Modeling the Semantics of Failure Context as a means to offer Context-Adaptive Maintenance Support

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ABSTRACT

Acting upon the data involved in typical diagnostics and prognostics tasks is often confounded by the complexity of the corresponding situation and needs to take into account domain-specific or even installation-specific knowledge considerations. While domain knowledge is often captured in various forms, such as is typically done in Fault Modes, Effects and Criticality Analysis (FMECA), the contextualisation of the captured data and related knowledge to a corresponding situation, in other words a situated-aware modeling of data and knowledge, is often missing. Our research leverages the efficiency of maintenance support for mobile actors. Investing in modern service provision technologies, this work targets the effectiveness of capturing and sharing field expertise. An analysis of both the modeling specification and the functional requirements for such an approach. is provided. The semantics of “Failure Context”, a context that guides user’s navigation towards relevant diagnostics and maintenance-related knowledge, are mapped into an appropriate data schema. Based on this, a system capable of managing the core information of the Failure Context, while offering adequate tools that support experts to build on, browse through, and reach contextually-relevant decisions is implemented. The development follows a reference-annotation design pattern to deliver on spot capture and enrichment of maintenance-related knowledge. Thus, the developed system provides the means for the effective management and exploitation of 'micro-knowledge fragments', associated with FMECA-related entities and knowledge. This is a significant enabler for the effective elicitation and management of field-captured expertise, enabling the enrichment and validation of maintenance-related knowledge.

1. INTRODUCTION

E-Maintenance has emerged from the fusion of maintenance practice with information and communication (Liyanage, Lee, Emmanouilidis, & Ni, 2009).Currently, a wide range of systems, from shop-floor sensing platforms to executive decision support tools have established their role and added value in scaling maintenance performance and tuning the optimization of its background economy (Mouzoune & Taibi, 2013, 2014).

E-Maintenance initially focused on technology integration efforts. The design scale of embedded systems and the versatility of SoC (System on a Chip) architectures enabled the integration of more powerful sensing infrastructure. Through time and advancements, sensor grids effectively evolved into self-aware WSNs (Wireless Sensor Networks) and e-Maintenance systems managed to align with the benefits of IoT (Internet of Things) trends (Emmanouilidis & Pistofidis, 2010a). Smart wireless sensors with embedded intelligence continue to be one of the main pillars of e-Maintenance and the reference implementation of Wireless Condition Monitoring (Emmanouilidis & Pistofidis, 2010b).

Aiming to produce schemas that provide optimal descriptive performance, data modeling has progressed at a different pace than software and hardware integration. Early on, standards, such as MIMOSA[1], achieved a solid coverage for a valid base of related concepts. Upon these standards research efforts targeted focused industrial testbeds, bringing insight into how to fuse data in order to compose maintenance knowledge (Savino, Brun, & Riccio, 2011).

Following the state of web 2.0 and mobile technologies, e-Maintenance reaches now to support users that exhibit a continuously context-changing access profile. Service-

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[1] MIMOSA Standard - http://www.mimosa.org/

oriented maintenance has allowed the compilation of tools into mutli-user web portals, where access is provided through flexible dashboard interfaces (Mouzoune & Taibi, 2014). Accommodating the needs of a mobile user and furthermore the needs of a shop-floor maintenance actor, modern e-Maintenance systems facilitate context-adaptive engines to compile portable views that support management over detailed and structured maintenance knowledge (Pistofidis & Emmanouilidis, 2012).

Filtered visualizations of maintenance data and knowledge navigation assistance have significant value, especially when personnel is expected to act/decide/perform on-spot and at a highly responsive and reliable level. Decision upon maintenance actions, at any level, should be driven by facts and evolving field expertise. Such knowledge is tacitly shared among maintenance experts but its elicitation, management and exploitation is not well-addressed by established maintenance and asset management solutions. To effectively manage shared knowledge, a process should be tuned to assist in its recording, management and evolution. This process needs to balance the synergy between two tasks: (i) proper provision of previously established knowledge entities as a reference and (ii) means for its effective review, evaluation and enrichment by fusion agents. On an industrial shop-floor, maintenance engineers and technicians can act as knowledge fusion agents, while an evolving FMECA-related information structure as reference for diagnostics-support.

Many e-Maintenance solutions focus on the efficiency of handling maintenance data and rigid knowledge. In practice knowledge is indirectly produced when a semantic map is placed upon solid data, commonly termed as metadata. Maintenance metadata management is less than adequately addressed in most software systems supporting maintenance and asset management. The majority of e-Maintenance systems opt to expand the descriptive scope of their models rather than introduce an extra layer of semantics. This decision eventually leads to an impressive support for standards, schemas and data formats, along with a huge volume of flat data, which are nonetheless too complex for human actors to process at any significant level. Data analytics emerge to serve with domain agnostic engines, aimed at porting and tuning mathematical models to test their ability in inferring maintenance knowledge from silos of maintenance history data. When working directly on flat data, this pattern may produce semi-functional mechanisms of maintenance intelligence that offer limited efficiency, while introducing overwhelming computational costs. Furthermore, it is a pattern that leaves experts largely unexploited, with limited contribution to shared knowledge and expertise. The engineers are called to study the findings extracted from monitored parameters of a past event. The context for such an event is often poorly recorded and the engineer lacks the necessary insight that was present when dealing with the problem in the first instance.

This paper presents research that addresses the mentioned requirements by employing modern technologies and delivering a metadata-oriented approach on managing maintenance knowledge. Maintenance insight can be collected on the shop-floor, prior to any back-office computation and act as the foreground of maintenance intelligence. As a data preparation stage, it benefits from the experts' fully contextualized cross-examination of approved maintenance profiles. To fulfill this task, the expert is provided with appropriate tools to review and annotate related data. An annotation schema of maintenance tags enables the user-labeling of events. The way this is achieved is explained by presenting the system behavior of an e-maintenance user that utilizes metadata and fuses shop-floor generated expertise with a constantly evolving unit of maintenance intelligence.

The remainder of the paper is structured as follows. The next section presents related work and emphases the need for more efficient on the field knowledge recording and management. Section 3 analyses the modeling principles for the refined semantics of a Failure Context, while section 4 outlines the design features for a portable implementation of a maintenance-support tool. Section 5 presents the developed Intelligent Maintenance Advisor (IMA), focusing on the way it is tuned to handle the underlying knowledge in an industrial lifts manufacturing application case. A summary of the main conclusions and future work targets is provided in section 6.

2. CONTEXT-AWARE MAINTENANCE SERVICES

Service-Oriented Architectures have evolved into software patterns that adapt service-provision and service-consumption to the specific needs of application domains. E-Maintenance has progressed through various solution designs, where different environments were employed as hosts of software agents and services. Identifying which SOA-ready devices are currently available and how they can functionally participate (functional roles: client, server etc.) in a modern SOA solution, is a key step when researching new SOA approaches for e-Maintenance (Cannata, Karnouskos, & Taisch, 2010).

Wireless connectivity has become a feature for the majority of e-Maintenance solutions. Apart from sensors and SOA architectures, e-Maintenance is currently investing on extensive utilization of portable devices. Portable data visualization, analysis and remote management has greatly surpassed the expectations of many problem spaces and is being studied as one of the main pillars for mobility in e-Maintenance (Emmanouilidis, Liyanage, & Jantunen, 2009). Migrating software logic away from servers and PC stations, both in terms of background analysis and client access, has allowed maintenance to port its functions in high trending technologies such as mobile (native and web) applications (Campos, Jantunen, & Prakash, 2009).

The management of physical asset management data has matured from digital repositories of periodic reports to massive distributed silos of monitoring parameters and domain knowledge. During the last years, while embedded interoperability followed a slow maturity pace, backend analytics of Big Data are making leaps of evolution. Many enterprise solutions rushed to benefit from the domain insights that could be offered by the constantly growing toolset of cloud analytics. The cloud can now be used for orchestrating complex tasks such as predictive maintenance planning and prognostics (Lee, Lapira, Bagheri, & Kao, 2013). The volume of aggregated data is transforming what was formerly perceived as a costly burden into a valuable corporate asset with significant exploitation prospects.

Apart from volume size and physical distribution, e-Maintenance data have undergone an important semantic transformation. Widely accepted schemas, such as MIMOSA (www.mimosa.org), follow strict cycles of re-composition, where extensibility and conformance to specifications is assessed and validated. One of the core concepts in simplifying the provision of complex services is the development of Context models. Context-awareness is a feature that requires the capturing, clustering and interpretation of refined semantics. These must include parameters that compile meaningful context snapshots, which in turn can drive desired adaptations of the system's functionality. Deciding the synthesis of useful contexts for the maintenance domain and extracting the rules and correlations that can effectively boost the performance of maintenance tasks is an intensive modeling process (Nadoveza & Kiritsis, 2013; Pistofidis & Emmanouilidis, 2013). Expanding context modeling further than location awareness and commonly accepted semantics, means producing domain-specific knowledge patterns that can act as triggering mechanisms of service adaptations. The end result is highly enriched information that can drive the provision of context-adaptive maintenance services.

A good example of such a context study is the field knowledge that populates an FMECA (Failure Modes, Effects and Criticality Analysis) data model. Managing FMECA knowledge with software tools has been a part of many modern commercial e-Maintenance systems (PTC Windchil FMECA[2], ReliaSoft Xfmeca[3]). The majority of them emphasize in supporting a constantly updated list of FMECA standards (i.e. MIL-STD 1629[4], IEC 60812[5], BS 5760-5[6], SAE ARP 5580[7], SAE J1739[8]), offering excessively complex desktop clients to access, enter and update the appropriate data. For many e-Maintenance suites, update and evaluation of the FMECA model, are tasks where only maintenance engineers and technical managers are authorized to contribute to. This pattern usually results in FMECA updates that primarily focus on how executive engineers perceive failures and not on how shop-floor technician experience and address failure. Furthermore, the maintained FMECA model is usually designed and utilized in a manner similar to its hardcopy counterpart: as a static digital report/table that records causality of failure events. This access model is lacking interactivity and feedback from the field practice it is designed to assist.

The majority of the above e-Maintenance systems disconnect the model of knowledge management from the one of reporting components. Usually, the intention to capitalize in capturing field expertise is translated into long non-contextualized forms for every different maintenance task. System's interaction with maintenance personnel is largely depended on exhaustive reports that require more time and information than currently available to the user. This approach suffers from the following drawbacks:

- **Repeated Knowledge** – Indirect reference to relevant assets, tasks or personnel in entities already associated with a direct link – commonly known as referencing loops. Many modern systems overload the referencing volume of their schemas to compensate for complexity and to achieve faster response. Such an approach can create consistency issues, in terms of valid maintenance correlations and information loops. Reliability issues can prove to be a deal-breaker for a diagnostics system.
- **Rigid Encapsulation** - Maintenance feedback, is often stored into records of a ticketing/reporting component. The schema holds their semantics tightly grouped in report-instances, limiting flexibility and blocking the scaling and reuse of knowledge, unless additional data services are built to manage them. Browsing a history of long non-validated reports, populated with unrelated data to the task at hand, is not an efficient way to handle knowledge reuse and provide decision support. The ability to pick modules of expert feedback and on-the-fly compile a targeted report history can be vastly superior.
- **Underpowered Fusion** - When conducting an FMECA analysis, history of maintenance assessments constitutes a primary source of background reference knowledge. Former model versions can be fused with insight extracted from validated events and shop floor facts. Modern systems employ off-line data analytics to cluster and classify reported observations and remarks. Models that do not employ solid connections between reported and approved knowledge are often in greater need of such analytics to drive the inference or creation of such correlations. Instead of introducing demanding

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[2] PTC Windchil FMECA - http://www.ptc.com/product/windchill/fmea

[3] ReliaSoft Xfmeca - http://www.reliasoft.com/xfmea/

[4] https://src.alionscience.com/pdf/MIL-STD-1629RevA.pdf

[5] http://webstore.iec.ch/preview/info_iec60812%7Bed2.0%7Den_d.pdf

[6] http://www.techstreet.com/products/1087481

[7] http://standards.sae.org/arp5580/

[8] http://standards.sae.org/j1739_200208/

prerequisites for data analytics, fusion can be designed to occur transparently and on-line, in parallel to model population and feedback provision. Semantic tags constitute a state-of-the-art web methodology for clustering and classification of knowledge. Their adoption for maintenance knowledge can prove to bring many benefits to both its management and analysis.

Nonetheless, the above potential is still left largely unexploited by e-Maintenance solutions. Effective collection of expertise relies heavily on parameters such as expert's context, concise input and connection with a valid knowledge base. These were core targets for our research.

3. REQUIREMENTS FOR DIAGNOSTIC MODELING

Building the model of an application-focused context is essentially a process of classification for semantics associated with a decided core entity set. The selected semantics must compile a meaningful framework that can provide insight into the state of both the entities and their relationships. Our research evaluates the semantics that compose a new context of maintenance diagnostics. This context serves as knowledge map for information linked to assets' failures. Next, the design specifications and data modeling for capturing such a context are described.

Conducting a successful FMECA analysis, produces a data table that constitutes a highly enriched unit of field knowledge. This reference unit is the result of an engineering study that involves many steps of documenting existing knowledge. FMECA quality is bound by the validity and the timely nature of the processed data. Aging repositories of outdated information can severely impact the performance of the supported diagnostics. Considering that both the functional behavior and condition state of a single machine can significantly change between different production profiles or life-cycle periods, implies that reference information, which can decisively influence a critical maintenance assessment, must be constantly re-evaluated based on qualitative feedback.

Compact Diagnostics Reference and Feedback – Whenever a user is prompt for an assessment, it is always helpful to provide a starting reference point. This reference information must be well connected and compact, facilitating the navigation on its semantics and browsing of its content. Modeling the user feedback must be similarly concise and well-framed. To effectively support the full scope of maintenance inspection and practice, reporting from current software tools tend to become excessively complex, often resulting in partially and incorrectly filled reports. Modeling the user feedback with semantics that simplify entry and leverage its value is crucial for balancing the users predisposition to the process, especially when a mobile maintenance actor needs ready-to-use and highly descriptive semantics to support a swift and valid entry.

Feedback to Approved Diagnostics – FMECA modeling semantics should be differentiated from the users' feedback. Most systems provide distinct entity sets to model the core diagnostics and the reported feedback. Creating a modeled intermediate, acting as the bridge between them, is a very useful feature for data maintenance and one that can be effectively incorporated in the form of Approved Data. Approved Data include user entries, identified as information of higher value and thus handled as reference points. Labeling mechanics for such a process can be supported by models enabling sharing and cross evaluations of assessments. Approved Data function as the pool of candidate knowledge that will be inserted to the Reference Diagnostics, during the scheduled FMECA re-evaluation.

Diagnostics Data Provenance – User diagnostics are tightly connected with time locality. Being a core dimension of all context interpretations, time can reveal patterns that impact maintenance diagnostics decisively. Every data entered in a maintenance system, or any modern software system for that matter, is time-stamped and the action is logged. Apart from system administration reasons and the obvious significance of knowing the time of an event, the meta-interpretation of a timeline from legacy data has proven to offer many new insights. Data Provenance refers to the ability to trace and verify the creation of data. It documents the inputs, entities and processes that influence data of interest, in effect providing a historical record of the data and its origins. Data Provenance of maintenance assessments can identify patterns that can constitute valuable evolving knowledge. The proper modeling of entity correlations can empower the fusion of such timelines, allowing highly informative overviews of events, thus providing to the maintenance actor the right context.

4. THE SEMANTICS OF FAILURE CONTEXT

Modeling FMECA has been addressed by various standards that approach the process through different design perspectives. The proposed model builds a framework of diagnostics utilizing MIMOSA as a starting point for the modeling of core related semantics. Extending upon these semantics, our model brings more depth in specific aspects of failure causality and proposes a new schema for structuring the user's reported feedback. MIMOSA is a solid schema with an extended range of supported maintenance sub-domains. While the depth of its entity-tree provides descriptive accuracy, it can also overload systems with unexploited dimensions of maintenance details. These may introduce a significant overhead. Our goal is to produce a model effectively tailored for a service-oriented backend logic that handles requests of mobile maintenance actors. Such architectures and content provision patterns require modular semantics, appropriate for fast composition and processing of enriched mashups. In order to achieve data management efficiency, the proposed context schema adopts a subset of MIMOSA semantics, customized to offer a balanced and lightweight handling of its depth. The concepts that participate in the core entity-set of the proposed failure context include (Figure **1**):

- **Assets:** The entity whose properties describes the attributes of an industrial asset. These included essential registry data, classification attributes, criticality scales and components hierarchy pointers.
- **Agents**: This entity corresponds to system actors that communicate data for both FEMCA knowledge and annotation semantics. Though initially populated by human actors, it's modeled to support integrated system actuators, such as sensors and external systems.
- **Actions**: The entity that focuses in the description of maintenance actions. These are modeled as appropriate solution steps/packages that address prevention or correction of the recorded failure modes.
- **Events**: The most essential component of the failure context. It addresses the modeling of both failure modes and the associated failure mechanisms. Failure mechanisms lead to failure modes and feature as their causes or effects. Extending the MIMOSA hypothetical event entity, we propose a schema that supports scaled effects semantics, assessing the quality of their impact.

Following the MIMOSA taxonomy of events, both Failure Modes and Failure Mechanisms are modeled by the same entity; the *Hypothetical Event*. While MIMOSA chooses to omit them, the proposed Hypothetical Event schema includes occurrence and detection scale to assess frequency and detection potentials. Along with severity, this set of attributes can drive an RPN-based (Risk Priority Number) evaluation of Failure progress. MIMOSA offers a generic and flexible approach for causality relationships, pairing Hypothetical Events through unclassified links. The proposed version provides direct and fixed semantics with attributes that map causes and effects upon a basis of scaled impact. While Causes are associated with Failure Modes, through one attribute, Effects are separated in three classes:

- **Symptoms** - They constitute effects of low significance for the related Asset and its environment. They provide the means to model "observations" as part of formally captured Failure Mode knowledge. Symptoms constitute events whose description can be characterized as vague, abstract and not easily quantifiable. Nevertheless they facilitate the integration of uncharted insight inside the reference model of Failure Modes.
- **Functional Failures** - These events model effects directly connected with specific functions of the related asset. Their role is to distinguish between events that manifest the dynamic change of functional behavior, from events that describe a static status or condition. They can be particularly useful in the analysis of propagating failures, where functional participation of assets in process workflows can produce chains of effects. The timeline of such effects can reveal the parallel progression and connection of failure modes.
- **Final Results** - These effects include the Failure Mode's most critical results. They are descriptions of events, that significantly impact the condition of the asset and its parent/child components. They record a final and usually irreversible failure status, and should invoke attention for the state of interfacing assets. These events must be well documented, since they constitute the most decisive evidence for the identification of a Failure Mode.

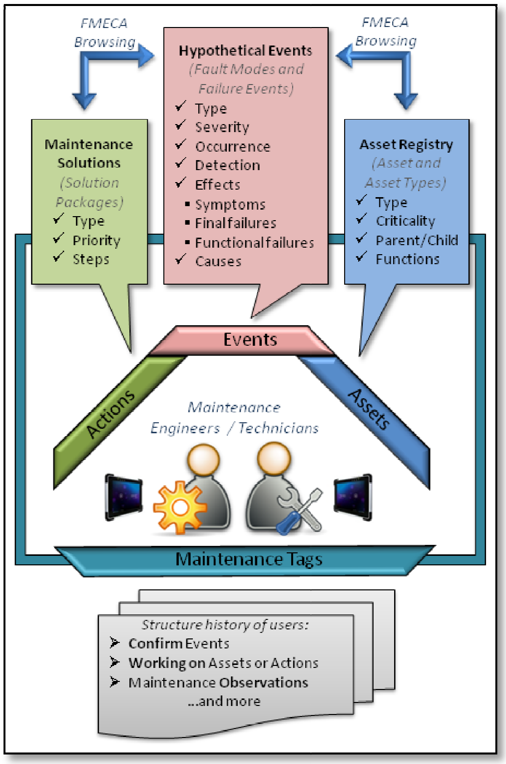


Figure 1. The knowledge dimensions of the Failure Context

Our research offers a new method for capturing the feedback of maintenance staff. The model invests on a data preparation process that can greatly enhance analytics. By building maintenance reports with multiple references to an approved FMECA table, we capitalize in the creation of pre-defined correlations. Supporting further modularity, we break these reports to smaller referencing units. Context fusion increasingly advertises the need to scale down exhaustive schemas and port semantics to refined knowledge units with metadata profiles. This is exactly our goal in modeling the Failure Context. The diagnostics annotation system is modeling user feedback by combining:

1. Maintenance Tags: Tags are keywords that can be applied to maintenance data objects as descriptive annotations (

2. Figure **2**). Their descriptive goal may vary and can be classified in categories of keywords. The semantic scope of tags in generic domains is usually unframed and their use can facilitate the creation of a tag cloud. A maintenance tag cloud is a simple and effective way to cluster semantics and infer their likely adoption.
3. Maintenance Remarks: Maintenance personnel are asked to input their evaluation in qualitative and quantitative manners. For an assessment, the importance of a tag can be augmented by a small note that provides more analysis, or a numeric value that quantifies belief. More automated response patterns, such as checkboxes and selection options are also favored to assure interfacing simplicity and fast input. This form of micro-knowledge fragments, if effectively managed and mined can become extremely valuable.

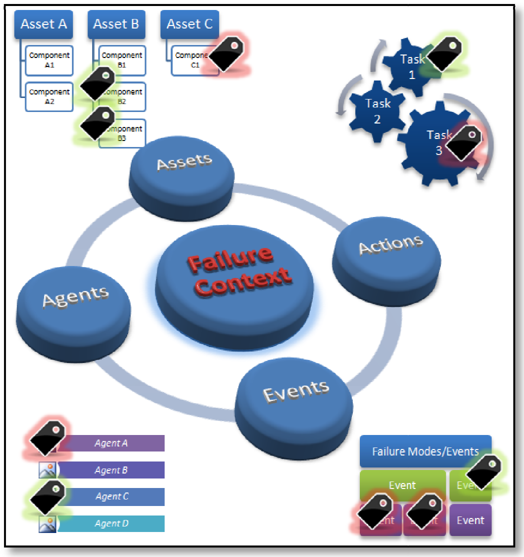


Figure 2. Managing the context of maintenance reference and annotations.

One of our aims is to offer a versatile schema that supports capturing and use of **maintenance micro-knowledge** by means of tags, with support for optional remarks. The model allows the creation of tag templates configured to map tacit knowledge embedded in maintenance practice. Tag instances are provided by staff in the form of annotations or metadata for approved diagnostics (FMECA core entities). Their title, category and compatibility can be configured and updated by maintenance engineers. Each tag template can be profiled to support the optional addition of: (i) textual notes, (ii) numeric values and (iii) a status lock. These optional fields are used to leverage the tags knowledge value and provide engineers with better insight on how they can expand and adjust the semantics of available tag templates.

Essentially this tagging process enables the instant sharing of assessments between maintenance professionals. The timeline of such maintenance tags creates a layer of metadata upon the validated knowledge of recorded failures modes and mechanisms. This collection of metadata and their direct connection to approved diagnostics compose an extended and validated FMECA. Furthermore, access and navigation in such layered maintenance information can provide the appropriate context for the successful completion of challenging maintenance tasks.

5. INTELLIGENT MAINTENANCE ADVISOR

Next we analyse the functional requirements of the WelCOM-IMA tool, the adopted design and implementation technologies, as well as its final implementation. As a first step, the provided e-Maintenance services are described and their focus is explained. The competitive advantages of a software tool that can manage the Failure Context are mapped onto industrial needs, using case-scenarios.

5.1. E-Maintenance Mobility

Mobile e-Maintenance involves potent smart portable devices, offering wide displays and powerful multi-core processors. The rapid evolution of mobile Operating Systems and their development frameworks, offer a fluid experience even for the most demanding web applications and enterprise portals. Our goal is to exploit such potentials and address the needs of mobile maintenance personnel:

Greater control over richer information – Early versions of e-Maintenance mobility used the 3-inch displays of industrial PDAs to provide sample history and brief reports. Instrumentation PDAs could also visualize spectrum harmonics and graphs. In most cases, the ability to store, handle and (rarely) process a greater volume of data introduced vendor-locked hardware/software specs with high cost. Recent medium-range tablets are able to hold GBs of local cached data, thus are capable of hosting a maintenance model, within a single native application. The performance of high speed memory affects the solutions' efficiency, as it defines the complexity of data that can be instantly accessed and processed by the mobile actor. Diagnostics can handle structured data with multiple requirements for handling similarly complex metadata. Therefore, mobile e-Maintenance should move much further than the provision of sample history.

Better connection patterns – Wireless communication is the main link between mobile components and e-Maintenance servers. A good example of how easily can a modern device facilitate mobility, is the fact that many industries and application domains have utilized tablets for remote desktop administration of suites and software tools that are physically installed on back-office stations. Mobile personnel can receive a fully compiled environment of a maintenance dashboard that is actually run and executed on a remote machine. Modern E-Maintenance portals offer total control over the workflow, configuration and invocation of e-Maintenance backend processing (i.e. diagnostics), physically distributed (hosted) in optimally integrated services. The developed system brings this kind of control to mobile users, through wide-screen tablets.

Intuitive Interaction and Multi-Access Environments – The majority of enterprise systems that participate in SOA architectures, currently invest in providing flexible interfaces for each employed access profile. This essentially means that their client environment is upgraded, both in terms of content visualization and navigation, to accommodate the needs of a mobile user too. Web technologies currently capitalize in the design of touch-friendly, personalized and context adapted interfaces for portable devices. Modern 10-inch tablets, while thinner and lighter than any industrial PDA, offer solid build and a generous layout for intuitive web environments. The proposed system aims to couple the versatile access context of a 10 inch tablet with Web 2.0 technologies to produce a well-balanced tool for managing maintenance knowledge. Though native applications exhibit a slightly better interaction experience, the mobile web version was favored because (Pistofidis & Emmanouilidis, 2012):

- Mobile web apps can **run on every tablet irrespective to its operating system** (android, iOS, wp8). Native applications constitute OS-locked implementations and require extensive re-engineering for cross-platform compatibility. Web applications can be upgraded to hybrid applications, enjoying the benefits of both. Accessing web applications from different devices requires no additional porting, as services and interfaces support uniform access from any available browser.
- Mobile web apps **do not require installation and do not ask for any kind of access** to personal account information. Recent mobile browsers can boost their performance in compiling even the most demanding and visually loaded interfaces.
- Mobile web apps **offer more options for efficient scaling**. Since they do not invest on local (portable device) logic, web applications tip the balance of complexity to the backend servers. This design feature is aligned with current trends in Cloud and Big-Data. Scaling and load balancing of backend logic is a much easier and streamlined process in web application SOA designs. Furthermore, web apps offer extensive scaling potential for the frontend e-maintenance interfaces too. Web applications can employ many versatile patterns and rich frameworks, to integrate different clients and service outputs into the same user environment. Such technologies allow for less coding and a more robust implementation when, for example, integrating CMMS functionality to an E-Maintenance platform.

Faster Input and Sharing - Social networks are dominating the digital extension of many personal and professional communication spaces. Users, whether at home or at work, require the provision of tools that allow them to provide input at a real-time manner and with many sharing options. Social network portals and their multi-user virtual environments are the most valid testbeds where analysts identify the interaction patterns that users adopt and favor. Some very interesting and useful points can be identified, from the popularity of certain actions by their mobile users:

- Users are most likely to complete fields that require short and concise feedback, than long detailed text.
- Users want to engage the process of feedback with the shortest possible navigation path.
- Users want to indicate approval and positive feedback with direct annotations.
- Users want to organize social assets into virtual collections, using annotations and tags.
- Users want to share in such environments and expect validation, acceptance or feedback from other users.
- Users prefer to view and manage a timeline/feed of events that summarize the status of the social context they have configured to participate in.

Indifferent to the above, most e-Maintenance systems have attempted to collect and map field expertise with exhaustive forms. Especially when addressing mobile maintenance, long forms and inefficient navigation lead to user rejection. Very often the usage of such mobile tools by technicians is done much later than it is supposed to and often after a maintenance task is completed, thus out of context input is likely. Our research uses the mentioned points and specifications to create a web tool designed and developed to encourage mobile use of FMECA-oriented knowledge.

5.2. Implementation Technologies for IMA

This work presents the development and functionality of a web application that benefits from mobile web and mobile cloud technologies, the WelCOM Intelligent Maintenance Advisor. Implementation details follow next.

Back-end logic – These components execute the background management of maintenance diagnostics. To implement WelCOM-IMA's web services we employed the flexibility of a Node.js platform, a runtime environment that can execute Javascript at the backend. At the core of Node.js, the V8 Chrome engine that allows support and integration of libraries/modules that can address a vast range of application requirements. Express.js is such a library and it facilitates the development of web applications on top of Node.js. Node.js can very efficiently virtualize both application and server instances. Thus, load balancing for the maintenance services of IMA can be easily incorporated with no re-engineering. All the services that address the creation, browsing and annotation of the system's Failure Context, are implemented with the flexibility offered by Javascript. This is aligned with a design decision to benefit from the synergy between Javascript components and JSON models, across frontend and backend logic.

Front-end interfaces – The interfaces of a system denote its support for various access patterns. WelCOM-IMA targets mobile actors and thus utilizes technologies that excel in producing mobile optimized web views. Tweaking and customizing the components of a rich web template, our frontend client employs HTML5, CSS and Javascript to build a fluid and touch friendly client interface. WelCOM-IMA facilitates jQuery along with a rich set of other Javascript frameworks, to provide adequate control over maintenance data and offer intuitive user experience. The template scripting language JADE powers a backend engine that dynamically compiles WelCOM IMA's interfaces. This engine makes the WelCOM IMA a fully modular and customizable client, able to comply with various needs in terms of maintenance data visualization and entry.

Physical Data Model – Modeling maintenance semantics is an essential process for the design of any e-Maintenance solution. Many implementations still use relational databases for the physical instantiation of data their models. XML maintenance schemas have dominated the formats of exchanged knowledge for many years, due to their lightweight, human-readable and easily parsed structure. MIMOSA publishes and maintains a very thorough and descriptive XSD schema for all the entities it supports. SOA architectures, especially ones with enterprise web components, are rapidly shifting from XML data to JSON data. JSON syntax is even more lightweight than XML and can be optimally parsed and processed by any programming technology. JSON is a technology coupled with the concept of mashups. A mashup implies the easy and fast integration of multiple data sources to produce enriched information units that can be transferred and consumed uniformly and in a multipurpose manner. JSON mashups are flexible modules of refined information, and thus currently drive the models of many knowledge management systems. WelCOM-IMA uses JSON to enable capturing FMECA-related information inside JSON data. The handling efficiency of JSON with frontend and backend Javascript components, is supported by the use of a noSQL database, namely MongoDB. The consumption of MongoDB's virtual collections, by WelCOM-IMA components, offers the transaction efficiency required by mobile templates and Node.js.

Extending upon a subset of MIMOSA's entities, we have produced a Schema (Figure **3**) that elaborates the attributes and the correlations of FMECA related maintenance data and tags. Hypothetical Event is the entity that maps all type of events participating in the Failure Context. While Failure Mechanisms and Failure Modes are both types of this entity, the instances of the former act as an initial stage for the instances of the later. While Failure Modes are events with a with causes, effects and solutions associated with them, Failure Mechanisms are events that lack such information but may be linked to a Failure Mode. If at some point the significance and the profile of a Failure Mechanisms are upgraded to include causality and proposed solutions, then the appropriate attributes are populated. In such a scenario, while the event's place in the FMECA structure remains the same, its diagnostic value is upgraded. This is a process that gradually builds an Asset Fault Tree. New Failure Events are better perceived and profiled with causes, effects and solutions, when employing the versatility of a Tag Instance entity. Users are able to evaluate and tag all event data and assets. Sorting and fusing this tag-cloud, can effectively point the FMECA review process to the right direction.

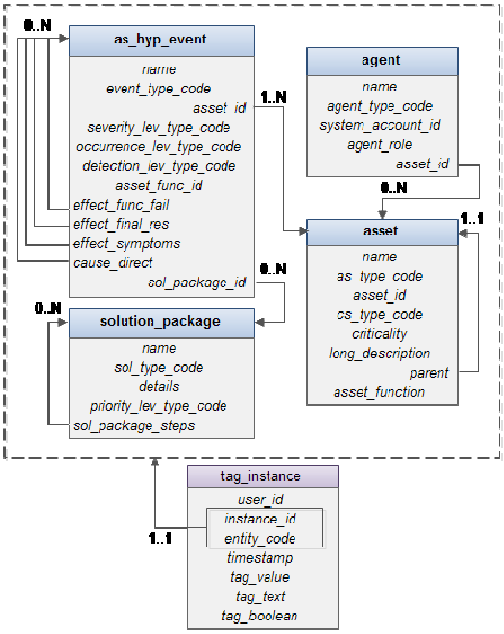
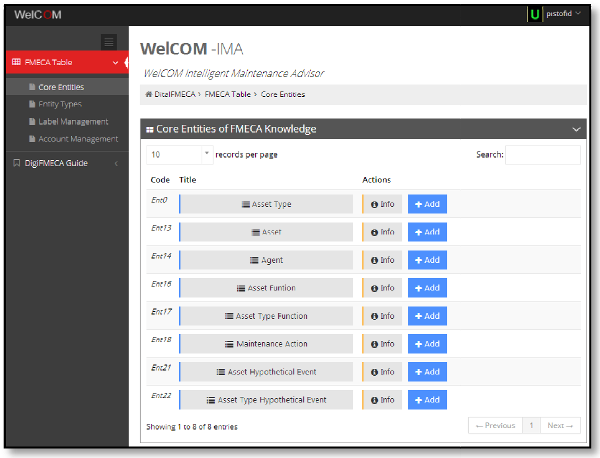


Figure 3. WelCOM IMA core entities schema

5.3. Instantiation in an Application Case

WelCOM-IMA is a part of an e-maintenance platform and comprises part of the platform's knowledge management functionality. It aims to serve the management and delivery of diagnostics knowledge to shop-floor staff. The WelCOM architecture is designed to integrate software components that operate on different systems contexts, such as sensors, servers and portable devices (Pistofidis, Emmanouilidis, Koulamas, Karampatzakis, & Papathanassiou, 2012). Starting from the sensor-embedded pre-processing of monitoring parameters, WelCOM middleware manages, processes and enriches a maintenance model to deliver higher level services for maintenance support and planning.

The WelCOM piloting takes place at KLEEMANN Lifts, a manufacturing industry the delivers complete lifts solutions and an international presence in the lifts industry, holding more than 2% of the global market. The industrial unit that holds key production and business value is the company's latest Electric Elevator. The testing tower at Kleemann's industrial facilities in Kilkis provides one of the test cases that are populating the system with FMECA-related information, whereas other primary and secondary production machinery are currently being studied in the tool.



Code	Title	Actions	
Ent0	Asset Type	Info	+ Add
Ent13	Asset	Info	+ Add
Ent14	Agent	Info	+ Add
Ent16	Asset Funtion	Info	+ Add
Ent17	Asset Type Function	Info	+ Add
Ent18	Maintenance Action	Info	+ Add
Ent21	Asset Hypothetical Event	Info	+ Add
Ent22	Asset Type Hypothetical Event	Info	+ Add

Showing 1 to 8 of 8 entries

Figure 4. WelCOM-IMA Core Entities Directory

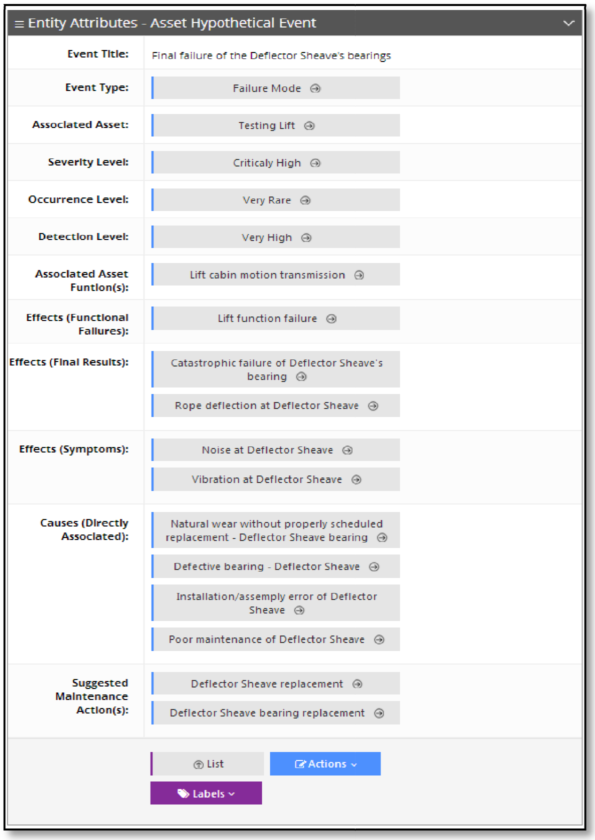
The WelCOM-IMA instantiation in this industrial case study employed use case scenarios to document how the user can browse and enrich maintenance knowledge, while also extending the available options for entity types and tags. The tool offers a core entity set that holds the reference maintenance knowledge. After inserting credentials for authentication the user is presented with a directory of FMECA core entities. A brief description of entity semantics and a button link to the appropriate instantiation form are seen in this first screen (Figure **4**).

5.3.1. Navigation through Diagnostics Context

The modeled knowledge is provided as a fully connected map of diagnostics. The user is able to list the instances of every entity and navigate through them following patterns of maintenance relationships (causality, supervision, solution, taxonomy etc.). Moving from agent to asset, from asset to event and from event to event (Failure Mechanism to Failure Mode), a user can browse details of the documented failure profiles of assets. At every step the navigation of the produced view is supported by profiled and highlighted buttons, drop down option lists and fully configurable data-tables with paging and search tools. Using the maintenance map, the shop-floor technician can traverse the details of events that match current evaluation and/or observations. Through them the search will lead to identifying a Failure Mode associated with most of related acknowledged events (as effects or causes). A Failure Mode screen presents a rich set of FMECA-oriented semantics. Causality attributes support the root-cause analysis of the on-going failure and the suggested maintenance action aids the decision on how to address it (Figure 5).

5.3.2. Maintenance Knowledge Enrichment

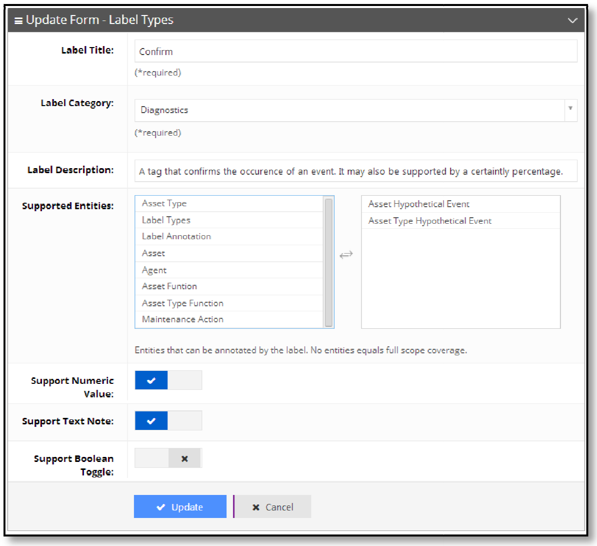
The developed system addresses the needs of both mobile technicians and office engineers, thus it was important to close the distance between them, offering a sharing space for collaborative exchange of maintenance insight. It supports their ability to offer fast and efficient feedback by prompting them to simply acknowledge and flag pre-defined semantics. Feedback is summarized by descriptive tags to assets, agents, events and solutions. Each tag can signify a state, action, an observation or an alarm, in short anything that matters in the context of diagnostics. A basic set of offered tags, includes "Confirm" (tagging the detection of a failure event), "Working here" (on-going maintenance action and proximity to an asset), "Observation" (logging of an observation).



Event Title:	Final failure of the Deflector Sheave's bearings
Event Type:	Failure Mode
Associated Asset:	Testing Lift
Severity Level:	Criticaly High
Occurrence Level:	Very Rare
Detection Level:	Very High
Associated Asset Funtion(s):	Lift cabin motion transmission
Effects (Functional Failures):	Lift function failure
Effects (Final Results):	Catastrophic failure of Deflector Sheave's bearing Rope deflection at Deflector Sheave
Effects (Symptoms):	Noise at Deflector Sheave Vibration at Deflector Sheave
Causes (Directly Associated):	Natural wear without properly scheduled replacement - Deflector Sheave bearing Defective bearing - Deflector Sheave Installation/assemply error of Deflector Sheave Poor maintenance of Deflector Sheave
Suggested Maintenance Action(s):	Deflector Sheave replacement Deflector Sheave bearing replacement

Figure 5. Information screen for an Asset Failure Mode.

Additionally, a "Confirm" tag may carry a certainty numeric value. All tags support input of textual notes, offering assessment details (Figure **6**). Analysis of the collected textual notes can reveal semantics for different applications, maintenance departments, policies, or even work teams. WelCOM-IMA offers the means to create new tag templates where engineers and maintenance directors can configure the semantics and the (optional) input profile of new tags (Figure 6). Configuration fields include taxonomy with tag categories, a description, a set of compatible entities and the support for numeric value, textual note and a status lock. These templates, upon creation, are instantly available for shop-floor and managerial personnel to use them and best capture/translate their assessments. The annotation task has to be swift and easy. WelCOM-IMA provides a "Label" drop list, in every interface that presents instances that can be tagged. This drop list offers the ability to annotate the instance with a new tag, or view the annotation history of this specific instance. Choosing to add a new tag, the user is presented with a touch-friendly interface listing all available tags that support the entity of the assessed instance. While the brief description and the category informative of the underlying semantics, a side-form facilitates the direct input of additional feedback, for each supported tag (Figure 7). The simple touch of the tag's button concludes the tagging process and records the new assessment as a timestamped entry in the instance's annotation history. Maintenance engineers can now view the annotation history of each asset and failure event. WelCOM-IMA provides three forms of annotation timelines: (i) instance-oriented, (ii) user-oriented and (iii) global. Each one enables a different view over assessments that can drive different sets of conclusions.



Label Title: Confirm
(*required)

Label Category: Diagnostics
(*required)

Label Description: A tag that confirms the occurence of an event. It may also be supported by a certaintly percentage.

Supported Entities:

- Asset Type
- Label Types
- Label Annotation
- Asset
- Agent
- Asset Funtion
- Asset Type Function
- Maintenance Action

- Asset Hypothetical Event
- Asset Type Hypothetical Event

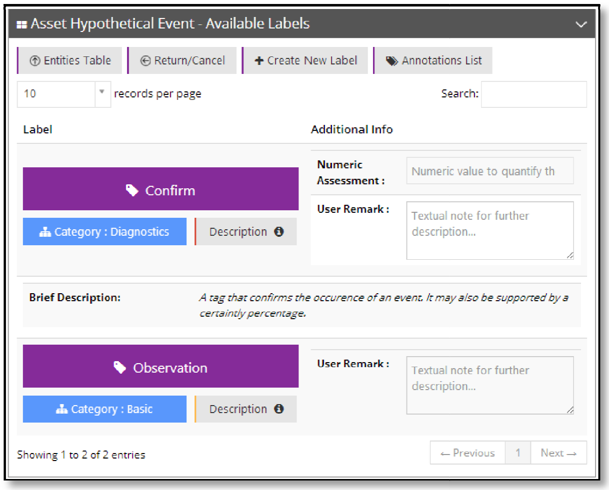
Entities that can be annotated by the label. No entities equals full scope coverage.

Support Numeric Value: ✓

Support Text Note: ✓

Support Boolean Toggle: ✗

Figure 6. Configuring a new tag template.

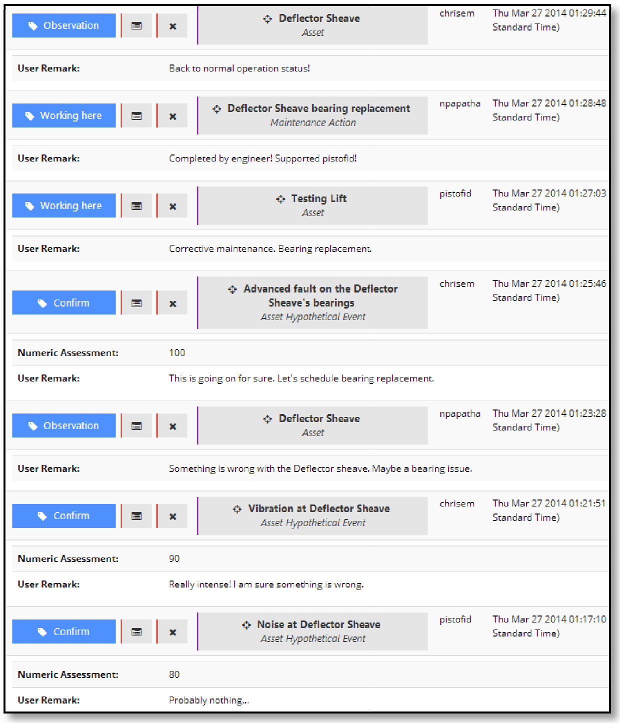


10 records per page

Label	Additional Info
Confirm Category : Diagnostics Description	Numeric Assessment : Numeric value to quantify th User Remark : Textual note for further description...
Brief Description:	*A tag that confirms the occurence of an event. It may also be supported by a certaintly percentage.*
Observation Category : Basic Description	User Remark : Textual note for further description...

Showing 1 to 2 of 2 entries

Figure 7. Use of supported annotation tags.



Observation	**Deflector Sheave** *Asset*	chrisem	Thu Mar 27 2014 01:29:44 Standard Time)
User Remark:	Back to normal operation status!		
Working here	**Deflector Sheave bearing replacement** *Maintenance Action*	npapatha	Thu Mar 27 2014 01:28:48 Standard Time)
User Remark:	Completed by engineer! Supported pistofid!		
Working here	**Testing Lift** *Asset*	pistofid	Thu Mar 27 2014 01:27:03 Standard Time)
User Remark:	Corrective maintenance. Bearing replacement.		
Confirm	**Advanced fault on the Deflector Sheave's bearings** *Asset Hypothetical Event*	chrisem	Thu Mar 27 2014 01:25:46 Standard Time)
Numeric Assessment:	100		
User Remark:	This is going on for sure. Let's schedule bearing replacement.		
Observation	**Deflector Sheave** *Asset*	npapatha	Thu Mar 27 2014 01:23:28 Standard Time)
User Remark:	Something is wrong with the Deflector sheave. Maybe a bearing issue.		
Confirm	**Vibration at Deflector Sheave** *Asset Hypothetical Event*	chrisem	Thu Mar 27 2014 01:21:51 Standard Time)
Numeric Assessment:	90		
User Remark:	Really intense! I am sure something is wrong.		
Confirm	**Noise at Deflector Sheave** *Asset Hypothetical Event*	pistofid	Thu Mar 27 2014 01:17:10 Standard Time)
Numeric Assessment:	80		
User Remark:	Probably nothing...		

Figure 8. Annotations global timeline: a Failure's Context.

The interpretation of these timelines can have a big impact in the performance of on-spot diagnostics. Having access to a timeline of annotations correlating assets and events is a tool that "connects-the-dots" of a Failure's Context (Figure 8). The time locality of events, the focused tag semantics and the annotated knowledge, offer a perception boost to the context-switching mindset of mobile personnel.

6. CONCLUSION

Studying the annotation history of a failure event or an asset empowers maintenance professionals to extract valuable patterns of machinery behavior. The ability to manage the underlying structured knowledge and perform analytics over the collective micro-knowledge of staff operating on the shop floor, constitute a powerful enabler that upgrades the level of knowledge management, by incorporating into the loop maintenance mobile actors. WelCOM-IMA offers an effective method to facilitate the contribution and participation of all maintenance staff in managing the evolution of maintenance events and knowledge. WelCOM-IMA enables the organization and collaborative evaluation of maintenance assessments based on semantic tags. Following a bottom up approach in knowledge composition, it delivers a tool that profiles, instantiates and shares the building blocks of failure diagnostics. Therefore, it can adapt the maintenance meta-model to semantics tuned for a specific application. This constitutes a significant enabler for the elicitation and management of field-captured knowledge, a feature often missing in many tools.

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