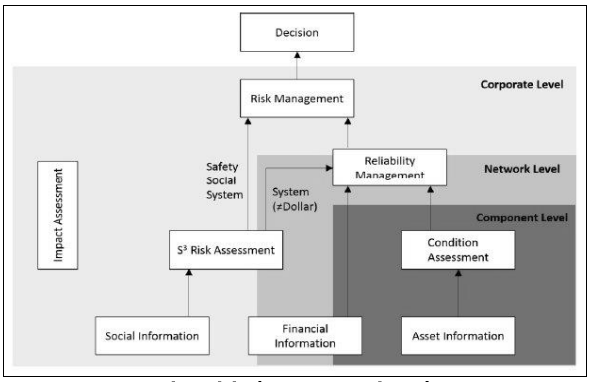

Figure 8 Conceptual Model of Decision-Making for Asset Management
(Source: [122])

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

IV. RISK MANAGEMENT AND DECISION-MAKING PROCESS IN ASSET MANAGEMENT

This section provides the reader with an overview of key relevant background aspects of the concept of a research component of major interest in the scientific community namely the concept of risk management (RM) and decision-making process in asset management at all levels such as risk-informed decision making (RIDM) and risk-informed asset management (RIAM).

A. Risk and risk assessment

International Organization for Standardization [123], International Organization for Standardization [124] standards define risk management (RM) as *"coordinated activities to direct and control an organization with regard to risk"*. Furthermore, Hubbard [125] describes RM as the identification and evaluation as well as prioritization of risks in addition to the coordination to either increase the fulfilment of opportunities or reduce the likelihood or effect of tragic events. Risk is characterized as *"an effect of uncertainty on objectives"[123, 124]*. An effect is "*a deviation from the expected. It can be positive, negative or both, and can address, create, or result in opportunities and threats"*. Risk is frequently stated in the matter of *"risk sources, potential events, their consequences and their likelihood" [123, 124]*. To rephrase it, risk can be characterized as the likelihood that an event will happen that unfavorably disturbs the realization of an organizational goal. Operationally, NASA procedural requirement NPR 8000.4 expresses risk as a set of three components: (i) the scenario(s), (ii) the likelihood(s), and (iii) the consequence(s) as shown in Figure 9 [126]. The latter authors mention that identifying risk in this manner helps RM since: *"(i) it distinguishes high-probability, low-consequence outcomes from low-probability, highconsequence outcomes, (ii) it points the way to proactive risk management controls, for example by supporting identification of risk drivers and the screening of low-probability, low-consequence outcomes; and (iii) It can point the way to areas where investment is warranted to reduce uncertainty".*

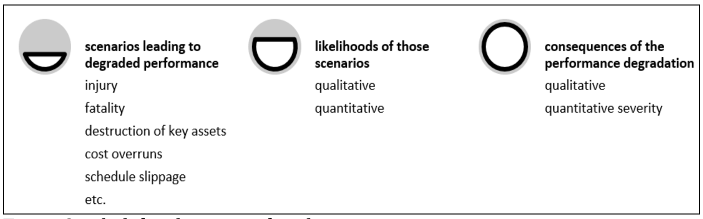

Figure 9 risk defined as a set of triplets
(Source: Own representation based on NASA/SP-2010-576 International Organization for Standardization [123])

In other words, it can be characterized as the resultant of an organization setting of objectives and priorities as well as actions to be undertaken against uncertainties of the environment such as uncertainty in worldwide markets deregulation, legal liabilities, technological innovation and risks from other events such as terrorist attacks, natural disasters, major geomagnetic disturbances and cyberattacks [108, 109].

Accordingly, uncertainties are a key aspect of risk, they are integrated in the assessment of likelihoods and

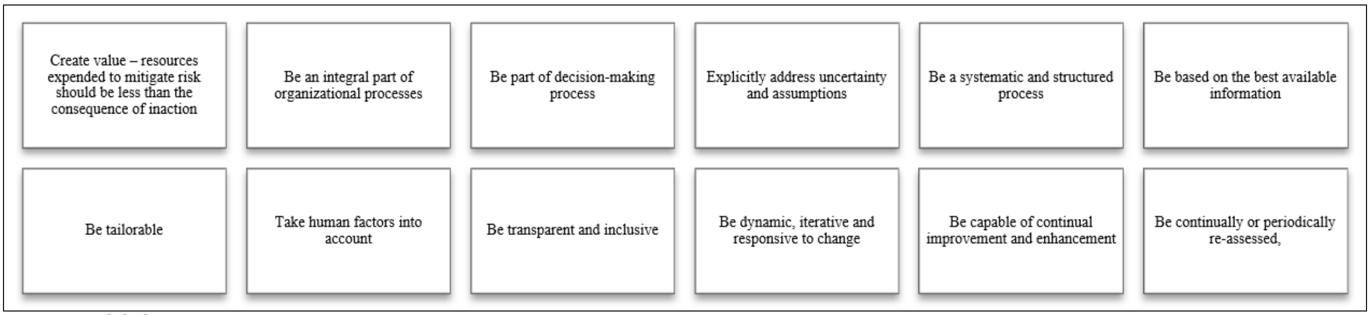

Figure 10 Global RM process in AM
(Source: Own representation based on International Organization for Standardization [123])

consequences. The uncertainty occurs from various sources including internal and external factors and impacts that can be sources of failure or delay attaining the corporate objectives [123, 124, 127, 128]. RM should include these subsequent principles (Figure 10).

Thusly, ISO 31000 standard points out that "*managing risk is iterative and assists organizations in setting strategy, achieving objectives and making informed decisions*". Studies show that RM is gradually considered as a means of enhancing the probability of achievement in strategic asset management and should be an integral component of all activities of an organization and its stakeholders [126, 129, 130]. The outcomes of the risk assessment and uncertainty analysis provide asset managers and practitioners with an unmistakably informed picture of the matter and helpful assistance when taking decisions to reason and deliberate in an assured manner [4, 108, 113, 131-135]. One can utilize risk acceptance criteria (RAC) methodology to assess whether the risk level is tolerable or not, through risk analysis and risk evaluation, as well as risk reduction and risk management, particularly while the consequence has a meaningful societal impact. The reader is referred to Marhavilas [136] and their bibliographic references for more details on RAC.

The following section addresses the risk-informed decision-making process (RIDM) which is an essential component of RM.

B. *Risk-Informed Decision-Making process*

The concept of risk-informed decision-making (RIDM) was established by the United States nuclear engineering industry in connection with safety concerns that come with nuclear power, and the Aerospace industry (the National Aeronautics and Space Administration (NASA) and the US Nuclear Regulatory Commission(USNRC)) [137].

Conventionally, risk management (RM) was deemed equivalent to continuous risk management (CRM). Traditionally, to perform Risk Assessment and Uncertainty Analysis, asset practitioners has used probabilistic analysis (known as Probabilistic Risk Assessment, PRA, or Quantitative Risk Assessment, QRA). Making decision involves numerous inputs which are very diverse in nature (qualitative inputs as the expert judgment, and quantitative as the risk assessment). Today, RM is labeled as encompassing both CRM process, and risk-informed decision-making (RIDM) process [126, 138, 139]. Proactive RM should combine RIDM (which focuses on the risk informed selection of decision alternatives to ensure successful methods to attaining objectives) and CRM (which tackles the execution of the chosen alternative to ensure that requirements are encountered). RIDM and CRM are complementary processes and should be combine into a single framework to enables effective and useful RM. Now, the trend is moving from a "*risk-based*" toward a *"risk-informed"* safety management approach wherein the perceptions given by the PRA (or QRA) and the deterministic method is treated as fundamental element of a decision-making process [4, 108, 113, 140, 141]. This approach is denoted *risk informed decision-making (RIDM)* when it is utilized for decisions-making process in relation to safety concerns [138]. In the same vein, Zio [113] remark that "*quantitative outcomes of risk assessment are only one component of the decision-making process, being combined with other criteria (such as social preferences, political concerns and budgetary constraints)"*. Dezfuli [126] draw attention to the fact that technical information cannot be the only basis for decision making. The latter authors point out that human judgment plays a key role in decisions. Likewise, Komljenovic [4] point out that Risk Assessment is just a portion of the complete RIDM process. Indeed, to be fruitful, RIDM embraces analyses in a broader scale such as engineering, risk, economic, societal, environment, regulatory.

NASA risk management procedural requirements NPR 8000.4 encompasses three parts broken down into six various process steps that constitutes the risk-informed decision-making (RIDM) process (NASA/SP-2010-576) as depicted in the following chart (Figure 11).

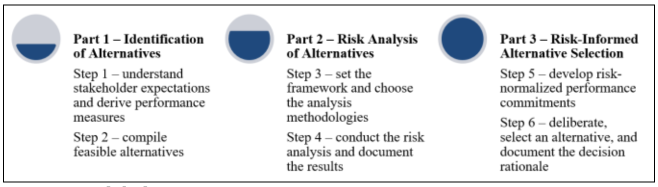

Figure 11 Global RIDM process
(Source: Own representation based on NASA/SP-2010-576 International Organization for Standardization [123])

Part 1 identifies decision alternatives (recognizing opportunities) in the context of objectives. *Part 2* performs risk analysis (integrated perspective) and development of the technical basis for deliberation. *Part 3* deliberates and selects an alternative and associated performance commitments informed by (not solely based on) risk analysis.

Zio [113] conducted a study overviewing and describing in detail, including an assessment of commonalities and

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differences in methodology, the RIDM processes developed by the NASA and the USNRC. This analysis provides the overall concepts, definitions and issues associated with the application of RIDM methods. It also provides reasons for the use of these methods as a complement to more conventional and established deterministic approaches to risk assessment. According to these authors, these are *"a structured processes which assist decision-makers when faced with high impact, complex decisions involving multiple objectives and the presence of uncertainty. They aim to ensure that decisions between competing alternatives are taken with an awareness of the risks associated with each option, and that all attributes of a decision are considered in an integrated manner".* Komljenovic [132], Komljenovic [133] suggested an approach to conduct RIDM process suitable for immense projects

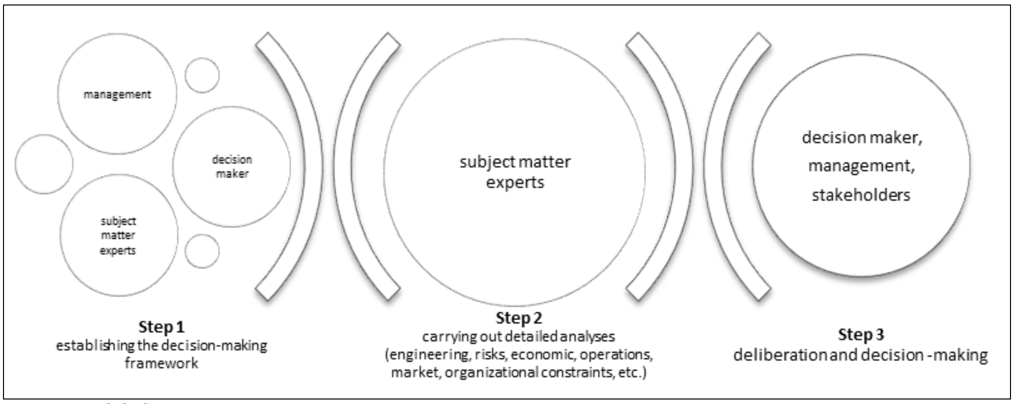

Figure 12 Global RIDM process in AM
(Source: Own representation based on Komljenovic [133])

dealing with Strategic Asset Management aspects, such as long-term performance and sustainability as follow and shown in Figure 12: (i) establish the decision-making framework, (ii) perform detailed analyses, and (iii) deliberate and make final decisions. However, the authors mentioned that this process is not useful for a day-to-day decision-making.

Today, this tool applies to other industries, such as aerospace and infrastructure safety such as aerospace and dam safety and provide useful decision support to decision-makers [108, 126, 129].

C. Risk-Informed Asset Management (RIAM) process

The concept of risk-informed asset management process (RIAM) is a risk-based decision analysis tool, initially developed for nuclear power stations, suitable for use in a market-driven industry. Simply put, the RIAM process provides plant executives with an instrument from planning

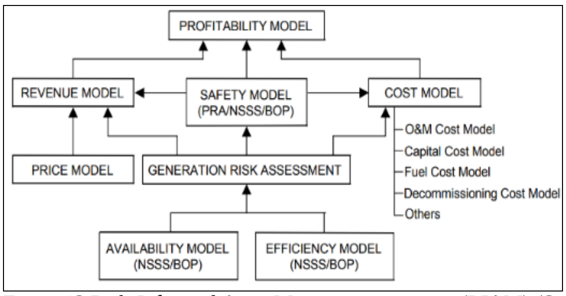

Figure 13 Risk-Informed Asset Management process (RIAM) (Source: [142])

project priorities and lifecycle management to developing long-term maintenance plans, budgeting, and awareness of economic risks, as well as the reliability and availability of the systems. Figure 13 depicts at a high-level, the conceptual model of RIAM resting upon the technical report of the development plan of the Electric Power Research Institute (EPRI) [142]. RIAM method is an additional method to the Nuclear Asset Management (NAM) method of managing nuclear assets. The latter uses risk management and defines business objectives to support investment decision-making in a long-term planning horizon throughout the life cycle of assets [142].

The RIAM process establishes several profitability models and performance metrics or decision support metrics (cost, safety, revenue, scheduling, etc.) to assist decision-makers in resources allocation and optimization. Hence, the RIAM process is as well a performance-based concept [143, 144].

Furthermore, Komljenovic [145] introduced the concept of a holistic risk-informed, performance-based asset management in mining (RIPBAMM) as a complementary tool to the current strategic mining activities. It is worth emphasizing that the latter author was the first to recommend the RIPBAMM process in further expanding the RIDM process in the mining sector.

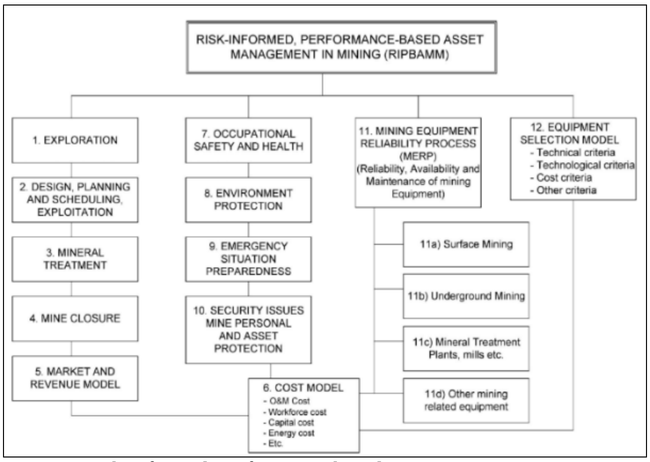

Figure 14 risk-informed, performance-based asset management in mining (RIPBAMM)
(Source Komljenovic [145])

The concept should provide key performance indicators to help asset management practitioners in key decision-making processes by using a combination of mathematical modelling and probabilistic quantification. The benefits of RIPBAMM process lies on the long-term profitability through continuous improvement on decision-making which contribute to enhance the net present value (NPV) of the mining industry. Figure 14 depicts the 12 modules at a high-level flow diagram of the RIPBAMM process proposed by the latter author including the key mine activities and performance models

V. RESILIENCE ENGENEERING

A. General concept of resilience

Asset management plays a key role for assets to cope with the external and internal organizational environment such as the ever-increasing competition, and markets deregulation, as well as technological innovation and risks from other events such as terrorist attacks, natural disasters, political environment, major geomagnetic disturbances and cyberattacks [108, 109]. Figure 15 depicts the hierarchy of these types of environments. The external environment remains neither correctly foreseeable nor accurately controllable or influenceable due to its complexity and profound uncertainty [146].

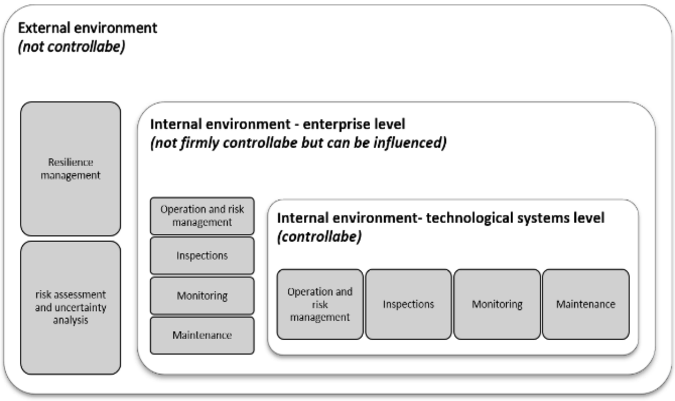

Figure 15 hierarchy of organizational types of ecosystems
(Source: Own representation based on Komljenovic [146])

To cope with this kind of environment, resilience management is a well-known approach suggested in RM and uncertainties analysis. A broad panoply of definitions of resilience arises from the scientific literature [95].

Table 31 depicts a no exhaustive directory of those definitions of resilience found in the scientific literature in relevant sectors. This variety in defining the resilience concept can lead to complexities in interpreting and measuring resilience [96]. The several distinctions and understandings of the concept of resilience are determined by which aspect of the subject matter of a resilient system is under study [162-164]. Vugrin [152] mentioned a broad range of interrelated domains for assessing system resilience: (i) technical, (ii) organizational, (iii) social, (iv) economic, (v) ecological and (vi) environmental. For e.g., Resilience engineering is a paradigm which has been promoted as a modern safety management concept to cope with complex socio-technical

Table 31 definitions of resilience
(Source: Own representation)

Discipline	Authors / Paper	Definition
Resilience engineering	Association [147] / Resilience	“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.”
	Fairbanks Fairbanks [148] / Resilience and resilience engineering in healthcare	“Resilience engineering is the deliberate design and construction of systems that have the capacity of resilience”
	Hollnagel [149] / 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 [150] / 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 [151] / The National Infrastructure Advisory Council, Resilience, Critical Infrastructure.	“The ability to reduce the magnitude, impact, or duration of a disruption”.
	Vugrin [152]/ 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	International Organization for Standardization [153]	“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”.
	[154] / Defining resilience.	“Resilience describes the characteristic of managing the organisation's activities to anticipate and circumvent threats to its existence and primary goals”.
	Denyer [155] / 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 [156] / 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: • 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 • 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 [157] / 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”.
	Home III [158]./ Assessing Behaviors that Create Resilient Organizations.	“The ability of a system to withstand stresses of environmental loading”
Resilience in socio-ecological systems	Holling [159] / Resilience and stability of ecological systems Walker [160]/ Resilience, adaptability and transformability in social-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” “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 feedbacks
Resilience in environmental systems	Tierney [161] / Conceptualizing and Measuring Resilience	“Both the inherent strength and ability to be flexible and adaptable after environmental shocks and disruptive events.”

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systems [165, 166]. It is associated with the integrity and reliability of physical infrastructure systems. In contrast, even though there exists some common ground with Resilience engineering, Socio-ecological resilience can be referred to as environmental and ecological concerns, security concerns, disaster response, business continuity, OHS, etc. [164]. Four common principles emerge from the literature review as shown in the following chart (Figure 16). These characteristics involves surviving change, either by lowering the effect of the disruption or adapting to it or recovering from it. It is worth emphasizing that the speed of the recovery is an important aspect of the resilience concept. Successful organizations are more resilient to predict and react to threats and opportunities in a complex and shifting environment.

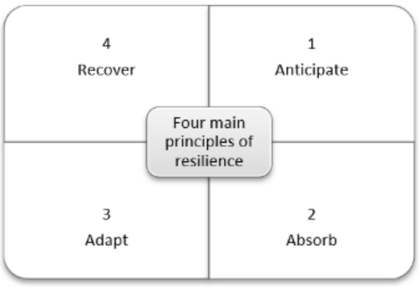

Figure 16 four common principles of resilience
(Source: Own representation)

It is worth emphasizing that resilience as an approach to deal with complexity and uncertainties should not be considered at the component level, nevertheless, should be view as an attribute at the system level to withstand severe conditions.

The general concept of resilience is depicted in the following chart (Figure 17).

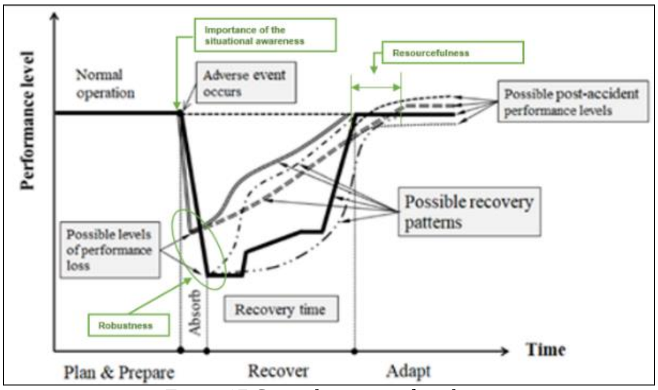

Figure 17 General concept of resilience
(Source: Komljenovic [167], Kurth [168])

It implies four phases: (i) *Planning* – this phase prepares and anticipates the arrival of an adverse event, (ii) *Absorption* – this phase implies the amount of loss of performance while an adverse event occurs, (iii) *Recovery* – this phase regains the performance after an adverse event occurs. The length of time to fully recovery following an adverse event is much longer if the magnitude of performance loss is larger or the required resources to recover the damage are unavailable. According to these, several recovery shapes are possible. (iv) *Adaptation* – this phase gathers information and acquires experiences on the adverse event and continue to improve the system resilience. Resilience entails a persistent continuous improvement and adaption as many aftermath performance levels are likely after recovery.

This general concept of resilience entails four main properties: (i) Robustness (*the capacity to absorb a shock, to withstand critical functions, to survive after an adverse event: namely absorbing and adapting*), (ii) Redundancy, (iii) Resourcefulness *(the capacity to plan for and make ready to withstand a disruption)*, and (iv) Rapid recovery *(the capacity to quickly return to operation and efficiently following an accident)* [164, 167].

To cope with these complexity and uncertainties challenges, for e.g., Komljenovic [167] has proposed a holistic methodology in managing the closure and abandonment of trailing ponds as shown in Figure 18.

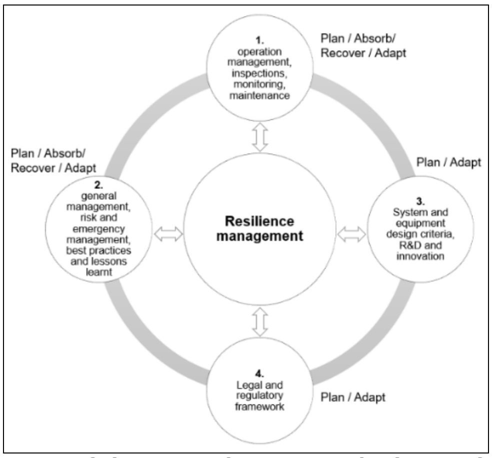

Figure 18 holistic approach in managing the closure and abandonment of trailing ponds
(Source: Komljenovic [167])

The proposed approach combines four blocks of functions and activities as shown in Figure 18 namely: (i) operation management; maintenance, monitoring and inspection management, (ii) General management, risk, and emergency management, return of experience and lessons learnt, (iii) establishing an adequate equipment and system design criteria; R&D and innovation, (iv) the fourth element relates to the legal and regulatory framework, which are appropriate to the four phases of the resilience idea. This study fosters a culture of anticipatory and preventive actions by recommending maintaining in all these activities an overall good performance to withstand severe conditions.

Finally, resilience as an approach to cope with complexity and uncertainties is a newly coined word and concept that has been established in the last decades to tackle mainly complexity of industrial systems and critical infrastructures involving the subsequent dimensions of resilience: organizational, technical/technological, operational, social, economic, financial, reputational, and business model [98, 167, 169, 170].

VI. STRATEGIC ASPECTS OF ASSET MANAGEMENT AND MAINTENANCE 4.0

The purpose of this literature review section is to provide the reader with an overview of key relevant background aspects of Strategic Asset Management (SAM) and Industry

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4.0 digital technology with a special emphasis on maintenance 4.0 tools.

SAM aims on aligning AM strategies with various levels of organizational strategy: corporate level strategy, business level strategy, and functional-level strategy. Figure 19 depicts the three levels of strategy pyramid:

Corporate level strategy: as a whole, this level of organisation establishes the strategic objectives for the organization. It gives direction to the business level strategy, and the

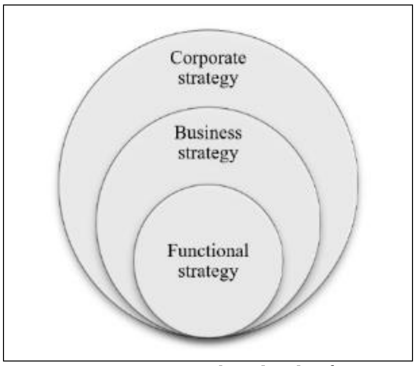

Figure 19 three levels of strategy pyramid
(Source: Own representation based on the literature)

functional-level strategy for development endeavors.

Business level strategy establishes the strategic objectives for the business unit. This level of organisation is informed by the corporate objectives.

Functional-level strategy establishes the strategic objectives to deliver on the organizational objectives and to keep on improving the functional-level strategy. This level of organisation is informed by the corporate objectives and the business strategic plans to establish a strategy to respond to those demands.

Asset management professionals will have to operate systems and infrastructures as well as decision-making processes at all levels of organizational strategy made up of a panoply of complex and uncertain technological objects including capital investment, definition of requirements, acquisition, installation, and commissioning and decommissioning of assets (O&M), shutdown and outage strategies, life cycle value realisation, etc. These systems and infrastructures are mostly complex, critical, and characterised by unpredictability relating the subsequent dimensions of resilience: organizational, technical/technological, operational, social, economic, financial, reputational, and business model [98, 167, 169-172]. Faced with this situation, AM constitutes a research element of major interest in the scientific community who is increasingly interested in SAM. The latter starts to be recognized as a basis of viable competitive advantages in the uncertain environment of enterprises.

In a wide variety of sectors, integrated risk management is gaining in importance. For instance, in the electrical power industry designing and operation, such as transmission and distribution, AM plays a determining role in the performance of assets to cope with power market deregulation, competition among players and risks from other events such as terrorist attacks, natural disasters, major geomagnetic disturbances and cyberattacks [4, 112, 133]. Recently, we have been observing an evolution from “Risk-based” to “Risk-informed” safety management methodologies since the quantitative outcomes of risk assessment are simply a portion of the complete Risk-Informed Decision-making process and should be combined with other criteria such as social preferences, political concerns, and budgetary constraints, etc.[4, 108, 113].

Furthermore, industry 4.0 tools have been affecting organizations on local and world-wide level, as well as AM economic models in which maintenance performs a starring role. Industry 4.0 has substantially evolved in terms of application domains and enabling technologies such as Intelligent Maintenance (Maintenance 4.0) in the form of self-learning and intelligent devices that predicts breakdown, analyzes behavioral patterns and trends through data, makes judgment, and prompts maintenance decisions [173, 174]. Applying Maintenance 4.0 technological solutions such as IIOT, Cloud, CPS, and Big Data Analytics to AM could decrease the challenges encountered by top management such as managerial, technological, and methodological challenges. Nevertheless, acquiring accurate data and knowledge from the systems as well as understanding the patterns associated to these data and maintenance decisions are the requirements in Maintenance 4.0 [175]. In the meantime, few research has comprehensively assessed the associated advantages and effects of SAM and Intelligent Maintenance (Maintenance 4.0) on the overall performance and limitations of physical assets. Gavrikova [109] conducted a study pointing out that current studies are generally case-specific in interpreting SAM and fall back on some theoretical concepts and approaches. Therefore, it is crucial to carry out scientific research to determining theoretical and methodological coherence and consistency in understanding the different aspect of SAM in recent developments and the future research directions. This will help to align SAM within the field of AM and its various levels of organizational strategy. For e.g., enormous pieces replacement while assets reach their lifespans or as technologies turn into obsolescence is a major challenge for Electrical Power Centers (EPC) [176]. Besides, Komljenovic [133] point out that globalization, free-market capitalism, and fierce competition make the operational and commercial environment of Electrical Power Services more and more uncertain and demanding in investments. These authors remark that “High-impact, low-frequency (HILF) events such as extreme weather/natural disasters, major geomagnetic disturbances and cyberattacks have become significant factors”.

Moreover, modern industries are characterized by smart and networking systems, connected units bringing new business opportunities such as reconfiguration and flexibility of systems [71, 175, 177]. These will be strongly influenced by technological advances such as the ubiquity of sensors in all sectors of activity at affordable costs (cheaper, ubiquitous sensors), the computing power (computational speeds), the capacity to store data and the power to move them quickly, as well as the contribution of Artificial Intelligence (AI) [178]. Today and tomorrow, the issue of dependability integrating reliability, maintainability, availability, and safety (RAMS) of production systems is the weak link in the management of physical assets. To face these sizeable challenges for the industry, radical changes to AM practices, especially Maintenance Management, are essential. The driving technologies of Industry 4.0, especially those of Intelligent

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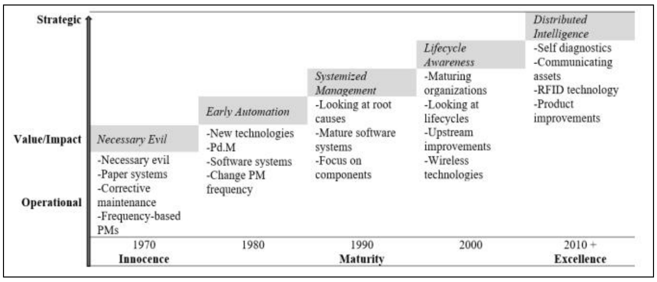
Maintenance (Maintenance 4.0), hold promise for SAM. It was shown in a recent survey led by ReliabilityWeb.com from 2014 to 2019 the top five benefits of asset management 4.0 that companies were most dedicated on: (i) Lifecycle cost reduction, (ii) Identifying and managing risk, (iii) Extracting data to support evidence-based asset management decisions, (iv) Determining the optimum maintenance approaches for assets, (v) Changing company culture.

Industry players are daily confronted with decision-making at all levels involving Big Data Analytics as well as the customization and reconfiguration of processes. In the era of the Smart Factory, with the advent of new Industry 4.0 technologies in recent years, assets are becoming increasingly critical and complex to ensure dependability [178-180]. Gradually, the maintenance function gained ground and evolved from a reactive approach under the denomination of Maintenance 1.0 to a preventive approach under the designation of Maintenance 2.0, then to a Maintenance 3.0 based on the condition of the asset, and finally to a predictive and normative maintenance under the name of Maintenance 4.0 based on technologies of industry 4.0 [179]. Indeed, the major shifts in Information and Communication Technologies (ICTs) capabilities has resulted in a promising move from conventional maintenance approach to a preventive and predictive approach namely e-maintenance whereby assets are remotely monitored and managed through the Internet, and intelligent maintenance over technologies such as IoT sensors on strategic equipment [181, 182].

AM has evolved from Maintenance 1.0 using printed paperwork and considered as a "Necessary Evil" to Maintenance 4.0 corresponding to the present position where AM activities are fundamental functions of SAM [183]. Table 32 depicts the evolution of AM and the understanding of the field by top management.

Table 32 Evolution of AM and corporate thinking
(Source: Own representation based on IBM, 2007)



Maintenance must play a key role to meet the challenges of Industry 4.0 and in turn, to minimize the effects of unforeseen failures as well as risks and disruptions in a context of digitized production [180]. Thusly, the ability to predict asset maintenance needs is one of the main issues and challenges of maintenance function and production operations. The aim of the maintenance function is to guarantee the productivity and sustainability as well as the dependability of assets, integrating reliability, maintainability, availability, and safety (RAMS). Maintenance performs a key role in AM as well as within industry 4.0 [175]. A recent portrait of the state of the art in the body of knowledge of Industry 4.0 positions the contribution of predictive maintenance (Pd.M.) to improving the dependability of assets, and to optimization costs as well as productivity and product quality [91]. In the same vein, Maletič [184] carried out surveys within Slovenian companies with the purpose of exploring the capacity to assimilate the complexity of new technologies of Industry 4.0. They note that most players are aware of the positive benefits provided by the digital transformation of companies. However, they remarque an absence of a roadmap as well as a clear vision for the implementation of digital solutions in connection with predictive maintenance. In the same vein, Sahal [72] signalled a set of prerequisites and conditions for e.g., in in the fields of transportation and energy. The latter authors observe a technological gap between the needs of digital technologies applications and the capacities of existing big data analytics opensource technologies for Pd.M. Moreover, Zonta [185] observe a lack of publications about predictive maintenance in connection with Industry 4.0. Indeed, most publications in the scientific literature are exclusively interested in the analysis of data and artificial intelligence machine learning methods for the optimization of processes and procedures. The use of new technologies from Industry 4.0 makes it possible to move from the old way of doing things to optimal Intelligent Maintenance called Maintenance4.0 [70]. For instance, IoT sensors on strategic equipment on a production line make it possible to monitor the condition of assets and their performance and prevent the arrival of failures or problems that could cause production stoppage or poor product quality. As a result, connected objects as well as their conditions and performance can be monitored and followed in real time through dashboards which centralize information from the equipment.

Table 33 Maintenance 4.0 Smart Technologies

Sensors	Data (acquisition, storage, and processing units)	Artificial Intelligence	Output Unit	Actuators
Temperature	SCADA	Expert systems	AR devices	Pumps
Pressure	Hard drives	Machine Learning	Interfaces	Valves
Cameras	Cloud	Numerical Methods	D/A converter	Relays
Humidity	DAQ cards	Physical models	Screens	Hydraulic pistons
Acceleration	CPU	…	Web services	Servomechanisms
Rotation	MCU		Phone apps	Piezoelectric actuators
GPS	…		…	Electric motors
…				…

In the same idea, Campos [181] conducted a study on the performance measurement in AM regarding the ICTs capabilities. These authors signal the contribution of innovative technology concepts such as Big Data Analytics and Data Mining in achieving the performance measurements in AM. Table 33 shows a list of smart technologies of Maintenance 4.0 also called Intelligent Maintenance [186].

The advent of Industry 4.0 affects all industrial spheres and integrates new modern and advanced technologies. These technologies capture, optimize and deploy Big Data. We are witnessing the emergence of the "Smart Factory" concept, which is an important link in Industry 4.0. Technologies such as IoT, AI, CPS and Cloud Computing communicate, interact, and adapt continuously [187]. the most popular technologies in the scientific literature are discussed below

Cyber-physical system: CPS is a computer system in which a mechanism is controlled or monitored by computer algorithms [188, 189]]. Khaitan [190], mention that CPS are a new class of engineering systems offering a close interaction between cyber and physical components. The software and hardware of these systems are interrelated and capable of functioning at different spatiotemporal scales and can interact

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with each other to change according to the context [190, 191]. In other words, CPS portray themselves as the convergence of the Physical and Digital Worlds by establishing Global Networks for the integration of manufacturing systems, machines, and warehousing systems [191, 192]. Examples of CPS include smart grids, industrial control systems, robotic systems and airplane autopilot, self-driving cars, medical surveillance. Indeed, the sensors and actuators of these systems and machines are controlled by microcontrollers of physical cyber systems exchanging information and data through on-board computer terminals or wireless applications or clouds [193]. CPS systems have been deployed over three generations of technologies[192]: (i) technologies such as RFID allowing the unique identification of objects using bar codes with centralized data management (storage and analysis), (ii) technologies equipped with sensors and actuators with a limited set of functions, (iii) technologies equipped with networked sensors and actuators capable of storing and analyzing data.

Internet of Things: The concept of the Internet of Things (IoT) describes the network of technological physical objects integrated with technologies such as sensors and software whose purpose is to connect and exchange data with other systems via the internet [194, 195]. IoT systems rely on cloud computing infrastructures and CPS. In other words, the concept of IoT refers to a system of correlated computing devices, mechanical and digital machines, objects, humans, or animals with Unique Identifiers (UIDs) with the ability transfer data over a network without requiring human interaction (H2H Human-to-Human interaction or H2C Human-to-Computer interaction) . IoT is also a category of software application programs for process control, real-time data collection from remote sites to control equipment and conditions, spontaneous extension of Supervisory Control and Data Acquisition (SCADA). The SCADA integrates hardware components that collect and feed the data into a computer to which the SCADA software is installed where it is then processed and presented in a timely manner [196]. Flexible Manufacturing Systems (FMS) and Reconfigurable Manufacturing Systems (RMS) are increasingly equipped with intelligence allowing communication between machines (Machine to Machine, M2M), the system and the human operator (Machine to Human, M2H / System to System, S2S). M2M refers to the connection of a device to the cloud (Cloud), its management and data collection [196, 197]. The concept of the IoT has evolved from M2M communication, that is, machines connecting to each other through a network without human interaction. IoT derives its success from its power to acquire and identify data for their use while ensuring confidentiality and security [198].

Cloud Computing: The term cloud computing or on-demand availability of computer system resources is a technology usually associated with the accessibility of computer services by many users through the cloud from a provider. The cloud mainly designates computing power and cloud storage (data storage) without direct active administration by the user [199, 200]. Three standard services models of cloud computing solutions are offered by cloud-computing providers [199]: (i) *Software-as-a-Service (SaaS)* such as integrated management software, Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Email, virtual desktop, communication, games, etc., available on the internet rather than installing it locally on a single PC. The consumers utilize the provider's applications operating on a *"cloud infrastructure"*. (ii) *Platform-as-a-Service (PaaS)* which allows customers to access applications in the cloud: execution runtime, database, web server, development tools, etc. The consumer manages and controls the implemented applications, for instance, configuration settings. However, the provider endorses the *cloud infrastructure* comprising network, servers, operating systems, or storage. (iii) *Infrastructure-as-a-Service (IaaS)* for data storage, virtual machines, servers, networks, and other vital computing resources. The consumer can install and run software featuring operating systems and applications. The consumer manages and controls the implemented applications, operating systems, storage, etc. The underlying *cloud infrastructure* is under the control of the cloud computing provider. Let us mention some market giants in terms of availability on demand of IT system resources [201]: Amazon Web Services (AWS) providing Platforms and Application Programming Interface (APIs) on demand on a pay-per-use basis, Google with Google Drive, Microsoft with Windows Azure, and IBM with Blue-Cloud. Nowadays, it is common to store data to the cloud with the explosion of cloud providers to support administer the data-driven and technology-leveraging decision making.

Cognitive Computing / Artificial Intelligence: Cognitive computing (CC) involves the reproduction of human thought process in a computerized model in complex situations. In other words, CC systems involve technological platforms based on AI and signal processing. It encompasses self-learning systems that use data mining, pattern recognition and natural language processing, to mimic the human brain [197, 202]. Indeed, machine learning algorithms perpetually acquire knowledge from data collected from systems based on rigorous statistical and mathematical formulas (Data Mining). The purpose of these technologies is to create automated systems with the ability of extracting information, performing tasks, and solving problems without requiring human intervention.

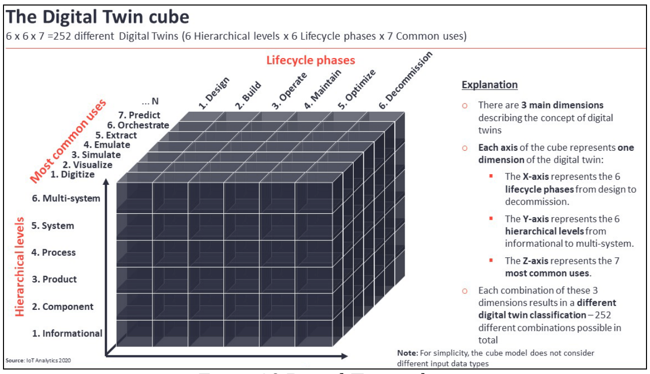

Figure 20 Digital Twin cube
(Source: IoT-Analytics [203])

Simulation Digital Twins (SDT): a digital twin (DT) is a virtual version that performs as the real-time digital equivalent of a physical thing. SDT provides asset practitioners to respond to disruptions with sound decision in real time and increase visibility on the effect of their decisions for a more resilient future. IoT-Analytics [203] defines DT as *"a digital abstraction or representation of a physical system's attributes and/or behavior on 3 distinct dimensions: (i) the hierarchical* *level on which it is structured, Lifecycle phases in which it is applied, and (iii) its use and input data type in practice"*. The various DT available in the market are framed in Figure 20: Digital Twin cube including the 3 dimensions as follows [203].

SDT mainly encompasses three advances to making optimal decisions: (i) "360° holistic view *(replicate an entire ecosystem)*", (ii) "dynamic simulation *(predict an organization growth in the future)*", (iii) "opportunity to connect and synchronize in real-time *(IoT can provide data into the DT, then decision making can be automated)*"[204].

VII. DISCUSSION

The volatile economic context and the rapid advance of technology are forcing industry players to adapt their economic AM models to cope with the challenges inflicted by the fierce competition of international economies. These organizations face significant uncertainties and dreaded risks of all kinds. These include the strategic, operational, organizational, and financial, as well as technological and technical issues that seriously influence all the company's business processes. Many researchers have been interested in AM models and the organizational transformation of the increasingly digitally focused business environment and its numerous tools for the development of business models to help practitioners in various industries (for e.g., electrical power centers).

The new era of the industry is shaping the future of organizations and will induce profound changes in workforce planning. The digital shift is inevitably accompanied by a host of new challenges related to the connectivity of digital technologies, cybersecurity, the standardization and reengineering of business processes, the redefinition of processes, products, and services, and labor (acquisition, maintenance, and training). It brings new opportunities, new challenges, and a new organization of work. Likewise, given the current uncertain business context caused by the coronavirus disease pandemic (COVID-19), the challenges will be of nature, among many other aspects, strategic, operational, regulatory, financial as well as health and safety. In a wide variety of sectors, integrated risk management (RM) is gaining in importance. Indeed, asset managers will have to operate infrastructures and decision-making processes made up of a panoply of complex and uncertain technological objects resulting from Industry 4.0. Furthermore, in the context of aging assets, organizations will face dependability challenges (Reliability, Availability, Maintainability and Safety - RAMS).

Face with this context of aging assets, the myriad of new technologies of Industry 4.0 such as simulation digital twins (SDT), artificial intelligence (AI), big data (BD), Internet of Things (IoT), Cyber-physical system (CPS), and cloud computing can help to cope with these challenges. For instance, in electrical power industries, SDT can support to enhance asset breakdown detection or prediction, manage the replacement of assets when they attain their life span, become obsolete or when transitioning to more economical and carbon-free power alternatives. Also, it can make easier to prioritize predictive maintenance as well as preventive maintenance and enhance asset replacement and optimize resource allocation. Concretely, for e.g., Velasquez-Contreras [205] have developed a broad AM mock-up for power transformers (*general asset management model for an electric utility, GAMMEU*). This platform enables data integration and provides systems with intelligence for maintenance planning and scheduling, breakdown detection and diagnosis, as well as reliability analysis by means of simulations and prediction models based on industry 4.0 technologies (SDT, AI, IoT, CPS, etc.). Figure 21 shows the block diagram of GAMMEU model encompassing the following module: (i) information technology platform for data integration, (ii) intelligent system for detection and diagnosis, (iii) failure rate estimation model, (iv) reliability analysis, (v) optimisation model for maintenance scheduling.

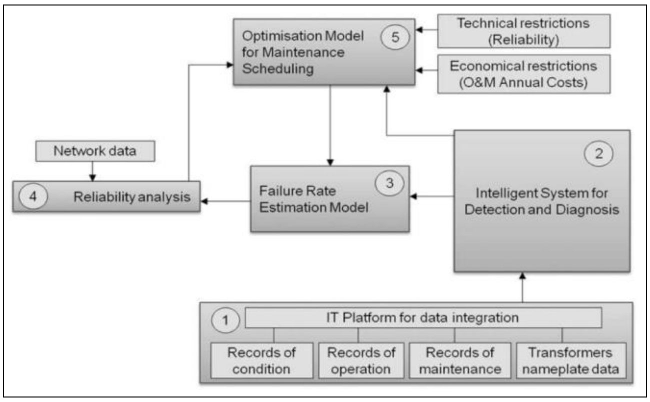

Figure 1 Block diagram of GAMMEU model
(Source: Velasquez-Contreras [205])

Recent studies in the Quebec manufacturing sector conclude that there is a significant delay in integrating the concept of Industry 4.0 and the technologies that accompany it despite the will of decision-makers [206]. The organizational transition and the digital context require substantial investments in new technologies and in the fight against computer crime (cyber crime) and network security. Indeed, remote management and data exchange through IoT and the panoply of opportunities provided by digital transformation require constant mobilization and vigilance to deal with any eventuality.

Thus, each organization will do better to reinvent its own business model and its way of making profits in the digital age by identifying possible changes that can disrupt its capacity [207, 208]. In other words, organizational, political, economic, and social challenges risk becoming a significant stumbling block compromising certain investment projects of organizations on the path to digital transformation [178, 209-212].

Ultimately, all these challenges are inherent in the acquisition and storage of massive data (big data), digital governance, as well as equipment connectivity, automation and robotization through IoT and CPS. All in all, to achieve digital maturity, organizations must ensure information excellence and digital governance as well as the challenges of talents acquisition and their retention in the workplace in addition to new communication technologies 4.0. Companies that fully understand and grasp the value of the benefits that emanate from digital maturity including industry 4.0 technologies will be best positioned to meet the challenges of the future. In addition, a survey by the firm KPMG indicates the priority of automation and digital governance in various industries. The results of the report reveal the emergence of new trends such as artificial intelligence, machine learning, the digitization of robotic processes and their positive influences on the company's value chain [213]. The report draws attention to the management of strategic, organizational, and operational issues, as well as the acquisition of talent and their retention in the workplace to improve the activities induced by the digital transformation.

In the same vein, Asset Risk Management practices (ARM) should be an integral part of physical asset management processes (AM) and strongly deemed to enable an effective AM as shown in a recent survey conducted in industrial manufacturing companies investigating the relationship and interdependency between ARM practices and their influences on maintenance performance outcomes [130]. Likewise, to cope with this kind of environment, resilience management is a well-established approach advocated in RM and uncertainties analysis. It has been promoted as a modern safety management concept to cope with complex socio-technical systems.

VIII. CONCLUSION AND FUTURE RESEARCH

Both practitioners and scholars have been interested in AM models and its numerous tools for the development of new economic models with the aim of optimizing the company's value chain. While making decision, it is crucial to come up with the proper balance between various challenging considerations for instance costs and benefits as well as opportunities and risks. Therefore, it is imperative to look thoroughly at this subject matter to grasp all the implications and identify the real demands that call for an answer at strategic level. Hence, the future target for this research is:

(i) to conduct a case study highlighting RIDM's contribution to Strategic Asset Management (SAM) for the management of physical assets that allow the achievement of the desired performance of electrical utilities such as transmission and distribution which are considered as capital-intensive assets and complex adaptive system of systems.

(ii) to conduct a case study highlighting the influence of industry 4.0 (Maintenance 4.0) in resilience engineering.

(iii) to conduct a case study highlighting the influence of Resilience engineering in SAM.

These case-studies would enable to identify approaches to potential policies and strategies for SAM. The outcomes will contribute to position and validate the link between SAM and RIDM, as well as Maintenance 4.0 and Resilience engineering inside the vast discipline of AM and the alignment with various levels of organizational strategy.

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