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Maintenance concepts evolution: a comparative review towards Smart Maintenance conceptualization

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Abstract

The implementation of Industry 4.0-like solutions for the maintenance of production assets is a relevant topic in the mainstream for researchers and industries around the world. As a matter of facts, the technology-based transformation of maintenance has been germinated since several years. In fact, the evolution of maintenance along with the development of the information and communication technologies has been studied in the literature since early 2000, and concepts like e-maintenance and intelligent maintenance have been largely addressed. Nowadays, the smart maintenance concept is getting more and more popular in the Industry 4.0-based literature. While e-maintenance, intelligent maintenance and smart maintenance are similar, they are not identical. From an evolutionary perspective, there has been little consideration on whether the definition, connotation, and technical development of the concepts are consistent in the literature. To address this gap, the work performs a qualitative and quantitative investigation of the scientific literature to clarify the relationship among the different maintenance related concepts. A bibliometric analysis of publication sources, annual publication numbers, keywords frequency, and top regions of research and development establishes the scope and trends of the currently presented research. Critical topics discussed include the evolutionary path of the different concepts. Moreover, the evidence collected through a case study involving nine production companies are discussed to report the perspective of industry about advanced maintenance, may it be defined smart, intelligent or e-maintenance. Finally, a definition of the smart maintenance concept is given, proposed as foundation of an advanced maintenance system in the digital era and as an integral approach inheriting the knowledge from past developments of e-maintenance and intelligent maintenance concepts.

Keywords: Maintenance, Smart Maintenance, Intelligent Maintenance, e-maintenance, review

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1. Introduction

In the current time, digital transformation is impinging upon the whole society and the industrial world (Loebbecke and Picot 2015). Looking at manufacturing, digital transformation affects a firm's strategy, its offerings, the IT infrastructure, the way to collaborate with partners, its organizational structure, overall process organization, and core competences, as well as the overall company culture (Pflaum and Gölzer 2018). In order to highlight the revolutionary potential of the digital transformation of industry, it has become popular to address it by the term 'Industry 4.0' as coined by Germany (Kusiak 2017). Such term, is now used to encompass varied concepts and solutions, including but not limited to Cyber Physical Systems (CPS), Internet of Things, Cloud and Big Data solutions (Gölzer and Fritzsche 2017; Zheng et al. 2018).

Building on them, the transformation implied in this digital era recognizes maintenance of production assets as promising ground where to implement Industry 4.0-like solutions (Bokrantz et al. 2017; Macchi, Roda, and Fumagalli 2017; Zheng et al. 2018). Keeping a perspective from the maintenance field, the current transformation can be interpreted as natural follow-up of past research and development activities (Macchi, Roda, and Fumagalli 2020). Indeed, a technology-based transformation of maintenance has been developed in the past years, preceding the discussion of this digital era. In fact, the evolution of maintenance with the development of the information and communication technologies (ICT) has been studied in the literature since early 2000, and concepts like e-maintenance and intelligent maintenance have been largely addressed (Alaswad and Xiang 2017; A.J. Guillén et al. 2016; Kwon et al. 2016; Muller, Crespo Marquez, and Iung 2008; Vogl, Weiss, and Helu 2016). Moreover, condition-based maintenance (CBM) was discussed as a relevant aspect of e-maintenance and intelligent maintenance. In the last years, together with e-maintenance and intelligent maintenance, concepts such as predictive maintenance, prognostics and health management, smart maintenance and Maintenance 4.0, are widely used in the Industry 4.0-based literature (Campos et al. 2016; Isaksson, Harjunkoski, and Sand 2017; Lee et al. 2018; Lee, Ghaffari, and Elmeligy 2011; Zheng et al. 2018). Overall, digitalized manufacturing is influent to rethink the way maintenance is done. Reviews by (Huang et al. 2020; Lundgren, Bokrantz, and Skoogh 2021) have found that the suggested concepts are not clearly defined. There is an overlap in these concepts, with a varied use of terminology, causing a lack of concept clarity (Lundgren et al. 2021).

The present work aims to clarify the differences and commonalities in terminology and to study the evolution of concepts as e-maintenance and intelligent maintenance, together with emergent concepts as smart maintenance and maintenance 4.0, with the purpose to shape the current understanding of the focal concepts at the background of an advanced maintenance system built on the characteristics induced by the digital transformation. This objective is developed building on the extant scientific background, backed by the findings collected from a multiple case study involving a selection of production companies, to align with current perceptions in real industrial settings.

To achieve this result, the paper is so structured: section 2 describes the research methodology; section 3 provides the bibliometric analysis of the literature findings; section 4 discusses the concepts evolution, also gathering the existing understanding of the different concepts; section 5 captures the current perceptions in industry, exploiting the evidence of the multiple case study, section 6 synthesizes all the findings in a definition of smart maintenance concept, proposed as foundation of an advanced maintenance system in the digital era and as an integral approach inheriting the knowledge from past developments of e-maintenance and intelligent maintenance concepts; finally, section 6 concludes with some stimuli for a future research agenda.

2. Methodology

Given the research objective, the methodology followed in this research is based on two methods: i) a systematic literature review and bibliometric analysis; ii) a multiple case study, involving experts of nine production companies. The following concepts were selected to be investigated: e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0.

Regarding the literature review, it develops the following methodological steps: (1) Conduct a systematic literature review by identifying papers through titles, abstracts, and keywords found in Scopus database, and then quantitatively analyze the top keywords with network analysis; (2) From the top keywords, review the state-of-the-art from the literature and identify key topics on the origin, development, and key technologies of e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0; also, identify the chronology and qualitatively examine similarities among common definitions and characterization principles; (3) Evaluate the relationship among e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0, and quantify co-occurrence of key issues; (4) Enumerate keywords frequency in order to evaluate the concepts evolutionary path also in term of enabling technologies and research topics.

Besides the scientific literature analysis, a multiple case study was set involving nine production companies. This method was chosen as case research has proven to be beneficial in the early explorative stages of theory development, when phenomena under study are not completely understood (Voss, Chris Tsikriktsis, Nikos Frohlich 2013). The companies were selected to have a representative sample: industrial users managing the maintenance of their production systems were chosen. In line with publications grounded on resource-based theory like (Jin et al. 2016), it was also decided to focus on large size companies, as several works prove that the effectiveness and choice of maintenance strategy (Jin et al. 2016; O'Donovan et al. 2015) and the readiness for advanced approaches based on the adoption of ICT (Aboelmaged 2014) are strongly correlated to the size of the company. Table 1 provides more detail about the sample of companies, the different industrial sectors they belong to, and the roles of the people that were interviewed in each company. The companies identified two key accounts for the study, in most cases maintenance manager and ICT/digital transformation responsible (at a corporate level, or of the subsidiary national level). It is in line with our intent of not limiting the research to the viewpoint of maintenance managers, also including the perspective of the ICT responsible for the digitalization process given the object of our investigation. A semi-structured interview was organized in each company by involving both key accounts and other participants. The interviews had a wide scope aimed at investigating the maintenance system achievable by means of on-going digital transformation projects. The data collected were analyzed through coding to implement cross-case comparisons, and to identify the differences and commonalities among companies (Voss, Chris Tsikriktsis, Nikos Frohlich 2013). In this work, the coded information due to the answers given to an open question about the definition of the maintenance system in the digital era is given.
On the whole, the methodology proposed by (Podsakoff, MacKenzie, and Podsakoff 2016) to create concept definitions was followed: the survey of the literature and the interviews to experts, as data collection methods, are joined to develop a good conceptual definition, in which core elements of the concept – defined in the reminder as attributes and consequences – are identified by collecting a representative set of definitions.

Case	Type	Sector	Core business*		People interviewed
A	Large	Steel	2410	Manufacture of basic iron and steel and of ferro-alloys	• Maintenance manager, • Maintenance Engineering Director • R&D Director
B	Large	Turbines	2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	• Technical service Director
C	Large	Energy	3511	Production of electricity	• Production Director • Plant Director, • Plant chief of maintenance team
D	Large	Steel	2550	Forging, pressing, stamping and roll-forming of metal; powder metallurgy	• Production Director • ICT Director • Maintenance Director
E	Large	Tyres	2211	Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres	• Global Maintenance Manager
F	Large	Industrial Gases	2011	Manufacture of industrial gases	• Production Plants Director • Plant Director
G	Large	Oil&Gas	1920	Manufacture of refined petroleum products	• Digital projects Coordinator • Maintenance Director • Inspections Director
H	Large	Steel	2420	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	• Technical Function and Maintenance Director • R&D and data science Director • Maintenance Engineering Director
I	Large	Mechanical	2932	Manufacture of other parts and accessories for motor vehicles	• Technical Functions Director • ICT Director

Table 1. Case study: involved companies - (*) NACE Rev.2 (EU 2008)

3. Bibliometric analysis on e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0

Bibliometric analysis evaluates current trends in the research literature, providing an overall outline and structure of the area, and guidelines and motivations for future research (Wang et al. 2020). Bibliometric data was gathered using ‘smart maintenance’ (SM), ‘intelligent maintenance’ (IM), ‘e-maintenance’ (eM) and ‘maintenance 4.0’ (M4.0) as the search query within publication titles, abstracts, and keywords. Moreover, the search was conducted also by using the following strings: ‘maintenance’ AND ‘industry 4.0’; ‘maintenance’ AND ‘digitalization’. These helped to scan the wide literature, by including both the terms typically associated to smart maintenance and its precursors or equivalents, and the terms enabling to more generally capture the digital transformation in maintenance induced by Industry 4.0. In this section, we compare research publication growth, country/region analysis and cooperation, top journals or conferences, and keywords co-occurrence frequency in the different maintenance concepts.

The search used Scopus as electronic database to collect academic research papers that: (i) were written in the English language, (ii) were published in journals, conference proceedings or book series between 1970 and 2020, and contained at least one of the identified terms in either the title, abstract, and keywords; (iii) were articles related to relevant subject areas for this study (excluding subject areas like medicine, biology, etc.). After removing duplicates, the papers were briefly reviewed by reading their titles, abstracts or content, to conclude about their inclusion or exclusion. Finally, all eligible papers (773 papers) were included in the analysis (Figure 1).

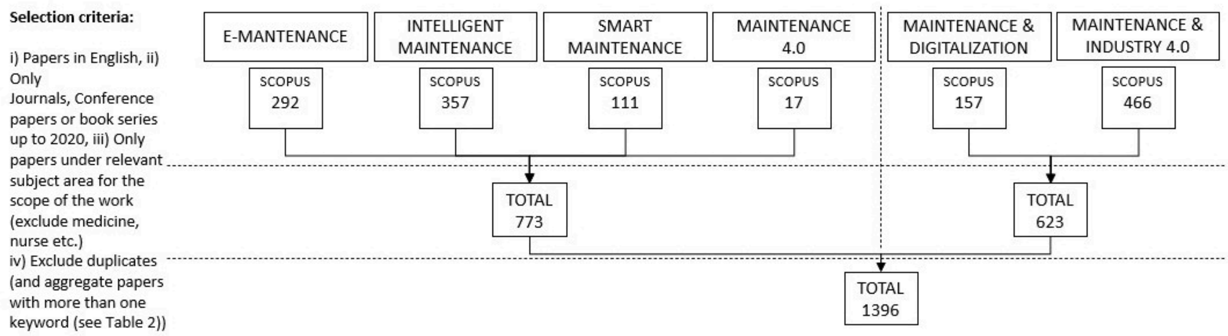


Figure 1. Synthesis of the extensive literature review

3.1. Annual publication volume

The annual publication volume indicates the interest by scholars in IM, SM, eM and M4.0 research, referring to the 773 papers identified through the literature review addressing one of the four main terms (Figure 2).

A first evidence is that the term ‘intelligent maintenance’ is spread along time. The first publication on IM found in database dates back to the late 80s mainly in the military and aerospace sectors (Johonson and Unkle 1989; Towne et al. 1988). The term ‘e-maintenance’ has emerged since early 2000 and reached its peak in 2010. The oldest paper that can be found in the set of papers we analyzed, is related to the ‘smart maintenance’ keyword. The work (Lahore 1984), a technical report by Boeing Aerospace Company, can be considered a pioneer in the field, proposing a program for applying Artificial Intelligence to electronic testability for the military sector. There are few other papers using the term ‘smart maintenance’ before 2000 and they are all related to the military sector. Most papers discussing about ‘smart maintenance’ are concentrated after 2014 (75% of papers related with the ‘smart maintenance’ keyword). The wording Maintenance 4.0 is seldom used in the scientific literature, as it can be noticed only 17 papers out of the total adopt such a wording.

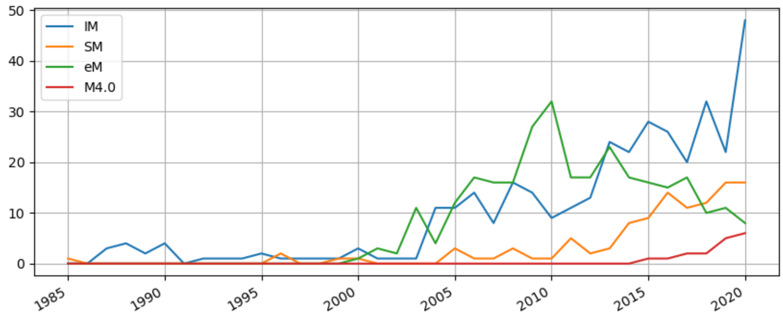


Figure 2. Annual publication volume on IM, SM, eM and M4.0 during 1970–2020 from Scopus database. Total records are 357 for IM, 111 for SM, 292 for eM, 17 for M4.0.

3.2. Country and institution analysis

The number of publications on a country basis is shown in Table 2. The country dominating IM publications is China followed by the United States and Brazil. The United States, together with Italy and Germany are the regions publishing more works on Smart Maintenance. These evidences are in line with what is reported in (Wang et al. 2020) about the fact that China is the region leading the number of publications on Intelligent Manufacturing, while the United States on Smart Manufacturing. France, Sweden and Spain lead the number of publications on eM, followed by Italy and China. M4.0 is a concept mostly introduced by German publications, even if the low publication volume does not allow to consider this evidence as robust as others. Collectively, China, United States, Italy, Germany, France and Sweden represent more than 75% of all publications about IM, SM, eM and M4.0 in Scopus database. Other countries appear to prefer one terminology over the others. For example, UK tends to use the eM concept, while Taiwan has more publications on IM.

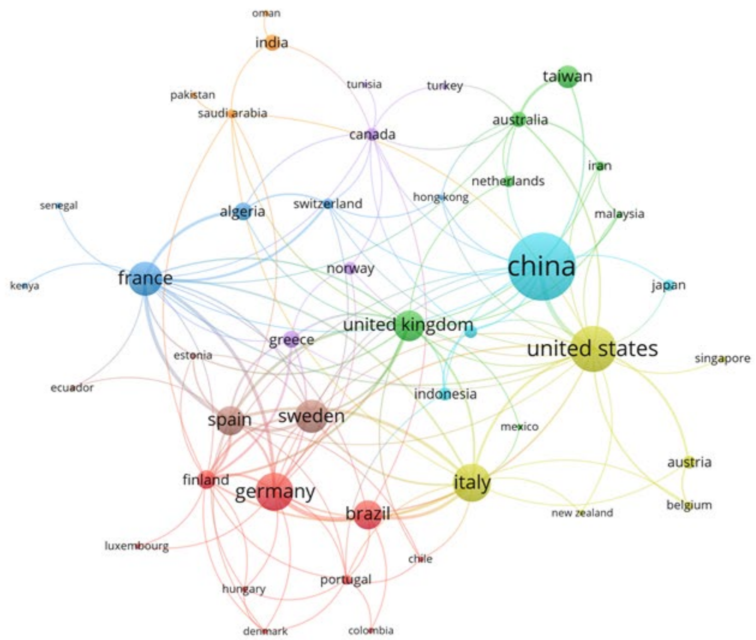
Total		Intelligent Maintenance		Smart Maintenance		e-Maintenance		Maintenance 4.0	
Country	**Count**	**Country**	**Count**	**Country**	**Count**	**Country**	**Count**	**Country**	**Count**
China	175	China	136	United States	19	France	46	Germany	4
United States	92	United States	49	Italy	19	Sweden	42	Poland	2
Italy	67	Brazil	42	Germany	15	Spain	35	Czech Republic	2
Germany	66	Germany	27	Sweden	8	Italy	33	Finland	2
France	55	United Kingdom	18	Austria	7	China	33	Turkey	2
Sweden	54	Taiwan	16	China	6	United Kingdom	23	Portugal	2
United Kingdom	47	Italy	15	United Kingdom	6	United States	23	Saudi Arabia	1
Brazil	44	India	11	Norway	4	Germany	20	Morocco	1
Spain	43	France	6	Japan	4	Algeria	18	India	1
Taiwan	28	Poland	5	Spain	4	Greece	17	Sweden	1

Table 2. Top countries publishing work on IM, SM, eM and M4.0 in Scopus database.

Figure 3 shows the cooperation among the publishing countries, plotted using VOSviewer (van Eck and Waltman 2013), a widely used information visualization tool. The size of the nodes represents the total linking strength, while the link thickness represents cooperation frequency between any two countries.

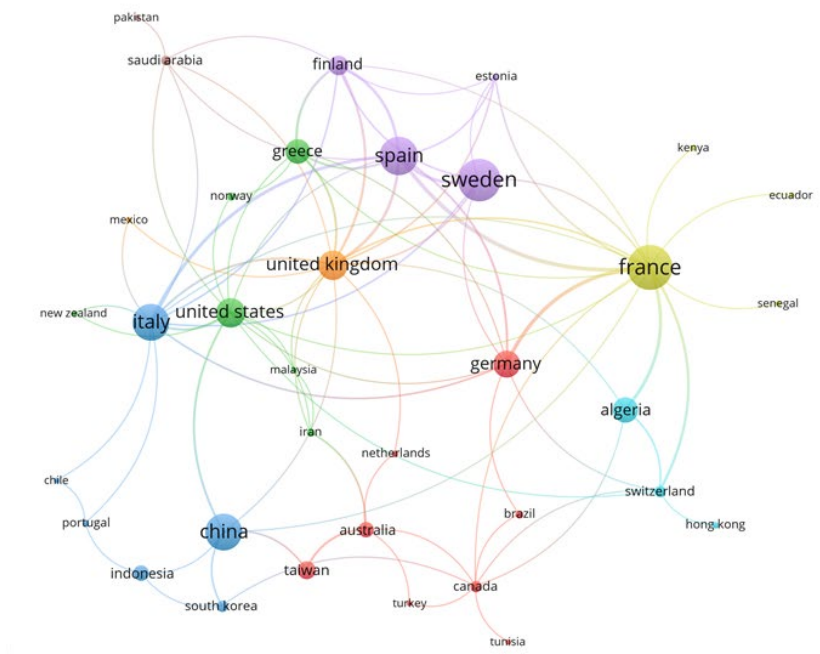
As seen in Figure 3(a), overall France, Spain, Germany, Brazil, Italy, United States and China are the countries cooperating most on IM, SM, eM and M4.0, meanwhile cooperation frequency is also strong in countries with fewer publications like UK, Sweden, Algeria, Australia, Taiwan.

As seen in Figure 3(b) China and United States and Brazil, Germany and Italy cooperate most on IM, meanwhile cooperation frequency is also strong in countries with fewer publications like France and UK. International cooperative research network on eM in Figure 3(c) shows higher cooperation frequency among France, Spain, Sweden, Italy and Germany; cooperation frequency is also strong in countries with fewer publications like Greece and Finland, and United States and China. As seen in Figure 3(d), most cooperation in SM is among China and the United States, and Germany in third place. Given the low number of scientific publications on M4.0, it is not relevant to analyze the cooperation among the different countries on this topic.

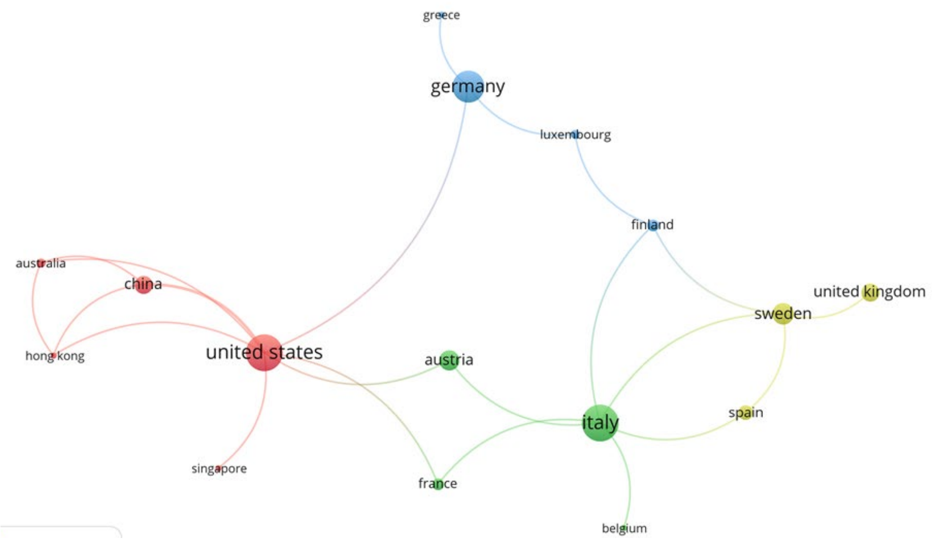


(a) International cooperative research network on IM, SM, eM and M4.0.

(b) International cooperative research network on IM



(c) International cooperative research network on eM



(d) International cooperative research network on SM

Figure 3. International cooperative research network on (a) IM, eM, SM; (b) IM, (c) eM, (d) SM

The number of institutions that published papers on IM, SM, eM and M4.0 is compiled in Table 3. Overall, top publishers are all universities, and the most prolific ones are Federal University of Rio Grande do Sul, Luleå University of Technology, Politecnico di Milano, Shanghai JiaoTong University, University of Münster and University of Cincinnati, being South America, Europe, Asia and North America all represented in top publishing universities.

For IM, the Federal University of Rio Grande do Sul is 2.9–1.9 times more prolific than each of the following top five universities. Luleå University of Technology, Politecnico di Milano and University of Seville are the top publishing organizations on eM, while publications about SM are spread almost equally among the top 5 publishing universities, two of them are from Italy (University of Bologna and Politecnico di Milano).

Total		Intelligent Maintenance		Smart Maintenance		e-Maintenance		Maintenance 4.0	
Organization	**Count**	**Organization**	**Count**	**Organization**	**Count**	**Organization**	**Count**	**Organization**	**Count**
Federal University of Rio Grande do Sul	28	Federal University of Rio Grande do Sul	28	Infineon Technologies Austria	4	Luleå University of Technology	23	Istanbul Technical University	2
Luleå University of Technology	27	University of Münster	15	Graz University of Technology	4	Politecnico di Milano	19	Poznan University of Technology	2
Politecnico di Milano	25	University of Cincinnati	12	University of Bologna	3	University of Seville	13	Lufthansa Technik	1
Shanghai JiaoTong University	17	Federal University of Rio Grande	12	Luleå University of Technology	3	ATHENA Research and Innovation Centre	11	Piri Reis University	1
University of Münster	16	Shanghai JiaoTong University	10	Politecnico di Milano	3	VTT Technical Research Centre	10	University of South Australia	1
University of Cincinnati	15	Federal University of Santa Catarina	9	East Japan Railway Company	3	Linnaeus University	9	MIMOSA	1
University of Seville	14	Tongji University	7	SMITEC S.p.A.	2	Fundación Tekniker	9	Czech University of Life Sciences Prague	1
Federal University of Rio Grande	12	Beijing University of Chemical Technology	7	AVL List GmbH	2	University of Nancy	6	University of West Bohemia	1
VTT Technical Research Centre	12	Università degli Studi di Bergamo	5	Università degli Studi di Milano-Bicocca	2	Shanghai JiaoTong University	6	Technischen Universität Wien	1
ATHENA Research and Innovation Centre	11	Chongqing University	5	Mälardalens University	2	National Taipei University of Technology	6	Montanuniversität Leoben	1

Table 3. Top organizations publishing works on IM, SM, eM and M4.0.

3.3. Top journal sources

The top sources for IM, SM, eM and M4.0 publications are compiled in Table 4. Overall, the IFAC-PapersOnLine has the highest number of publications. For IM, the IFAC-PapersOnLine has over four times the number of publications to its closest rivals, Lecture Notes in Mechanical Engineering, Applied Mechanics and Materials and Procedia CIRP. For eM, IFAC-PapersOnLine is also ranked number one, followed by Journal of Quality in Maintenance Engineering and Computers in Industry. SM and M4.0 appear distributed among the different sources without letting emerge a principal one.

Total		Intelligent Maintenance		Smart Maintenance		e-Maintenance		Maintenance 4.0	
Journal	**Count**	**Journal**	**Count**	**Journal**	**Count**	**Journal**	**Count**	**Journal**	**Count**
IFAC-PapersOnLine	54	IFAC-PapersOnLine	28	Lecture Notes in Electrical Engineering	4	IFAC-PapersOnLine	24	Lecture Notes in Mechanical Engineering	2
Journal of Quality in Maintenance Engineering	20	Lecture Notes in Mechanical Engineering	7	Procedia CIRP	3	Journal of Quality in Maintenance Engineering	16	ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb	2
Computers in Industry	13	Applied Mechanics and Materials	7	Productivity Management	3	Computers in Industry	10	Smart Innovation, Systems and Technologies	1
Procedia CIRP	11	Procedia CIRP	7	IFIP Advances in Information and	2	International Journal of Systems	9	Proceedings of International Conference on	1

				Communication Technology		Assurance Engineering and Management		Computation, Automation and Knowledge Management, ICCAKM 2020	
IFIP Advances in Information and Communication Technology	11	Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014	6	AUTOTESTCON (Proceedings)	2	E-Maintenance	8	Management and Production Engineering Review	1
International Journal of Systems Assurance Engineering and Management	11	AUTOTESTCON (Proceedings)	6	Journal of Applied Engineering Science	2	International Journal of Performability Engineering	7	Cognition, Technology and Work	1
Applied Mechanics and Materials	10	Journal of Quality in Maintenance Engineering	5	Computers in Industry	2	Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS	5	Proceedings - 2020 5th International Conference on Logistics Operations Management, GOL 2020	1
Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS	9	Lecture Notes in Electrical Engineering	4	Proceeding - 2015 IEEE International Conference on Industrial Informatics, INDIN 2015	2	IFIP Advances in Information and Communication Technology	5	IEEE International Conference on Emerging Technologies and Factory Automation, ETFA	1
Lecture Notes in Mechanical Engineering	9	Chinese Journal of Scientific Instrument	4	Proceedings of 3rd International Conference on Internet of Things and Applications, IoT 2019	2	Engineering Asset Lifecycle Management - Proceedings of the 4th World Congress on Engineering Asset Management, WCEAM 2009	5	IFAC-PapersOnLine	1
AUTOTESTCON (Proceedings)	8	IEEE Aerospace Conference Proceedings	4	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	2	Zhongguo Jixie Gongcheng/China Mechanical Engineering	5	Applied Ocean Research	1

Table 4. Top journals publishing works on IM, SM, eM and M4.0.

3.4. Keywords co-occurrence frequency

VOSviewer was also used for showing the keywords co-occurrence frequency analysis results. The word count (Table 5) in fact enables to analyze the keywords co-occurrence frequencies, while excluding the keywords used to designate the concepts, the general keyword Maintenance and any keyword referring to specific sector of application.

It results that Fault Diagnosis, Predictive Maintenance, Condition Monitoring, Condition-Based Maintenance and Artificial Immune Systems make up over 50% of the top keywords co-occurring with Intelligent Maintenance and IM systems in the research literature. The top 50% of keywords co-occurring with SM include Industry 4.0, Internet of Things, Condition Monitoring, Predictive Maintenance and Machine Learning. Other top concepts include Digitalization, Augmented Reality and Condition-Based Maintenance. Regarding eM, the word count finds that Condition-Based Maintenance, Diagnostics, Knowledge Management, Prognostics, Web Services and Condition Monitoring make up over 50% of the top co-occurring keywords. The top 50% of keywords co-occurring with M4.0 include Industry 4.0, Sustainable Maintenance, Internet of Things, Predictive Maintenance, Human Error and Maintenance Operations. Overall, keywords usage frequency indicates a wide coverage of topics in IM, SM, eM and M4.0, both looking at the application side of supported programs, processes, activities (Condition-Based Maintenance, Predictive Maintenance, Condition monitoring, Fault Diagnosis, Diagnostics and Prognostics) and at the digital technology perspective (Industry 4.0, Internet of Things, Web Services, Knowledge Management, Machine Learning, Multi-Agent Systems, Augmented Reality, Artificial Intelligence, Ontologies).

Total		**Intelligent Maintenance**		**Smart Maintenance**		**e-Maintenance**		**Maintenance 4.0**	
Keyword	**Count**	**Keyword**	**Count**	**Keyword**	**Count**	**Keyword**	**Count**	**Keyword**	**Count**
e-Maintenance	128	Intelligent Maintenance	48	Smart Maintenance	36	e-Maintenance	127	Industry 4.0	6
Maintenance	74	Intelligent Maintenance Systems	39	Industry 4.0	17	Maintenance	40	Maintenance 4.0	5
Intelligent Maintenance	49	Fault Diagnosis	23	Maintenance	13	Condition-Based Maintenance	20	Sustainable Maintenance	2
Intelligent Maintenance Systems	40	Maintenance	19	Internet of Things	8	Diagnostics	14	Internet of Things	2
Condition-Based Maintenance	38	Predictive Maintenance	14	Condition Monitoring	7	Knowledge Management	12	Predictive Maintenance	2
Smart Maintenance	37	Condition Monitoring	13	Predictive Maintenance	6	Prognostics	11	Ship Pms	2
Industry 4.0	35	Condition-Based Maintenance	13	Railway	4	Web Services	11	Human Error	2
Predictive Maintenance	32	Artificial Immune Systems	8	Machine Learning	4	Condition Monitoring	10	Maintenance Operations	2
Condition Monitoring	31	Fault Detection	8	Digitalization	4	Predictive Maintenance	10	Ship Maintenance	2
Fault Diagnosis	29	Case-Based Reasoning	7	Augmented Reality	4	Multi-Agent Systems	10	Industrial Maintenance	2
Diagnostics	21	Spare Parts Supply Chain	7	Condition-Based Maintenance	4	Ontologies	9	Maintenance	2
Prognostics	18	Decision Support Systems	7	Power Transformer	3	Unified Modeling Language	7	Fuzzy-Ahp	1
Internet of Things	17	Industry 4.0	7	Web Services	3	Information And Communication Technologies	7	Migration	1
Web Services	15	Cyber-Physical System	7	Fuzzy Logic	3	Reliability Centered Maintenance	7	Human Factor	1
Knowledge Management	14	Expert Systems	6	Smart Factory	3	Remote Maintenance	6	Operational Safety	1
Machine Learning	14	Prognostics	6	Smart Manufacturing	3	Machine Learning	6	Human Reliability	1

Multi-Agent Systems	13	Feature Extraction	6	Diagnostics	3	Building Information Modelling	6	Ship Auxiliary Machinery	1
Augmented Reality	11	Artificial Intelligence	6	Interoperability	3	Reliability	5	Sohra	1
Artificial Intelligence	11	Rolling Bearing	6	Asset Management	3	Proactive Maintenance	5	Heart	1
Ontologies	10	Fuzzy Logic	6	Digital Twin	2	Industry 4.0	5	Iiot	1

Table 5. Top frequency keywords related to IM, SM, eM and M4.0.

4. Evolutionary comparison of e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0

4.1. Concepts evolution in different temporal phases

The bibliometric data summarized in Section 3 was used to analyze and compare the evolution of e-maintenance, intelligent maintenance, smart maintenance and maintenance 4.0 concepts. Examining their evolutionary path can provide a better understanding of the consistency of concepts development. From the growth in annual publications shown in Figure 2, as well as reflecting the study by (Wang et al. 2020), the evolutionary phases of the research on the identified concepts are hypothesized to occur in four phases: Phase I (1985–2000), Phase II (2001–2010), Phase III (2011–2015), and Phase IV (2016–2020), as shown in Table 6.

Total	Phase I 1985-2000	Phase II 2001-2010	Phase III 2011-2015	Phase IV 2016-2020
Keywords	Analytic Hierarchy Process, Fuzzy Logic, Information Systems, Decision Support Systems	Condition Monitoring, Diagnostics, Web Services, Prognostics	Fault Diagnosis, Condition Monitoring, Knowledge Management, Fault Detection	Industry 4.0, Internet of Things, Fault Diagnosis, Machine Learning
Concepts Percentage	**76% IM** 19% SM 5% eM	37% IM 4% SM **59% eM**	**45% IM** 13% SM **41% eM** 1% M4.0	**51% IM** 23% SM 21% eM 5% M4.0
Paper number in Scopus	21 papers	236 papers	216 papers	290 papers
High Citation Papers	(Labib, Williams, and Connor 1998) (Deb, Pattipati, and Shrestha 1997) (Kobbacy, Proudlove, and Harper 1995)	(Lee et al. 2006) (Muller et al. 2008) (Tsang 2002)	(Lee et al. 2015) (Kumar et al. 2013) (Chen et al. 2011)	(Selcuk 2017) (Berredjem and Benidir 2018) (Antonio J. Guillén et al. 2016)

Table 6. Evolution of e-maintenance, intelligent maintenance, smart maintenance and M4.0 concepts from literature analysis perspective.

- Phase I (1985–2000): 21 papers were published during this period. The keywords most used in these papers include, in order of their frequency, Analytic Hierarchy Process, Fuzzy Logic, Information Systems and Decision Support Systems. In this phase, the most mentioned and clearly dominant concept is IM, whereas a few papers refer to SM and eM.
- Phase II (2001–2010): 236 papers were published during this period. The keywords most used in these papers include Condition Monitoring, Diagnostics, Web Services and Prognostics. In this phase, the most mentioned concepts are, in order of frequency, eM and IM, and a few papers referring to SM.
- Phase III (2011–2015): 216 papers were published during this period. The keywords most used in these papers include Fault Diagnosis, Condition Monitoring, Knowledge Management and Fault Detection. In this phase, the most mentioned concepts are, in order of frequency, IM and eM almost equally used, and SM, and very few papers referring to M4.0.

- Phase IV (2016–2020): 290 papers were published during this period, showing a further increase in maintenance interest. The keywords most used in these papers include Industry 4.0, Internet of Things, Fault Diagnosis, Machine Learning. IM comes back as most commonly used concept; SM appears to be more often used overcoming eM in term of usage frequency. Still few papers refer to M4.0.

The bibliometric comparison of the four concepts evolutionary path shows that keywords have changed as research into enabling technologies and research hotpots changed.

The evolutionary path of each single concept was also analyzed, as shown in next Tables. Looking at the most used keywords with intelligent maintenance (Table 7), it is possible to assess that the IM term is commonly outlined in light of the decision-making support, rather than the ICT systems (Huang et al. 2005; Kobbacy et al. 1995; Labib et al. 1998). Nevertheless, it is also evident that enabling technologies are at the background and, especially in the most recent phases, a higher growth of technology perspective is observed (in the most cited keywords such as, e.g. Industry 4.0, Artificial Immune Systems, and Artificial Intelligence). Most publications about e-maintenance (Table 8) (Jonsson, Holmström, and Levén 2010; Voisin et al. 2010) clearly address the use of technologies in the ICT domain, as different Internet technologies, and subsequent e-collaboration principles for maintenance. Collaboration is in fact a core element in e-maintenance related publications, in order to share and exchange not only information but also knowledge and (e)-intelligence in order to facilitate reaching the best maintenance decisions (Muller et al. 2008). Correspondingly, technologies to implement collaborative approaches are traced along the evolution of the eM concept (see keywords such as Multi-Agent Systems, Knowledge Management, Ontologies, Web Services, Unified Modeling Language, Building Information Modelling). More recently, the eM concept is also influenced by the technologies of the current digital era (as evidenced by the keywords of Industry 4.0 and Machine Learning). Papers about Smart Maintenance and Maintenance 4.0 are more recent, mainly concentrating in Phase IV (Table 9 and 10). The digitalization is central and closely related to these concepts as Industry 4.0 and Internet of Things are the most cited keywords.

Total	**Phase I 1990-2000**	**Phase II 2001-2010**	**Phase III 2011-2015**	**Phase IV 2016-2020**
Keywords	Analytic Hierarchy Process, Fuzzy Logic, Information Systems, Decision Support Systems	Fault Diagnosis, Case-Based Reasoning, Knowledge-Based Systems, Fuzzy Logic	Fault Diagnosis, Artificial Immune Systems, Condition Monitoring, Fault Detection	Fault Diagnosis, Industry 4.0, Rolling Bearing, Artificial Intelligence
Paper number in Scopus	16 papers	87 papers	98 papers	148 papers
High Citation Papers	(Labib et al. 1998) (Deb et al. 1997) (Kobbacy et al. 1995)	(Mahulkar et al. 2009) (Iung, Morel, and Léger 2003) (Yuniarto and Labib 2006)	(Lee et al. 2015) (Espíndola et al. 2013) (Hongxia et al. 2015)	(Berredjem and Benidir 2018) (Shang et al. 2018) (Antoni and Borghesani 2019)

Table 7. Evolution of intelligent maintenance from literature analysis perspective.

Total	**Phase I 1990-2000**	**Phase II 2001-2010**	**Phase III 2011-2015**	**Phase IV 2016-2020**
Keywords	NA	Diagnostics, Multi-Agent Systems, Prognostics, Condition Monitoring	Knowledge Management, Ontologies, Web Services, Unified Modeling Language	Building Information Modelling, Industry 4.0, Machine Learning, Smart Manufacturing
Paper number in Scopus	1 paper	140 papers	90 papers	61 papers
High Citation Papers	(Hamel 2000)	(Lee et al. 2006) (Muller et al. 2008) (Tsang 2002)	(Kumar et al. 2013) (Chen et al. 2011) (Aboelmaged 2014)	(Selcuk 2017) (Antonio J. Guillén et al. 2016) (Karim et al. 2016)

Table 8. Evolution of e-Maintenance from literature analysis perspective.

Total	Phase I 1990-2000	Phase II 2001-2010	Phase III 2011-2015	Phase IV 2016-2020
Keywords	NA	Context-Based Services, Automatic Fault Detection, Condition Monitoring, Novelty Detection	Power Transformer, Security, Fuzzy Logic, Fault Diagnosis	Industry 4.0, Internet of Things, Condition Monitoring, Digitalization
Paper number in Scopus	4 papers	10 papers	27 papers	69 papers
High Citation Papers	(Breuker, Rossi, and Braun 2000)	(D'Elia et al. 2010) (Munzinger et al. 2009) (Shannon et al. 2005)	(Lesjak et al. 2015) (Yokoyama 2015)	(Bumblauskas et al. 2017) (Flammini, Pragliola, and Smarra 2017) (Rakyta et al. 2016)

Table 9. Evolution of smart maintenance from literature analysis perspective.

Total	Phase I 1990-2000	Phase II 2001-2010	Phase III 2011-2015	Phase IV 2016-2020
Keywords	NA	NA	NA	Industry 4.0, Internet of Things, Ship PMS, Human Error
Paper number in Scopus	NA	NA	1 paper	16 papers
High Citation Papers	NA	NA	(Nemeth et al. 2015)	(Cachada et al. 2018) (Jasiulewicz-Kaczmarek and Gola 2019) (Kans, Galar, and Thaduri 2016)

Table 10. Evolution of maintenance 4.0. from literature analysis perspective.

4.2. Attributes and consequences of the focal concepts: findings from literature

Following the methodology by (Podsakoff et al. 2016), the aim is now to review the literature in order to gather existing understanding of the different concepts. To this end, we collected a subset of papers, focusing on well cited publications in peer-to-peer journals and published in the last twenty-five years; moreover, the papers were selected as they provide explicit definitions of the focal concepts. Therefore, we selected papers addressing intelligent maintenance or e-maintenance or smart maintenance (maintenance 4.0 is not considered due to the limited number of papers), and we analyzed how the concepts are defined in their core elements identified by each paper.

The objective is to distinguish the core elements in attributes – intended as features used to characterize the focal concept – and consequences – intended as objectives or expected benefit aimed by the focal concept. In particular, we codified a set of attributes (A.x) and consequences (C.x) emergent from the selected papers: Based on data analytics (A.1); Self-learning (including machine, human and/or organizational learning) (A.2); Based on condition monitoring (A.3); Predictive and dynamic (with real-time response) (A.4); Revolutionary change (A.5); Enabled by new technology (A.6); Enabled by human capital resource (A.7); Integration and Collaboration (A.8); Support to human decision-making (C.1); Allowing intra-company or inter-company integration (such as, e.g., intra-company integration between maintenance and production, or integration of end-user with key suppliers/machine vendors) (C.2); Aimed at maintenance optimization (as cost-effective decision-making and/or the performance of maintenance as a business function) (C.3); Aimed at increasing asset performance / asset cost (along the lifecycle) (C.4).

The selected papers are classified according to the addressed focal concept (IMx, EMx, SMx, respectively for intelligent maintenance, e-maintenance and smart maintenance) and the designated codes for attributes and consequences (Table 11). The selected papers are enlisted in the reminder: (Kobbacy, Proudlove, and Harper 1995) (IM1); (Labib, Williams, and Connor 1998) (IM2); (Moore and Starr 2006) (IM3); (Lee et al. 2006) (EM1); (Muller, Crespo Marquez, and Iung 2008) (EM2); (Iung et al. 2009) (EM3); (Munzinger et al. 2009) (SM1); (Bumblauskas et al. 2017) (SM2), (Bokrantz et al. 2019) (SM3).

	C.1 Support human decision-making	C.2 Allowing intra- or inter-company integration	C.3 Aimed at maintenance optimization	C.4 Aimed at increasing asset performance / asset cost	*Tot*
A.1 Based on data analytics	IM1, SM3	EM2, SM3	IM1, EM1, EM2, SM2	EM1, EM2, SM2	*5*
A.2 Self-learning	IM1, SM3	SM3	IM1	/	*2*
A.3 Based on condition monitoring	IM2, IM3	IM2, EM2	IM2, IM3, EM1, EM2, SM2	EM1, EM2, SM2	*5*
A.4 Predictive and dynamic	/	EM2	EM1, EM2, SM2	EM1, EM2, SM2	*3*
A.5 Revolutionary change	/	EM2	EM2	EM2	*1*
A.6 Enabled by new technology	IM3, SM3	EM2, EM3, SM3	IM3, EM1, EM2, EM3, SM2	EM1, EM2, SM2	*6*
A.7 Enabled by human capital resource	SM3	SM3	/	/	*1*
A.8 Integration and Collaboration		EM2, EM3	EM2, EM3	EM2	*2*
Tot	*4*	*4*	*7*	*3*	

Table 11. Attributes and Consequences identified about the different maintenance concepts

On one hand, looking at the consequences, all papers addressing the intelligent maintenance concept focus on the objective of supporting human-decision making (C.1); this is also recalled by one of the selected papers about smart maintenance. Interestingly, the papers dealing with e-maintenance and smart maintenance recognize the aim at increasing asset performance and/or asset cost (along the lifecycle) (C.4) as an important consequence, whereas, all the concepts consider Maintenance optimization (C.3), especially the intelligent maintenance and e-maintenance. Another relevant consequence for e-maintenance is integration (C.2), which is also remarked by one paper about intelligent maintenance and one paper about smart maintenance. On the other hand, looking at the attributes, papers referring to e-maintenance have a strong focus on enabling technology (A.6); nevertheless, enabling technology is a key attribute evident across the different concepts, this is in fact remarked by two of the selected papers of the smart maintenance concept and one paper on intelligent maintenance. A specific relevance across concepts is also provided both to data analytics (A.1), commonly referred by e-maintenance and smart maintenance (two papers each) and intelligent maintenance (one paper), and to condition monitoring (A.3), commonly referred by e-maintenance and intelligent maintenance (two papers each) and smart maintenance (one paper).

Combining this analysis and the trend observed through time (Figure 2), we can reasonably confirm that the evolution of the intelligent maintenance and e-maintenance concepts created the background for the more recent development of the smart maintenance concept. Indeed, nowadays it seems that two perspectives are jointly emerging – both a human decision-making support perspective and a technology perspective – within the smart maintenance concept. Amongst the selected papers, it is worth raising the attention on the recent publication by (Bokrantz et al., 2019) (SM3 in Table 11), claimed by the authors to be the "first empirically grounded definition of smart maintenance". Building on focus groups and interviews with more than 110 experts from over 20 different firms, it aims to conceptualize smart maintenance and, as a result, it identifies four aggregate dimensions – data-driven decision-making, human capital resource, internal integration, and external integration – as core elements further described with lower order categories. The categories and the theoretical reflections reported within the paper, enable to recognize the relevance of both technology and human capital resource (A.6 and A.7) as enablers, with a particular remark on the role played by data analytics (A.1). Besides, the support to human decision-making (C.1) and both the intra- and inter-company integration (internal and external integration in the publication) (C.2) are clearly remarked as consequences of the focal concept application. Overall, these evidences appear to be a further development subsuming knowledge already achieved by past concepts as intelligent maintenance (C.1) and e-maintenance (A.1, A.6, C.2), with a reinforcement on the emphasis on the human capital as key resource (A.7) brought about by the smart maintenance concept.

5. Evidence from multiple case study

5.1. Definitions and understanding from industrial experts

In the multiple case study, we conducted semi-structured interviews by including, as first question of the interview's protocol, the definition of smart maintenance (or even Maintenance 4.0 or similar phrasings as equivalent terms) gathered from the interviewees' perspective. We then followed the same process used for the literature review findings, by identifying the attributes and consequences of the concept. The following list reports some definitions provided by the experts as exemplary quotations.

- (Case A) "Maintenance within Industry 4.0 – or Smart Maintenance – is the step beyond the predictive, intelligent maintenance that helps not only from the point of view of machine availability but helps to improve the quality performance. An activity that helps to aggregate data, to go beyond the technical specifications. Not just a set of alarms, but also evaluations of whether the asset is working well or not well and how, so you can improve performance".
- (Case B) "Smart Maintenance is an evolutionary path that, starting from big data and new skills, can allow us to predict faults and therefore increase performance improving the reactivity of the system".
- (Case C, expert #1) "To go deeper and deeper in looking at the signals that the system gives you and going towards their intelligent interpretation, integration from the production management point of view with the predictive maintenance must be done".
- (Case C, expert #2) "I am sure not to confuse the maintenance concepts with what Industry 4.0 brings: 4.0 can be a tool to implement predictive maintenance in the best way but it is not a maintenance philosophy. Integration is a cornerstone of the future for increased effectiveness in database and risk management. 4.0 done in an organic way gives me the opportunity to prioritize and guide investment choices. Often when we talk about 4.0 we forget a fundamental asset: competence. There is no effective digitization without know-how. You need people who can analyze and use algorithms."
- (Case E) Smart Maintenance for us is a completely new paradigm that culturally shifts maintenance into a world of predictions and prevention of failure, which fits into a more traditional culture where maintenance mixes are based on Reliability Centered Maintenance. The maintenance technician must always be more knowledgeable about the data and the process".
- (Case G, expert #3) "Known the human genome and known the disturbing factors, we can predict diseases and estimate the remaining life: studying digital maintenance is like studying the DNA of a human body"
- (Case H, expert #1) "Maintenance 4.0 – or Smart Maintenance – is an evolutionary path that starts with the evolution of classic maintenance, of operative nature, to move towards Maintenance Engineering. To develop Maintenance 4.0, it is necessary to have some additional capabilities, such as the necessary resources, the mentality and, therefore, the training for the use of the digitalization of the data of the production process. This, then, leads to a better knowledge of the impact in terms of asset degradation,

thus obtaining a better capacity for decisions on policies and maintenance plans, which are more based on operational data and information, and on knowledge of real trends".

- (Case I) "Having the right person (qualified people with appropriate tools) in the time and place exactly (predictive) before the failure. Maintenance 4.0 is not a revolution, but an evolution of maintenance".

On the whole, the definitions herein reported are a sample useful to illustrate the current understanding of concepts related to advanced maintenance systems. It is worth observing that some industrial experts are providing more futuristic definitions than others, relying on the use of some metaphor (i.e., human body and alike); nevertheless, the most of interviews revealed more an evolutionary path, with novel issues enhancing past developments. Two main perspectives emerge.

- On one hand, some experts foresee an important and not avoidable evolution of the way of doing maintenance in the Industry 4.0 context, leading towards a new intelligent, predictive and dynamic maintenance, and allowing to increase the performance of the industrial assets based on the predictive capability.
- On the other hand, it is perceived that "traditional" maintenance processes will have the opportunities to be improved, being supported by the technologies of Industry 4.0 introduced as advanced supporting tools. In this perspective, it is also fostered an increased integration with other business functions (e.g. production, quality).

Both perspectives – both asset and business process/function-oriented – reveal a common understanding of digitalization as important lever to move the maintenance evolution ahead.

5.2. Attributes and consequences of the focal concepts based on the multiple case study findings

The multiple case study was helpful to provide some focused change to the attributes' list emerged from the literature findings, now slightly revised based on the experts' interviews. In particular, Table 12 provides the evidence gathered from the nine companies involved in the multiple case study.
Firstly, the evolutionary change (A.5b) provides a diverse viewpoint with respect to the original statement emerged in literature findings, i.e. the revolutionary change (A.5a). Secondly, a particular remark is now given on the prominence of integration and collaboration, stressing more a flavor of organizational aspect, rather than technological one (A.8): this attribute leads to reinforce a double-view on the aspect of integration and collaboration, being both a requirement to be improved from the organizational side to enable a technology implementation to be successful (A.8), and a consequence resulting from the application of technology (C.2). Last but not least, an additional insight confirms the relevance of the human capital resource, remarking the requirements of new skills and capabilities (A.9), that was identified as a new attribute based on the case study evidence. It is interesting to observe that the core elements are confirmed by the case study, such as the relevance of technology and, in particular, data analytics to achieve a predictive and more dynamic maintenance. Only self-learning never emerged as an attribute directly from the coding, while condition monitoring was (sometimes explicitly, sometimes implicitly) assumed during the interviews as a necessary step towards a predictive capability.

Attributes and Consequences		**Company**									
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**Tot**
A.1	Based on data analytics	X	X	X		X		X	X		6
A.2	Self-learning										/
A.3	Based on condition monitoring	X		X	X			X	X		5
A.4	Predictive & dynamic		X	X	X	X		X		X	6
A.5a	Revolutionary change					X					1
A.5b	**Evolutionary change**	X	X		X		X	X	X	X	7

A.6	Enabled by new technology			X			X	X	X		4
A.7	Enabled by human capital resource		X	X		X			X	X	5
A.8	**(Requires) an improved integration and collaboration**			X		X			X		3
A.9	**Requires new skills & capabilities**		X	X		X			X		4
C.1	Support to human decision-making			X	X	X		X	X		5
C.2	Allows intra- or inter-company integration			X							1
C.3	Aimed at maintenance optimization							X		X	2
C.4	Aimed at increasing asset performance / asset cost	X	X					X			3

Table 12. Attributes and consequences about the 'smart maintenance' concept identified through the case study (A = attribute, C = consequence, in bold letters the newly added or modified attributes)

6. Discussion

The potential brought by the Industry 4.0 vision is moving ahead the digitalization of manufacturing, leading to a transition towards Smart Factories that encompass varied concepts and solutions including, among others, Cyber Physical Systems, Internet of Things, Cloud and Big Data solutions. This transformation implies a change relevant both to debate new scientific directions, and to establish a new manufacturing practice.

Broadly speaking, there are evidence of different ways on how Smart Manufacturing and Intelligent Manufacturing have been addressed in the literature as key paradigms linked with the industrial revolution (Barari et al. 2021, Wang et al. 2021), nominally designated in different streams of research but at the same time entailing features and research foci with a partial overlapping in subsequent concepts and technology development. This general observation is confirmed by our findings in regard to the evolution of maintenance of production assets.

Intelligent maintenance and e-maintenance have a long and well developed history, relevant for creating a solid knowledge background to build advanced maintenance systems. Nowadays, smart maintenance is also a promising concept, showing a rapid growth observed over the last five years, but in its infancy if compared to the previously developed concepts. We are confident to assert that intelligent maintenance has a key role as a background, as it is also demonstrated by its persistence through different temporal phases in concepts evolution (Table 6). Its special emphasis to the capability of intelligent decision support is a footprint to lead the future technology-based transformation of maintenance development. E-maintenance is a key concept as well, because of its contribution to build an essential knowledge base, developed especially during its "golden age", concerning programs, processes, activities target of application of technologies in maintenance domain, i.e. Condition-Based Maintenance, Predictive Maintenance, Condition monitoring, Fault Diagnosis, Diagnostics and Prognostics. In particular, the special emphasis on integration and collaboration of resources promoted by e-maintenance is meaningful for the future, moving towards a facilitation of maintenance decisions. Nowadays, smart maintenance is growing parallel to the significant role of intelligent maintenance, leaded by countries in different regions worldwide, the United States and China being the top countries respectively for the two concepts. It confirms the evidence on the general trend for the Smart Manufacturing and Intelligent Manufacturing paradigms.

Overall, along their evolutions, intelligent maintenance, e-maintenance and smart maintenance concepts are evidently sharing a blend of digital technologies, majorly in the ICT domain, for application in maintenance (Industry 4.0, Internet of Things, Web Services, Knowledge Management, Machine Learning, Multi-Agent Systems, Augmented Reality, Artificial Intelligence, Ontologies). It is quite natural to reflect on the fact that these are emerging along different temporal phases as a sign of the times in the technology development. Given the technology development, in this research work we aim at discussing a condensation of the attributes and consequences proposed in previous sections (section 4 and 5), to finally synthesize the entire knowledge associated to the focal concepts, in a definition helpful with the purpose to inform the use of technologies in the maintenance field. This is done by leveraging on the findings both from literature review and the multiple case study, according to the guideline from (Podsakoff et al. 2016). In particular, the perceptions found by multiple case study were deemed enough to describe the focal concepts background of an advanced maintenance system, to finally develop a definition in line with the expectations of literature findings.

Combining these findings, we provide a definition of smart maintenance concept: 'smart maintenance is an evolutionary change of maintenance, enabled by new technologies and by human capital resource, and requiring the development of new skills and capabilities and an improved organizational integration and collaboration. The consequence is advanced support to human decision-making in a collaborative work with other business functions within and outside the company, aimed at optimizing maintenance and at increasing asset performance and cost along the asset lifecycle'.

This definition is proposed both to embed knowledge from past evidences and recent literature findings. A particular benchmark for a definition of a similar kind, is (Bokrantz et al. 2019). Similar to this publication, we are asserting the relevance of integration as organizational matter as well as human capital as a source of knowledge and skills for advanced maintenance. Our peculiar remark, within our findings, is the objectives addressed by a smart maintenance concept, clearly aimed at a better maintenance performance and, as potential, at a better contribution to the lifecycle performance and cost of the assets. Moreover, we have underlined the major perception of an evolutionary change, building on the past achievements, both from science and practice, determining a definition of smart maintenance that finds its roots in previous focal concepts development.

Concluding, we think that the provided definition can help synthesizing the key core elements that are common between e-maintenance and intelligent maintenance playing the role, based on our understanding of the findings reported in this paper, as a kind of precursors of what is currently brought by smart maintenance in the digital era. Having this mind-set, we do believe that the different concepts will be still continuing to be adopted along with their own routes and research foci, with the final end of implementing new technologies in order to innovate maintenance to make it smarter/more intelligent.

7. Conclusions and future research agenda

The present paper investigated the evolution of maintenance of production assets as promising ground where to implement Industry 4.0-like solutions. The final aim was to shape the current understanding of the focal concepts at the background of an advanced maintenance system built upon the characteristics induced by the digital transformation.

We initially provided a bibliometric analysis especially focused on connotation and technical development of the concepts along the years, i.e. the intelligent maintenance, e-maintenance and smart maintenance as the focal concepts majorly discussed in literature. The evidence is the existence of evolutionary paths where the three concepts (and other close concepts, as Maintenance 4.0) have in common a trend of maintenance-related technologies and advanced maintenance systems built upon ICT. Indeed, the literature review confirms the expectation that smart maintenance occurs more frequently with keywords of Industry 4.0, Internet of Things, Condition Monitoring, Predictive Maintenance and Machine Learning. Nevertheless, it makes evident also that common aspects are addressed by all concepts, including Condition monitoring, Predictive Maintenance, Diagnostics and Prognostics, as well as a wide set of technologies from the ICT domain such as Internet of Things, Machine Learning, Augmented Reality, Artificial Intelligence, Ontologies, etc.

The state of the art along the evolutionary paths prepared the ground to reflect on the co-evolution of focal concepts, also stimulating their characterization for the maintenance practice. This was in fact achieved after the selection of most cited papers from literature including explicit definitions of the three majorly adopted concepts, and the subsequent identification of the core elements of such concepts – designated as attributes and consequences. Starting from the coding of literature review of the core elements, the multiple case study enabled us to refine and finally shape the current understanding of the focal concepts at the background of an advanced maintenance system. This was possible through a concrete definition of the smart maintenance concept, built upon the most significant attributes and consequences.

This enables materializing the change of maintenance practice in the future, also being aware of the special importance of intelligent maintenance and e-maintenance as a knowledge background and, in particular, of intelligent maintenance as a persistent concept through different time epochs. It is in fact not just a matter of defining one or the other concept, it is more important to find common traits on which to act in order to bring about the change in maintenance practice. Based on literature and the feedback from the multiple case study we then remarked the balanced relevance of the enabling factors of new technologies and human capital resource, to drive building advanced support to human decision-making in a collaborative work environment. This is the key issue we can see for the future agenda, considering the role of maintenance not just for what concern the business function per se, but for its contribution to the lifecycle performance and cost of industrial assets.
This calls for future research works to further understand and implement the smart maintenance/intelligent maintenance in manufacturing.

- Looking at technology as enabler, smart/intelligent maintenance of production assets will rely upon the improved predictive capabilities resulting from Artificial Intelligence technologies (Machine learning, Deep Learning) and the joined use of data and virtual (digital) models within the emergent technologies of Digital Twins. Moreover, considering the importance of advanced support to human decision-making, the cognitive aspects will be essential, which may result in the growth of importance of the augmentation technologies.
- Looking at human capital resource as enabler, smart/intelligent maintenance of production assets still looks for a better capability to develop and manage knowledge. This will ask to define knowledge, skills and abilities required by the maintenance personnel in the digital era and, subsequently, a renewal of education programmes within maintenance fitting such requirements. In this change, novel forms of interdisciplinary education may be also expected (e.g., by developing innovative laboratory activities on industrial case projects and/or by involving different disciplines such as mechanical engineering and data science).
- Considering integration and collaboration, the double-view of this aspect calls for a co-evolution of key enabling technologies and business roles and processes. This is not a new problem per se as it was already evident during the e-maintenance epoch. We think that it is today important bringing it to practice, leading to exploratory researches to validate a theory on the best practice to implement collaborative approaches between maintenance and key business functions along the lifecycle of the assets within and outside the company.

To complement the perspective provided in our analysis, we consider also useful to conduct an explanatory research that, starting from the attributes and consequences associated with smart/intelligent maintenance, addresses the implementation challenges and expected benefits in small and mid-size enterprises and large-size enterprises belonging to different industrial sectors. This may provide further insights to systematically understand the promise brought about by smart/intelligent maintenance in real industrial settings.

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