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On the focal concepts of Maintenance in the Digital era

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Abstract: This work aims to reflect on the focal concepts in the background of an advanced maintenance system built on the characteristics induced in the digital era. The focal concepts are firstly analysed by giving prominence both to past and recent evolutions, making a literature review in regard to intelligent maintenance, e-maintenance, smart maintenance and maintenance 4.0 as main keywords. Based on the literature findings, a set of attributes and consequences as core elements of the focal concepts is codified; these are further adopted in a multiple case study analysis aimed to explore the perceptions from industry.

Keywords: Intelligent maintenance, E-maintenance, Smart Maintenance, Maintenance 4.0

1. INTRODUCTION

In the current time, digital transformation is impinging upon the whole society and the industrial world (Loebbecke & Picot, 2015). Looking at manufacturing, it is popular to address digital transformation by the term 'Industry 4.0' as it was coined by Germany (Kusiak, 2017). Such term embeds a variety of concepts and key enabling technologies, including but not limited to Cyber Physical Systems, Internet of Things, Cloud and Big Data (Gölzer & 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, Skoogh, Berlin, & Stahre, 2017; Macchi, Roda, & 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 activities. 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 communication and information technologies (ICT) has been studied in the literature since early 2000, and concepts like e-maintenance and intelligent maintenance have been largely addressed (Alaswad & Xiang, 2017; Guillén, Crespo, Macchi, & Gómez, 2016; Kwon, Hodkiewicz, Fan, Shibutani, & Pecht, 2016; Muller, Crespo Marquez, & Iung, 2008; Vogl, Weiss, & Helu, 2016). Moreover, condition based maintenance (CBM) was discussed as a relevant aspect of e-maintenance and intelligent maintenance, and the evidence that predictive maintenance and its application in machine health prognosis are becoming very popular in the Industry 4.0-based literature (Campos, Sharma, Jantunen, Baglee, & Fumagalli, 2016; Isaksson, Harjunkoski, & Sand,

2017; G.-Y. Lee et al., 2018; J. Lee, Ghaffari, & Elmeligy, 2011; Zheng et al., 2018), can be interpreted as a natural consequence of the past discussions. In our understanding, it is relevant to organize the knowledge under development at the current time, considering a solid reference to past achievements as the ground on top of which new Industry 4.0-like solutions are built. Therefore, this work studies the evolution of concepts as e-maintenance and intelligent maintenance, besides the 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. As an overall result, it appears relevant the definition and use of a concept of smart maintenance. This term is well aligned with the current trends while embedding the past knowledge due to e-maintenance and intelligent maintenance. Moreover, specific issues are remarked, induced by the digital era, with special emphasis to human and organizational aspects.

To achieve this result, the paper is so structured: section 2 describes the research methodology; section 3 describes the literature findings; section 4 captures the current perceptions, exploiting the multiple case study; section 5 discusses all the findings to synthesize the definition of a smart maintenance concept, proposed as foundation of an advanced maintenance system in the digital era; finally, section 6 concludes with some stimuli for a future research agenda.

2. RESEARCH METHODOLOGY

The methodology is based on two steps: i) an extensive literature review; ii) a multiple case study, involving experts of nine production companies.

As far as the literature review regards, we applied it to search, appraise, synthesize and analyse the studies relevant to extract the concepts representing an advanced maintenance system within the digital era. More in details, the different phases of the literature review are shown in Figure 1. In order to obtain a comprehensive set of papers, the search was constructed using the following main keywords: ‘smart maintenance’, ‘intelligent maintenance’, ‘e-maintenance’ and ‘maintenance 4.0’. Moreover, the search was conducted also by using the following strings: ‘maintenance’ AND ‘industry 4.0’; ‘maintenance’ AND ‘digitalization’. These helped to scan the literature, by including different perspectives on the terms. Overall, the review includes the precursors or equivalents of current terms (‘intelligent maintenance’, ‘e-maintenance’), as well as terms needed to generally capture the digital transformation in maintenance induced by Industry 4.0.

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 1984 and 2019, and contained at least one of the identified terms in either the abstract, title 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 (1315 papers) were included in the analysis (Figure 1).

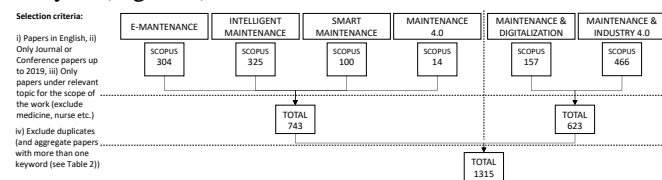


Figure 1. Synthesis of the extensive literature review

Besides the scientific literature, a multiple case study was set in nine production companies. We selected this methodology 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). Thereafter, we chose the cases on a conceptual ground, to have a representative sample: we analysed industrial users dealing with production systems and their maintenance mainly internally; in line with publications grounded on resource-based theory like (Jin et al., 2016), we 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, Leahy, Bruton, & O’Sullivan, 2015) and the readiness for advanced approaches based on the adoption of ICT (Aboelmagd, 2014) are strongly correlated to the size of the company.

Table 1 provides more detail about the sample 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 given the object of our investigation. Thereafter, 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 analysed 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, we will report only the coded information due to the answers given to an open question about the definition of the maintenance system in the digital era. Indeed, we followed the methodology proposed by (Podsakoff, MacKenzie, & Podsakoff, 2016) to create concept definitions: 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.

Table 1. Company and people interviewed as case studies

Case	Sector	Roles of the people interviewed
A	Steel	Maintenance manager, Maintenance Engineering Director, R&D Director
B	Turbines	Technical service Director
C	Energy	Production Director, Plant Director, Plant chief of maintenance team
D	Steel	Production Director, ICT Director, Maintenance Director
E	Tyres	Global Maintenance Manager
F	Industrial Gases	Production Plants Director, Plant Director
G	Oil&gas	Digital projects Coordinator, Maintenance Director, Inspections Director
H	Steel	Technical Function and Maintenance Director, R&D and data science Director, Maintenance Engineering Director
I	Mechanical	Technical Functions Director, ICT Director

3. LITERATURE FINDINGS

3.1 Overview

The literature was analysed to identify a representative set of definitions. This was done by looking at concept proliferation in the literature resulting from the different terms adopted at different times, while capturing the same conceptual domain space. A descriptive evidence of literature findings, proving the proliferation issue, is the trend in terms of number of papers using different terms (as shown in Figure 2).

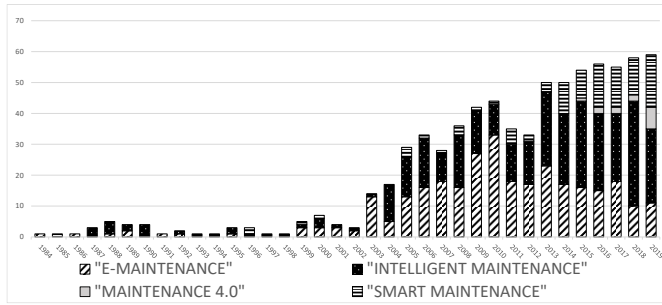


Figure 2. Trend of different terms: 1984-2019

Looking at the 743 papers identified through the literature review addressing one of the four main terms previously identified, the term ‘intelligent maintenance’ is spread along time. The first publications using the term, date back to the late 80s mainly in the military and aerospace sectors (Johanson & Unkle, 1989; Towne, Munro, Pizzini, Surmon, & Wogulis, 1988). In general, such term is generally used with less connection to the ICT with respect to the others, and more related to the decision-making support (Huang *, Xi, Lee, & Liu, 2005; Kobbacy, Proudlove, & Harper, 1995; Labib, Williams, & Connor, 1998). The term ‘e-maintenance’ has emerged since early 2000 (Hamel, 2000; Levrat, Iung, & Crespo Marquez, 2008) and reached its peak in 2010 (Jonsson, Holmström, & Levén, 2010; Voisin, Levrat, Cocheteux, & Iung, 2010). Most publications about e-maintenance 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, 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). The oldest paper that can be found in the set of papers we analysed, is related to the ‘smart maintenance’ keyword. The work (Lahore, 1984) 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).

Table 2. Combination of keywords in selected papers (i.e. number of papers selected from the literature search)

Combinations of keywords	#
Maintenance & I4.0 AND Maintenance & Digitalization	24
Smart Maintenance AND (Maintenance & I4.0 OR Maintenance & Digitalization)	18
E-Maintenance AND Intelligent Maintenance	9
(E-Maintenance OR Intelligent Maintenance) AND (Maintenance & I4.0 OR Maintenance & Digitalization)	8
Smart Maintenance AND Intelligent Maintenance	2
Maintenance 4.0 AND (Maintenance & I4.0 OR Maintenance & Digitalization)	6
Smart Maintenance AND E-Maintenance	2
TOTAL	69

Table 2 reports the papers presenting more than one of the keywords under search either in title, abstract or keywords’ list. Based on this sample, an evidence emerges: the recent

increasing trend to talk about ‘smart maintenance’ in connection with digital transformation, is confirmed by the fact that most papers addressing digitalization or Industry 4.0 talk about smart maintenance, rather than e-maintenance or intelligent maintenance. Instead, the wording Maintenance 4.0 is seldom used in the scientific literature (in this sample only 6 papers are identified, while the overall set in the trend of figure 2 presents just 14 papers adopting such a wording).

3.2 Attributes and consequences of the focal concepts

Following the methodology by (Podsakoff et al., 2016), the aim is now to review the literature in order to gather existing understanding of the focal 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 or even clear evidence of the related core elements. Thus, we selected papers addressing ‘intelligent maintenance’ or ‘e-maintenance’ or ‘smart maintenance’, and we analysed how the concepts are defined in their core elements, distinguishing both the attributes (or features) and consequences (or objectives) identified by each paper. 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 (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 (e.g. intra-company integration between maintenance and production; integration of end-user with key supplier/machine vendor) (C.2); Aimed at maintenance optimization (cost-effective decision-making or business function performance) (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 3).

Table 3. Attributes and Consequences identified about the focal concepts

	C.1	C.2	C.3	C.4	Tot
A.1	IM1, SM2, SM4	EM2, SM4	IM1, EM1, EM2, SM2, SM3	EM1, EM2, SM2, SM3	6
A.2	IM1, SM4	SM4	IM1	/	2
A.3	IM2, IM3	IM2, EM2	IM2, IM3, EM1, EM2, SM3	EM1, EM2, SM3	5
A.4	/	EM2	EM1, EM2,	EM1, EM2,	3

			SM3	SM3	
A.5	/	EM2	EM2	EM2	1
A.6	IM3, SM2, SM4	EM2, EM3, SM4	IM3, EM1, EM2, EM3, SM2, SM3	EM1, EM2, SM2, SM3	7
A.7	SM4	SM4	/	/	1
A.8		EM2, EM3	EM2,E M3	EM2	2
Tot	5	4	9	5	

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 Jung 2008) (EM2); (Jung et al. 2009) (EM3); (Munzinger et al. 2009) (SM1); (Cusano and Napolitano, 2017) (SM2); (Bumblauskas et al. 2017) (SM3), (Bokrantz et al. 2019) (SM4). Amongst them, the most cited papers are about e-maintenance, followed by the papers dealing with intelligent maintenance. As smart maintenance is issued only in recent years (see trend), the number of citations per paper cannot be high; therefore, we included more papers in the analysis.

Considering the ‘intelligent maintenance’ concept, all papers addressing it focus on the objective of supporting human-decision making (C.1). This focus is not apparent within the papers centred on ‘e-maintenance’, while is recalled in the paper about ‘smart maintenance’. On the other hand, papers referring to ‘e-maintenance’ have a strong focus on enabling technology (A.6), which is also remarked by the ‘smart maintenance’ concept. Interestingly, the papers concerned with ‘smart maintenance’ recognize the aim at increasing asset performance and/or asset cost (along the lifecycle) (C.4) as an important consequence, and this is aligned with what appears in ‘e-maintenance’. Another relevant consequence for ‘e-maintenance’ is integration (C.2), which is typically fostered by ICT-based integration, collaborative principles, and platforms (A.8).

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, it seems that two perspectives are jointly emerging – both a human decision-making support perspective and a technological perspective – within the ‘smart maintenance’ concept. Amongst the selected papers, it is worth raising the attention on the recent paper authored by (Bokrantz et al., 2019) (SM4 in table 3). This is a relevant publication, claimed by the authors to be the “first empirically grounded definition of smart maintenance”. Based 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, A.7) as enablers. Besides, support to human decision-making (C.1) and both intra- and inter-company integration (internal and external integration in the publication) (C.2) are clearly remarked. This is a further evidence that the ‘smart maintenance’ concept subsumes knowledge achieved by past concepts as e-maintenance and intelligent maintenance.

Eventually, the focus over the asset performance / cost (along the lifecycle) is interestingly reinforcing the role of ‘smart maintenance’, as a kind of legacy of the initial seeds found in the ‘e-maintenance’ concept. This is nowadays a relevant potential in order to link to the wider framework of lifecycle management of industrial assets.

4. EVIDENCES FROM MULTIPLE CASE STUDY

In the case studies, 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) 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 increasing 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 analyse 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 RCM. 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”.

It is worth observing that some experts are providing more futuristic definitions than others, often relying on the use of some metaphor (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, there are some experts who 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, allowing to increase the performance of the industrial assets based on predictive capacity; on the other hand, it is perceived that traditional maintenance processes will have the opportunities to be improved and supported by the new technologies of Industry 4.0, implemented as new and advanced supporting tools (at hand of the maintenance processes). Both perspectives reveal a common perception of digitization as important lever to help maintenance evolution.

Eventually, going beyond the definitions while discussing the related attributes and consequences, we found two attributes to add, emergent from the interviews, not risen from literature with such relevance. The former is a real novel aspect as it remarks the requirements of new skills and capabilities (A.9); the latter – evolutionary change (A5.1b) – provides a diverse viewpoint with respect to the original statement emerged in literature findings – revolutionary change (A5.1a). Besides these new attributes, other core elements were confirmed by the case studies; in that regard, it is worth observing that, in some cases, a particular remark was given on the prominence of integration and collaboration, stressing more a flavour of organizational aspect, rather than technological one (A.8).

5. DISCUSSION

We are now providing a discussion, building on the identified attributes and consequences of the concepts discussed so far. Indeed, the condensation of the attributes and consequences

is now done by comparing what found in the literature review with the findings from the case studies. Then, in accordance to (Podsakoff et al., 2016), the perceptions found by means of the case studies were deemed enough in order to establish a description of the concept, without being confused with others, so to enable a definition in line with the expectations of literature findings. As a conclusion, we define the smart maintenance concept as ‘an evolutionary change of maintenance, enabled by new technologies requiring integration and collaboration as well as the development of new skills and capabilities in the organization. The main consequence is a better support to human decision-making, aimed at optimizing maintenance and at increasing asset performance and cost (along the asset lifecycle)’.

This confirms 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 (obvious to say) 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 past achievements, both from science and practice. E-maintenance and intelligent maintenance are clearly a cornerstone and smart maintenance is promising but still in its infancy.

6. CONCLUSIONS

This work investigates on the evolution of the concepts of e-maintenance and intelligent maintenance, to transform into smart maintenance. Indeed, smart maintenance appears to be a promising concept to shape advanced maintenance systems built in the digital era. Grounding on the existing scientific background, backed by the findings collected from a multiple case study involving a selection of production companies, the investigation proposes a set of attributes and consequences characterizing this kind of systems; a definition of the smart maintenance concept is also derived based on our findings. We consider this achievement merely as a starting point in order to stimulate further advances.

Smart maintenance is not consolidated as focal concept: more works are required to set its boundaries and characteristics; we recommend empirical evidences and the development of new models, built on different attributes of such a concept.

Organizational and human aspects of smart maintenance are interesting aspects by themselves for a direction of study. A specific focus could regard the way processes and roles are changing with the technologies brought by Industry 4.0 in maintenance, as well as the skills and competence required in the future. In particular, it will be interesting to clarify the kind of expected developments, whether “machine-centered” or “human-centered”, in view of the contingencies of specific manufacturing contexts. In this scope, it will be relevant to investigate i) the role of prescriptive approaches to guide the human work; ii) the role of smart technologies to empower the cognitive aspects of operators in field.

Asset lifecycle management is also a potential area where to investigate the impact of smart maintenance: we suggest to develop more insights in theories that could be established in this scope; it could be interesting to look for collaborative projects with companies, especially in high-tech sectors (with high-tech assets), which may be useful to reveal future trends. Last but not least, it is clear that other relevant concepts are being discussed such as PHM (Prognostics & Health Management), driving towards technological enhancement to move towards predictive and prescriptive maintenance. PHM has not been a specific focus of this search even if it is inherently built in the discussion. Henceforth, besides enlarging the focus to PHM, literature findings should be treated to enrich their analysis by a systematic way to provide more details over technological and management aspects related to the new concepts under development in the digital era.

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