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Management of linked knowledge in industrial maintenance

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Abstract

Purpose – Field expertise in industry is often poorly recorded and unexploited. The purpose of this paper is to introduce a methodology and tool that incorporates a knowledge validation loop to leverage upon human-contributed field observations in industrial maintenance management. Starting from a failure mode, effects and criticality analysis (FMECA) model, it defines a collaborative process that links FMECA knowledge with field maintenance practice.
Design/methodology/approach – A metadata management system is designed to encourage staff involvement in enriching knowledge with field observations. The process supports easy feedback and collaborative annotation and is pilot tested via an industrial case study.
Findings – Streamlining FMECA validation is welcomed by maintenance staff, empowering them to exert more control over the management, usage and versioning of reference knowledge.
Research limitations/implications – The methodology for metadata management in industrial maintenance enables staff participation in a collaborative knowledge enrichment process. Metadata management is a pre-cursor and therefore an important step to drive future analytics.
Practical implications – Industry personnel are more inclined to contribute to organisational knowledge if the process is based on reference knowledge and requires minimal interaction.
Social implications – Facilitating individual contribution to collective knowledge strengthens the sense that each staff member can have organisational impact.
Originality/value – The paper introduces a methodology and tool to stimulate human-contributed knowledge in industrial maintenance, strengthening collaborative organisation knowledge flows.

Keywords FMECA, Linked data, Maintenance management, Metadata management system
Paper type Research paper

1. Introduction

Many methods related to knowledge discovery from databases and data mining have been put forward in manufacturing applications (Choudhary *et al.*, 2009). Blending such knowledge with more conventionally structured knowledge and expanding it with human-contributed knowledge is less well explored. Maintenance and asset management play an increasingly important role in preserving and advancing the

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value-producing capacity of an enterprise. E-maintenance employs modern web-based and mobile technologies to offer advanced maintenance services (Iung *et al.*, 2009; Emmanouilidis *et al.*, 2009). These services have been incorporated into Computerised Maintenance Management or ERP systems and can produce, manage, consume and disseminate maintenance data to support maintenance processes (Nikolopoulos *et al.*, 2003). The advent of Internet of Things has boosted data generation, with real-time sensory data now driving decision making for condition monitoring and recommendations for proactive maintenance (Bousdekis *et al.*, 2015).

Maintenance knowledge representation can capitalise on both conventional knowledge and maintenance data. Ontologies constitute examples of knowledge formalisations, capable of powering the traversing of scalable semantic graphs (Kamsu-Foguem and Noyes, 2013). Maintenance domain ontologies can model advanced maintenance aspects and drive reasoning and inference mechanisms (Karray *et al.*, 2011; Matsokis and Kiritsis, 2012). The quality of reasoning and the efficiency of managing data from heterogeneous sources can be enhanced by the introduction of mechanisms for metadata management, provided by metadata management systems (MMS) (Gao *et al.*, 2010; Dawes *et al.*, 2008). These systems enable users to organise, define and validate annotations with semantics that can reveal associations with domain knowledge. Semantic enrichment can produce metadata to enable application-focused analytics (Fang *et al.*, 2010). The ability to index data based on descriptive properties makes metadata a significant knowledge mediator between flat information and enriched knowledge.

Failure mode, effects and criticality analysis (FMECA) comprises structured knowledge related to reliability-centred maintenance. Typically considered as a design-stage tool, FMECA involves weak feedback loops with periodic contribution from experts. FMECA ontologies (Zhou *et al.*, 2014) have been studied as means to support fault diagnostics and decision making. Other efforts focus on conventional knowledge elicitation through interviews and questionnaires (Walls *et al.*, 2005), and more advanced ones through well-focused maintenance ontologies (Potes Ruiz *et al.*, 2013). A knowledge enrichment and validation loop via engagement of field personnel is typically missing in such approaches.

This paper proposes a framework that manages and enriches relevant knowledge by combining a valid maintenance reference with mechanisms of knowledge capturing through user feedback. It adopts FMECA and offers a methodology that creates an effective knowledge management loop between the design, operation and maintenance of engineering assets. The proposed methodology uses the linking nature of annotations to deliver a maintenance MMS. We extend the FMECA review process from being a periodic team-based task to also benefit from collaborative evaluation by maintenance staff. We focus on making such personnel part of a collaborative network (Durugbo, 2014) that collectively manages FMECA knowledge. To support this we create a tool that allows collaborative tagging of FMECA content, cross-evaluation votes, effective visualisation of annotation timelines and on-demand mobile access.

The rest of the paper is structured as follows. Section 2 positions the current work against the backdrop of relevant research, identifying needs and requirements arising from them. Section 3 introduces the knowledge model, analysing the FMECA reference and the maintenance annotation semantics, as well as the knowledge purpose and the maintenance focus of each modelling construct. Section 4 introduces the developed tool as part of a wider e-maintenance architecture. System piloting in an industrial application case is outlined, demonstrating the system's role and contribution to the maintenance knowledge management process. The final section is the conclusion.

2. Current state and research drivers

Demanding application domains, such as e-finance, e-science and e-government, have brought into attention the crucial role of metadata on the organisation of data. This has led to active research into MMS (Hüner *et al.*, 2011). Such systems implement an important step that precedes the execution of analytics and configures them for better performance (Smith *et al.*, 2014). Pre-processing may involve transforming, linking and formatting relevant data, to assure consistency and provide preliminary insights (Chongwatpol, 2015). Availability of metadata tools constitutes an indication of how cloud-ready an application domain is for knowledge fusion and even knowledge commercialisation.

The data produced by the management of physical assets have grown from digital repositories of periodic reports to massive distributed silos of monitored or processed parameters. E-maintenance providers pursue compatibility with established data standards, such as MIMOSA (www.mimosa.org) and reference specifications, such as PAS 55, offering wider support for cross-domain data semantics (Bangemann *et al.*, 2006; Campos and Márquez, 2011). The shift of interest towards maintenance knowledge has led vendors to explore available knowledge structures and technologies. Hence, industrial informatics seek to focus more on metadata to describe maintenance data, and less on descriptive data properties (Vnuk *et al.*, 2012). In this context, linked data (LD) have emerged as a methodology of publishing data interconnected with referencing links and relationships, forming semantic graphs. When a system is able to traverse such graphs it can discover knowledge and answer complex queries, as needed in knowledge management (Bizer *et al.*, 2009). With increasing adoption, LD is currently supported by formalisation frameworks, built on technologies that can efficiently instantiate knowledge representations (RDFa, JSON-LD).

The maintenance and asset management functions involve personnel from different disciplines, with technical, engineering, financial and managerial responsibilities. The actual value of data can be enhanced by providing the right information and services to the right persons at the right place and time in a certain business process instance (Lee and Martinez Lastra, 2013). Effective adaptation of services is sought via context-adaptive computing (Perera *et al.*, 2014; Nadoveza and Kiritsis, 2013). When contextualised with the support of informatics tools and organisational factors, this process can positively affect the adoption of knowledge management solutions by personnel (Lin, 2014).

An FMECA study facilitates the organisation and instantiation of maintenance knowledge related to risk and reliability. As such it has been particularly useful in handling both the design as well as the operation and maintenance of complex technical systems in failure analysis tasks. FMECA knowledge is mainly managed and reviewed by staff involved in design, quality, risk and reliability assessment. Personnel involved in operations and maintenance do not often contribute to the versioning process of FMECA. Yet, such staff carries valid tacit knowledge that is relevant to failure analysis. Enhancing enterprise learning flows is quite important in order to compose and sustain the intellectual capital inside any competitive industry (Vargas and Lloria, 2014). Capturing field expertise with tools that enable group interaction is a catalyst for producing actionable knowledge (Cao, 2012) and this can benefit the maintenance function. Enterprise social software can support knowledge management goals, effectively serving the sharing and collaborative building of key knowledge assets (Richter *et al.*, 2013). Research in web 2.0 virtual communities indicates that experience flows are essential for achieving employee creativity and encouraging further knowledge contribution (Yan *et al.*, 2013). Creating a communal knowledge pool inside an enterprise can foster purposeful connections to actualise access to expertise (Fulk and Yuan, 2013).

Our research aims to support maintenance knowledge management, including sharing, validation and extension of knowledge. A key research goal was to create a knowledge-capturing process that supports FMECA enrichment by simplifying and encouraging personnel feedback. This is a principle similar to how crowdsourcing intelligence from individual contributions is exploited in recommender systems. The challenge was to find an approach that can bring direct benefits to maintenance practice, while also succeeding in serving the qualitative revision of a risk-analysis asset. These goals raised three important research questions:

RQ1. How can we model, instantiate and provide FMECA knowledge in a way that maintenance personnel can easily access, browse and use it for the benefit of their own distinct roles.

RQ2. How can we motivate useful feedback, using a reporting paradigm that minimises user input and transparently links FMECA to maintenance practice.

RQ3. How can the linked knowledge support the FMECA revision, and provide evidence for the identification of gaps, mismatches and errors.

The aim is not to rectify limitations in the well-established FMECA practice. On the contrary, the objective is to build on this practice to provide something new: offer the opportunity to maintenance staff to register and record otherwise unrecorded knowledge based on a solid knowledge framework.

3. Modelling the failure context

To address the research questions we first introduce an FMECA model that adopts core semantics from the MIMOSA schema. We retain a reduced set of MIMOSA abstractions, enhancing them with maintenance focused semantics, and define a linking schema that supports maintenance metadata creation and customisation. Adopting the focus and features of LD and Semantic Tags, we introduce the concept of "Failure Context", as the combined knowledge about the FMECA failure mode and the event circumstances, obtained by feedback from maintenance practice.

Semantic tags act as the means to FMECA enrichment and metadata instantiation. We employed the "tagging" fast-interaction paradigm and studied its ability to support one-touch-input evaluations, observations and directives from staff that reference and receive advice from FMECA knowledge. Maintenance tags constitute an upgraded version of the string-tags that drive the semantic annotation of web content. Our methodology elevates them into configurable annotation class-types for reviewing FMECA knowledge. Each tag can mark FMECA with "how", "why" and "when" its knowledge is linked with "what" maintenance personnel experiences or evaluates. These bindings are instantiated by maintenance metadata and we refer to them as "maintenance micro-knowledge".

3.1 Entities for FMECA knowledge

Core FMECA entities are key information components of failure analysis and constitute the backbone of our FMECA model. They include Assets, Asset Functions, Agents (system actors/users), Hypothetical Events and Maintenance Actions (Figure 1). Classification entities model classifying concepts that support the taxonomy of core FMECA semantics, such as Types (of Asset, Event, Function, Maintenance Action, Agent), Agent Roles, and Levels/Scales (of Criticality, Severity, Occurrence, Detection and Priority).

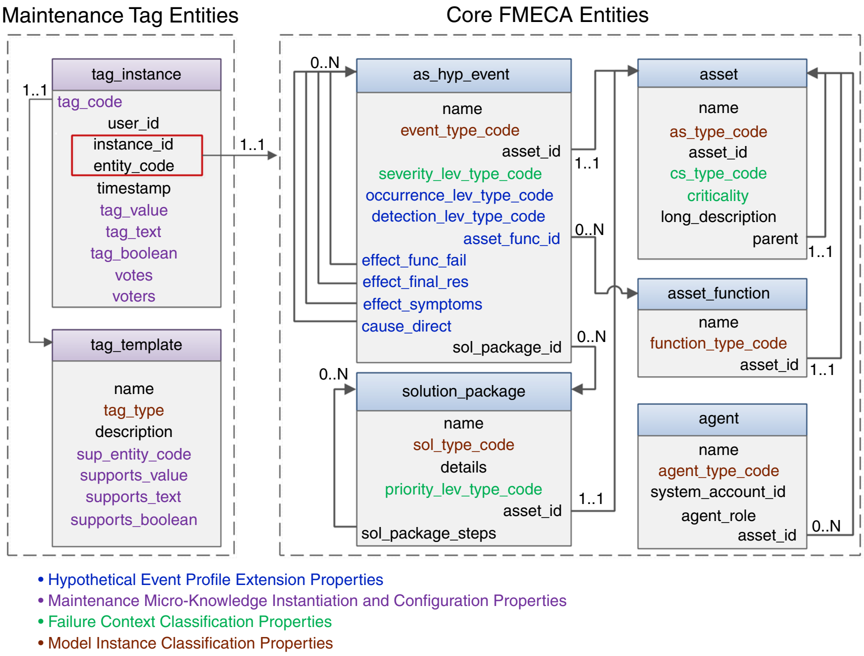


Figure 1.
A model to support the semantic annotation of FMECA

MIMOSA provides domains of entities including semantics appropriate for modelling FMECA. In MIMOSA failure events are denoted as "Hypothetical Events". The term "hypothetical" refers to probable rather than actual events. In our model (Figure 1) we define Event Profile Extension Properties. These include properties that link to semantics of occurrence and detection ability, as often included in FMECA. Along with the MIMOSA-inherited property for the Event's severity, these levels can drive RPN-based (Risk Priority Number) failure mode evaluation. A property that links to Asset Functions directly affected by the studied Event is also included. Connecting such semantics indicates how the Asset should work and why (cause) or how (effect) it does not. Finally, the extension properties provide distinct Cause and Effect links with other events. The Type property of our Hypothetical Event entity dictates the extent of information available in Event Profile Extension Properties. A Failure Mode indicates the way in which something can fail and is the key modelled hypothetical event Type, having most extension properties populated.

In more detail, effects are classified and mapped to:

- Symptoms – their presence can be indication of a failure mode occurrence. Symptoms constitute events whose description may be vague, abstract and not always easily quantifiable.
- Functional failures – they model effects directly connected with specific asset functional failures, rather than simply describing a condition.
- Final results – these events include the failure mode's most critical results, which impact on the condition of the asset and its parent/child components. They record a final failure status and should invoke immediate attention.

Suggested actions (*sol_package_id*) link each Event profile to one or more maintenance actions (solution packages) that resolve, prevent or state the appropriate maintenance response to it.

3.2 FMECA knowledge formalisation

Having presented the extended FMECA entities, we now introduce the corresponding knowledge formalisations, employing standard Propositional Logic (PL) (Russell and Norvig, 1995). Instead of using a more technical representation, we employ PL to better convey the semantics of FMECA knowledge. Propositions allow us to use explicitly targeted statements and formalise how we interpret linked FMECA entities. FMECA propositions represent relations between core FMECA entities (Table I-A). Each event participating in the FMECA model can be described by a logical proposition (P_4) that denotes whether it belongs to the set of admissible events for a specific asset. FMECA propositions are required to be brief and informative well-formed propositions, to facilitate the modular management of knowledge.

The FMECA model propositions contain knowledge that has been previously captured, and adopted as FMECA reference knowledge. Their content will only be

<table>
<tr><th colspan="5">FMECA Core Entities</th></tr>
<tr><td>As : Asset</td><td>Ag : Agent</td><td>Fn : Asset Function</td><td>E : Hypothetical Event</td><td>Ac : Maintenance Action</td></tr>
<tr><td>A.</td><td colspan="4">FMECA Knowledge Propositions</td></tr>
<tr><td colspan="2">P_1</td><td colspan="3">< As1 > is parent of < As2></td></tr>
<tr><td colspan="2">P_2</td><td colspan="3">< Fn > is function of < As ></td></tr>
<tr><td colspan="2">P_3</td><td colspan="3">< Ac > is applicable to < As ></td></tr>
<tr><td colspan="2">P_4</td><td colspan="3">< E > may occur on < As ></td></tr>
<tr><td colspan="2">P_5</td><td colspan="3">< E_1 > may be the cause of < E_2 ></td></tr>
<tr><td colspan="2">P_6</td><td colspan="3">< E_1 > may be the effect of < E_2 ></td></tr>
<tr><td colspan="2">P_7</td><td colspan="3">< Ac > is a suggested action for < E ></td></tr>
<tr><td>B.</td><td colspan="4">Micro Knowledge Propositions</td></tr>
<tr><td colspan="2">"Confirm" tag</td><td>M_c (Ag , E)</td><td colspan="2">< Ag > Confirmed the occurrence of < E ></td></tr>
<tr><td colspan="2">"Issue" tag</td><td>M_i (Ag , As)</td><td colspan="2">< Ag > detected unknown Issue on < As ></td></tr>
<tr><td colspan="2">"Schedule" tag</td><td>M_s(Ag , Ac)</td><td colspan="2">< Ag > Scheduled < Ac > for execution</td></tr>
<tr><td colspan="2">"Working on" tag</td><td>M_w(Ag , As)
or
M_w(Ag , Ac)</td><td colspan="2">< Ag > is Working on < As >
or
< Ag > is Working on < Ac></td></tr>
<tr><td colspan="2">"Observation" tag</td><td>M_o^f(Ag , X)</td><td colspan="2">< Ag > observed F on X
where:
• F is the Additional Feedback Proposition
• X any FMECA core entity (As, Ag, Fn, E, Ac)</td></tr>
<tr><td>C.</td><td colspan="4">Additional Feedback Proposition</td></tr>
<tr><td colspan="5">F (< <i>textual note</i>>, < <i>numeric value</i> >, < <i>status lock</i> >)
M is reported with note < <i>textual note</i> >, value < <i>numeric value</i> > and at < <i>status lock</i> > state
<i>Micro-knowledge with additional feedback</i> - M^f : M ∩ F</td></tr>
<tr><td>D.</td><td colspan="4">Vote Proposition</td></tr>
<tr><td colspan="5">V(Ag , M) : < Ag > agrees with M
<i>Micro-knowledge with n votes</i> - $M^{(n)}$: M ∩ V(Ag_1 , M) ... ∩ V(Ag_n , M)</td></tr>
</table>

Table I.
Knowledge formalisations with propositions

revisited when FMECA knowledge is under review. For some of them validity stems from static facts of asset hierarchy (P_1), operational behaviour (P_2) and maintenance actions planning (P_3). On the other hand, the hypothetical nature of events (P_4), along with the probable nature of the relation between them, such as the relation between causes (P_5), effects (P_6) and recommended actions (P_7), leaves space for additional knowledge, directly associated with the failure context. This is discussed next.

3.3 Entities for micro-knowledge

Our model (Figure 1) is designed to use semantic tags as a layer that annotates FMECA knowledge. Each tag has a straightforward use and purpose, described in its tag template. The default set of tag templates is configurable and extensible. A tag instance is the modelling entity for maintenance metadata. In more detail, Maintenance Tags are modelled with:

Tag classification: creating a taxonomy of annotation semantics with tag categories, allows better organisation of user annotations, offering greater usage depth and improved analysis potential.

Tag annotation profile: each tag template has a property that contains the list of supported FMECA core entities, specifying which content can be annotated with the specific tag.

Tag additional input: every tag template profiles what type of additional feedback can accompany the tagging action. This is by default optional and is captured via a tag mini-form that supports a textual note, a numeric value and a status lock. The textual note offers the option to briefly record insight that can further specify the annotation's purpose. The numeric value can quantify the semantics of the tag. The status lock can declare a specific state for the assessment. The goal is to enable maintenance personnel to refine their input with more qualitative and quantitative options.

Tag voting: we specify a very thin third level of semantics, on top of maintenance metadata, that conveys practical benefits for managing maintenance knowledge. We expanded the maintenance tag model with properties for positive votes, a semantic construct tightly connected with ranking and sharing features. Every tag instance contains a counter for votes along with a voters' list.

The default set includes the following tags:

- "Confirm": it is the most basic maintenance tag and stands as a confirmation that an event has occurred. Its enrichment value heavily resides on the timely nature of the annotation.
- "Issue": this tag allows the early reporting of an asset issue that has not been properly identified or mapped to an FMECA event. Early detection and flagging of such generic issues can invoke awareness and prompt inspections or further adequate actions.
- "Schedule": a "schedule" tag is used to select a maintenance action as the solution for a confirmed failure mode. Knowledge of past scheduled actions can offer insight for unresolved or re-occurring failures along with maintenance action efficiency.
- "Working on": this tag is used to annotate either an Asset or a Maintenance Action. Tagging an Asset declares a status of involvement with an unspecified task (operation or maintenance) for the specific Asset. Tagging a Maintenance Action declares a state of involvement with the specific action.

While the first provides more context information about the environment context (where the user is), the second clarifies the function context (what the user does).

- "Observation": this tag provides additional annotation flexibility for any FMECA core entity. It has no strict pre-defined function and can be used to report any observation related to the annotated entity. The observation is inserted as a textual note, using the tag's mini-form.

3.4 Maintenance micro-knowledge formalisation

To model maintenance micro-knowledge we employ again PL. As we aim to support metadata creation, a more technical and structured representation (JSON Schema) can also be used here, aligned with our tool's implementation technologies and aim for future analytics. However, we choose to employ PL again to offer a better understanding of how tags annotate FMECA with semantics drawn from maintenance functions. Introducing a methodology that stimulates and shares human-contributed knowledge, we prioritise the use of a formalism that can more effectively interpret and explain our metadata's practical knowledge both here and later in our case study.

Micro-knowledge propositions represent knowledge that can only be validated by personnel. These propositions describe what has just now occurred, manifested, been scheduled or performed on the relevant assets (Table I-B). They do not constitute part of FMECA, but instead are tightly coupled with the time context and are part of the Failure Context. The content of additional feedback can be used to define (textual note), quantify (numeric value) and validate (state value) a new proposition. This proposition is associated with the tag proposition and is modelled as a part of the tag instance (Table I-C). An event proposition can be validated by different users at different times via tag votes. The user who annotates FMECA content and is the first to validate a micro-knowledge proposition gains ownership and "first credit" for the maintenance assessment it represents. Consecutive users with similar assessments may add votes to the shared tag instance (Table I-D). Using votes to add more value on a micro-knowledge proposition is a step forward to metadata refinement.

The propositions defined in this section can be used to formalise our metadata layer above the FMECA model. For every failure mode's confirmation, we can track and study micro-knowledge relevant to its occurrence, composing part of the Failure Context. This forms a set of metadata created from the annotation of assets, actions (suggested actions) or events (causes and effects), directly linked to the failure mode's profile. From each such set we can assess the progress window of the respective occurrence. This window starts at the timing of the earliest relevant findings: an early "Issue" tag for the related asset, an early "Confirm" tag for any of the potential effects and ends at the exact timing of the failure mode's "Confirm" tag.

Studying the validation patterns of multiple sets can provide evidence for re-assessing the validity of the FMECA model propositions: multiple validations of different M_i may reveal a new P_4; multiple validations of the same M_c validate the corresponding P_4; sequences of different M_c validations can validate one or more P_5 and P_6; sequences of M_c and M_w can validate an P_7. Such knowledge is contributed via maintenance tags and their synthesis can lead to the enrichment and verification of FMECA knowledge, enhancing management of maintenance knowledge contribution and validation.

4. Implementation and case study

To implement and test the methodology presented in the previous section, a web-based application, namely, Intelligent Maintenance Advisor for FMECA (IMA-FMECA), was developed and employed in an industrial case study. The process and the key results are presented next.

4.1 Piloting methodology

IMA-FMECA was developed to serve a larger e-maintenance platform (WelCOM), implementing part of its knowledge management functionality (Pistofidis *et al.*, 2012). The overall architecture is designed to integrate maintenance services that operate at different layers, thus vertically coordinating maintenance activities. IMA-FMECA's middleware services offer transparent management and access to both the FMECA model and the maintenance metadata. Its core activities are placed at the 3rd layer of the ISA-95 standard between enterprise and control systems (Figure 2).

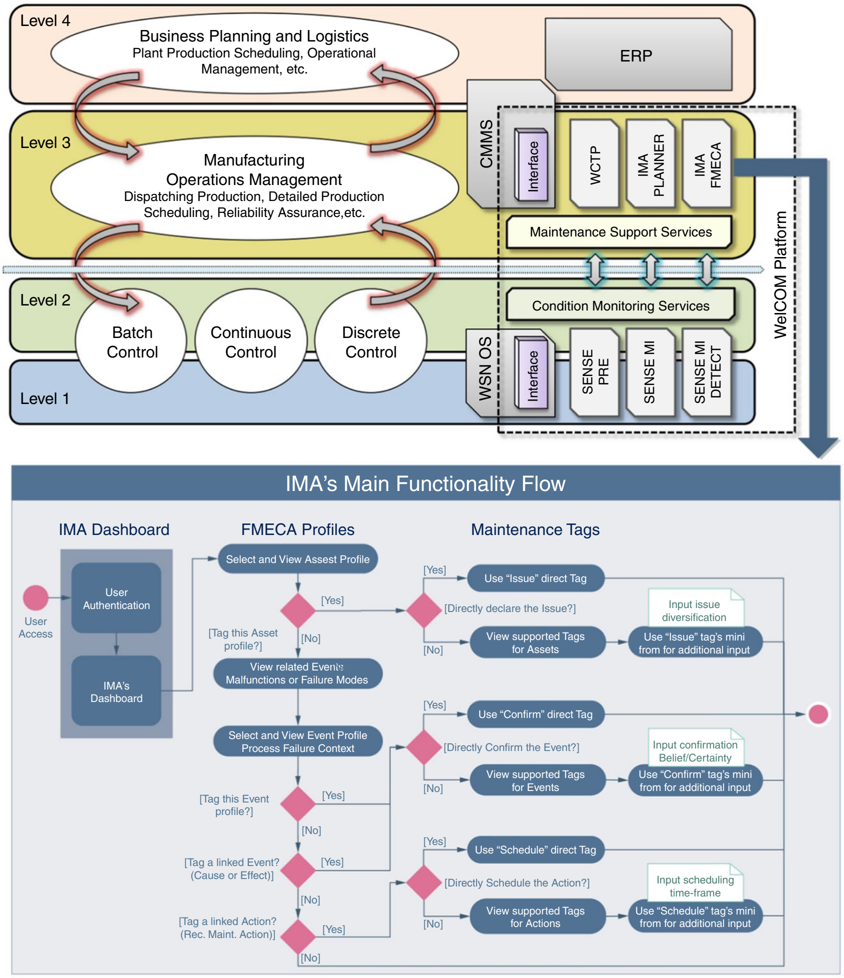


Figure 2.
E-maintenance architecture and IMA-FMECA functionality

FMECA enrichment creates an interface between the third and fourth layer and involves simple functional flows. An example is displayed in Figure 2, explaining the usage pattern for some of IMA's default tags.

Implementation technologies that impact on the performance of the delivered e-maintenance services were selected, following the model-view-controller design pattern. Aiming for fluid interfaces and a configurable rendering engine, we utilised HTML-5 and CSS-3.3, which excel in producing mobile-optimised web views. The Node.js framework was adopted as the runtime environment that executes back-end services. This technology stack ensures performance and integration stability from the synergy and uniform facilitation of Javascript and JSON at the frontend and backend of IMA-FMECA. Data persistency is powered by MongoDB, a JSON native NoSQL database. NoSQL can effectively manage data with dynamic schemas and changing structures. We employed this flexibility to serve test and assess various modifications of the FMECA model and tag mechanics. NoSQL capabilities are applicable in social enterprise applications where collaborative actions can easily produce a large volume of diverse JSON metadata. Our current concern was not the best possible transaction efficiency, but integration, scaling and schema flexibility. To perform an initial assessment of our approach and derive pointers for further improvements, we have employed a pilot case study. The case study methodology was as follows:

(1) Define and plan the pilot case study – decide the number and type of studied assets. Select roles and members for the FMECA and piloting team. Schedule meetings, tutorials and piloting periods.

(2) Train personnel – Hands on tutorials and sessions for IMA-FMECA's usage. Guides to achieve the best results from referencing and annotating FMECA.

(3) Conduct the study – Collaborative work to produce the first version of the FMECA study and enter it in IMA-FMECA.

(4) Perform, monitor and support the case study - Follow IMA-FMECA usage; support staff to perform tasks, during piloting.

(5) Evaluate pilot results – use evaluation questionnaires and perform interviews to record feedback and discuss results.

(6) Produce recommendations and make improvements – use IMA-FMECA findings to review and improve FMECA knowledge. Identify prospects and desired extensions for its functions.

4.2 Industrial piloting and analysis

Piloting took place in a manufacturing industry that delivers complete lift solutions. The application case involved industrial personnel and engineering assets. Three specific assets were selected for more in-depth focus:

(1) Electrical testing lift – the goal is to identify the added value that IMA-FMECA can bring as a service to installation partners and maintenance service providers.

(2) A hydraulic lift – a personnel office lift with heavy usage and an operation profile, making it a valid reference asset for identifying potential failures and measuring maintenance efficiency.

(3) Air compressor – a typical asset of generic usage in industry; beyond the application-specific (lifts) value of the tool, this asset refers to general applicability.

To explain system usage, we focus on the representative case of the hydraulic lift, as this has wide residential and office installation base. The lift, operating for approximately ten years, has a cabin move distance of 6,610 mm, 600 kg of load carriage capacity and a movement of 0.5 m/sec, involving three stops. Preventive maintenance is performed on a monthly basis. In parallel with IMA-FMECA piloting, a prototype monitoring system was used to monitor vibration at the cabins' roller wheels (Katsouros *et al.*, 2015).

Figure 3 displays a process flow that describes the IMA-FMECA usage during piloting. Visualisation is provided for the timelines of relevant micro-knowledge captured as part of the Failure Context. The case developed as follows:

(1) A maintenance engineer entered initial FMECA information for the lift.

(2) A maintenance technician detects a distinct noise inside the cabin. Unable to find an FMECA event that accurately mapped the observed noise, the technician tagged the lift with an issue and a textual note describing the sound.

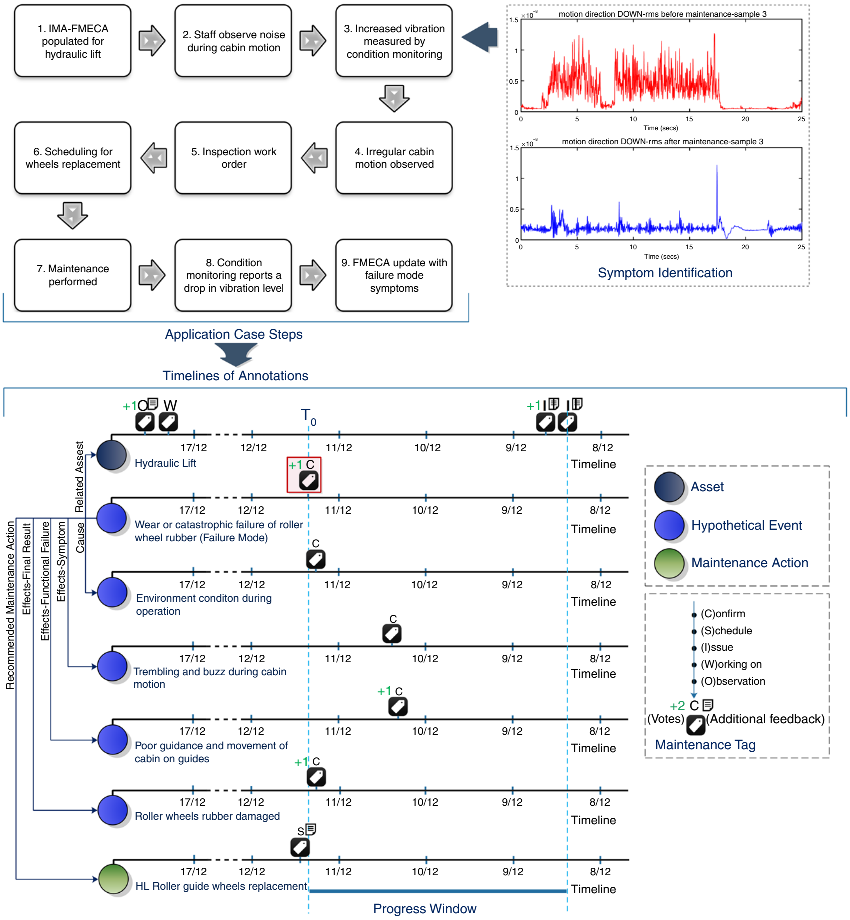


Figure 3.
Hydraulic lift application case – steps and annotation timelines

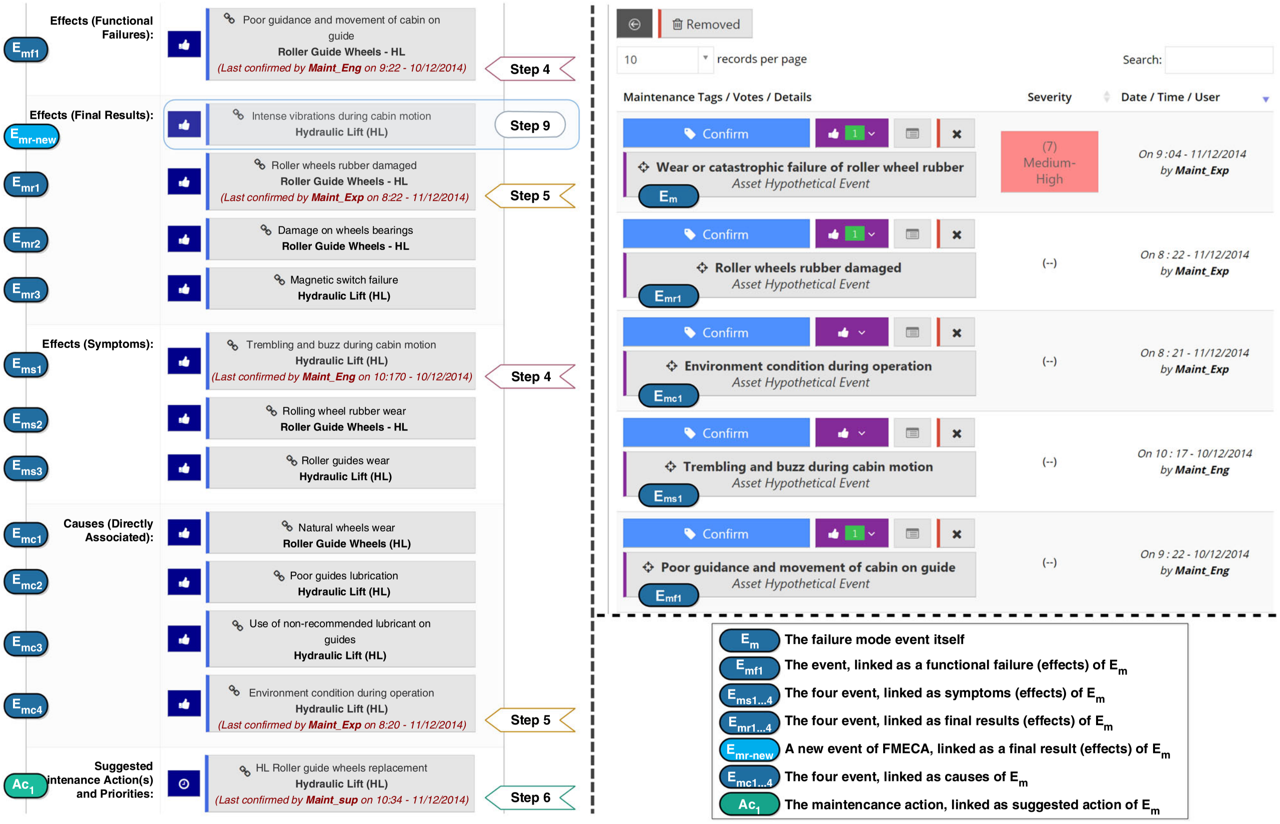
(3) The monitoring system records observed higher vibration and an engineer tags the lift with an issue and a textual note describing the observed vibration.
(4) Two days later, a maintenance engineer felt a tremble inside the cabin, a sign of poor movement of the cabin on the guides. The corresponding FMECA events were tagged as confirmed.
(5) A maintenance expert, having viewed the tags, suspected a problem with the roller wheels and ordered an inspection. The lift has a glass exterior and is exposed to sun-heat and dust. The dirt on the roller wheels gradually damaged their rubber. The respective FMECA events were tagged by the expert, confirming wear on the roller wheel rubber (failure mode), alerting the supervisor.
(6) The maintenance supervisor, having access to the tags, schedules a recommended action for wheel replacement. Using the tag mini-form, he labelled the action to be of moderate urgency and thus scheduled with the next regular maintenance. Votes were applied to key assessments.
(7) The next scheduled maintenance was six days later. Thanks to confirmed tagging, the team was ready, working with all necessary spare parts for the replacement.
(8) The monitoring system records lower vibration levels.
(9) An engineer issues an observation tag to note that the record of step 3 is a typical case of worn rubber on roller wheels and the current state as recorded in step 8 is normal operation. In the future these will become exemplars in the monitoring system for event detection. IMA-FMECA is updated with new vibration symptoms for the failure mode.

Figure 4 displays two representative interfaces from the use of IMA-FMECA in our application case. They are snapshots of the failure mode's event profile (left) and the tagging/voting history for events (right). The profile's snapshot provides a view of the current Failure Context, showing linked events and actions, along with information about their last annotation. The annotation history provides information about the sequence of event confirmations. Both snapshots have been edited with labels for the respective events and action to facilitate our analysis.

Table II tracks the validated propositions. Sequence information (scenario step) is also listed, along with additional feedback and number of votes. The lack of annotations for some effects, causes or suggested actions is also noted here, as the repeated lack of specific effect's confirmations may question their link with the reoccurring failure mode, or identify a monitoring deficiency for the related asset. All these can be actionable knowledge when accessed and interpreted by appropriate staff. Table II is an example of how knowledge can be incrementally captured for a failure mode. Each new custom tag template can expand the table's knowledge capacity with additional propositions. The enriched profile and annotation history of Figure 4 visualise the information of Table II, and offer a knowledge overview of the process that enabled maintenance staff to better detect, interpret and handle the failure mode's occurrence.

4.3 Piloting discussion

Overall 16 staff members participated in the case study and completed questionnaires through interviews. The majority reported familiarity with portable devices, having a positive view of e-maintenance mobility. Focusing on the research questions posed, we observe the following.



Effects (Functional Failures):

E_{mf1} — Poor guidance and movement of cabin on guide
Roller Guide Wheels - HL
(Last confirmed by Maint_Eng on 9:22 - 10/12/2014) — Step 4

Effects (Final Results):

E_{mr-new} — Intense vibrations during cabin motion
Hydraulic Lift (HL) — Step 9

E_{mr1} — Roller wheels rubber damaged
Roller Guide Wheels - HL
(Last confirmed by Maint_Exp on 8:22 - 11/12/2014) — Step 5

E_{mr2} — Damage on wheels bearings
Roller Guide Wheels - HL

E_{mr3} — Magnetic switch failure
Hydraulic Lift (HL)

Effects (Symptoms):

E_{ms1} — Trembling and buzz during cabin motion
Hydraulic Lift (HL)
(Last confirmed by Maint_Eng on 10:170 - 10/12/2014) — Step 4

E_{ms2} — Rolling wheel rubber wear
Roller Guide Wheels - HL

E_{ms3} — Roller guides wear
Hydraulic Lift (HL)

Causes (Directly Associated):

E_{mc1} — Natural wheels wear
Roller Guide Wheels (HL)

E_{mc2} — Poor guides lubrication
Hydraulic Lift (HL)

E_{mc3} — Use of non-recommended lubricant on guides
Hydraulic Lift (HL)

E_{mc4} — Environment condition during operation
Hydraulic Lift (HL)
(Last confirmed by Maint_Exp on 8:20 - 11/12/2014) — Step 5

Suggested Maintenance Action(s) and Priorities:

Ac_1 — HL Roller guide wheels replacement
Hydraulic Lift (HL)
(Last confirmed by Maint_sup on 10:34 - 11/12/2014) — Step 6

Maintenance Tags / Votes / Details	Severity	Date / Time / User
Confirm 1 Wear or catastrophic failure of roller wheel rubber Asset Hypothetical Event E_m	(7) Medium-High	On 9 :04 - 11/12/2014 by Maint_Exp
Confirm 1 Roller wheels rubber damaged Asset Hypothetical Event E_{mr1}	(--)	On 8 : 22 - 11/12/2014 by Maint_Exp
Confirm Environment condition during operation Asset Hypothetical Event E_{mc1}	(--)	On 8 : 21 - 11/12/2014 by Maint_Exp
Confirm Trembling and buzz during cabin motion Asset Hypothetical Event E_{ms1}	(--)	On 10 : 17 - 10/12/2014 by Maint_Eng
Confirm 1 Poor guidance and movement of cabin on guide Asset Hypothetical Event E_{mf1}	(--)	On 9 : 22 - 10/12/2014 by Maint_Eng

E_m The failure mode event itself
E_{mf1} The event, linked as a functional failure (effects) of E_m
$E_{ms1...4}$ The four event, linked as symptoms (effects) of E_m
$E_{mr1...4}$ The four event, linked as final results (effects) of E_m
E_{mr-new} A new event of FMECA, linked as a final result (effects) of E_m
$E_{mc1...4}$ The four event, linked as causes of E_m
Ac_1 The maintencance action, linked as suggested action of E_m

Figure 4.
Hydraulic lift's (HL) failure mode profile and tagging/voting timeline

Table II. Pilot case micro-knowledge and votes propositions

FMECA entity	*Scenario step*	*Maintenance tag*	*Micro-knowledge proposition*	*Votes*	*Additional feedback*	*Validated*
As	2	*"Issue"*	$M_i^{(1)f}$(Maint_Tech, As)	1	Textual note	True
	3	*"Issue"*	M_i^f (Maint_Eng, As)	0	Textual note	True
	7	*"Working on"*	M_w^f (Maint_ Tech, As)	0	–	True
	9	*"Observation"*	$M_o^{(1)f}$ (Maint_ Tech, As)	1	–	True
E_m		*"Confirm"*	$M_c^{(1)}$ (Maint_Exp, E_m)	1	–	True
E_{mf1}	4	*"Confirm"*	$M_c^{(1)}$ (Maint_Eng, E_{mf1})	1	–	True
E_{mr1}	5	*"Confirm"*	$M_c^{(1)}$ (Maint_Exp, E_{mr1})	1	–	True
E_{mr2}	–	*any*	–	0	–	False
E_{mr3}	–	*any*	–	0	–	False
E_{ms1}	4	*"Confirm"*	M_c (Maint_Eng, E_{ms1})	0	–	True
E_{ms2}	–	*any*	–	0	–	False
E_{ms3}	–	*any*	–	0	–	False
E_{mc1}	–	*any*	–	0	–	False
E_{mc2}	–	*any*	–	0	–	False
E_{mc3}	–	*any*	–	0	–	False
E_{mc4}	5	*"Confirm"*	M_c (Maint_Exp, E_{mc4})	0	–	True
Ac	6	*"Schedule"*	M_s^f (Maint_Sup, Ac)	0	Textual note	True
Agent	*Scenario step*	*Voted micro-knowledge*	*Vote proposition*			
Maint_Sup	6	$M_i^{(1)f}$(Maint_Tech, As)	V(Maint_Sup, M_i^f (Maint_Tech, As))			True
Maint_Sup	6	$M_o^{(1)f}$ (Maint_ Tech, As)	V(Maint_Sup, M_o^f (Maint_ Tech, As))			True
Maint_Sup	6	$M_c^{(1)}$ (Maint_Eng, E_{mf1})	V(Maint_Sup, M_c (Maint_Eng, E_{mf1}))			True
Maint_Sup	6	$M_c^{(1)}$ (Maint_Exp, E_{mr1})	V(Maint_Sup, M_c (Maint_Exp, E_{mr1}))			True
Maint_Sup	6	$M_c^{(1)}$ (Maint_Exp, E_m)	V(Maint_Sup, M_c (Maint_Exp, E_m))			True

Q1. Maintenance staff found it very useful to access FMECA knowledge at the shop-floor and agreed that field expertise can contribute to its quality. Most staff positively rated the FMECA model's coverage of appropriate maintenance knowledge. Both technicians and engineers reported that instant access to FMECA is preferred to hardcopy manuals, making it easier to identify a failure mode and cutting in half the time needed to exclude non-relevant cases. Specifically:

- They identified failure effects as the most beneficial knowledge in FMECA. They reported that manuals document effects in a very technical and binary manner. They found that FMECA could offer knowledge for effects whose contribution to failure's progress was more complex, not easily detected and based on hidden qualitative aspects. Classification of effects was also appreciated, helping them better understand and thus detect the nature and significance of each effect's impact.
- Contrasting the received tool support with that offered by technical manuals, they rated suggested actions as the second most valued FMECA knowledge. FMECA at shop-floor was reported as a great reference for alternative solutions, while also providing more depth (action steps) and sequence support (action priority) in maintenance practice.

Testing IMA-FMECA's functionality, participating staff appreciated its appearance, usability and responsiveness. Engineers had no problem in navigating FMECA, and provided useful feedback on how to prioritise the display of information. Both technicians and engineers reported a fluid browsing experience, acknowledging the importance of a touch-optimised layout for on-demand access of structured content such as FMECA.

Q2. The usage of tags was positively perceived by the majority of participants. Maintenance engineers instantly identified the potential to streamline the reporting process for later analysis. They appreciated the automated clustering of maintenance feedback around FMECA and its classification based on the well-defined tag semantics from the maintenance function. Technicians preferred tags over software that requires significant off-duty data entry. The lack of mechanisms to record timely input and the disconnected mindset of the maintenance user were stated by engineers as important factors behind the empty forms of maintenance software. Almost half of the tags used in our pilot case were followed by textual notes, recording a positive stance towards the provision of additional feedback. Maintenance staff reported that the mini-forms' optional usage and the tags' straightforward purpose gave them better control over when, why and what they wanted to report. Furthermore, having used maintenance tags in the piloting, engineers showed interest in creating new tag templates and organising them with more categories, evidence of higher motivation to offer additional insight.

Q3. Textual notes for "Issue" and "Observation" tags allowed the identification and input of previously uncharted events. In a time-span of two months this input was enough to trigger an FMECA revision by the selected team. Browsing the appropriate tagging timelines and discussing the meta-interpretation of additional feedback, the FMECA team was able to quickly define, classify and link new events to the respective failure modes. This review process was not achievable before at this rate, ease or quality. Furthermore, acknowledging the improvement of hydraulics lift's FMECA, the team's design engineers reported that deeper knowledge of how wheel failures manifest themselves can directly help to better plan and configure hydraulic lift installations. It is a statement that verifies that our approach also enables a knowledge validation loop over Design FMECA.

Overall, the case study provided evidence of how the introduced approach supports on-the-job knowledge management in industrial maintenance. Our knowledge pool is a representation of LD between two important maintenance knowledge sources: FMECA and maintenance practice. The pilot case demonstrated how a MMS can effectively bridge and improve such knowledge, and does so by encouraging maintenance personnel and experts to drive its enrichment functions. It has also provided pointers for further research, as outlined in the concluding section.

5. Conclusion

This paper introduced a novel way of handling maintenance metadata by capturing knowledge from shop-floor expertise. The main contribution was to formalise, model and functionally support an enrichment loop over a well-established maintenance reference, namely, FMECA. It is a collaborative knowledge management process that extracts, defines and disseminates practical maintenance knowledge. The methodology differs from the more conventional pattern, where maintenance staff are directly prompt to produce the required knowledge with weak or no connection to already available knowledge. Instead of reports and forms, maintenance feedback is created through the use of tags, a feedback methodology that minimises interaction time and maximises knowledge linkage. The tags create timelines of evaluations, profiling each maintenance event and helping personnel to understand the relevant failure context and reach appropriate decisions.

An industrial piloting case study involved staff with experience in maintenance support systems, which evaluated its usage and provided answers to key research questions, making also recommendations for improvements. Maintenance engineers welcomed their role as supervising mediators for fusing metadata timelines into

FMECA's new version. Linking and semantically enriching data with relevant metadata is a natural precursor to applying cloud analytics as a next step. Participating engineers and experts expressed great interest in future analytics that could identify patterns linked to FMECA quality. These analytics can process the collected metadata of each failure mode's confirmation's history and follow the validity, timings and sequence of relevant micro-knowledge. Mining over such parameters may yield insight into the likelihood of each linked event (effect or cause) and the applicability or efficiency of each suggested action. Furthermore, trending the usage of each tag and text-mining the textual notes of voted tags may reveal important insights for new tag templates and FMECA improvements. Following IMA-FMECA's evaluation, maintenance managers discussed the prospects for two possible extensions: the use of IMA-FMECA for the collaborative evaluation of other shared knowledge assets, directly (programme or plan) or indirectly (policy or strategic objectives) associated with the maintenance process; and the integration of IMA-FMECA with existing legacy or enterprise systems to facilitate annotation for better versioning and management of their shared model. Towards these goals our tagging functions can evolve into a plug-in component that couples with third-party services, residing on top of different maintenance data models. Using our approach for diverse models and industrial applications can involve additional case studies to verify its efficiency. This methodology will allow IMA-FMECA to scale into a MMS that can reference, annotate and organise distributed heterogeneous maintenance data and services. Such an integration of ubiquitous maintenance resources can also bring e-maintenance closer to effective usage of cloud and analytics technologies.

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