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MECHANICAL DESIGN LABORATORY (MeDiLab D.U.Th)

TECHNOLOGIES AND SYSTEMS FOR REMOTE MONITORING AND DIAGNOSIS SUPPORT

Doctoral Dissertation of:

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Statement of Original Authorship

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at D.U.Th or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at D.U.Th or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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Summary

Modern manufacturing environments have become increasingly populated with "intelligent" asset, while most industrial platforms have already adopted the use of "smart" portable devices and "smart" sensors. Using software services and interfaces, the integration of such systems and components provides uniform access, across all layers of industry, to advanced information structures and the tools to effectively manage, if not also enrich them. Facilitating the respective context of technologies and architectures, e-Maintenance platforms have recently invested a lot in smart wireless sensors that can reliably and autonomously detect events and identify abnormal behaviour. Furthermore, the extensive use of portable devices inside and outside the industrial field, has provided many options for remote access to services and information properly adapted to the role and task of each engineer, operator, technician or expert.

As more such systems come to serve the requirements for a wider range of industrial processes, new challenges emerge for the utilisation of the information they manage. The volume and the heterogeneity of this information is extended with constant incorporation of new data streams, driven by either technical systems or human input. Industry continues to explore the potential added value hidden inside its information silos, consistently evaluating the state of the art for knowledge management systems and steadily adopting mature methodologies and well-established techniques. Asset Life-Cycle Management and Maintenance, are domains that have already produced standardised structures and mechanisms to study, analyse and organise purposeful knowledge. The Failure Mode, Effects and Criticality Analysis (FMECA) comprises knowledge that maps and analyses the profile of potential failure modes for critical assets of an industrial plant, sector or productions line. It is a knowledge asset that serves as a maintenance reference and can support fault diagnostics and failure handling. FMECA is also extensively used for risk-analysis tasks and contributes in the definitions of risk-based policies. Properly adapted structures and services are available for modelling, managing and updating this knowledge. Examples of other maintenance knowledge assets include maintenance policies, strategy and plan, along with every organised taxonomy that can drive analytic services and support decision making for experts.

Continuous evaluation and consistent quality control are equally important tasks for maintaining or upgrading the value of a knowledge asset. FMECA knowledge is a compact and refined version of reliability-related maintenance knowledge that is being developed by maintenance engineering experts. Producing or reviewing an FMECA table, is an engineering, commonly scheduled as a repeated knowledge management process. This study involves the contribution from a team of experts, with specific background and set of skills. A key aspect of an FMECA review process is the analysis of diagnosed failures, detected events and completed maintenance actions, all recorded by working on the relevant asset. FMECA provides comprehensive knowledge of diagnostics, distilled from engineering and maintenance practice, and thus appropriate to support shop-floor maintenance tasks. A knowledge validation and refinement loop is weakly supported in practice. In the majority of cases, maintenance staff only have access to datasheets and manuals that feature tables with limited knowledge, simply listing common faults with one single appropriate solution. This is knowledge that requires no analysis and leaves no space for skill improvement. As a result FMECA knowledge is disconnected from experts that can benefit from it, and also hold tacit maintenance knowledge to expand it.

The lack of shared FMECA knowledge can negatively impact the capturing of shop-floor expertise. FMECA knowledge is often reviewed once or twice per year. During this process, engineers and maintenance experts are called to analyse and correlate effects, failures and actions, on the basis of existing knowledge and latest

available evidence. However, this disconnected context of sharing and processing is not sufficiently exploiting such latest evidence when it is based on analysing uneven and unstructured maintenance reports. The overhead can be further amplified by the fact that reporting methodologies rarely use intuitive mechanisms and do not communicate well their goals, or potential benefits. Exhaustive forms and non-formalised responses make reporting a time-consuming and ineffective process, failing to capture key aspects of recorded events or actions, eventually reducing staff motivation to contribute. The above issues make FMECA review a task that may produce once or twice per year a slightly improved version, while missing timely field feedback, which is more likely to identify gaps and mismatches and thus lead to producing more accurate FMECA knowledge. In order to engage a sharing mentality and feel motivated to contribute, maintenance professionals need to be able to access, study and process the current version of FMECA knowledge. This version provides a starting point and act as reference or a template to ease and guide contribution, thus constituting the first step of the desired knowledge building process.

This thesis is inspired by the techniques and modern technologies of Semantic Web. The presented research builds on their ability to collect, organize and capture knowledge, contributed from users that engage a reviewing mentality when referencing, processing and consulting a comprehensive reference. Techniques such as semantic annotations with semantic tags, have been extensively adopted by tools that support the editing of shared information. Today, the majority of modern collaborative environments integrate similar features, as means of collective management and enrichment of existing knowledge. Social networks offer a good example of how comments and semantic tags can be used to enrich shared knowledge. Each comment or tag is the minimum amount of useful information a user can or is willing to contribute and share. It is a simple process, making it easier for working staff to actively participate. Yet, this linked information can be easily modeled and classified, scales very fast, and its analysis may offer many useful insights. With a well-defined set of tags, semantic annotations can drive the creation of highly focused knowledge, given an appropriate starting point.

The goal of this thesis is to use the above methodology in an industrial context, and create an enterprise knowledge flow between maintenance management and shop-floor practice. This flow makes FMECA a shared knowledge asset that is being analyzed and studied by maintenance management, while being validated and enriched by shop-floor staff. The first step of this research was to design a model that can share and properly convey FMECA knowledge to shop-floor personnel. The knowledge complexity of this model is balanced, so that it effectively supports maintenance practice and diagnostics for staff that constantly move, change working contexts and follow a tight schedule. This model invests in knowledge that describes: (i) failure mode effects, classifying them in three distinct groups according to their impact; and (ii) suggested maintenance actions, allowing their further analysis with prioritized steps. The entities used for modeling failure modes and maintenance actions, both include recursive links. This design choice allows cause - effect relationships to link multiple failure modes in a form of graph that can map relevant knowledge. The above FMECA model is designed to adopt Linked Data (LD) specifications, and developed to be referenced by maintenance personnel through the use of portable devices and a wireless connection.

This thesis proposes the use of semantic enrichment as a new method for capturing and linking field expertise with FMECA knowledge. This method facilitates maintenance personnel semantic annotations to systematically review and validate FMECA knowledge. Maintenance observations, evaluations and decisions are entered as annotations of FMECA. Each annotation is the result of using a maintenance tag on a relevant FMECA component (asset, event or action). As "maintenance tags" we define a set of semantic tags capable of describing the relevancy of FMECA knowledge with what is observed, experienced and decided on the shop-

floor and during everyday maintenance practice. This reporting methodology translates detected symptoms, diagnosed failures, decided maintenance actions, and other forms of field knowledge, into FMECA's semantic enrichment. The term "failure context", is used in this thesis to define the confluence of available FMECA knowledge for a specific failure mode, with the set of relevant maintenance tags during one of its verified occurrences. Each such tag creates an annotation that links "*What is known about this failure mode?*" with "*How this failure mode manifests itself now, at the shop-floor?*". To enable maintenance personnel to suggest corrections and additions for FMECA, the annotation process supports the optional use of mini-forms that allows the input of additional feedback. Offering a quantitative value, a binary state and/or a brief comment, experts have the opportunity to use this form and explain how their evaluation or experience is different from what is stated by the annotated FMECA knowledge. Each distinct annotation validates FMECA knowledge or suggests its update, and therefore constitutes contribution of field knowledge and expertise. We term this contribution as "maintenance micro-knowledge" and its role, to link and describe maintenance knowledge, is identical to the role of metadata in the semantic web.

The presented methodology was implemented into a web application that provides maintenance support by sharing and managing FMECA knowledge. This application was designed to be accessed and used with portable devices and touch screens. The enrichment of FMECA knowledge and the management of maintenance micro-knowledge use mechanisms and components that identify this application as a metadata management system. The piloting took place at KLEEMANN Lifts, a large enterprise with global presence in the lifts industry. The recorded use was shown to have a positive reception by personnel in supporting them in their activities on selected assets. These assets included manufacturing machinery, along with product testing and service installations of the end product. We employ a detailed case study to analyze system usage and the knowledge processing cycle, when managing processes related to the occurrence of a failure mode. The system's performance during the piloting were evaluated with the use of a questionnaire, and the analysis of its results drives our conclusions for improvements and our suggestions for next steps.

Keywords

Maintenance Management, E-Maintenance, Context, Knowledge Management Systems, Wireless Technologies, Enterprise Applications

Περίληψη

Το σύγχρονο πεδίο παραγωγής αξιοποιεί ολοένα και περισσότερο "έξυπνες" φορητές συσκευές και "έξυπνους" αισθητήρες, συνεισφέροντας στην αναβαθμισμένη λειτουργία του με χρήση "έξυπνων" παγίων. Η ασύρματη διασύνδεση επιμέρους συστημάτων και η ολοκλήρωση των λειτουργιών τους με υπηρεσίες λογισμικού, επιτρέπει σήμερα σε όλα τα επίπεδα της βιομηχανίας να έχουν πρόσβαση σε αναβαθμισμένη πληροφορία και τα απαραίτητα εργαλεία για να τη διαχειριστούν, ή ακόμη και να την εμπλουτίσουν. Αξιοποιώντας παρόμοιες τεχνολογίες, οι πλατφόρμες ηλεκτρονικής συντήρησης χρησιμοποιούν τα τελευταία χρόνια ασύρματους κόμβους ικανούς να παρακολουθούν και να εντοπίζουν συμβάντα και σφάλματα μηχανών. Αντίστοιχα, η χρήση φορητών συσκευών εντός και εκτός του πεδίου παραγωγής, όταν υποστηρίζεται από κατάλληλο λογισμικό, παρέχει διαβαθμισμένη πρόσβαση σε προσαρμοσμένες υπηρεσίες και πληροφορία, συναφή με τον ρόλο και την εργασία του κάθε μηχανικού, χειριστή, τεχνικού και γενικά εμπειρογνώμονα.

Καθώς τα παραπάνω συστήματα εξυπηρετούν όλο και μεγαλύτερο φάσμα βιομηχανικών διεργασιών, αναδύονται νέες προκλήσεις στην αξιοποίηση της πληροφορίας που διαχειρίζονται. Ο όγκος και το είδος της πληροφορίας επεκτείνονται με αυξανόμενες ροές δεδομένων, οι οποίες παράγονται τόσο από τεχνικές υποδομές όσο και από έμψυχο δυναμικό. Διερευνώντας τις προοπτικές της προστιθέμενης αξίας αυτής της πληροφορίας, η βιομηχανία αξιολογεί τη στάθμη τεχνικής των συστημάτων διαχείρισης γνώσης και σταδιακά υιοθετεί τις πιο ώριμες και αποτελεσματικές μεθοδολογίες και τεχνικές. Πιο συγκεκριμένα, η διαχείριση κύκλου ζωής και η συντήρηση βιομηχανικών παγίων, αποτελούν τομείς που ήδη διαθέτουν προτυποποιημένες δομές και διαδικασίες για τη μελέτη, ανάλυση και οργάνωση γνώσης με συγκεκριμένο στόχο. Ο πίνακας Ανάλυσης Τύπων Αστοχίας, Επιπτώσεων και Κρισιμότητας (Failure Mode, Effects and Crticality Analysis - FMECA) αποτελεί πρότυπο μελέτης που αφορά τη συστηματική και αναλυτική περιγραφή των πιθανών τύπων αστοχίας που έχουν καταγραφεί για κρίσιμα τεχνικά πάγια, σε επίπεδο εγκατάστασης, τομέα ή γραμμής παραγωγής. Πρόκειται για στοχευμένη γνώση, η οποία συνιστά σημείο αναφοράς για την έγκυρη διάγνωση και τη σωστή αντιμετώπιση σημαντικών βλαβών και σφαλμάτων, ενώ παράλληλα καθοδηγεί την ανάλυση κινδύνου και συνεισφέρει στη διαμόρφωση ανάλογων (risk-based) πολιτικών. Η γνώση αυτή συγκροτείται σε κατάλληλα προσαρμοσμένες δομές, ενώ η διαχείριση και ενημέρωσή της γίνεται από εξειδικευμένα συστήματα και υπηρεσίες.

Η συνεχής αξιολόγηση και ο τακτικός ποιοτικός έλεγχος είναι εξίσου σημαντικές διεργασίες για τη διατήρηση ή και την αναβάθμιση της αξίας μιας δομής γνώσης. Η γνώση που περιλαμβάνεται στο πίνακα FMECA αναλύει και περιγράφει εμπειρία που αναπτύσσεται στο πεδίο εφαρμογής της συντήρησης. Η σύνθεση και αναθεώρηση του πίνακα FMECA υλοποιείται κυρίως ως μια επαναλαμβανόμενη μελέτη, και υποστηρίζεται από ομάδα εμπειρογνωμόνων συγκεκριμένης σύνθεσης και επιστημονικού υποβάθρου. Κύριος άξονας της αναθεώρησης μιας μελέτης FMECA είναι η ταξινόμηση και ανάλυση βλαβών, εντοπισμένων συμπτωμάτων και εντολών συντήρησης που έχουν καταχωρηθεί κατά τη λειτουργία του εξοπλισμού. Ωστόσο, πολύ συχνά η γνώση FMECA δεν είναι προσβάσιμη στο προσωπικό συντήρησης και συνήθως είναι καταχωρημένη σε συστήματα ανάλυσης κινδύνου, που διαθέτουν λίγες ή καθόλου δυνατότητες διαμοίρασής της στο πεδίο παραγωγής. Στην πλειοψηφία των περιπτώσεων, το προσωπικό συντήρησης έχει πρόσβαση μόνο σε τεχνικά εγχειρίδια, όπου προσφέρονται πίνακες πιθανών συμβάντων και προτεινόμενων ενεργειών. Στους πίνακες αυτούς, τα συμβάντα δεν συσχετίζονται με κάποιο τρόπο, ενώ οι ενέργειες δεν προσφέρουν εναλλακτικές προσεγγίσεις και βήματα. Πρόκειται για πληροφορία που δεν αφήνει πολλά περιθώρια επιλογής και ανάλυσης. Αποτέλεσμα των

παραπάνω είναι η γνώση FMECA να μην είναι κατάλληλα διαθέσιμη στο προσωπικό συντήρησης που μπορεί να την αξιοποιήσει και συλλογικά να την επεκτείνει.

Η απουσία διαμοίρασης της γνώσης FMECA λειτουργεί αρνητικά στη διαδικασία συλλογής και αποτύπωσης σχετικής γνώσης πεδίου. Η αναθεώρηση της γνώσης FMECA προγραμματίζεται συνήθως σε ετήσια ή εξαμηνιαία βάση, όποτε και οι εμπειρογνώμονες από το πεδίο παραγωγής καλούνται να αναλύσουν και να συσχετίσουν συμπτώματα, βλάβες και ενέργειες που συνέβησαν μήνες πριν. Στην ετεροχρονισμένη αυτή επαφή τόσο με την γνώση FMECA όσο και με το ιστορικό συντήρησης, έρχεται να προστεθεί η δυσκολία ανάλυσης αναφορών με ανομοιογενή και ελάχιστα κωδικοποιημένη πληροφορία. Το παραπάνω πρόβλημα ενισχύεται, καθώς η μέθοδος αποτύπωσης γνώσης σπάνια υιοθετεί εύκολους μηχανισμούς, ή επικοινωνεί αποτελεσματικά τους στόχους και τα οφέλη της. Οι εξαντλητικές φόρμες και η έλλειψη υποστήριξης για συνοπτικές και κωδικοποιημένες απαντήσεις, κάνουν χρονοβόρα και δύσκολη τη σωστή αναφορά βλαβών και εργασιών συντήρησης. Η ευρύτερη νοοτροπία και διάθεση ανταλλαγής γνώσης, ενεργοποιείται ελάχιστα στο προσωπικό συντήρησης, καθώς δεν διατίθεται αρχική γνώση FMECA ως βάση ή πρότυπο καθοδήγησης και συνεπώς το προσωπικό δεν νιώθει ότι έχει επαρκή κίνητρα να συνεισφέρει στη διαδικασία. Η παραπάνω διαδικασία αναθεώρησης επικαιροποιεί τη γνώση FMECA, μια ή δύο φορές τον χρόνο, και δεν αξιοποιεί επαρκώς την εμπειρία που μπορεί να προσφέρει το προσωπικό που δραστηριοποιείται στο πεδίο, σε καθημερινή βάση.

Η παρούσα διατριβή είναι εμπνευσμένη από τις τεχνικές και σύγχρονες τεχνολογίες Σημασιολογικού Ιστού. Η έρευνα που παρουσιάζεται, βασίζεται στην ικανότητά τους να συλλέγουν, να ταξινομούν και να αποτυπώνουν την κριτική στάση και κατ' επέκταση την προστιθέμενη γνώση που προσφέρουν οι χρήστες, όταν αναλύουν και συμβουλεύονται μια περιεκτική δομή γνώσης. Τεχνικές όπως η σημασιολογική επισημείωση (semantic annotation) με χρήση σημασιολογικών ετικετών (semantic tags), έχουν υιοθετηθεί εδώ και χρόνια από εργαλεία που υποστηρίζουν τη διόρθωση και τον σχολιασμό διαμοιρασμένης πληροφορίας. Σήμερα, τα περισσότερα σύγχρονα συνεργατικά περιβάλλοντα ενσωματώνουν παρόμοιες δυνατότητες, ως μέσο συλλογικής σύνθεσης και εμπλουτισμού υπάρχουσας γνώσης. Χαρακτηριστικό παράδειγμα αποτελούν τα σχόλια και οι τυποποιημένες σημασιολογικές ετικέτες που προσφέρονται στις πλατφόρμες κοινωνικής δικτύωσης. Ένα σύντομο σχόλιο ή μια ετικέτα είναι η ελάχιστη χρήσιμη πληροφορία που μπορεί ή είναι πρόθυμος ένας χρήστης να προσφέρει, για να εμπλουτίσει μια αρχική γνώση. Η διασυνδεδεμένη αυτή πληροφορία αποτυπώνεται και ταξινομείται εύκολα, κλιμακώνεται γρήγορα και η ανάλυσή της μπορεί να οδηγήσει σε πολλά χρήσιμα συμπεράσματα. Η ευκολία χρήσης ετικετών και εισαγωγής σχολίων, ενθαρρύνει τους χρήστες να συμμετέχουν. Σε συνδυασμό με ένα μελετημένο σύνολο ετικετών, οι σημασιολογικές επισημειώσεις μπορούν να οδηγήσουν στην σύνθεση αρκετά εξειδικευμένης γνώσης, με σημείο αφετηρίας την κατάλληλη αρχική πληροφορία.

Ο στόχος της παρούσης διατριβής είναι να αξιοποιήσει τις παραπάνω τεχνικές και να προσφέρει μια αμφίδρομη ροή γνώσης ανάμεσα στο διαχειριστικό επίπεδο που μελετάει και αναλύει τη γνώση FMECA, και στο πεδίο παραγωγής που την επικυρώνει και αξιοποιεί κατά τη συντήρηση. Ως πρώτο βήμα, έχει σχεδιαστεί ένα ευέλικτο μοντέλο γνώσης FMECA, με στόχο την αποτελεσματική αποτύπωση και διαμοίρασή της στο προσωπικό συντήρησης. Το μοντέλο έχει προσαρμοστεί για την αποτελεσματική υποστήριξη της διάγνωσης και αντιμετώπισης σφαλμάτων από προσωπικό που κινείται στο πεδίο παραγωγής και ακολουθεί ένα πιεστικό πλάνο εργασιών. Συγκεκριμένα, το μοντέλο επενδύει σε γνώση που αφορά: (i) τις επιπτώσεις κάθε τύπου αστοχίας, ταξινομώντας τες σε διακριτές κατηγορίες αναλόγως της σημασίας τους, και (ii) τις προτεινόμενες ενέργειες συντήρησης, επιτρέποντας την ανάλυσή τους με βήματα ξεχωριστής προτεραιότητας. Οι οντότητες με τις οποίες μοντελοποιούνται οι τύποι αστοχίας και οι ενέργειες συντήρησης, υποστηρίζουν αναδρομή στις σχέσεις τους. Η σχεδιαστική αυτή επιλογή επιτρέπει στις σχέσεις αιτίας-αποτελέσματος να συνδέσουν αλλεπάλληλους τύπους αστοχίας σε ένα γράφο, ικανό να αποτυπώσει τη συναφή γνώση. Αντίστοιχα, οι σχέσεις ενέργειας-βήματος μπορούν να κλιμακώσουν την πολυπλοκότητα των ενεργειών συντήρησης, περιγράφοντας τεχνικές και μεθόδους που αποτυπώνουν πιο σύνθετη ιεραρχία και ροή εργασιών. Η παραπάνω γνώση FMECA, έχει μοντελοποιηθεί υιοθετώντας προδιαγραφές Συνδεδεμένων Δεδομένων (Linked Data - LD) και προσφέρεται στο προσωπικό συντήρησης, μέσω φορητών συσκευών και ασύρματου δικτύου.

Η διατριβή αυτή προτείνει τη χρήση τεχνικών σημασιολογικού εμπλουτισμού, για μια νέα μέθοδο αποτύπωσης και διασύνδεσης της γνώσης πεδίου με την γνώση FMECA. Στην μέθοδο αυτή, το προσωπικό συντήρησης χρησιμοποιεί σημασιολογικές επισημειώσεις για να οδηγήσει τη συστηματική αναθεώρηση και επικύρωση της γνώσης FMECA. Συγκεκριμένα, οι παρατηρήσεις, οι εκτιμήσεις και οι αποφάσεις του προσωπικού εισάγονται ως σημασιολογικές επισημειώσεις. Κάθε επισημείωση υλοποιείται με την απόδοση της κατάλληλης ετικέτας συντήρησης σε σχετικό στοιχείο (πάγιο, συμβάν ή ενέργεια) της γνώσης FMECA. Ως "ετικέτες συντήρησης", ορίζουμε ένα σύνολο σημασιολογικών ετικετών, ικανών να περιγράψουν τη συνάφεια της γνώσης FMECA με ευρήματα και αποφάσεις του πεδίου παραγωγής και της καθημερινής εφαρμογής της συντήρησης. Η παραπάνω μεθοδολογία αναφοράς μεταφράζει τον εντοπισμό συμπτωμάτων, τη διάγνωση βλαβών, την απόφαση για εκτέλεση ενεργειών συντήρησης, καθώς και άλλες μορφές γνώσης πεδίου, σε σημασιολογικό εμπλουτισμό της γνώσης FMECA. Ως "πλαίσιο γνώσης αστοχίας" (failure context) ορίζουμε το συνδυασμό της γνώσης FMECA, για ένα συγκεκριμένο τύπο αστοχίας, με το σύνολο των ετικετών που χρησιμοποιήθηκαν κατά την εξέλιξη μιας επιβεβαιωμένης εμφάνισής του. Κάθε τέτοια ετικέτα υλοποιεί μια επισήμανση που συνδέει το "*Τί είναι γνωστό για τον τύπο αστοχίας;*" με το "*Πώς εμφανίζεται και εξελίσσεται τώρα ο τύπος αστοχίας, στο πεδίο παραγωγής;*". Προκειμένου να μπορεί το προσωπικό συντήρησης να προτείνει την διόρθωση και επέκταση της γνώσης FMECA, η χρήση κάθε ετικέτας συνοδεύεται από προαιρετική συμπλήρωση μιας μικρής φόρμας, για την εισαγωγή επιπρόσθετης ποιοτικής πληροφορίας. Εισάγοντας μια ποσοτική εκτίμηση, μια δυαδική κατάσταση και/ή ένα συνοπτικό σχόλιο, το προσωπικό έχει τη δυνατότητα να περιγράψει με αυτή τη φόρμα, το πώς διαφοροποιείται η εκτίμηση ή η παρατήρησή του σε σχέση με την επισημειωμένη γνώση FMECA. Κάθε ξεχωριστή επισημείωση επικυρώνει ή προτείνει την ενημέρωση της γνώσης FMECA, και επομένως συνιστά συνεισφορά γνώσης πεδίου. Στην παρούσα διατριβή, η συνεισφορά αυτή ορίζεται ως "μικρο-γνώση συντήρησης". Ο ρόλος της να συνδέει και να περιγράφει γνώση συντήρησης ταυτίζεται λειτουργικά με το ρόλο των μεταδεδομένων στο σημασιολογικό ιστό.

Η μέθοδος που αναλύθηκε, έχει υλοποιηθεί σε ένα διαδικτυακό εργαλείο για την υποστήριξη της συντήρησης, μέσω της διαμοίρασης και διαχείρισης γνώσης FMECA. Το εργαλείο αυτό είναι κατάλληλα σχεδιασμένο για χρήση από φορητές συσκευές (tablets) και οθόνες αφής. Η επέκταση της γνώσης FMECA και η σύνθεση της μικρο-γνώσης συντήρησης υιοθετούν τεχνικές και δομές που καθιστούν το εργαλείο να λειτουργεί ως ένα σύστημα διαχείρισης μεταδεδομένων. Η πιλοτική χρήση της υλοποίησης πραγματοποιήθηκε από το προσωπικό συντήρησης της KLEEMANN, μιας βιομηχανίας που δραστηριοποιείται στο χώρο της σχεδίασης και κατασκευής ολοκληρωμένων λύσεων ανελκυστήρων. Η χρήση του εργαλείου έτυχε της θετικής αποδοχής από προσωπικό που υποστήριξε την διάγνωση και αντιμετώπιση βλαβών σε επιλεγμένα πάγια, που συνδέονται με τη παραγωγή είτε με το τελικό προϊόν. Υιοθετώντας τη μεθοδολογία μελέτης περίπτωσης και εστιάζοντας αναλυτικότερα στην παρουσίαση της πιλοτικής χρήσης του συστήματος σε ένα παράδειγμα χαρακτηριστικού τύπου αστοχίας, η διατριβή περιγράφει τη χρήση του συστήματος και στοιχειοθετεί τη διαδικασία διαχείρισης της παραγόμενης σχετικής γνώσης. Η αξιολόγηση του εργαλείου πραγματοποιήθηκε με κατάλληλο ερωτηματολόγιο, και η ανάλυση των αποτελεσμάτων οδηγεί τα συμπεράσματα μας για βελτιώσεις και επόμενα βήματα για την έρευνα.

Λέξεις Κλειδιά

Διαχείριση Συντήρησης, Ηλεκτρονική Συντήρηση, Πλαίσιο Συνάφειας, Συστήματα Διαχείρισης Γνώσης, Ασύρματες Τεχνολογίες, Διαδικτυακές Υπηρεσίες

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Contents

List of Figures

List of Tables

1 Introduction

1 INTRODUCTION

Industry is aware of the knowledge discovery prospects that reside in the data volumes stored in enterprise databases. Many methods that fall into the realm of knowledge discovery from databases (KDD) and data mining (DM) 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 value producing capacity of an enterprise. This is emphasized by the recently adopted ISO 55000 standard on Asset Management. e-Maintenance is often employed as the term to document modern web-based and mobile technologies that offer advanced maintenance services (Iung et al., 2009, Emmanouilidis et al., 2009). These services have now been incorporated into ERP systems and can produce, manage, consume and disseminate maintenance data to support demanding maintenance processes (Nikolopoulos et al., 2003). Furthermore, modern Condition Monitoring (CM) systems and Computerized Maintenance Management Systems (CMMS) are able to orchestrate workflows of such services and manage maintenance data before and after their analysis. The advent of Internet of Things (IoT) has boosted data generation with real-time sensory data, driving decision making for condition monitoring and offering recommendations for proactive maintenance (Bousdekis et al., 2015). In this context, e-Maintenance has become a valuable facilitator of industrial intelligence, transforming maintenance data into actionable knowledge.

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). Metadata provide important building blocks of knowledge, facilitating the definition, instantiation and integration of relationships between data entities. Their ability to compose indexing and classification models based on descriptive and structural data properties, makes metadata an efficient mediator between flat information and enriched knowledge (Duval et al., 2002).

Metadata management systems offer a transparent layer that addresses the challenge of semantic integration and data enrichment. Employing semantic enrichment can create metadata that enable application-focused analytics (Fang et al., 2010). As a precursor to successful analytics, the annotation of vast data pools becomes an important step for any industry switching from local data generation and management to large distributed data silos. Metadata can formalize semantic relationships and properties, so that this step is made in the direction of a more efficient elicitation and management of associated knowledge. Metadata repositories bring important benefits to knowledge management, including: (i) consistency of definitions, (ii) clarity of relationships and (iii) clarity of data lineage/provenance. Metadata are tightly coupled with Linked Data. They both facilitate the organization and management of large data sets (Gao et al., 2010), commonly produced by data acquisition systems (Dawes et al., 2008). A maintenance metadata schema can mature to formalize the semantics of Linked Data. At that state, systems compliant to the schema will be able to integrate better and exchange data more efficiently.

A Failure Mode, Effects and Criticality Analysis (FMECA) comprises structured knowledge related to Reliability - Centred Maintenance (RCM) (US-DoD, 1980). Initially composed as a military standard, FMECA was soon acknowledged for its value and adopted by industry. 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. Some efforts focus on conventional knowledge elicitation through interviews and questionnaires (Walls et al., 2005), while more advanced ones employ well-focused maintenance ontologies (Potes Ruiz et al., 2013). A knowledge enrichment and validation loop via engaging field personnel is typically missing in such approaches.

This thesis 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 metadata management system. It extends the FMECA review process from being a periodic team-based task to also benefit from collaborative evaluation by maintenance staff. Adopting the focus of enterprise social systems this methodology is mapped on a system design that delivers a shared knowledge space where maintenance personnel can be part of a collaborative network (Durugbo, 2014) that collectively manages FMECA knowledge. To support this, an enterprise web application was developed that allows the semantic tagging of FMECA content, cross-evaluation votes, effective visualisation of annotation timelines and on-demand mobile access.

1.1 Motivation

The motivation of this research spawned initially from the findings of the evaluation process for an e-Training platform, designed to act as knowledge centre and a self-evaluation tool for maintenance professionals. Conducting piloting session across four different countries, such professionals were asked to review the final system and provide pointers for content improvements, corrections and extensions (Papathanassiou and Emmanouilidis, 2010). Maintenance managers and skilled experts, coming from all the levels of maintenance practice and management, exhibited a very focused and methodical feedback behaviour, providing multiple key evaluations and insightful review comments. The extent of their input allowed for the collection of a significant pool of field expertise with valid points for improvements (Emmanouilidis et al., 2010, Emmanouilidis et al., 2011). Taking one step further, the analysis of their feedback and its ranking based on structure and knowledge value, led to the conclusion that the most useful comments were: (i) short and accurate, (ii) referencing very specific content and (iii) linking maintenance knowledge with case studies and real scenarios from the professional's field experience. The above experience indicated that in order to successfully capture rich and accurate knowledge from maintenance experts, they have to become members of a collaborative network. In this network, shared feedback is encouraged to be brief, and conveniently classified evaluations should be available to support the review of reference knowledge. It is a methodology that aims to produce a large pool of compact and concise maintenance evaluations that directly link field experience to existing knowledge

The Failure Mode, Effect and Criticality analysis constitutes a maintenance knowledge asset mainly associated with risk analysis and reliability. It is also a reference for diagnostics, where knowledge for failure modes and their solution is mapped onto a web of relationships connecting events and actions. It comprises knowledge that can benefit both management and shop-floor tasks and processes. While management level analysts use FMECA as a complex structure for risk modelling and projections, shop-floor engineers know it as a supporting reference for finding the appropriate solution to a specific problem. While these uses can have a critical impact on maintenance planning and practice, many industries follow an FMECA revision plan that provides only annual updates and often fails to effectively engage and combine the evolving knowledge of shop-floor engineers and management analysts. Instead of becoming a knowledge interface, FMECA mostly remains bound to two disconnected and rigidly evolving counterparts: (i) a sophisticated model for analytics that is overly complex for shop-floor staff to handle and consume and (ii) a flat and concise problem-solution table that is overly simplified for any kind of knowledge capturing. The solution relies in maintaining a knowledge validation loop for FMECA, by continuously enriching it with field expertise and thus effectively transforming it into an important enterprise knowledge flow between management and shop-floor.

In this research, the knowledge capturing features extracted from the e-Training platform evaluation, are utilised to deliver an efficient methodology for FMECA enrichment. This work studies the modelling and usage of a maintenance information context that is fused by the recorded knowledge of a valid reference with the dynamically progressing expertise. This expertise is encapsulated inside the problem solving skills of experts that detect and deal with failure first-hand. A modern design and implementation are offered, for a new feedback paradigm that allows maintenance personnel to access and build an upgraded model for FMECA knowledge. The primary motivation of this research, are the benefits and the added value that stem from the collective enrichment of FMECA knowledge, when done by a collaborative network of maintenance experts that span from data analysts to shop-floor gurus.

1.2 Research Questions and Objectives

The presented research aims to support maintenance knowledge management, including sharing, validation and extension of knowledge. Producing an FMECA table is a multi-stage engineering study and one that requires the contribution of many maintenance roles and knowledge stakeholders. To better organize, coordinate and perform the revision of such a knowledge asset, industry commonly schedules it to happen at regular intervals, typically once or twice a year. This research introduces a methodology that aims to improve the FMECA reviewing process, by creating a shared model that supports shop-floor experts and at the same time motivates their feedback and contribution in assessing its validity and knowledge value. Experts will report their findings and evaluations by flagging the relevance of FMECA with their everyday shop-floor experience. Imprinting the detection, progression and solution of failures upon FMECA, will gradually deliver its fusion with shop-floor maintenance expertise. The author of this research claims that the knowledge context that derives from this fusion is scalable, and that semantically enriched FMECA provides the optimal starting point for its revision, leading to FMECA 2.0. Therefore, the research questions that this research aims to address are:

- **Q1:** How can an FMECA model be extended, so that it balances its knowledge complexity between what shop-floor engineers can reference and benefit from, and what analysts can study and use for better knowledge management?
- **Q2:** How can the FMECA knowledge enrichment process be collectively driven and not only centrally managed? How can such a process be continuous and transparent, allowing its mechanisms to be easily understood and adopted by maintenance experts?
- **Q3** How can maintenance experts be motivated to contribute in a knowledge capturing process? How can they be encouraged to invest and use the knowledge enrichment process for FMECA?
- **Q4:** How can maintenance Linked Data support the FMECA revision and provide evidence for the identification of gaps, mismatches and errors?
- **Q5:** How can the enrichment of FMECA knowledge support maintenance analytics? Can semantic enrichment lead to better understanding of maintenance knowledge?

In order to address question 1 this work starts from the solid semantics of the widely used MIMOSA model, and scales down their complexity with more descriptive relationships. The objective here is to bring causality into the problem-solution references of maintenance manuals and balance the risk-analysis semantics from back-office FMECA models. This research aims towards the middle-ground of knowledge depth where the FMECA profile provides actionable information for both shop-floor and management level decision making.

To answer questions 2, 3 and 4, the introduced methodology replaces reporting forms with a new feedback paradigm that minimises user input and heavily resides on a single-step interaction pattern. To motivate useful feedback, the proposed approach prompts maintenance experts to tag and flag how specific FMECA components relate to their evaluations and observations. The objective here is to promote the provision of short insights, comments and timed validations that allow experts to have control over what, when and how they report it. Starting from predefined tags and being able to scale their maintenance value with fully customizable and optional notes and quantifications, experts are essentially asked to annotate and verify FMECA knowledge on the job, while being on the shop-floor and experiencing the failures occur and being dealt with. It is a paradigm that invests in modularizing and simplifying maintenance input, to encourage its provision. The objective of their linking nature is to cluster input around FMECA knowledge of higher relevancy to maintenance practice. The type of annotations and the potential additional feedback identify if this relevancy points towards FMECA corrections and knowledge gaps, or signifies the FMECA knowledge applicability and practical value. The goal is to achieve the collection of a larger number of pre-classified insights, a principle similar to how crowdsourcing intelligence from individual contributions is exploited in recommender systems.

To address question 5 this works delivers the design, implementation and industrial piloting of a Metadata Management System (MMS) that facilitates the knowledge capturing process. The MMS objective is to act as a collaborative tool and a shared space for a multi-user environment that offers a stronger basis for both FMECA and maintenance metadata management, processing and exploitation by services of high added value. Delivering a well-designed MMS is a key enabler for enhancing knowledge generation, provision and consumption from maintenance experts.

The overall aim of this research 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.

1.3 Research Methodology

The methodology followed in this work is illustrated in Figure 1.1, depicting the phases that comprised the research plan. Each phase involves a number or topics or tasks that were assessed or completed to deliver a specific result, necessary for the work in the next phase. At the end of each phase a short evaluation was conducted to measure the progress towards the research objectives. This feedback allowed the research to review its long term goals at key milestones, compare its findings with related research and align itself with modern specifications and standards. This process is incorporated into horizontal tasks, primarily responsible for the constant evaluation of the research focus, the modelling approach, the design choices and the implementation, with respect to new research initiatives, emerging methodologies and state of the art technologies.

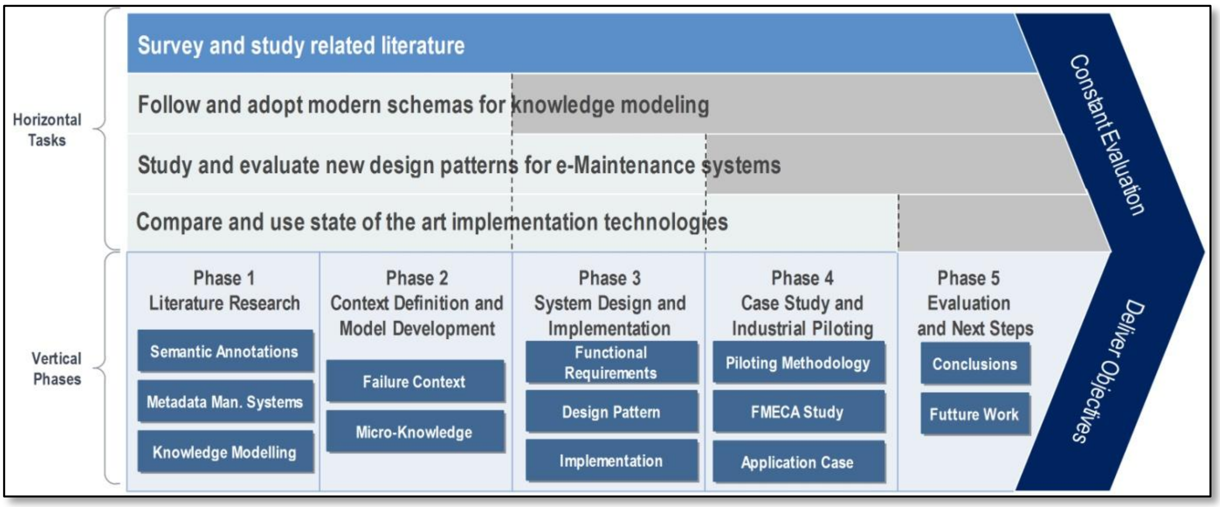

Figure 1.1. Research methodology, phases and tasks

During the first phase, an extensive literature review has recorded the background work and research state of topics such as semantic annotations, metadata management systems and knowledge modelling for engineering asset management and particularly maintenance. In reference to the targeted provision pattern and system architecture, mobile e-Maintenance, context-based maintenance and big data were also surveyed and studied to record design insights and technology trends. Studying and analyzing this research provided the appropriate knowledge background to detect research gaps that could be addressed and solutions that could be extended or improved. In detail, while surveying semantics compatible with the FMECA concept and evaluating structures already used to instantiate its maintenance value, certain approaches were detected missing proper attention or left unexplored. These approaches address critical aspects of FMECA, such as its revision and validity. This research identified a new promising approach that stems from modern semantic web technologies, and offers versatile annotation mechanisms to enrich FMECA.

The second phase involved the modelling of the FMECA knowledge and the synthesis of a new knowledge context tightly coupled with maintenance diagnostics. The **failure context** was defined as the fusion of failure mode knowledge with semantics of shop-floor evaluations. The components that enrich and produce this context are termed as maintenance **micro-knowledge** and represent the contextual evaluation of FMECA. For each type of maintenance micro-knowledge the appropriate knowledge formalisations were created, and their maintenance value evaluated with respect to potential interpretations.

In the third phase, the system design is produced for an enterprise application participating in a larger e-Maintenance platform. The design pattern is decided according to specifications that derive from the research objectives and the final system is developed and delivered as a web-based application. It is comprised of services that empower mobile maintenance staff to collectively manage FMECA knowledge and collaborative enrich it through the use of maintenance tags.

The fourth phase includes the case study of this research. This phase incorporates the implementation of a multi-stage piloting methodology that was separately studied and planned with the industrial end user. The case study was aimed towards recording how FMECA access and its enrichment process can play an active role, during shop-floor maintenance practice. The piloting methodology started with scheduling and practising a complete FMECA study for critical assets with key production value, and a reference model of the final product (an electric lift). The FMECA study was followed with training sessions and hands on tutorials, to familiarise maintenance personnel with the concept and process of FMECA enrichment. The piloting of the final system was scheduled into separate sessions, during which various maintenance roles used the tool to reference and enrich FMECA, while dealing with emerging issues and failures. The collected maintenance metadata demonstrated the system's ability to record FMECA relevancy before and after the execution of important maintenance actions, and to visualize informative timelines for the occurrence and solution of severe failure modes. The piloting concluded with the system's evaluation, via the completion of an extensive questionnaire by participating experts.

In the fifth and final phase, the evaluation results were studied and analysed, suggesting improvements and possible future extensions of this work. The next steps in terms of new functionality, improved performance and model expansions were also discussed.

1.4 Contribution

There are four major aspects for the contribution of the presented research. Some aspects address the adoption of good practises or well established techniques, while others improve the performance of important knowledge management processes in maintenance.

1. Provide an FMECA model for knowledge focused on supporting shop-floor maintenance practise and mobile experts.

Shop-floor personnel does not have the time to study very long and very descriptive information profiles, but also cannot benefit much from very flat diagnostics. The requirements for diagnostics support changes with each role and always targets knowledge that can be easily referenced and traversed. This work offers the design of a model that is able to map balanced FMECA knowledge. The model expands on linking a failure mode with better classified potential effects and more structured proposed solutions. These extensions bring FMECA closer to a level of knowledge that: (i) maintenance experts probably know and may consult during diagnostics, (ii) maintenance engineers may not know and should reference when deciding a solution and (iii) maintenance technicians often don't know and have to follow while performing maintenance. For each different role and level of expertise, the experience of consulting FMECA is also different and provides diverse support. This research offers an FMECA model that manages to adapt risk-analysis knowledge for the problem solving needs of shop-floor maintenance staff. It constructs a balanced reference that manages to support maintenance tasks, while also allowing the validation, enrichment and expansion of each role's knowledge background.

2. Capture maintenance knowledge with a new feedback methodology that can be better understood and thus adopted by maintenance experts.

Leveraging upon one of the most significant enterprise assets, namely the human factor, is the key to facilitating more effective knowledge flows within the enterprise. 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 offer brief input at a real-time manner and with many sharing options. Many social environments use semantic tags as a platform for evaluating assessments. Furthermore the use of votes stimulate virtual interaction and conduct a social contextualization of shared content for the users. The following expectations are likely to hold in enterprise social networks for user input:

- ✓ 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 virtual assets into shared collections, classifying them with semantic tags.
- ✓ Users expect acceptance, validation, credit or even simple feedback from other users.
- ✓ Users prefer to view and filter a timeline of events that provides an overview of their social/service context.

Nonetheless, the above potential is still left largely unexploited by e-Maintenance solutions. The effective capturing, sharing and cross-evaluation of expertise relies heavily on parameters such as expert's context, concise input and connection with a valid knowledge base. The present work adopts this concept and introduces it in the scope of e-Maintenance services. In this research, maintenance staff is empowered and encouraged to participate in knowledge flows with minimal, intuitive and natural interfaces. Maintenance experts are able to manage and configure a set of semantic tags that shop-floor personnel can use to produce concise and organized maintenance feedback. The proposed methodology:

- ❖ Allows maintenance personnel to easily report an event or failure and decide appropriate action by simply tagging the relevant FMECA content.
- ❖ Enables experts to expand and analyse their reported feedback with small forms that classify its content. These are optional forms that help clarify the evaluation.
- ❖ Support the creation of new tag templates to better configure how FMECA can be annotated and thus expand the reporting options.

This feedback methodology is easier to follow and use, and thus more likely to secure staff participation. It is a process that focuses in addressing the natural need of employees to offer quick and meaningful feedback on their work activities and eventually appreciate that their feedback counts. This research proves once more that comprehending the role of an expert systems is more effective when processes are more transparent and users have more control over them.

3. Develop a knowledge management tool for the validation and enrichment of FMECA knowledge.

This research proposes a new knowledge building process, with the creation of maintenance metadata upon a valid reference FMECA model. Metadata is a knowledge construct that can be easily understood by experts and engineers, being a popular and widely used component of web technologies. In our work, metadata instantiate maintenance annotations, which in turn are made through the use of maintenance tags. While the first is a modelling construct, the latter two are techniques of semantic enrichment. This research facilitates metadata to contextually describe FMECA knowledge. The product of this enrichment is a termed as **failure context,** and is introduced by our work as the integrated knowledge of: (i) how FMECA profiles a failure mode, and (ii) how maintenance evaluations have recorded its occurrence.

Using modern cloud and web-based technologies a maintenance Metadata Management System is designed and implemented, to help personnel navigate and collaboratively enrich the failure context. The implemented services:

- Render failure mode profiles that present the respective failure context with the latest relevant annotations.
- Allow the direct tagging for each accessed type of FMECA knowledge.
- Support the provision of additional feedback with intuitive forms and formalised input.
- Provide the option to vote and validate recorded evaluations in every listing.
- Offer the ability to search, sort and filter relevant maintenance metadata with informative timelines.
- Enable editing of FMECA knowledge, extending its type-semantics and the creation of new tag templates.

The analysis of metadata timelines and enriched failure mode profiles, can support experts identify unknown and validate known patterns of failure progress. The annotation options can encourage the capturing of a large number of suggestions and comments, clustered around specific FMECA content. The instant sharing and voting features allow further ranking of candidate knowledge that is user-created, collaboratively evaluated and fused to be inserted in the next version of FMECA, during scheduled re-evaluation.

1.5 Document Structure

In Chapter 1, the motivation for this research is discussed, describing the events that inspired its approach and the problem that offered the challenge. The research questions are also stated here with the respective objectives specified. Furthermore, the research methodology is presented with a brief description for each phase and its role in the overall research plan. Finally, the contribution of this work is summarised and the document structure explained.

In Chapter 2, a literature review studies topics closely related with key aspects of this research. The current work is positioned against the backdrop of relevant research initiatives and enabling technologies. Following the literature review, the problem statement is discussed, and the research gaps that indicate the need for this research, are identified.

In Chapter 3, the concept of the Failure Context is introduced and defined. The knowledge entities of the FMECA model are specified with emphasis on hypothetical events and their extended set of causality links. The FMECA enrichment through its semantic annotation is explained, along with the role of each tag belonging to the default set of maintenance tags. Maintenance micro-knowledge is also introduced in this chapter, defined as the knowledge product of FMECA enrichment and instantiated into maintenance metadata. Most importantly, this chapter provides knowledge formalisations for the micro-knowledge produced by each specific maintenance tag, and explains its potential value in the FMECA revision process.

In Chapter 4, the design and development of IMA-FMECA are explained and discussed. An overview of the WelCOM architecture is provided, stating its main components and IMA-FMECA's role and function in it. The functional requirements and the mobile service provision are translated into specifications that define IMA-FMECA's client-server design pattern and further specify the selection of implementation technologies. Finally, a list of IMA-FMECA's exported services is provided, and their use is explained in integration scenarios.

In Chapter 5, the case study for this research is planned, recorded and evaluated. Each stage of the piloting methodology is explained and its delivered results documented. This chapters starts with explaining all the steps of the conducted FMECA study and then offers brief descriptions for the training use cases, employed during the hands on tutorials. Moving into the chapter's primary focus, an application scenario and its failure context are thoroughly analysed. The relevant micro-knowledge is studied, listed, visualised and explained, leading to FMECA updates and other interesting meta-interpretations. The chapters closes with a discussion for the results of the system's evaluation.

In Chapter 6, the conclusions of this thesis as well as the possible future extensions of this work are discussed.

2 Literature Review

2 LITERATURE REVIEW

In this chapter a better understanding of the targeted problem space will be provided, initially by examining the current state of the art and providing a literature review. This literature review focuses on domain topics tightly connected with aspects that have been studied, analysed and addressed by the conducted research (Figure 2.1). This will be followed by a discussion that pinpoints facts and gaps which led to our research questions and properly frame the research problem.

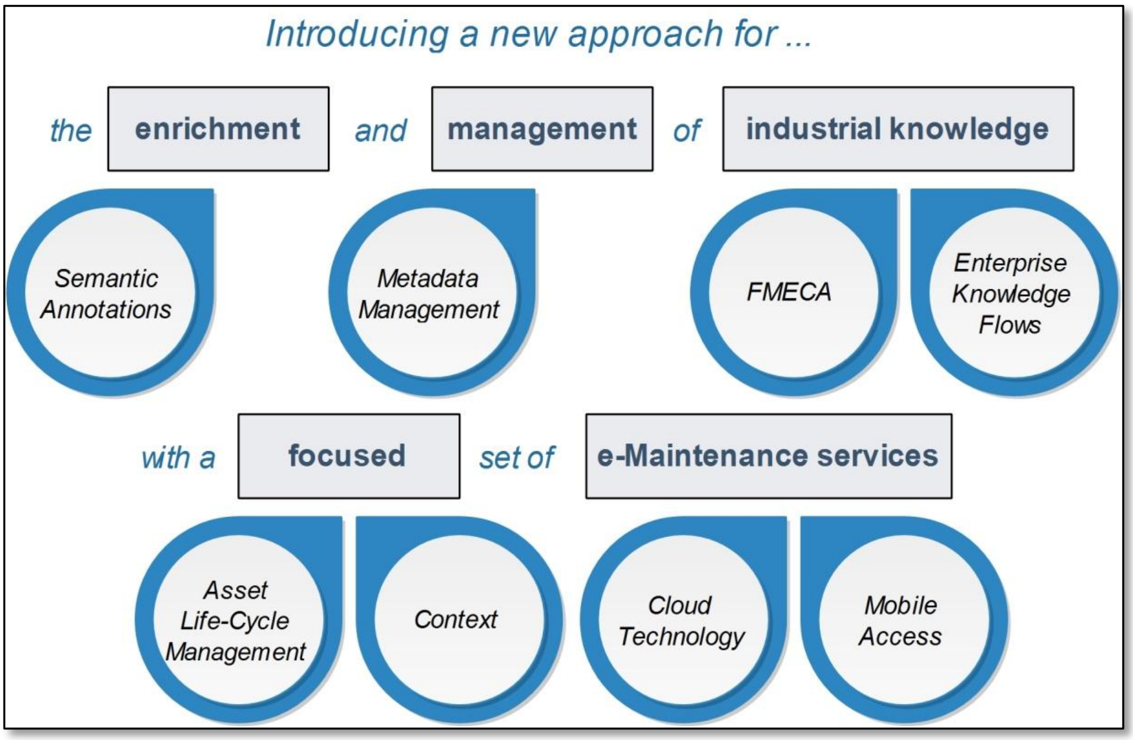

Figure 2.1. Domains linked to the research and topics for the literature review

2.1 Current State of the Art

2.1.1 e-Maintenance and Asset Life Cycle Knowledge Management

Knowledge management in e-Maintenance has been an ongoing challenge for balance between state of the art technologies and validated practical benefits. While knowledge components and intelligent functions have been evolving and emerging from various domains of ICT, industry has been quite cautious when adopting trends that will impose information re-engineering and do not promise definitive advantages. During the latest years e-Maintenance has increasingly adopted intelligent and smart services, by aligning its focus with knowledge-oriented agents and components (Lee et al., 2013a). Modern technologies offer intelligent services that allow e-Maintenance systems to upgrade from reactive maintenance policies to proactive ones (Liyanage et al., 2009). Knowledge management is slowly but decisively embedded in many systems that serve maintenance policies such as corrective maintenance, condition-based maintenance, planned maintenance, preventive maintenance, predictive maintenance, proactive maintenance, reliability centred maintenance and value driven maintenance. This knowledge must be properly formalized so that experts and maintenance actors in general, can easily consume, manage and enrich it when engaging the use of the respective support and decision making tools (Kamsu-Foguem and Noyes, 2013). Figure 2.2 displays the long-time cost effectiveness of the most common maintenance policies, versus the knowledge required to power their functions.

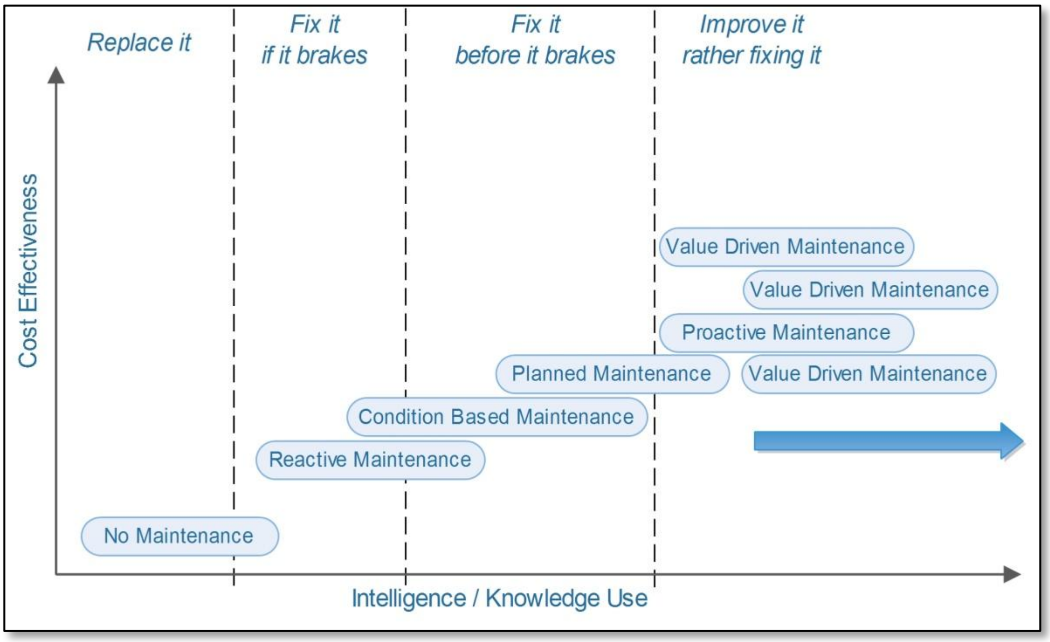

Figure 2.2. Maintenance policy cost effectiveness and knowledge use (Kamsu-Foguem and Noyes, 2013)

Knowledge has been considered as a concept often designed for, managed and consumed by higher tiers of e-Maintenance architectures. As an upgraded form of information, knowledge was commonly associated with services that reside in high performance and distributed infrastructures that can handle its complexity and address its requirements for processing capacity. Recently, and through the use of semantic web technologies, the purpose, range and instantiation of knowledge has been more accurately perceived and adopted by various application domains. Knowledge can now be produced and consumed by components that reside in both a condition monitoring infrastructure and an e-Maintenance platform. Smart sensors are able to detect events, diagnose and predict based on local history and using collective intelligence (Emmanouilidis et al., 2006). What can now be received from state of the art IoT infrastructures, is a product of embedded analysis and classification; a pre-processed stream of information. Instead of measurement vectors, e-Maintenance platforms can utilise such filtered streams of information to offer more advanced and refined services (Emmanouilidis and Pistofidis, 2010). Both the service layer and the monitoring infrastructure can now participate in an incremental knowledge building process, where each component can contribute in an enrichment process irrespective to its implementation scale or its hosting environment.

Knowledge is shifting the medium of information exchange, between state of the art e-Maintenance components. Instead of flat data and remote commands, modern systems share knowledge components such as **ontologies and metadata**. These components can scale from serving a single smart sensor up to leading the process complexity of a robotic arm (Chioreanu et al., 2014). Monitoring rooms are now able to integrate and sustain maintenance knowledge, by creating an on-going enrichment loop. Inside these rooms, smart software agents (producers) and agile hardware component (consumers) participate in a collaborative system that coordinates how knowledge evolves and expands. This knowledge is currently embodied in semantic models that have been studied and designed to focus on the operation and maintenance phase of the product's lifecycle (Koukias et al., 2013). The semantic connections of these models are able to link aspects of asset performance and availability with decision making and strategic policies, much more efficiently than static schemas. The resulting ontologies become wrappers of maintenance knowledge, modules of reusable maintenance intelligence, effectively attuned to drive demanding reasoning tasks. Designing knowledge models always hides two important challenging tasks: (i) balance complexity and (ii) constantly monitor applicability and consistency (Medina-Oliva et al., 2015). The first requires a continuous evaluation of how the knowledge model reflects and maps the existing information framework. Increased semantic depth can often induce a high-cost (time and money) re-engineering process for porting data to ontologies or metadata. The second challenge refers to a monitored design process that avoids unrealistic assumptions and creates semantic rules that materialize specific goals and guide knowledge capitalization.

Maintenance is a key concept of **Product Life-Cycle Management (PLM)** and an impactful contributor to asset life cycle management. These are domains that connect very well with higher level of semantics. Investigating the stages, interfaces and progression mechanisms of asset's life cycle, leads to refined knowledge models. These models constitute a thorough engineering study that by definition engages the meta-interpretation and meta-modelling of inter-process information. There is significant research and progress made on how knowledge management and the use of ontologies can leverage asset management and benefit closed-loop life cycle management (Matsokis and Kiritsis, 2012, Kiritsis, 2013). Interoperability and effective integration is the primary goal of this research, targeting for abstractions and tools that transparently link and manage knowledge from all the phases of an assets life-cycle. This knowledge pool is valued as a solid base for building context aware services for the end user. In similar research, the integration target is further narrowed, to address very specific operation aspects of an asset life cycle. In (Abele et al., 2013), the introduced knowledge-engineering methodology seeks the integration of resource (i.e. energy) monitoring information, across the life-span of an asset. The research in (Masood et al., 2014) studies the definition of 'engineering service knowledge' and examines the integration of such knowledge in a feedback model that links product design and manufacturing.

From a different perspective, we find process-oriented approaches that focus on the collective expansion of the life-cycle knowledge (Felic et al., 2014). In this research both knowledge modelling and management services invest on advanced sharing patterns and a **motivating collaborative environment**. Such environments are often able to capture user interactions and correlate them with several dimensions of a reference context model. Studying this methodology in a PLM scenario, the research in (Scholze et al., 2012) monitors and captures the active and passive knowledge contributed by the users of a collaborative working environment. The enrichment process is essentially an engine that models the user-context and adapts the environment to improve knowledge flows between the users of networked enterprises. In many such environments, access control and security are very important for ensuring a safe and monitored collective management of sensitive and even confidential knowledge (i.e. between industrial stakeholder and business partners) (Fabian et al., 2012). Fusion of user or expert knowledge is a challenging priority and a difficult design choice for a collaborative knowledge management system. It requires safe functions and extensible semantics to support a constant enrichment loop, while ensuring a balance between consistency and added value for the final knowledge result. Creating and preserving knowledge flows that facilitate the exchange and management of maintenance expertise is a difficult process. It requires detailed profiling of the targeted expertise and seamless integration of the management mechanism in everyday tasks. While the first part has been adequately covered and studied by current research, the second requirement still lacks well-established practices and suitable approach mechanics. Modern ICT has served e-Maintenance well, in terms of knowledge modelling and management tools. The challenge now is to adapt such tools and processes with features that scale user motivation and engagement.

2.1.2 Metadata Management and Linked Data

Industry gradually appreciates that any sheer volume of flat data can provide little information if not accompanied by an adequate **metadata schema** and the means to manage it. Such a metadata descriptive profile, acting as a second layer of semantics, holds much higher value than the data itself, mapping the data under a taxonomy with dynamic grouping. Data taxonomy characterizes the data importance, while dynamic grouping instantiates templates for virtual collection of assets, agents, events or actions. Both have the potential to provide enhanced insight into asset management knowledge, with machine failures and production stoppages being examples of high significance. Widely accepted schemas, such as MIMOSA (MIMOSA), implement strict cycles of re-designing, where extensibility and descriptive depth are assessed and validated by practical benefits in maintenance intelligence and field-knowledge management. The volume of descriptive attributes that populated the profiles of maintenance IT components is now extracted to create dynamic relationships and not static connections. Every maintenance action, agent, event and asset that participates in the logic and functionality of an e-Maintenance system, can benefit from data that can be annotated, thus **dynamically enriching** their value. This is essentially a first step to port from the rigidity of data models to the enrichment prospects of metadata models. Figure 2.3 presents the central role of metadata during the life cycle of data, contributing to their creation, management and transaction processes.

Apart from volume size and physical distribution, e-Maintenance systems undergo important semantic re-engineering. In (Nastasie et al., 2010) an elaborate discussion is offered to document the progress of semantics and the integration prospects of established Asset Management standards. Investigating various standards, the need for an appropriate medium is recorded for servicing interoperability of Asset Management systems within organisations (internal interoperability) and between organisations (inter-organisational interoperability). Under the same scope, e-Maintenance providers pursue compatibility with established data standards, such as MIMOSA and reference specifications, such as PAS 55, offering wider support for cross-domain data semantics (Bangemann et al., 2006) (Campos and Márquez, 2011). A need to shift research focus and application usage, from maintenance data to maintenance metadata is emerging. To address this, maintenance models need to be brought closer to enhanced knowledge instantiation, employing ontologies and metadata schemas. Witnessing success in other IT service domains, e-Maintenance vendors are starting to consider their role as **proxies to metadata management**. Among their goals is to shape the metadata semantics that profile desired maintenance intelligence and appropriately contextualize their services. To overcome the lack of trust hurdle, investment in ensuring security of data and their anonymity is needed.

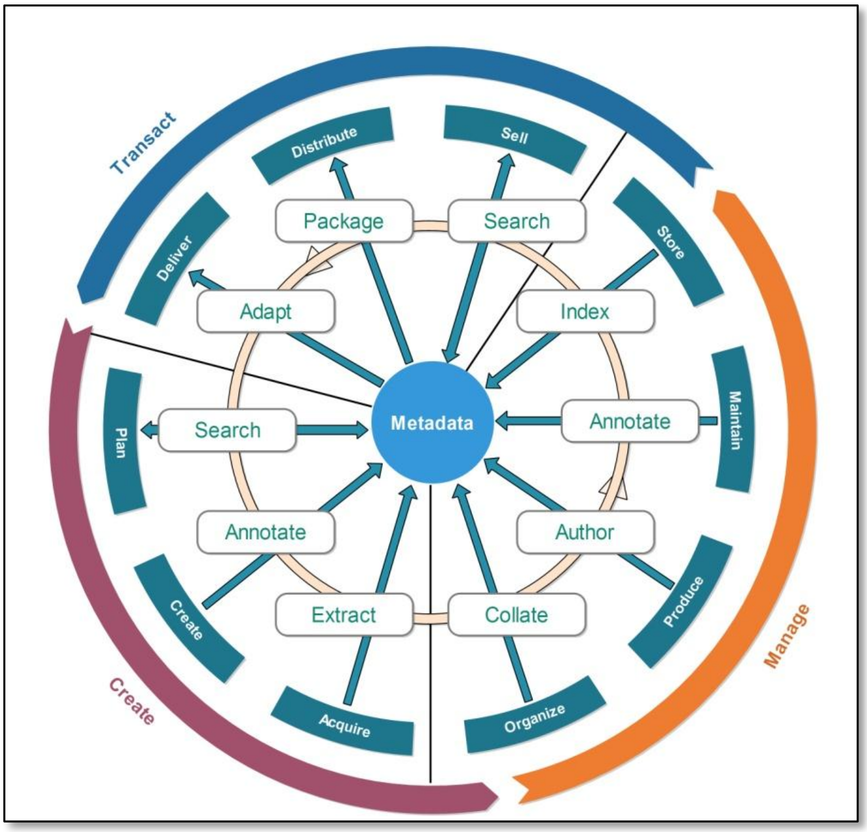

Figure 2.3. Metadata's central role in data life cycle (Smith and Schirling, 2006)

Demanding application domains, such as multimedia, e-finance, e-science and e-government, have brought into attention the crucial role of metadata on the organization of data. **Meta-database management systems** do not contain the data itself. Instead, they contain information about the actual data (metadata). The actual data are left in place and the metadata are used to describe, index and sort them according to specifications of business intelligence and other analytics. This has led to active research into metadata management systems, identifying them as an efficient tool for the collaborative handling of business metadata, or corporate knowledge in general (Hüner et al., 2011). With recent application and research trends in IoT, the majority of modern e-Maintenance services involve the collection, management and process of multiple sensor streams. Metadata management, coupled with annotations are able to facilitate the organisation of such sources, allowing the capturing of semantics behind higher level data processing steps (Dawes et al., 2008). These semantics are particularly useful in understanding data processing workflows and enhancing their productivity. Industrial informatics now seek to focus more on metadata to describe maintenance data, and less on descriptive data properties. In (Vnuk et al., 2012) the use of metadata, in the demanding scope of Asset Management, is thoroughly explored. The research suggests that an efficient and effectively managed metadata environment is instrumental in improving data and metadata quality, enabling **timely and well-informed decision-making**, as well as **better interoperability across systems and teams**. Figure 2.4 presents the requirements for a metadata management system, in order for it to achieve usability and comprehensive knowledge. It is worth noticing that ease of use and low effort are identified as key success factors for collaborative management; with itself being equally important for creating a motivating context for user involvement. Furthermore, as a primary objective of a metadata repository, the timely consumption or creation of metadata is tightly connected with the clarity and concise structure of comprehensible semantics.

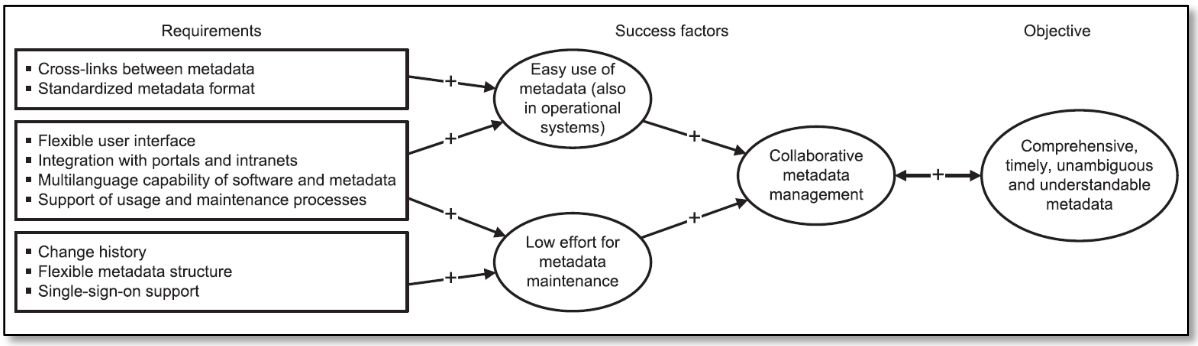

Figure 2.4. Requirements for a metadata repository (Hüner et al., 2011)

The use of metadata management systems has also emerged as a valid method to drive **pre-analytics data preparation**. They implement an important step that precedes the execution of analytics and essentially configures them for better performance (Smith et al., 2014). Specific Big-Data functions that benefit directly from the management of metadata include: (i) data migration, (ii) data consolidation, (iii) ad hoc analysis, (iv) data discovery, (v) addressing data gaps, (vi) detecting defects and erroneous data and (vii) agile integration of new data sources. These functions along with other pre-processing tasks that involve transforming, linking and formatting relevant data, are often key enablers for assuring consistency and providing preliminary insights for industrial analytics and specifically for prognostics (Chongwatpol, 2015). The role of metadata management is decisive in distributed infrastructures and Grid environments. Data with a high degree of heterogeneity, like Grid data, often compile complex knowledge infrastructures that require strict collaborative management from multiple participating organizations (Hartung et al., 2010).

Allowing collective editing of semantic metadata can significantly impact the organization of data and allow the evolution of a customisable schemas. The extensive use of such metadata repositories and systems is essentially empowering the design, customisation, testing and evaluation of a metadata schema. This is a process that steadily leads to a common acceptance and the wide adoption of solid metadata schemas for any application domain (Heery and Patel, 2000). The goal of such schemas is to overcome the divergent interpretations of data and the absence of universal reference, both preventing organizations and industry from seamless data exchange, integration of enterprise systems and the delivery of cross-domain services. In (Shukair et al., 2013) an Asset Description Metadata Schema is introduced as a common representation and exchange format for e-Government repositories. In this schema, explicit definitions of properties for indexing and classification, allow the diversity of government data audience to identify subsets of online resources in a multitude of digital collections. Addressing the need for such schemas, in (Gao et al., 2010), the lack of engineering asset management specific metadata standards is identified, connecting this fact with the critical challenges an engineering asset management organisation face for managing information processes and for coping with data quality issues. Metadata schemas are once again tightly coupled with the ability to extract value from existing data repositories with confidence, and subsequently supporting the success of core operations such as data warehousing and enterprise application integration.

Metadata editing and management systems are currently providing online services to allow cloud access and facilitate multi-user environments. In (Aguilar et al., 2010) such an online tool has been developed, using modern web technologies and a native XML database. In this work and commonly in most on-line management tools, metadata are better handled and configured, when their instantiation is supported by natively structured databases, such as native XML or NoSQL. An extended set of tools are also developed in (Schissel et al., 2014) to support the tracking, cataloguing and integration of scientific data, with metadata. Metadata allow for better orchestration of data analysis and better workflows that create, transform or disseminate data. The use of these tools proves that generous provisioning of metadata, including data provenance and data relations, is critical to leverage data sharing and to allow data sustain its usefulness over extended periods of time. In general, availability of metadata tools constitutes a good indicator of how cloud-ready an application domain is for knowledge fusion and even knowledge commercialization. The large majority of CM and CMMS platforms, currently lack such effective metadata management support.

In the context of the above tools, **Linked Data (LD)** has 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). Performing linkage analysis on LD graphs, can often reveal potential partners in an industry social network or establish a link between distant procedures that improves productivity and creates innovative business intelligence (Lian and Li Da, 2012). LD is able to bridge the gap between industrial data from mixed sources and with a varying format. It is a form of representation that leverages interpretation between systems and furthermore, between knowledge management services. Data and knowledge structures can be integrated on-the-fly employing the correct adapters or by complete migration (Graube et al., 2011). LD can also benefit the orchestration of applications that support industrial workflows through the use of mobile maintenance (Graube et al., 2013). With increasing adoption, LD is currently supported by formalisation frameworks, built on technologies that can efficiently instantiate knowledge representations. These are build on technologies that can efficiently instantiate knowledge representations. One such framework, RDFa (Adida and Birbeck, 2008) extends Web standards to employ annotation and tagging of important content. Another framework, JSON-LD (Sporny et al., 2014), provides mobility and contextualization of Linked Data, using a widely established data construct (JSON).

While the adoption of these technologies in e-Maintenance is gaining pace, the produced metadata are often more process oriented rather than application oriented. This means that metadata are not studied as a linking component for e-Maintenance knowledge but instead are mostly facilitated as a semantic product of e-Maintenance tools that employ web technologies. This approach leaves many LD prospects unexplored and limits e-Maintenance systems' potential to test, evaluate and refine new connections between their core concepts. This is an important LD modelling process, and one that can lead to qualitative metadata schemas. A metadata management system can offer a thin, versatile and collaborative environment, where maintenance experts can create, modify and use comprehensible metadata that they value as good candidates for actionable linked data.

2.1.3 Semantic Annotations for Knowledge Management and Enrichment

Semantic annotations constitute a widely used enrichment method that allows experts or expert systems to disambiguate the meaning, relations or purpose of data or information (Kiryakov et al., 2004). It is a natively linking process that extends knowledge entities with new descriptive dimensions. Annotations techniques and frameworks have recently gained increased attention and usage in managing, creating and organizing existing knowledge. Offering a platform of mutual understanding, annotation schemas provide the foundation to achieve semantic interoperability and the tools to address semantic heterogeneity.

Semantic annotations provide a versatile tool for versioning and updating reference knowledge. In (Levy et al., 2010) this practice is studied and applied in the demanding knowledge domain of rules and policies. Policies and regulations often extend to become quite a complex knowledge structure. Versioning of reference knowledge is a crucial process and one often embedded in decision support systems designed to define, deploy, execute, monitor and maintain it. The contribution of semantic annotations in such systems provides and enhances the manual mechanisms that drive knowledge consistency, availability and integration. The paper provides an insightful discussion, arguing that semantic annotation can achieve a better knowledge integration in decision support systems than automated parsing. The requirements for semantically annotating decision models are extensively studied in (Deokar and El-Gayar, 2012), pinpointing their importance in the design and management of service systems. The proposed model representation scheme, termed Semantically Annotated Structure Modelling Markup Language (SA-SMML), extends Structure Modelling Markup Language (SMML). The methodology adopts and leverages recent advances from semantic web and semantic web services. Finally, the research emphasizes the importance of model discovery and composition, when studying the design considerations of semantic linkage for models managed in distributed environments.

Acting as functional pointers on top of shared knowledge, semantic annotations are often part of collaborative systems that power the collective maintenance and exploitation of knowledge. **Provenance** is a key concept for designing and managing models that carry increased knowledge value and depth. In (Altintas et al., 2011) a data model for "collaborative provenance", is presented, extending common workflow provenance models with attributes addressing the nature of user collaborations as well as their strength (or weight). Provenance metadata and annotations are employed inside the context of e-Science and three major benefits of their use are identified:

1. They help users build upon existing knowledge and extend it without the need for the re-architecture of knowledge components.
2. They allow for extensions with effective integration of more collaborating entities e.g. sensors and external interfacing systems.
3. They fuel a methodology that brings together knowledge consumers and producers, allowing for proper tracking of contribution and usage.

The contribution of semantic annotations in provenance and maintenance of information models, is also discussed in (Zhao et al., 2011). The paper addresses the challenge of making sure that any member of a knowledge sharing community has the means to correctly interpret and consume information, possibly a long time after it was produced. The proposed methodology involves creating observational or experimental data with various types of annotations, as well as with other contextual metadata. The research, targets the use and production of provenance metadata, which describes the way information is created and evolves. To achieve that, semantic annotations are employed with semantics from domain-specific terms and an agreed-upon vocabulary.

Semantic enhancement is often used to interpret and contextualize an existing knowledge repository. This is very commonly needed for repositories of process models. In (Mturi and Johannesson, 2013), an annotation model is proposed to aid users in searching, navigating and understanding more efficiently the process models. In Figure 2.5 the stages of development for an annotation model are displayed, explaining the inputs, outputs and feedback required for each phase. Focused towards contextual accessibility and knowledge reuse, the paper defines a solid set of requirements for the annotation model, that includes:

- **High annotation consistency:** Annotations created by different users should be consistent, i.e. when two users annotate the same entity, this should result in the same or similar annotations.

- **High annotation correctness:** The annotations produced should create valid knowledge.
- **High perceived ease of annotation:** The semantic annotation process should be easy.
- **High perceived ease of use:** Searching and navigation of the annotated model should be easy.
- **High usability.** Searching and navigation should be more effective, efficient and satisfactory when traversing annotated elements.
- **Enhanced understandability:** The produced annotations should support users improve their understanding of the annotated model.
- **High discriminatory power:** The annotation model should be capable of implementing clear and fine distinctions between annotated elements.
- **Extensibility:** Possible extensions and customisations should be easily implemented for the annotation model.

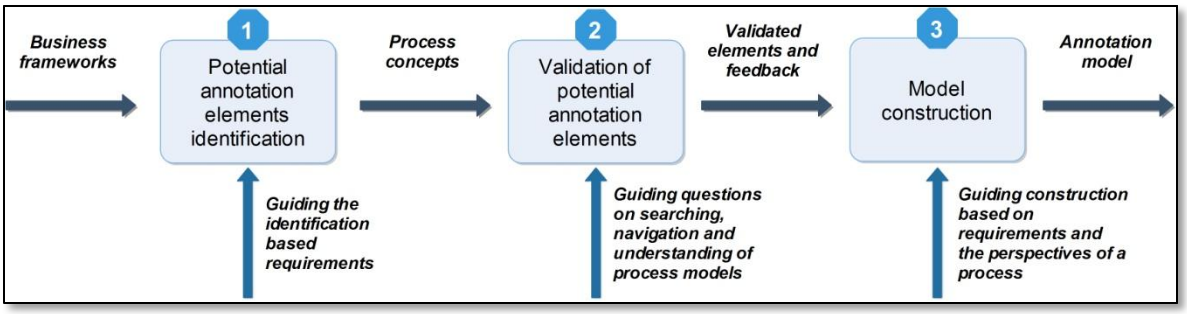

Figure 2.5. Annotation model development process (Mturi and Johannesson, 2013)

Aiming also for more understandable semantics, there is research that facilitates semantic annotations to enrich organisational models (Vazquez et al., 2013). In this context, the annotations create links between model elements and specific domain concepts. This linkage manages to leverage the prospects of analysis and reuse of the annotated information. The annotation process is also termed as "labelling", since organisational models are examined through visual modelling. The paper concludes that enrichment through annotations allows users to clarify the elements of the model and their attributes. Annotations are deemed as a decisive tool for achieving interoperability between knowledge domains, and for promoting reuse of knowledge components (i.e. when versioning). Since knowledge comprehension and analysis can receive significant upgrades through semantic enrichment, it is expected for such a methodology to be extensively adopted in e-Learning, and in general for enhancing and maintaining educational knowledge. The research presented in (Vidal et al., 2014) uses semantic annotations to create knowledge subgraphs from educational content. These graphs constitute instantiations of LD that provide highly accurate descriptions and appropriate context information for the annotated material. Once more, improved indexing and classification are recorded as direct benefits of annotations, with computational compatibility making them a precursor for analytics and data extraction.

Semantic tags are essentially an implementation of semantic annotations. Their use is closely related with taxonomies based on contextually descriptive terms. Semantic tag clouds can offer considerable advantages when dealing with Linked Data and methods to explore scalable knowledge. (Zhang et al., 2014) introduces contextual tag clouds as summaries of the distribution of relevant data that allow the user to quickly gain an understanding of patterns and changing contexts. Helping the user to understand the impact of semantics on the data, the paper proposes a query building assistant that can act as an exploring tool for casual users, or a diagnosis tool for data providers. An interesting aspect of this research is the treatment of tags as classes and properties that help visualize patterns of co-occurrence and provides summaries of the instance data. These patterns allow users to better monitor the tagged knowledge and effectively detect special facts or errors. Both as part of tag clouds and as independent entities, semantic tags provide the building blocks for taxonomies and indexing. In (Tsui et al., 2010) a core set of taxonomy terms is mined to generate a hierarchical structure that allows users' information navigation behaviour to drive personalization. With simple tag clustering and pattern matching, large collections of tag instances can transform collaborative social tagging into a potent knowledge capturing tool.

In (Liao et al., 2013), a formalization of semantic annotations is proposed for PLM. The approach targets contextualized interoperability of knowledge between interfacing enterprise systems and related stakeholders. Taking a step back and addressing PLM as a domain, Liao later conducts in (Liao et al., 2015) a detailed survey of literature that applied semantic annotations on different objects, inside the context of enterprise systems. Focusing on enterprise application architectures and frameworks, the generated classification is based on the annotated entity and its description. The drawbacks and the strengths of each formalization approach are discussed to extract possible research directions. Advised next steps for semantic annotations research include:

1. **The novel application of semantic annotations.** More research efforts are required to apply semantic annotations on new domain subjects and for new knowledge objects.
2. **The standardization of the semantic annotation process.** Contribute in the standardization of the essential annotation procedures and base semantics. Create and propose annotation frameworks and formalization methods, which can be easily adopted by other researches.
3. **The maintaining of annotation consistency.** While supporting the versioning of annotated objects and the evolution of annotation schemas, there is a challenge of sustaining consistency and compatibility.

2.1.4 FMEA/FMECA Knowledge and Enterprise Flows

Managing FMECA knowledge with software tools is a fundamental service of modern commercial maintenance support systems (PTC Windchil FMECA[1], ReliaSoft Xfmeca[2]). The majority of them emphasize the support of related standards (i.e. MIL-STD 1629 (US-DoD, 1980), IEC 60812 (Committee, 2006), BS 5760-5, SAE ARP 5580 (ARP, 2001), SAE J1739 (Standard, 2002)), offering both desktop and web clients to access, enter and update the appropriate data. Research for implementing FMEA/FMECA as a web service, has been recorded early, alongside with the booming of cloud technologies. These approaches, essentially constitute the first attempts to port the appropriate design tools into what is currently considered the Cloud. The work in (Rodriguez and Al-Ashaab, 2005) places FMEA, as a key system component for collaborative product development systems. The study suggests that FMEA services, as a part of a knowledge driven web-based architecture, require the input from the product life cycle experts through a "**virtual meeting environment**". The research in (Huang and Mak, 2003) conducts a thorough and well-organised study of the strengths and weaknesses for three initial versions of a web-enabled or web-based FMEA. The remote access pattern and the collaborative shared space, make these web applications an early version of decision support tools, or what Huang calls "**virtual consultants**".

The respective service components of modern software suites or cloud platforms have supported many research initiatives that investigate diagnostics and operational behaviour for critical assets. The qualitative nature of the FMEA/FMECA knowledge allows it to couple very effectively and link with reliability field data. Studying these

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

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

relationships can provide leads and insights that may significantly benefit and optimize the maintenance plan and strategy for complex modern assets. Recorded research scales from wind turbines (Arabian-Hoseynabadi et al., 2010), up to the risk analysis of a geothermal power plant (Feili et al., 2013). Moving one step forward into knowledge management, modern e-Maintenance platforms now target information integration and adaptable behaviour. To better pinpoint what is currently trending in e-Maintenance, (Kothamasu et al., 2009) provides a very accurate and extensive survey on paradigms and technologies that empower monitoring and prognostics. After examining **FMEA support systems**, amongst others, the survey concludes with pointers for promising or required next steps: (i) development of modelling technologies that are precise, adaptive, comprehensible and configurable (by user) and (ii) integration of the qualitative information that can be extracted from FMEA or FTA into the quantitative analysis that generates diagnostic recommendations. While the first suggestion drives attention to context adaptive tools, the second identifies the need to mine and exploit the knowledge link between FMEA/FMECA and FTA. This is a link that is proven able to fuel the risk analysis and design optimization of sophisticated assets and control systems (Katsavounis et al., 2014).

Focusing on knowledge management and integration, FMEA and FMECA have lately been studied through the use of several modern representation technologies. Intelligent FMECA can be achieved in three ways (Ying et al., 2012): (i) numerical simulation, (ii) expert systems and (iii) reasoning. Numerical analysis includes a wide range of statistical methods applicable to process and decode FMECA relationships, in order to produce actionable recommendations. The linking nature of failure-oriented structures such as FMEA and FTA, have already provided a solid backbone to guide data logging and profile the statistical processing of failure information to improve the reliability of maintenance system components and the optimization of maintenance strategy (Botsaris et al., 2012). Fuzzy logic has been employed in (Braglia et al., 2003) for criticality assessment, devoted to support maintenance staff. In (Chiang et al., 2008) a series of back propagation neural networks are used to create a hierarchical framework supporting the implementation of an intelligent FMEA. (Teoh and Case, 2004) proposes an FMEA approach that targets the reuse of knowledge through knowledge modelling and functional reasoning. (Cândea et al., 2014) also targets the efficiency of FMEA knowledge reuse, by employing case-based reasoning and delivering software that creates a collaborative web environment.

An ontology for intelligent fault diagnostics is proposed in (Zhou et al., 2014), addressing the extraction of shallow knowledge and deep knowledge. The first represents the experiential knowledge of domain experts, while the second constitutes reference knowledge about the structure and basic principle of diagnosis objects. Their fusion is deemed very important to achieve completeness of component fault information in FMECA. So the question arises on how to elicit knowledge from maintenance experts (**shallow knowledge**) and couple it with validated reference diagnostics. In (Walls et al., 2005) the process of eliciting engineering knowledge from experts is achieved with the help of a facilitator that acts as an interface and ensures data integrity and domain relevancy. The proposed capturing method is straightforward and implemented via interviews. The direct nature of this approach requires appropriate preparation for the facilitator and a careful selection of expert representatives. Using more advanced techniques, the capturing process in (Potes Ruiz et al., 2013) is supported by a well-focused maintenance ontology designed to deliver on three main goals: (i) knowledge formalization with a domain vocabulary that leverages the communication and knowledge sharing among experts and technical actors, (ii) multi-expert knowledge management to support collaborative decision making, and (iii) maintenance problem solving.

Taking a step back from FMEA/FMECA, we identify that investing in **enterprise learning flows** is very important, in order to compose and sustain the intellectual capital inside any competitive industry (Vargas and Lloria, 2014).

Maintenance experts and engineers comprise the part of human capital that can contribute in a loop of continuous improvement for knowledge assets such as FMECA. Capturing such field expertise with tools that enable group interaction is a catalyst for producing actionable knowledge (Cao, 2012) and this can benefit the maintenance function. Figure 2.6 displays how the implementation of Philips' FMEA software tool is integrated into the corporate R&D process to support collective knowledge improvement and bring the strength of various departments together (Ying et al., 2012). This collaborative approach is even more important in an inter-organizational context, where conflicts between knowledge management objectives and the applicable field expertise can occur. In (Krenz et al., 2014) a knowledge intermediary is introduced that supports value creation structures, processes and artifacts, which ensure an appropriate symbiosis between diverse knowledge consumers and producers.

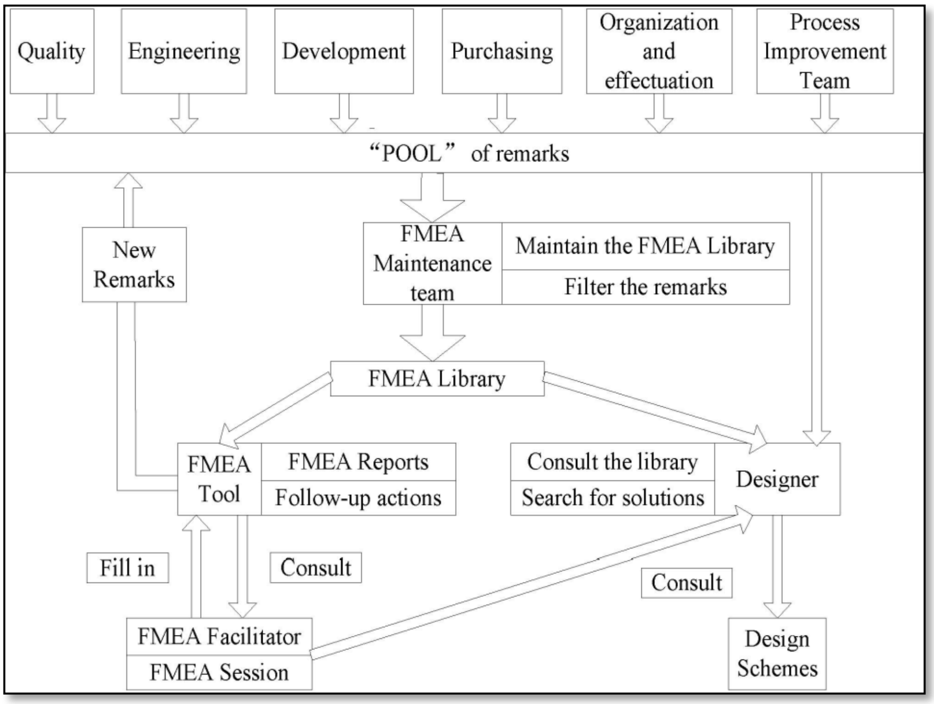

Figure 2.6. FMECA schematic implementation in Philips (Ying et al., 2012)

Knowledge management diffusion is a challenging process and an impactful factor in preserving and upgrading knowledge assets. Knowledge management adoption and implementation can benefit from IT components that deliver a balanced and intuitive sharing environment (Lin, 2014). Enterprise applications have evolved to become contextually engaging platforms that adapt, filter and personalize access and contribution to complex assets of business or industrial intelligence, such as FMECA. Enterprise social software now support knowledge management goals, effectively serving the sharing and collaborative building of key knowledge assets (Richter et al., 2013). Furthermore, corporate social software are now emerging to support new ways of interaction and allow for fundamental changes in knowledge management processes, like the facilitation of user participation along the value chain or fostering employee-to-employee communication. 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).

Ensuring **knowledge integrity** and consistency is a critical requirement for knowledge assets with strategic value. Knowledge is constantly being scaled and linked between domains and model's that were never coupled before. Without the appropriate tools to monitor and validate such integration by experts, the quality of the resulting knowledge can be highly questionable. The FMECA study is a periodically scheduled knowledge management process that involves several maintenance experts, key facilitators and a specific set of **validation and versioning** goals. It is a process that is supported by two commonly disconnected systems, namely: (i) a failure reporting system and (ii) an FMECA risk-analysis component of a back-office suite. Integrating component's that can efficiently act as interfaces between the models of these two systems, can significantly improve and streamline the above process. The technology for semantic engineering and the methodology for a collaborative validation environment already exist (Li and Yoo, 2011). Applying the methodology and configuring the use of respective technologies, for knowledge assets such as FMECA, is a research task that requires the study of diagnostics-oriented design rules and sharing policies.

2.1.5 e-Maintenance Mobile Services and Context Based Maintenance

The rapid technological progress in mobile device and mobile application development has fuelled the construction of “smart” environments in both business and industrial environments. Such environments are equipped with a wide range of devices, identification tags and interaction panels, capable of sensing, recording, interpreting and reacting to human activity and presence. **Mobile and portable technologies** have been early on employed to couple with web solutions and support the functional needs of maintenance tasks (Liyanage et al., 2009). Industrial PDAs and Tablets allowed e-Maintenance systems to interact with mobile actors (maintenance personnel). The emerging trend has already displayed valid evidence that mobile technologies have the ability to redefine and re-engineer the conventional setting of e-Maintenance. They already offer advanced and smart solutions to remotely manage complex, high-risk, and capital-intensive assets, regardless of the geographical location, building agile information and knowledge networks (Emmanouilidis et al., 2009). Coupling enterprise systems with mobile applications is bringing impactful benefits in the integration of heterogeneous maintenance data, systems, and processes. Moreover, the **wireless technologies** are rapidly eliminating connecting cables between the monitored equipment and monitoring systems, thus providing a more flexible plant layout and the potential for significant scaling (Campos et al., 2009). Figure 2.7 displays the various channels, in integrated e-Maintenance, where mobility has provided a platform for on-demand and on-line expert collaboration. The platform augments and multiplies the available knowledge links between the higher tiers of maintenance management and the shop-floor level of maintenance practice.

Engineering asset management involves multi-disciplinary teams and decision making processes, with application focused and field-derived specifications. The utilisation of innovative features that spawn from state of the art mobile technologies, is seen by Campos (Campos, 2009) as an important pillar of an enterprise wide maintenance grid; a platform that will integrate maintenance services and connect all IT components to improve end-to-end e-maintenance and e-manufacturing processes. The emerging need for effective interoperability and service integration, is well analysed in (Arnaiz et al., 2010), where the collaborative participation of mobile components inside a wider e-Maintenance environment is directly linked with openness, modularity and standardized communication. Mobility can play a key role in such platforms and environments, bringing speed and accuracy in capturing data and knowledge, while also enriching channels of communication between personnel engaged in the maintenance process (Bankosz and Kerins, 2014). **Remote mobile access** has decisively changed the scale of contribution in collaborative systems. By contributing to the effective management of organisational knowledge and identifying the resulting organisational benefits, maintenance staff can become increasingly involved in achieving collective knowledge development and process learning (Hislop, 2013).

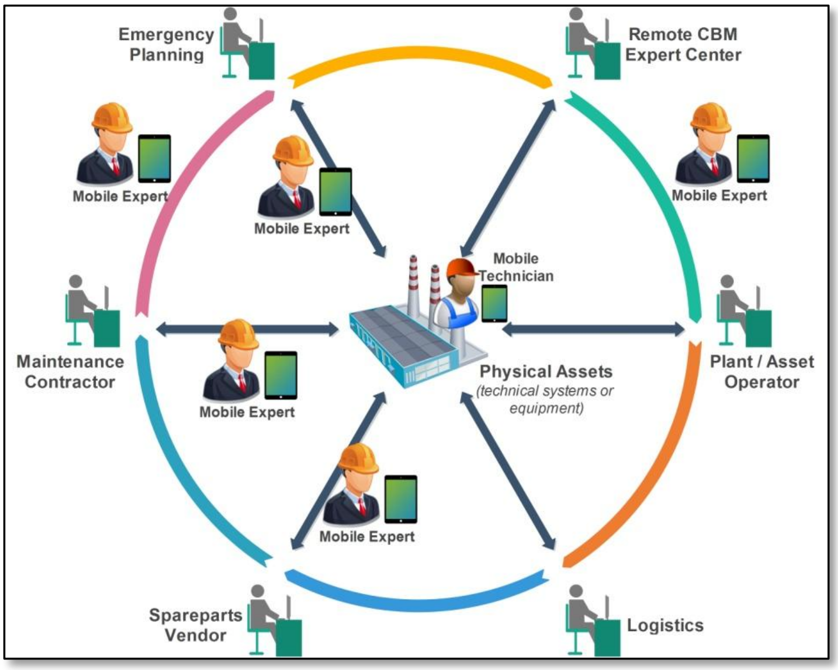

Figure 2.7. Mobility integrated in e-Maintenance (adapted from (Liyanage et al., 2009))

The maintenance and asset management function involves personnel from different disciplines, with technical, engineering, financial and managerial responsibilities. Data and knowledge applicable to certain staff roles may be irrelevant to others. Maintenance and asset management information systems must account for such variations in the roles and responsibilities of different staff. Effective adaptation of services and data provisioning is sought via context-adaptive computing, which is becoming more relevant to enterprise information systems (Perera et al., 2014). The actual value of data can be enhanced via contextualising data provisioning services, that is by providing the right information to the right persons at the right place and time to serve the right needs and purposes in a certain business process instance (Lee and Martinez Lastra, 2013). This becomes a definitive requirement, when these services lead diagnostics and support decision making by fusing information from collaborating maintenance and monitoring systems (Galar et al., 2015).

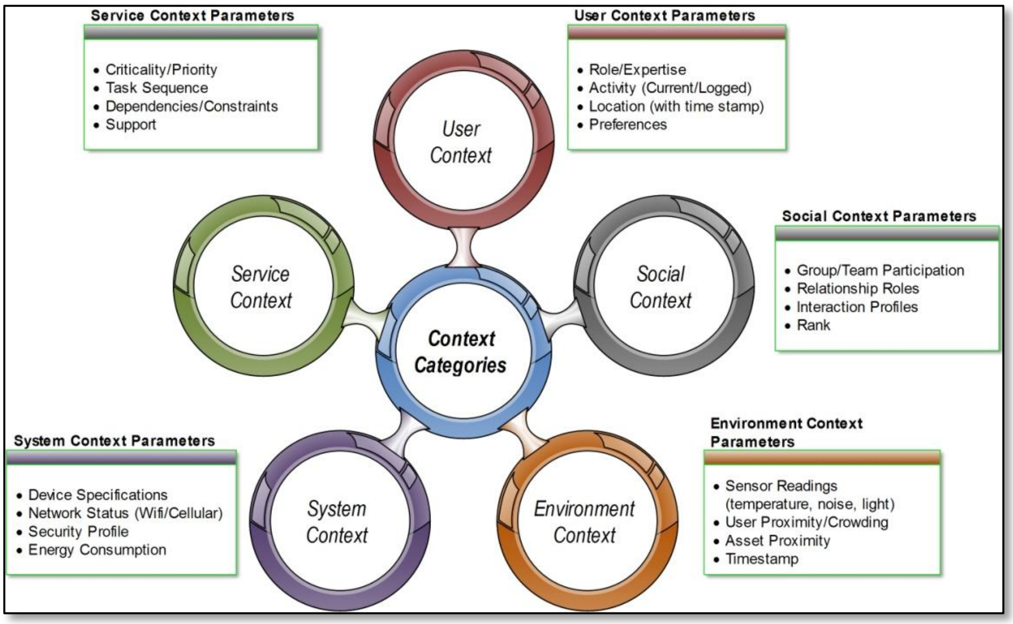

Figure 2.8. Context in mobile maintenance (Pistofidis and Emmanouilidis, 2013)

As a result, **context data models** are increasingly adopted by application-focused initiatives that compete in translating maintenance mobility and context awareness into specific benefits for maintenance performance and remote monitoring (Stack, 2012). The facilitation of well-framed context information can leverage the profiling of key maintenance processes and filter the information exchanged between integrated mobile and cloud components (Pistofidis and Emmanouilidis, 2013). Figure 2.8 presents context categories that carry meaningful semantics to adapt maintenance services:

- **User Context** (*individuality*) – It maps the semantics behind the information included in user profile, system preferences and logged activity. Profile information designates personnel's expertise, maintenance roles and system credentials. Preferences express a set of property values that allow user-defined adaptation of services and console personalisation.
- **System Context** (*facilitator*) – It holds the semantics for describing device features, along with other non-functional information, such as the connection status and network availability (e.g. availability of Wi-Fi networks and/or 3G signal strength), power level and system performance/status, etc.
- **Environment Context** (*location*) – It addresses the location coordinates or code of the personnel proximate position (asset/segment → position). It also includes a set of property values that describe constituents of the sensed industrial environment (temperature, noise, humidity, light).
- **Service Context** (*activity*) – The context of the user assigned functions and services. It contains the semantics about the service participation in a larger workflow (sequence number in maintenance plan), its criticality/priority and its dependences with other services/functions.
- **Social Context** (*relations*) – This context describes the dynamics of group participation and collaboration between industrial agents such as personnel. The semantics here draw a constantly updated linked graph, where flow of knowledge and authority identify individual skills for co-operative efficiency and effective supervision.

All the above contexts can be closely coupled with the dimension of time and provide provenance timelines for their progress and alteration.

Context-awareness introduces the capturing, clustering and interpretation of the above contexts in order to balance and enrich the provision of content and services. The value adding context-based services have found their way into various e-Maintenance architectures, with their developers receiving support from rapidly growing frameworks, APIs and communities. Context capturing and functional adaptations are gradually evolving with a pool of features available for all the design patterns of mobile services (Pistofidis and Emmanouilidis, 2012). Recent mobile data models and maintenance services have achieved standardized decentralizations and adaptations, using layered interfaces and customisable components. Web and rich internet applications have efficiently took upon and adequately served this trend, delivering personalised dashboards for various tasks and processes (Groger and Stach, 2014). These dashboards offer the challenge to create overviews for large amounts of data, by processing contextual factors that deem their relevancy to each user's status, task and environment (Nadoveza and Kiritsis, 2013). Such context-aware mechanisms become even more important, when the adapted content is meant for training purposes and the services drive the workflow of relevant learning objects (Papathanasiou et al., 2014).

Introducing the concept of context in knowledge management systems may go beyond adaptation features and enable organizations to empower staff to become active knowledge contributing-actors. A promising path for the fusion of maintenance knowledge with shop-floor expertise, is the contextualization of e-Maintenance capturing services and knowledge flows. According to (de Reuver and Haaker, 2009) the main challenge in designing service components is the uncertainty about the added value of context awareness and personalization for specific user segments. This makes it very difficult to define valuable context-aware propositions, which is quite critical for the success of any business model. Inside an organization, different members have different demands for knowledge in different contexts. In (Zhen et al., 2010), the model for an inner-enterprise recommender system is introduced, providing design principles and investigating context enabling technologies for maintaining a knowledge sharing and capturing loop between experts. The importance of an agent perspective is argued in (Zacarias et al., 2010), capable of contextualizing and essentially aligning the individual and collective view of an organisation. Acting as a mediating interface, the agent adapts structural information and creates a common shared perception, and thus knowledge, between experts and system components. Taking one step further in knowledge scale and integration, (Skopik et al., 2010) highlights important concepts of context-aware human interactions in cross-organizational processes. In these interactions human experts are flexibly involved in key steps of workflows that support single tasks owners to address emerging issues. Experts are discovered based on dynamically changing contextual constraints, such as problem areas and required expertise, using Web 2.0 communication facilities.

Context is commonly translated, system-wise, into a set of parameters that define a descriptive state or a profile. The environment and the system context are often the most easily exploitable contexts for producing system adaptations that impact users experience. The user context is a much wider context with a large pool of custom or domain-oriented parameters that can drive the "personalization" of services. Moving into the service context and the social context, the parameter semantics become more abstract and less tangible or measurable. These contexts can easily be expanded with better focused semantics that instead of supporting state or values, they hold descriptive knowledge. The process of creating a knowledge building process is essentially the process of designing meta-contexts. E-Maintenance has not experimented much with such processes. They incorporate mechanics that can enable maintenance experts to dynamically configure the semantics they want to link with the base knowledge (i.e. FMEA/FMECA). Providing a base FMECA context and monitoring its enrichment from the users, is essentially a collaborative design process. Metadata management systems are able to promote the identification of new contexts by offering an environment that is part a knowledge management application and part a design tool. It is exactly this freedom that can trigger an experts contribution and imprint new context dimension on comprehensible metadata.

2.1.6 Cloud and Big Data

The data produced by the management of physical assets has matured from digital repositories of periodic reports to massive distributed silos of data and monitored or processed parameters. During the last years, back-end management of **Big Data** has made leaps of evolution. Industry has been actively collecting for years a wealthy set of primitive and processed data that describe the majority of its process contexts. Initially the focus was to optimally map data semantics to all extended monitoring needs and aspects of these contexts. As a result industrial models and standards emerged to unify the information structure and to ensure a qualitative record base for each industry and even process context (i.e. supply chain, maintenance, operations, management). It is only in late years that industry acknowledges the greater value of aggregated data and seeks to identify its prospects (Figure 2.9). The concept of Big Data is initially introduced in domains with more knowledge aware functions and adaptive executive strategy. In (Perrons and Jensen, 2015) the concept of Big Data is studied as a facilitator and an enabler of modern oil and gas industry. Evaluating the extend and availability of domain silos that can be labelled as Big Data instances, the paper explains the required shift in perspective, when evaluating such repositories and technologies. According to this shift industry tends to regard metadata as information that describes the state of an asset, while leaders in Big Data, by stark contrast, realize that metadata is a valuable asset in and of itself. Towards the same goal (Holdaway, 2014) offers an extensive study of how Big Data can serve the optimization of high demanding processes such as exploration and production in the oil and gas industry. It is worth noticing that the book investigates data modelling issues and requirements, pinpointing the need for designing information semantics aligned to specifications of manageability and analytics preparation.

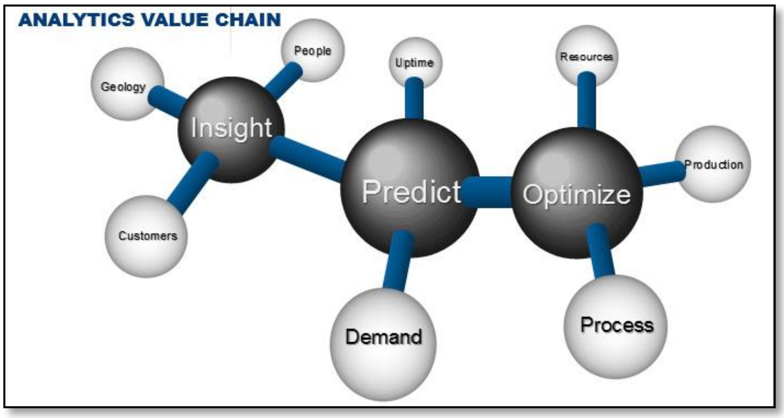

Figure 2.9. Exploration and production value propositions (Holdaway, 2014)

Industry is an early adopter of advancements that upgrade or enhance its monitoring infrastructures. Data acquisition and monitoring are rapidly expanding in any shop-floor comprised of critical assets. The benefits of sustaining such infrastructures aligned to emerging technologies is often validated from their contribution in information quality and lately in knowledge density. That is why **Cloud** met better acceptance when it was perceived as a technology that could leverage the potentials of most monitoring infrastructures. Sensor cloud is a concept and a methodology that currently has a wide range of applications (Alamri et al., 2013). The architectures and technologies that support sensor clouds are consistently evolving to adapt and comply with a constantly increasing pool of specifications from diverse application domains. Sharing a common problem space with Internet of Things (IoT), sensor cloud has emerged as its major enabler and a modern instantiation of pervasive or ubiquitous computing. In (Zaslavsky et al., 2013) the Sensing-as-a-Service model is extensively studied, discussing its importance for managing and coordinating huge repositories of monitored data (sensed Big Data). Identified as a handling mechanism that can facilitate the management of such silos, sensor clouds appeared as a solid and viable solution for industries heavily invested in condition monitoring. Indicative of this market's prospects is the fact that Google has recently employed its extensive cloud background, to study various aspects of cloud in industry and patented the results (Maturana et al., 2014b, Maturana et al., 2014a).

From the perspective of a larger context, cloud manufacturing is a concept that has been investigated and studied from early on. Focusing on the core features of cloud facilitation, industry can gain important benefits from sharing and circulating manufacturing resources and capabilities (Zhang et al., 2012). Virtualizing these entities with interoperable services, allows modern **Service Oriented Architectures (SOA)** paradigms to achieve the orchestration of workflows that deliver demanding functions such as failure/energy/transaction management. At the heart of a manufacturing cloud, knowledge becomes the fuel of these middleware functions and a promising product of business intelligence. Sharing this knowledge to the extended user-base of a cloud is a challenge, progressively addressed by versatile collaborative environments. User groups coupled to different manufacturing contexts (engineering, operations or maintenance) allow the optimal adaptation of these access environments, abstracting the complexity of the manufacturing cloud. More importantly, the classification of services in groups enables advanced cloud management with prioritization features that ensure robustness of service workflows and consistency of shared knowledge (Karnouskos et al., 2012).

Following the evolution path of SOA, e-Maintenance gradually adapts further into the adoption of cloud technologies. The potential and the need to outsource management and utilization of maintenance-derived resources, is studied by many industries. Both in terms of computational capacity and storage, these industries assess that the accumulated volume and complexity of data and analytics is significantly surpassing their capacity to handle them. IaaS (Infrastructure as a Service) presented Data Centers as the first choice of a cloud maintenance solution. Despite the fact that many industries acknowledge the prospects of this solution, security concerns continues to keep a large number of them from facilitating third party cloud analytics. Abiding to industry's concerns, e-Maintenance vendors maintained their business analytics with in-house deployment features and almost zero cloud facilitation. Only lately, the availability of generic analytics (Bohlouli et al., 2013) with semantic agnostic services, have brought more trust and a spike of interest to cloud analytics and big data frameworks. Following this trend industry uses, evaluates and appreciates the cloud as a versatile tool that unlocks a whole new range of business intelligence and knowledge management aspects. As a result, e-Maintenance currently moves to adopt many Web 2.0 design patterns and implementation technologies that offer cloud features and support big data.

Modern e-Maintenance enterprise solutions benefit from domain insights produced by a growing toolset of cloud analytics. The cloud effectively addresses the computational requirements, the data handling and the orchestration of typical maintenance-related services, such as event detection, diagnostics and prognostics, to drive sophisticated tasks such as predictive maintenance planning (Lee et al., 2013b). Cloud services are transforming what was formerly perceived as a costly burden into a valuable corporate asset with significant exploitation prospects. The performance improvements and the added value brought by such a transformation can be significantly influenced by certain factors that define how cloud-ready an e-Maintenance system is. These factors involve the compatibility of technologies between the cloud provider and the e-Maintenance vendor, along with pre-analytics profiling of the maintenance data. In (Santos et al., 2013) this fusion of technologies is presented through a system of distributed streaming analytics. Data born from the connected devices of a monitoring infrastructure are leveraged in a distributed topology to gain business and operational insight. State of the art Web 2.0 technologies couple with distributed analytics management services, to coordinate the creation and visualization of knowledge streams for web and mobile clients. The research provides a solid example of how a design pattern can effectively abstract the distributed nature of cloud analytics, while making the most out of its underlying power.

2.2 Discussion

When considering the increasing availability of maintenance data within industry and the body of knowledge related to maintenance engineering and management that has grown over many decades, a significant challenge emerges on how to benefit from both in order to advance industrial decision making. Whereas data-driven knowledge-based systems and computational intelligence-enabled decision tools have sought to fuse expert knowledge with data, they have left unexploited a critical source of contextually-relevant knowledge, namely the knowledge generated on the job by personnel. This is primarily due to the complexity of modelling and managing such knowledge, thereby making interfacing with personnel equally cumbersome.

2.2.1 Agile semantics in e-Maintenance model design and instantiation

A large portion of modern e-Maintenance repositories, while gaining complexity with ever-expanding depth, have also gradually lost flexibility and purpose. There is a clear need for a more modular and linking methodology to help address the density of information and effectively move e-Maintenance models closer to knowledge. While porting these models to more agile semantics is gaining pace, handling their use by the legacy services requires extensive use of translating/wrapper mechanisms. E-Maintenance vendors invest limited development effort in the compliance of their services with constantly expanding standards. At the same time industry has become increasingly aware of knowledge structures, such as metadata, and the prospect benefits of their collaborative existence along with data. Witnessing their successful use for business intelligence in various other domains, has resulted in greater expectations from e-Maintenance vendors. Currently, e-Maintenance systems vary significantly in terms of data model design. In reference to their metadata-compatibility we classify them in three main categories:

- **Legacy Data Models**: These include IT structures designed to meet a wide range of modelling criteria. Their schemas excel in providing static support for diverse maintenance information, and may evolve accordingly. This essentially translates to e-Maintenance records with excessively descriptive profiles.
- **Adapting Data Models**: Such models were implemented by a set of technologies that later became the means for building maintenance metadata. While not initially supporting data correlations, their schemas have the potential to extract static attributes and create meaningful metadata regarding the application context. In asset management IT solutions, the majority of such models and systems were implemented to drive web-based enterprise e-Maintenance systems. The architecture of these systems allows them to identify beneficial knowledge dimensions, pinpoint value-adding techniques and incorporate the appropriate metadata patterns and handling mechanisms.
- **Metadata Models:** This is the least common state for an e-Maintenance system. The schemas here heavily invest on creating semantic maps that generate metadata instances of specific knowledge value. This is an increasingly relevant model for modern enterprise systems, and one currently largely unexploited by e-Maintenance. In such systems, assets, actions, events and agents participate in organized virtual collections, following the metadata semantics defined to serve specific analytics. The use of metadata for classification is a methodology that aims to solidify greater layers of generalizations, and in turn allow the integration of interfacing knowledge domains.

Engineers use workflow scripts to orchestrate the automatic monitoring and pre-processing of data as it is generated, or prepared for subsequent analysis. In such cases, the information of the workflow, state or connection of data is embedded in metadata, which are typically not well documented nor easily visible to collaborators. Experience has shown that as the associated metadata are better organized and more complete, the underlying data become more useful and accessible. Furthermore, the appropriate tools to automatically create, discover, display or explore the semantic relationships of complex data from maintenance processes do not currently exist, though concepts or paradigms from the semantic web may prove useful. Therefore, there is presently an unmet need to better document maintenance metadata that annotate, transform, or disseminate data and capture (and later present) data provenance. Provenance refers to the lineage of data products. Generous provisioning of metadata, including data provenance and data relations, is critical to enhance data sharing, to allow data to retain its usefulness over extended periods of time, and to provide traceability of results. The motivation of this research is to greatly increase the value of reference e-Maintenance knowledge, allowing it to evolve through continuous enhancement.

2.2.2 A validation loop for e-Maintenance reference knowledge assets

FMECA is a formal way of structuring relevant knowledge related to Reliability - Centred Maintenance (RCM). Typically considered as a design-stage tool, FMECA usually features weak feedback loops with periodic or on-demand contribution from maintenance experts. It often also functions as a structured reference of diagnostics to support shop-floor maintenance practice. It comprises the result of an engineering study, where maintenance experts participate as both the contributors and the users of enterprise maintenance knowledge.

An FMECA study produces a reference table that facilitates the proper organization and instantiation of maintenance knowledge related to risk and reliability analysis. As such it has been particularly useful in handing both the design as well as the operation and maintenance of complex technical systems in failure analysis tasks. The provided knowledge correlates assets with failure modes and maintenance actions, in a manner that facilitates interpretation of related failure. Scaling from common symptoms, up to severe failures with impact to operation or production, the table acts as a knowledge map, where causes and effects are linked together to support failure analysis at the design, testing and operating phases. The quality, and therefore the maintenance value, of FMECA knowledge is directly affected by the validity of the information it is based upon. It is well proven that the functional behaviour, and as an extent, the failures of an asset can significantly vary between different deployments, production profiles and life-cycle stages. Therefore, FMECA knowledge has to be validated continuously, throughout the timeline of relevant events and in correlation to experts' feedback.

FMECA ontologies are recently studied as means to bring reasoning mechanics in fault diagnostics (Zhou et al., 2014). This type of approach, though it uses powerful fixed semantics, it brings new challenges, especially on how to validate and indeed revise and refine the initial expert knowledge based on actual observations and knowledge feedback from the field. Other research initiatives seek to exploit expert knowledge in more conventional ways, such as interviews and questionnaires (Walls et al., 2005), or in more advanced ways through well-focused ontologies that map maintenance expertise (Potes Ruiz et al., 2013). While the first can ensure a positive and controlled process of extracting knowledge from experts, the later can automate the capturing and elicitation of a wider range of knowledge. Seeking to elicit knowledge from workers and using their input to populate the semantics of a complex ontology, can be prove to be too complicated and too distant from the baseline understanding of knowledge management from non-IT experts. This gap in transparency, with abstracted functions that make the concept of knowledge capturing more obscure, can directly discourage participation. The target goal for the present work is motivating greater involvement, which can be achieved when professionals have better knowledge and control over the capturing process and over the way they can contribute. Simplifying input and interaction patterns in knowledge capturing processes can be a critical factor for their success.

In the majority of available software suites, FMECA usage is confined mainly to designers, maintenance engineers and technical managers. 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. Machine operators and shop floor technicians typically neither participate nor do they directly benefit from FMECA knowledge, partly because of its complicated nature. However, it is exactly such staff that fuse and expand the most updated field expertise relevant to the shop floor practice. Disconnecting background maintenance intelligence from field-practice leaves unexploited multiple rich channels of enterprise knowledge flow.

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 of its semantics and browsing of its content. Instead of defining and using FMECA in a static manner similar to its hardcopy counterpart, relevant knowledge should be enriched and validated through the experience of the user-base it is designed to assist. FMECA semantics and users' feedback are in practice separately modelled by most modern systems. A distinct software entity stores core diagnostics, while another stores the feedback from reporting. Modelling the later with semantics that simplify their entry, and linking them with semantics of the former, is crucial for the predisposition of experts towards the process of combining FMECA knowledge with their field expertise. This is even more important in the case of a mobile maintenance actor. Shop floor personnel need intuitive interactions with minimal requirements for data entry, otherwise they tend to reject software tools. This is a common stance, when they don't see direct benefits that justify the required learning curve to familiarize themselves with their use.

2.2.3 Summary of Literature Review Findings and Research Gaps

Modern knowledge management systems feature a level of complexity that blocks or limits their ability to properly convey their value, purpose and benefits to the prospect or targeted experts. Maintenance personnel and shop-floor experts are commonly more cautious when adopting the use of expert systems. This is heavily due to the fact that such systems are by default introduced to them as black boxes with little to none information about how the internal process works or how knowledge is build inside them. A methodology is needed to produce and handle maintenance knowledge components in a comprehensible manner for every level of expertise and maintenance role. This methodology should allow for an enrichment process to be at the same time simple and scalable, transparent and contextualized. Table 2.1 presents the key research gaps and the specific needs that were detected throughout our analysis of the state of the art and current literature.

Table 2.1. Identified research gaps and important needs

Versioning and validation of industrial knowledge assets
❖ There is a lack of methods to support the continuous versioning and validation of reference diagnostics, such as FMECA and other key industrial knowledge assets.
❖ Current approaches implement periodic updates or on-demand reviews of knowledge.
❖ There is a need for a transparent method that manages to break this validation and revision into a series of small everyday reviewing tasks.
Engaging industry experts and capturing field expertise
❖ Knowledge capturing methods haven't achieved to find the pulse for maintenance and industry experts' contribution.
❖ The strict and time-consuming feedback paradigm of enterprise reporting forms, inspire the minimum possible contribution and collect knowledge in its most rigid and outdated form or structure.
❖ The out-of-context engagement severely limits the ability of mobile and multitasking experts to recollect, focus and facilitate the appropriate mindset that can deliver and produce the desired input in terms of both quantity and quality.
❖ The intimidating profile of the adopted "expert" systems, trigger the least possible motivation form maintenance experts that cannot interpret, compute or even understand the mechanisms and the benefits behind their use.

Creating and sustaining knowledge flows across maintenance management and shop floor practice
❖ Critical knowledge assets, such as maintenance plans and references of diagnostics, remain unavailable and disconnected from field experts that carry the knowledge to effectively improve them and translate them to practice.
❖ Knowledge management and fusion is mostly driven by automated mechanisms, predefined analytics and management-level specifications. There is lack of support mechanisms for shop floor experts, enabling them to supervise the capturing, clustering and classification of failure related information.
❖ There is a gating issue that prevents field expertise from profiling, deciding and communicating what has short term and long terms knowledge value for the maintenance department and the industry itself.
❖ e-Maintenance approaches for collaborative knowledge management, lack modern features of enrichment, sharing and cross-evaluation. There is a selective adoption of web technologies that leaves unexploited several methods that can collectively validate and enhance knowledge assets.

2.3 Conclusion

In this chapter an extensive literature review was conducted to present the state of the art in domains that interface with our research. These domains map the current research status in aspects that include knowledge modelling, semantic linkage, enterprise knowledge flows and service provisioning. Examining the adoption of such aspects in e-Maintenance, and reporting the available adaptations and implementations of the respective services, an overview for the context of this research has been provided, in terms of methodology and available technologies. The knowledge modelling approach through maintenance metadata and the application focus in FMECA versioning and usage, were discussed as means to address emerging requirements from industry.

The main focus of the presented research is to address the need for formalizing, modelling and functionally supporting the enrichment loop of a well-established maintenance knowledge model; the FMECA study. It is an important knowledge asset, and one that requires a collaborative management process to transform experts' feedback into components of its sustainable value. Experts need access and new ways to contribute practical maintenance knowledge, controlling its enrichment and scaling into something new; a new version of FMECA. This research proposes a new approach and a system that instantiates, configures and shares the formalized knowledge, imprinting field expertise into maintenance metadata. It is an approach that enables the capturing and profiling of shop-floor evaluations big or small, early or late, important or trivial, motivating staff to engage in this process.

3 Context Modelling for Maintenance Knowledge

3 CONTEXT MODELING FOR MAINTENANCE KNOWLEDGE

This chapter studies the knowledge modelling process of this research and analyzes the semantic structures and formalization that support it. Initially, a brief discussion explains how the results and findings of previous research stimulated this work's modelling approach and contributed with a set of design specifications. Studying the reviewing and evaluation methodology of maintenance experts, a new context of information is identified as the dynamic coupling of their background expertise with reference knowledge. Following this linking methodology, the FMECA model is employed as the reference knowledge and its semantics are studied in detail. The starting point of this model along with its extensions, are discussed, explaining their knowledge value as part of the introduced Failure Context. The concept of maintenance micro-knowledge is then defined as the product of FMECA's enrichment process. The annotation purpose and the instantiation of these knowledge components are mapped to specific aspects of knowledge enrichment. The final section of this chapters provides knowledge formalizations for both the FMECA knowledge model and maintenance micro-knowledge, to better represent the linking semantics of the produced metadata. The understanding of this knowledge building process is also facilitated with an example of a Failure Context composed by maintenance micro-knowledge. The chapter ends with a short summary and a set of key modelling points.

Both data structures and knowledge representation have significantly evolved in the application context of e-Maintenance. Modelling maintenance data has been up-scaled to include modelling maintenance semantics. This directly connects with the fact that e-Maintenance systems are expected now to focus on formalizing, handling and even producing knowledge, rather than data. Such formalization is an essential requirement before a system can instantiate and manage knowledge. LD provides the means to create semantic graphs, where information from different contexts can be linked and integrated. Practically, LD aims to connect content and information that reside on different systems and different hosting environments. As more links are formed, the semantic graph grows in density. Adopting this focus and features, we introduce the concept of "*Failure Context*" **as the confluence of factors contributing to the occurrence of a failure** (Pistofidis et al., 2014). The Failure Context holds the combined knowledge of the FMECA failure mode and the time-relevant feedback of maintenance practice (Figure 3.1). Building upon the established semantics of an FMECA study, we provide the means to extend its knowledge capacity by formalizing and instantiating this context. Adopting structures and components from the established MIMOSA schema, we have customized our FMECA model to empower the creation of an event map (Figure 3.2); a semantic graph where Failure Events act as the core nodes.

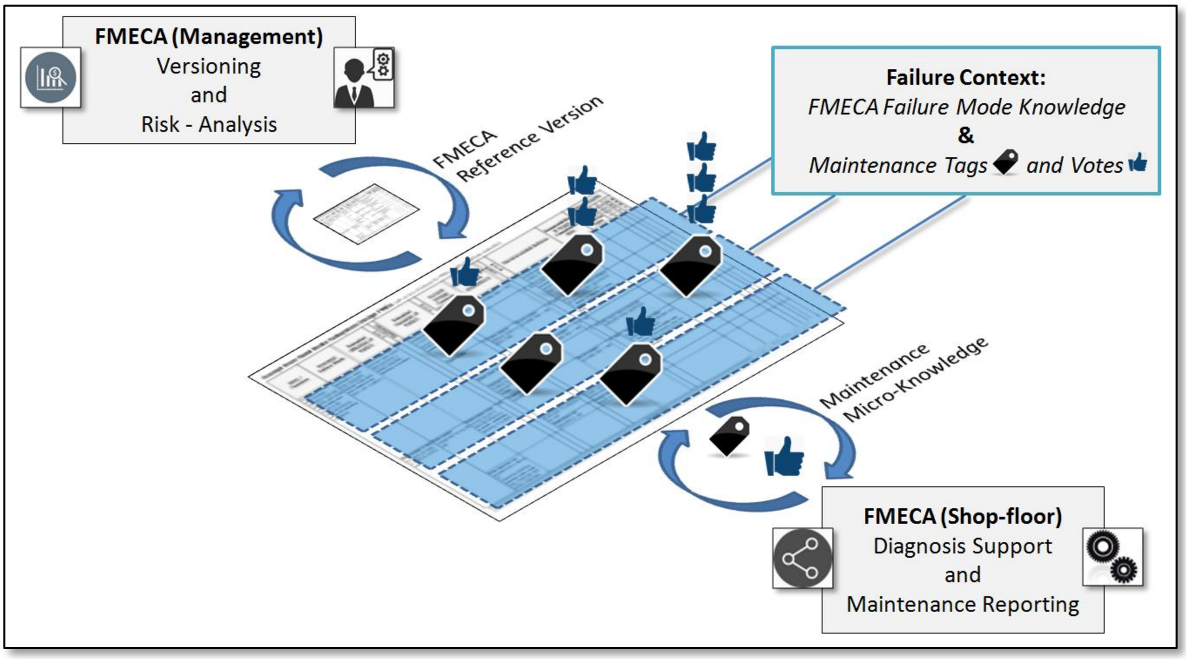

Figure 3.1. Failure Context contributing factors

The model of our approach gradually builds a knowledge graph that binds the FMECA event map with context driven field evaluations. The two most important specifications of this design are also its innovative points:

- **Balance FMECA knowledge, investing on event linkage and not on event complexity**. The first point addresses the challenge to model knowledge that can be easily consumed and support mobile staff on various maintenance contexts. We address this challenge with an FMECA model that scales event connections rather than event information profile. Traversing a rich event map can more effectively create the appropriate mindset for solving or interpreting a maintenance event. While FMECA is capable of including a wide range of information, we refine and structure the FMECA model to directly benefit mobile staff on everyday maintenance tasks. Our model adopts a complexity level that is higher than a simplified text-book fault-solution coupling and lower than an overly complicated reliability analysis database.
- **Provide a feedback model that capitalizes on ease of use, modularity and ready-to-use semantics**. The second point aims to port a very successful feedback paradigm into the maintenance reporting process. The modelling of semantic tags and concise input as mean of fast user response is left unexplored in e-Maintenance, while dominant in social collaborative tools and business analytics. Our modelling approach uses Maintenance Tags and tag mini-forms to deliver a knowledge capturing process that again invests in linking field expertise with FMECA rather than requesting the latter's direct expansion. We provide a default set of tags that allow staff to timely and easily flag contextually relevant FMECA knowledge. Its relevance or diversification can be further explained or quantified with optional brief input in the tag's mini-form. The versatility of user defined Maintenance Tags and the meta-ranking of tag usage with votes extent the application range of our approach and upgrade its interoperability.

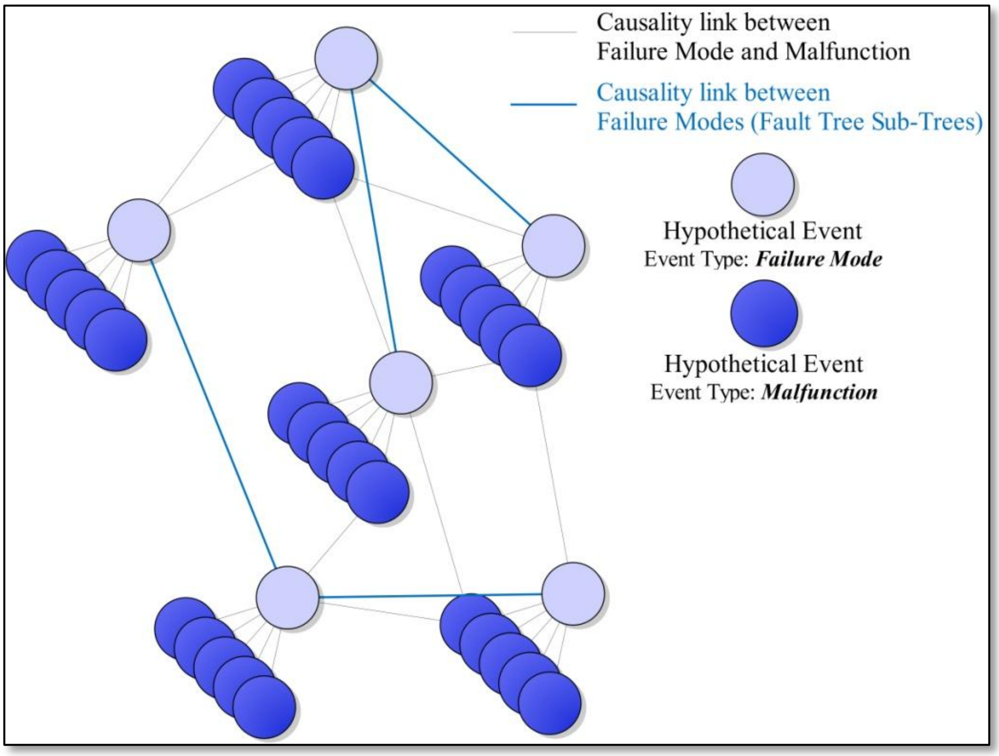

Figure 3.2. A causality semantic graph of events

3.1 From e-Learning Content Evaluation to FMECA Validation

e-Training technologies are constantly moving towards more modular and contextualized services (Papathanasiou et al., 2012). Modern platforms currently facilitate features and metrics that follow and capture the learning curve of each individual trainee. These are employed by services that dynamically process learning objects whose content is aligned with the training goals, the verified knowledge rank, and the identified gaps of each trainee. Building an accurate profile for each trainee is a process both user-driven and system-driven. Such a profile allows these platforms to efficiently address the demanding scope of professional training. Learning objects for such training are often authored and structured to offer expert insights and solid methodologies with well-picked case studies and scenarios. The corresponding theoretical background is balanced to strategically build a required underlying knowledge and does not extend to topics that do not link with a specific goal or skill set. All referenced content and supporting media is filtered by cross-referencing the trainee's profile, so as to achieve the best possible contextualization with the least possible distraction. When the above content and process is indented to serve a mobile trainee via an on-demand paradigm, certain metrics and provision features attain crucial role. These features include modularity of content, small functional paths and brief user interaction/input.

e-Training platforms are currently moving their service into the world of portable devices and the cloud. Mobile training or m-Training is gradually gaining pace and aims to serve a much more on-demand model. The trainee receives well-adapted mini-courses whenever and however he or she chooses to (Papathanasiou et al., 2013). Many e-Training platforms already provide touch optimized web environments and native applications for tablet users. On-line courses are structured in units that now aim for less time and greater focus. The trainee can use such content either as a crash-course, as an introductory overview, or a reference point for a very specific topic. This is a scope where e-Training and decision support systems couple their forces to treat training as a time-constrained challenge. Time is of essence and adaptive modularity is the key to unlock the potentials of m-

Training. Both users and the system are in power to customize and fine-tune the learning experience. In order to drive this control effectively, many features can be used to define the quantity and type of the learning objects. Ranging from casual learners to professionals, modern platforms provide the tools for users that want (i) the freedom to schedule their learning experience and have control over the workflow/pace of training, (ii) to select and customize the representation of knowledge and the format of the course. Knowledge is structured in a such a versatile model that when processed by a contextualization engine it can adequately and effectively serve both as a quick reference and a full-hour course.

In the context of maintenance practice, maintenance professionals can range from entry-level technicians and shop-floor trainees to highly skilled engineers and strategic planning managers. What they need and expect from an e-Training platform can be quite diverse. In iLearn2Main (Papathanassiou et al., 2013, Emmanouilidis et al., 2011, Papathanassiou and Emmanouilidis, 2010) we utilized the widely established Moodle platform to design, customize and populate a Learning Management System for maintenance professionals. Course structure, user profiles and the syllabus where carefully defined to create a web-based environment that could support the training needs of context changing professionals. Courses where organized with topics that span from condition monitoring up to maintenance management. The goal was to familiarize highly skilled shop-floor experts and management directors with a platform that can effectively tailor and provide a maintenance oriented e-Training experience. The e-Training process was extensively evaluated with numerous piloting sessions on different countries and from professionals with diverse maintenance backgrounds. A self-assessment system was also made available to support the ranking of knowledge gained and the identification of knowledge gaps. All content and services where rated by the professionals with an extensive questionnaire and dedicated interviews.

The evaluation results provided interesting findings that allowed us to profile the professionals' stance on both the system and the content. Maintenance professional exhibited great interest and involvement when prompted to evaluate the system, course content and knowledge focus. Our research capitalized on this rich feedback and we investigated possible connections between content rating and content features. For each course professionals could rate and comment on the following chapters separately: (i) Introduction, (ii) Theoretic background, (iii) Case Studies, (iv) Assessment, (v) Glossary and (vi) References. A set of 15 parameters were used as metrics to create a profile for each content component. These metrics quantified properties closely related with content complexity and structure, referenced resources and knowledge density. A thorough study was then conducted, cross-examining the collected ratings and feedback with the parameters of each course chapter. The analysis results revealed interesting patterns that document how the studied content parameters affect the training experience and contribute in an appropriate learning context (Papathanassiou et al., 2013).

One very interesting conclusion reached by the overall analysis and the project itself, was the positive stance of maintenance professionals towards evaluating both the e-Training system and the learning objects. Provided they had a reference knowledge to evaluate, all levels of maintenance staff where more than happy to provide ratings and comments. Even when asked to rate separate course modules, engineers and managers offered full evaluations for all the modules of all the courses they had followed. There were many cases, where extensive comments were provided for very specific content aspects and focus points. This feedback was studied and mined to extract valuable insight on how to make the training workflow both interesting for the trainee and useful for his or her role. Piloting and interviews helped us understand the importance of context and role in a knowledge capturing or knowledge serving process. Whenever maintenance professionals were prompt to provide verbal or written feedback on how to cover a certain maintenance topic, methodology or practice, their response was minimal. This was not the case for collecting their feedback when reviewing existing points on maintenance topics and piloting training material. Setting up a context where professionals evaluate knowledge and are not prompted to produce it stimulated a critical stance and a knowledge sharing attitude. This shift of motivation was sometimes enough to retrieve more insight than the evaluated content.

Studying the evaluators' comments we identified specific features that were repeatedly requested as advanced functionality or content consumption techniques. One such feature was the ability to create brief notes and link them to a specific training phase or content. Maintenance managers pointed out the usefulness of available means to flag important content both as a trainee and an editorial user. While the first would use notes to pinpoint content relevant to his current training needs, the later could facilitate notes to address improvements, corrections and in general keep track of a progressive reviewing process. They themselves offered extensive feedback on functional aspects that addressed topics such as course attendance flow, system access patterns and platform feature discovery through navigation (i.e. glossary, references, self-evaluation section). This implied that the incorporation of an annotation tool would allow users to contribute their feedback and become active participants of an on-going knowledge enrichment process.

Understanding the dynamic nature of digital training material, all professionals offered significant insight on how content relevant to their background could be enhanced, linked or presented better. As another widely requested feature, comments from technical staff gave significant weight to knowledge flow and linkage of learning object and cross-referenced materials. Short structured content with multiple references was favoured and valued. Glossary terms, external references and rich media/illustrations linked to tables and ordered lists, were highly rated as well-balanced content. Content for theoretical background and application techniques, was requested by technicians and engineers to be uniformly structured in steps and always referencing resources from recent case studies and real application cases. Knowledge assimilation was reported much higher when the trainee could concurrently consume the template methodology in parallel with linked information about its most modern industrial practice, occurrence and instantiation.

Maintenance professionals and experts were more motivated to **enhance existing knowledge rather than offer it as a starting point**. Knowledge refinement is a much more extended and incremental process and does not entail the responsibility or ownership of producing original knowledge. Nevertheless, the role of a knowledge creator and a knowledge reviewer, while different, become quite similar when serving a knowledge capturing context. Studying comments and requests from experienced maintenance personnel we extracted our core design aspects for both the FMECA model and the knowledge capturing methodology through tags. Facilitating modern technologies and popular semantic tools, we brought FMECA closer to field practice, as a reference to be advised, validated and reviewed with the aid of the same integrated tool. The delivered model, discussed more extensively in the next sections, aims to instantiate timely maintenance findings and decisions upon a dense event map that is created to interpret the first and drive the second.

3.2 Building FMECA Knowledge

Modelling FMECA, as an engineering study and a reference for diagnostics, is targeted by standards based on diverse design perspectives. The proposed model utilizes MIMOSA as a starting point for drawing a subset of its core semantics. Extending these semantics, the model expands in aspects of failure causality and other means that enable the creation of a Failure Events graph. MIMOSA is a schema with a wide scope of support for maintenance sub-domains. While its schema depth provides descriptive accuracy and versatility, it can also sometimes overload a compliant system with unexploited sub-classing of maintenance entities. Since our goal is to produce a model effectively tailored for a lightweight service-oriented backend logic, we implemented abstractions and integration of semantics. Focusing on the efficient consumption of our services by mobile clients, our model is designed to fuel the effective handling and presentation of e-Maintenance data and knowledge, including maintenance metadata and micro-knowledge through maintenance mashups.

3.2.1 Core FMECA Entities

Core FMECA entities map the backbone of a Failure Analysis study and constitute the nodes of our FMECA graph. Their semantics include (Figure 3.3):

- **Assets:** This entity defines the attributes of industrial assets and describes how they connect with other FMECA components. It includes registry-based static information, links between parent and child assets (component hierarchy), and links to asset classification entities. The classification is supported with links to specific Asset Types (Asset Classes) and the use of a Criticality taxonomy. The later is achieved by a link to the supported Criticality Scale and the actual value that maps the Asset's criticality.
- **Asset Functions**: Asset Function is a concept usually modelled as a supporting entity. The MIMOSA schema places this entity among core semantics. We adopt this design decision and model Asset Functions as an important node of our semantic graph linked to the dynamic nature of Assets. We utilize Functions not only as a linked node to Assets, but more importantly as a linked node to Events. We support a direct link between Events to Asset Function, and we extend it by introducing a separate class of Effects in the profile of Failure Modes. To assess the context of a Failure Mode we model how an Asset malfunctions, i.e. deviates from its expected Function set. An Asset Function's profile is classified by means of links to Asset Function Types.
- **Agents**: This entity defines the system actors. Its semantics include basic naming, links to classification entities and a link to the associated system account. The later is optional, since not all Agents may have system interaction right from the start. A system account supports the ability to tag and alert the event in the system. For Agent classification, Agent Types and Agent Roles are linked to provide a taxonomy based on physical features and operational authorities, accordingly. To elevate the profile of the later, Agent entities can be also linked to Assets he/she/it is responsible for (monitoring, operating, inspecting).
- **Maintenance Actions**: This entity models how Maintenance Actions participate in the FMECA graph. They define recommended actions or solutions for the prevention or correction of specific failure events. MIMOSA uses the title "solution package" to name the corresponding entities. Following this, we have incorporated the linking mechanism that facilitates the recursion of modelling a maintenance action as internal step of another one (packaged). Each maintenance action is classified by its priority, employing a link to the appropriate level. This level can define its global priority inside a wider maintenance plan, or simply the sequence priority as another action's step. Finally, an optional Asset link is also provided. Maintenance actions are primarily linked to Events that instantiate Failure Modes. As such, their Asset link can be inferred by the Event's one. A maintenance action may constitute a scheduled, preventive or generally a stand-alone action that is not somehow associated with the occurrence of an Event. In these last cases, the Action's Asset link is utilized.
- **Events**: We address Events as the most important FMECA entities. Populating the backbone of the targeted semantic graph, we have focused in ranking and expanding on the models ability to meaningfully link various Event instances. We discuss their model later on, offering more details on specific design aspects.

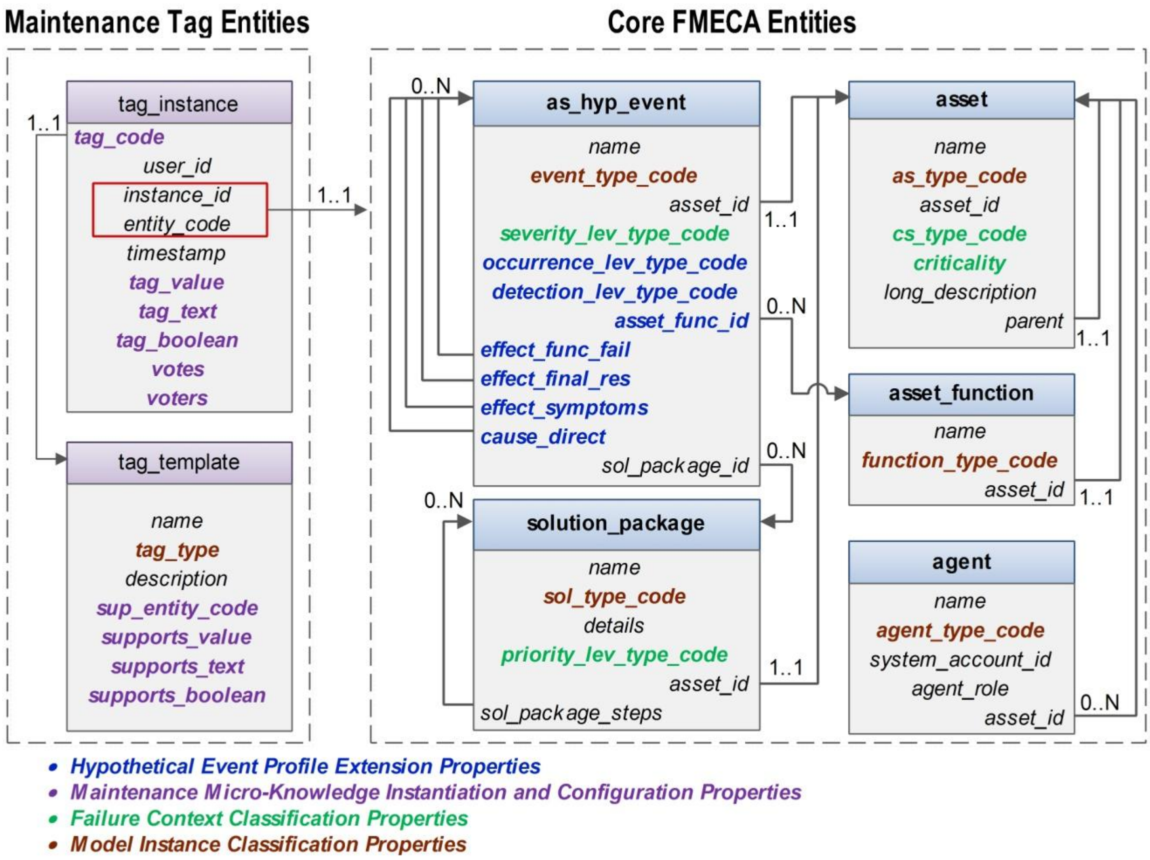

Figure 3.3. A model to support the semantic annotation of FMECA

3.2.2 FMECA Classification Entities

This is comprised by a set of entities that model categories, types, scales, roles and other classifying concepts that support the taxonomy of core FMECA semantics. This entity set, essentially, brings control over organizing FMECA information. It is a very simple and effective way to allow the end-user fine-tune the FMECA's descriptive capabilities, so that the final model properly meets the desired specifications. This set includes:

- **Asset Types**: Entity to populate and expand the types of Assets that participate in the FMECA. Referenced from Assets.
- **Event Types**: Entity to populate and expand the types of Events that participate in the FMECA. The initial set includes the default types of Failure Modes and Malfunctions. Referenced from Events.
- **Function Types**: Types that classify Asset Functions. The initial set includes Primary, Secondary and Supporting. Referenced from Functions.
- **Maintenance Action Types**: Types that classify Actions, based on the type of maintenance they serve. The initial set includes Corrective, Preventive and Scheduled. Referenced from Maintenance Actions.
- **Agent Types**: Types that classify Agents, based on their physical instantiation and their interaction pattern with the system. The initial set includes System User and External System. Referenced from Agents.
- **Agent Roles**: A taxonomy of roles that can be assigned to an Agent. More than one roles can be assigned. The initial set includes Maintenance Technician, Maintenance Engineer, System Administrator and Technical Manager. Referenced from Agents.

- **Criticality Scales**: This entity models the available scales that can be used to quantify the criticality of an Asset. It includes attributes that hold minimum and maximum values of the Scale. Initial set includes 10_Level_Scale, 100_Level_Scale, 3_States_Scale and Binary_Scale. Referenced from Assets.
- **Severity Levels**: Entity that models the levels of a global Severity Scale. Event profiles are linked to a severity level. Each level entry has a title and a value. The initial scale offers a range of 1-10 mapped levels. Referenced from Events.
- **Occurrence Levels**: Entity that models the levels of a global Occurrence Scale. Event profiles are linked to the level that signifies their frequency. Each level entry has a title and a value. The initial scale offers a range of 1-10 mapped levels. Referenced from Events.
- **Detection Levels**: Entity that models the levels of a global Detection Scale. Event profiles are linked to the level that signifies how detectable they are. Each level entry has a title and a value. The initial scale offers a range of 1-10 mapped levels. Referenced from Events.
- **Priority Levels**: Entity that models the levels of a global Priority Scale. Action profiles are linked to the level that signifies how important they are as a part of a plan or a series of tasks. Each level entry has a title and a value. The initial scale offers a range of 1-10 mapped levels. Referenced from Maintenance Actions.

The above entities support the taxonomy of FMECA core components. All the corresponding *type* and *scale* properties feature single cardinality, allowing only one instance to be linked. Agent *role* is the only entity that supports N cardinality. These classification properties serve (Figure 3.3): (a) the essential type-based taxonomy of model instances, inherited by MIMOSA; and (b) the functional scaling of Failure Context semantics. While the first supports the organization and structure of the FMECA model, the later elevates its maintenance value as a helpful reference of diagnostics.

3.2.3 Extended MIMOSA FMECA Event Entity

MIMOSA provides domains of entities relevant to Engineering Asset Management study. When focusing on RCM, this includes the semantics of an FMEA/FMECA study. Inside this domain MIMOSA models failure events with the entity *Hypothetical Event*. The term "hypothetical" is there to declare that an FMECA Table provides a map of probable events. It is a reference to guide RCM activities and not a registry that records when Failure Modes actually occur. Though our FMECA modelling goals are aligned with MIMOSA's design rules, our failure context's targeted knowledge extends the approach and incorporates such a registry.

MIMOSA models Hypothetical Events with attributes that compose a profile for supported event types. The greater the importance of an Event Type, the more properties need to be completed in the Event profile. In our model (Figure 3.3), we have extended the Event profile with properties that link to semantics of occurrence and detection ability. They facilitate the ranking of Events' frequency and detection probability. Along with the MIMOSA inherited property for the Event’s severity, these levels can drive an RPN-based (Risk Priority Number) evaluation of a Failure Mode occurrence instance. Our Hypothetical Event model also includes a property that links to Asset Functions directly affected by the studied Event. Connecting such semantics with Failure Modes is common in FMECA Tables, contrasting how the Asset should work and why (cause) or how (effect) it doesn't.

Hypothetical Event is the entity that acts as the building block of the Failure Context. A "malfunction" and a "failure mode" are both types of this entity. Failure modes are linked with causes, effects and solutions associated with them. A malfunction may be linked to a failure mode or later become one, if its context expands with associated causes and effects. This is a process that gradually builds the knowledge infrastructure for an Asset Fault Tree.

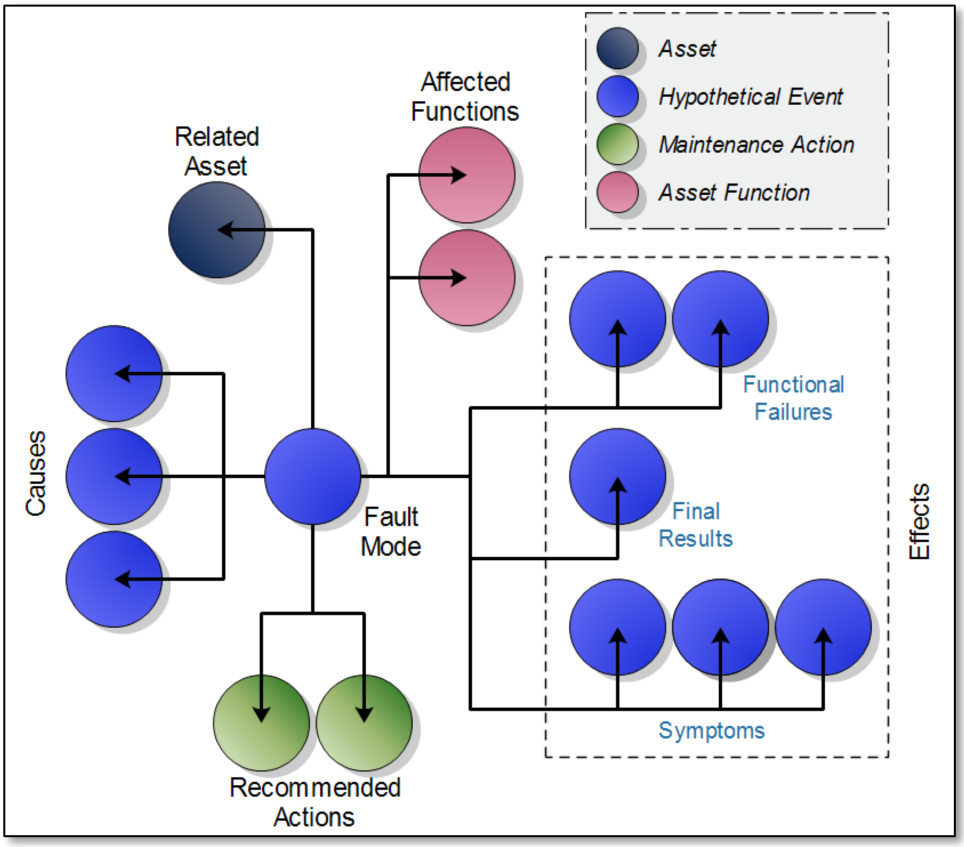

Figure 3.4. Hypothetical Event linked status

The Cause and Effect relationship of events is modelled by MIMOSA as a distinct coupling entity, the Hypothetical Event Link. Much like a SQL JOIN table, this entity facilitates the desired cardinality for events connection. This offers a generic and flexible approach for pairing Hypothetical Events through unclassified links. The drawback is that no added semantics (and thus knowledge) are offered to sort or rank these links. One of the main features of LD is that it supports the modelling of unique semantics. Instead of abstractions and generalizations, LD favours accuracy of semantics. This is achieved by providing (i) definitive descriptive goals and (ii) a context for every data component and every link between them. This builds a methodology that can lead to unique global identifiers for the corresponding semantics (Bizer et al., 2009).

We define an Event profile that supports distinct Cause and Effect links. Each Event can link to Cause and Effect Events through dedicated referencing attributes. While Causes are served by one referencing attribute, Effects are further analyzed and ranked. Causes and Effects are only required for Events that comprise Failure Modes (Event Type). In greater detail, effects are mapped to (Figure 3.4):

- **Symptoms** - They constitute effects of lower 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 model effects directly connected with specific functions of the related asset. Their role is to distinguish between events that manifest the change in functional behaviour, from events that merely describe a condition. They can be used in analyzing evolving failures' impact, where functional participation of assets in process workflows can produce chain effects. The timeline of such effects can reveal the progression and connection of failure modes. Cross examining the Event's linked Functional

Failures and Asset Functions draws a more accurate picture of the Asset's operational status and the Events overall impact.

❖ **Final Results -** These effects include the Failure Mode's most critical results. They are descriptions of events, that significantly impact on 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 other affected assets. These events must be well documented, so as to warn staff to take prompt preventive actions and help identify their occurrence, as they constitute decisive evidence of the Failure Mode they are linked to.

One of the most important aspects of Event's model, is the set of suggested actions. Each Event profile can be linked to one or more Maintenance Actions that resolve, prevent or state the appropriate maintenance response to it. Modelling action workflows can be implemented through the use of recursion, with links to action's steps.

3.3 Modelling Added Knowledge through User Feedback

While core knowledge is modelled through FMECA entities, human-contributed field knowledge can be captured and form an additional value-adding knowledge layer. Our research explores a new way of capturing the feedback of maintenance staff, investing on imprinting the users' evaluation into concise maintenance metadata. These metadata are formulated by semantic links between established FMECA content and predefined shop-floor directives. This process is implemented through the use of maintenance semantic tags.

A tag-cloud is a common semantic-web component, used to reveal the annotation patterns of web users. Tags can effectively drive the user's experience while navigating, searching and interacting with linked content. Semantic tags offer the building blocks of a constantly evolving semantic map and signify the content's context. Tag clouds increase in size with each new keyword used by users for searching or evaluating the content. Users annotate information they assess as important, and try to embed the "how important?" in the tag's title. They also browse the tags of others, since they have a natural interest to utilize and cross-examine the "most common" tags. The concept of tagging and annotation is a recursive one, powering the creation of tags for tags and thus the fusion of new meta-contexts. It is simple to use and at the same time lends itself to indexing mechanisms, facilitating the handling of information in content management systems.

We adopt this methodology into a model that instantiates shop-floor maintenance findings and couples them with documented field knowledge. The model is designed to support the use of maintenance semantic tags and extent the instantiated knowledge with additional feedback from mini-forms.

3.3.1 Introducing Maintenance Micro-Knowledge - Tag Engineering Data

Our model is designed to use semantic tags as a layer of enriching FMECA knowledge. Each tag has a straightforward use and annotation purpose that is defined by its tag template. The default set of tag templates is configurable and extendable. Maintenance engineers can create, modify and adjust the type and purpose of any template. Tag instances are the modelling entity for maintenance metadata. Every annotation action creates a tag instance, which couples the tag template's descriptive value with the referenced FMECA content's value. Each tagging action instantiates a timestamped link that connects the tag's semantics with the corresponding FMECA content, a process facilitating the quick capture of field knowledge fragments. Tag instances are shared and can be searched or filtered by users. Their knowledge can be further enriched with tag votes (declaring agreement) and tag mini-forms (additional feedback). We term every such instance as **Maintenance Micro-Knowledge** (Figure 3.5).

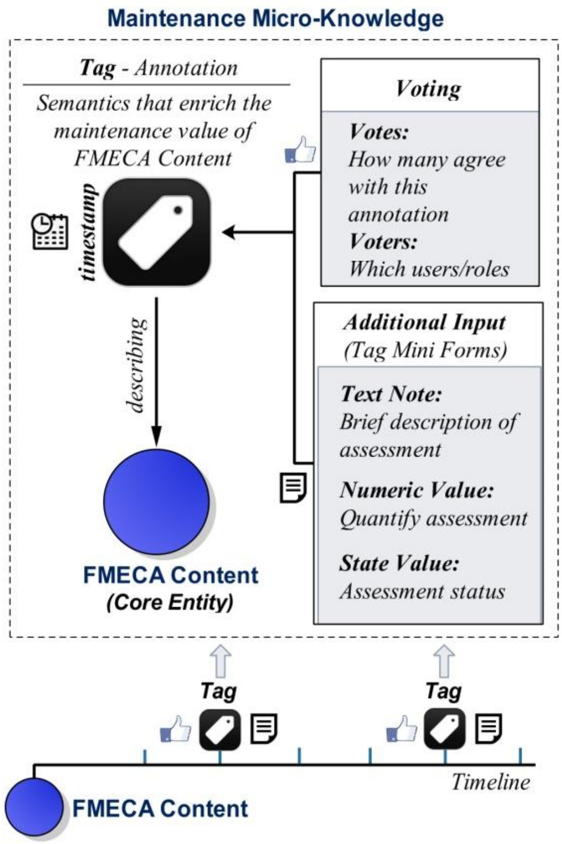

Figure 3.5. Maintenance Micro-Knowledge

From a Linked Data perspective, this process leads to forming a Context, where each maintenance tag has specific descriptive value. If used outside our system, this Context can be referenced to facilitate shared maintenance semantics. Linked Data defines unique semantics through the combination of a global identifier for the context (URIs / URLs), along with an internal identifier for each tag. Our model leads to identifying a Maintenance Failure Context by collecting and managing Maintenance Micro-Knowledge.

In greater detail, Maintenance Semantic Tags are modelled with the following features (Figure 3.3):

- ✓ Tag Classification: Offering categories to organize maintenance tags is a concept similar to having types, roles and scales to classify FMECA content. The proposed model facilitates this as a property of the tag template entity. Creating a taxonomy of semantic tags provides a profiling pattern for the annotation tool itself. It builds elevated semantics and thus leads to maintenance knowledge. Such a taxonomy allows better organisation of user annotations and thus offers greater depth to their use and improved analysis potential.
- ✓ Tag Annotation Profile: Each tag template has a property that contains the list of supported FMECA core entities. This property defines which content can be annotated with the specific tag. It enables a dynamic configuration of how our model can link tag semantics with FMECA content. Support for more than one entities is an effective way to leverage the tag's versatility with cross-entity annotations.
- ✓ Tag Additional Input: The tag instance entity is modelled to store a timestamp, a user id, the tags semantics link and the tagged content's link. Along with these properties, our model is extended to store additional dimensions of the user's feedback. Every tag template includes properties that describe and profile what type of additional feedback is supported during the annotation action. This feedback is by default optional and not required from the user. It may include one of each of the following: (i) a textual note, (ii) numeric value and (iii) a status lock. The textual note offers users the option to briefly analyze any insight that can further

specify their annotation's purpose. The numeric value is used to quantify the semantics of the maintenance tag, according to the templates description. Finally, a status lock can declare a specific state that is defined in the templates description. The overall goal is to enable maintenance personnel to refine their input/evaluations with more qualitative and quantitative options.

- ✓ Tag Voting: FMECA content comprises a first layer of semantics. On top of that, a second layer can be formed by maintenance tags (metadata). We specify a very thin third level of semantics that conveys practical benefits for managing maintenance knowledge. Investing and experimenting more with the concept of meta-contexts, we employed well-established concepts to create higher abstractions of maintenance semantics. We expanded the maintenance tag model with properties tightly connected with ranking and sharing features; the maintenance tag votes (Figure 3.5). Each maintenance tag contains a counter for positive votes along with a list of the related voters. Each tag instance, when created, is instantly visible and shared by the appropriate users. Supporting a collective evaluation context and avoiding the repetition of similar tags by different users, votes provide widely used semantic means to upgrade metadata. Votes introduce an additional metric for assessing the value of the micro-knowledge that is instantiated when FMECA content is tagged. Indicative of a tag-consensus or tag-acceptance, votes offer social insights, such as personnel collaboration patterns and users predisposition on feedback cross-evaluation. This form of micro-knowledge fragments, if effectively managed and mined can become extremely valuable.

3.3.2 Tagging FMECA Content - Default Maintenance Tags

Creating maintenance micro-knowledge involves simple functional flows, where personnel use available tags to report their findings and decisions. One such flow is displayed in Figure 3.6. It explains the usage pattern for some of the default maintenance tags of our final system. The default set includes the following maintenance tags:

- ❖ **"Confirm" tag:** It is the most basic maintenance tag and stands as confirmation that an event has occurred. Its enrichment value heavily resides on the timely nature of the annotation. Its place on a timeline of related annotations and its distance from the confirmation of a larger and more significant events can offer valuable insight about its role in their progression and occurrence.
- ❖ **"Issue" tag:** This tag allows the early reporting of an asset issue that has not been properly identified or mapped to an FMECA event. Though more of alerting nature than concrete FMECA knowledge, early detection and flagging of such generic issues can invoke awareness and prompt inspections or further adequate actions.
- ❖ "**Schedule" tag:** The scheduling of maintenance actions is often a task handled by a CMMS, with appropriate planning and assignment of work orders. A "schedule" tag is used to pinpoint a maintenance action as the appropriate solution for a confirmed failure mode. Knowledge of past scheduled actions can enrich the Failure Context with insight for unresolved or re-occurring failures along with maintenance action efficiency.
- ❖ **"Working on" tag:** 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" tag:** 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. Since its maintenance value is solely dependent on the additional feedback, "Observation" tag is the only tag that requires its provision.

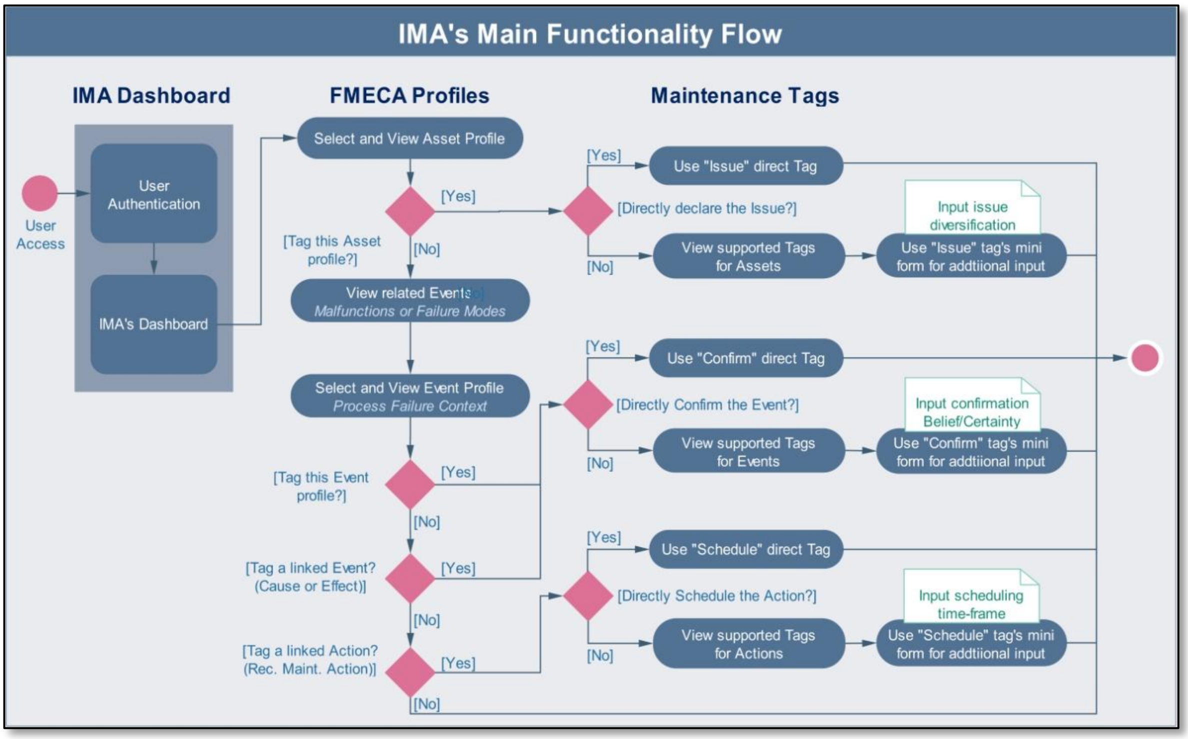

Figure 3.6. IMA-FMECA's main activity diagram

3.4 Maintenance Knowledge Formalizations

Knowledge formalizations work as components that effectively represent the knowledge handled by a process or a system. Their role is quite important, offering an interface and a translation mechanism for knowledge commuted between the user and the system. The main goal of these formalizations is to functionally and structurally represent knowledge so simple and useful, and at the same time distributed over enough and appropriate people, that their system use and user adoption will come intuitively and naturally. Many and various approaches have been utilized, all customized and adapted to address the context of the system that implements the knowledge capturing or sharing process. Three major and well established categories for such systems are: (i) Social Semantic Tagging Systems, (ii) Semantic Wikis and (iii) Semantic Games with a Purpose.

To address our models formalizations we invest on five properties that allow us to define knowledge management and tailor the process to maintenance users' needs and context:

✓ **Simple**: Formalizations should be simple enough, so that their knowledge value can be understood with little or no training. Their instantiation functions should also require little effort and time from users and should not be limited or locked to experts. Compared to a traditional ontology engineering approach, semantic tagging is a much easier methodology to understand and use.

✓ **Collaborative**: Formalizations should map knowledge produced and managed jointly in a group. Knowledge ownership and contribution should be allocated over multiple persons; the knowledge sharing cost needed from every person is reduced. Currently, all Web 2.0 knowledge formalization approaches have collaboration at their core. Semantic tags are inherently supporting collaborative annotations with various meta-contexts (tags for tags), such as votes for tags.

- ✓ **Incremental**: Not everything needs to be formalized at once, formalization can be done incrementally. Providing extensibility with customized knowledge components allows users to introduce new typed relations incrementally, as time is available for them to distil them from their needs. Semantic tags are not a dense or rigid knowledge component, and thus their representations and formalizations are simple enough to be user-defined by supporting tools.
- ✓ **Partial**: The formalizations should allow the system model to incorporate data instances that are only partly formalized; that contain data at different levels of formality. Instead of overloading the knowledge value of a tag and limiting its usage with a very focused annotation description and purpose, we utilize the versatility of formalizations for additional feedback from tag's mini-form. This loosely formalized feedback will complement the tag's main formalization and refine its value. Each tag's annotation purpose and thus formalization should only scale or change if the collected additional feedback dictates a pattern that requires it to.
- ✓ **Immediate**: Formalizations should represent knowledge that can be used immediately, directly bringing some benefits to the user and the overall knowledge model status. While ontologies offer the medium towards inference and reasoning, their benefits are not direct and sometimes require various intermediate phases of profiling and configuration. Semantic tags formalizations represent much less dense knowledge, but their descriptive value can be immediately exploited and shared.

Investing on the above properties and points we produced the formalizations that represent FMECA knowledge and Maintenance Micro-knowledge. The following sections describe these formalizations and analyze their purpose and value in the failure context.

3.4.1 FMECA Knowledge

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. Each event participating in the FMECA model can be described by a logical proposition (P4) that denotes whether it belongs to the set of admissible events for a specific asset. This proposition is structured by the basic components of the event's profile, namely the associated asset's title and the event's description.

FMECA propositions are required to be brief and informative well-formed propositions (wfp), to facilitate the modular management of knowledge. When not corresponding to failure mode event instances, propositions should be as simple as **atomic propositions**. When describing failure mode semantics, event propositions, may be extended and more structured, inheriting the event's description complexity. Propositions can be formed for all the relations of the core FMECA entities. Logical propositions that describe and map FMECA knowledge are provided in Table 3.1-A. In all cases, these propositions are required to be **well-formed propositions** *(wfp)*.

The FMECA model propositions, contain maintenance knowledge that has been previously captured, studied and embedded in the FMECA reference knowledge. Their content will only be revisited when the FMECA knowledge is under review. For some of them, validity derives directly 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 knowledge is discussed in the next section.

Table 3.1. Knowledge formalizations with propositions

<table>
<tr><td colspan="5">FMECA Core Entities</td></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 <u>P</u>ropositions</td></tr>
<tr><td colspan="2">P₁</td><td colspan="3">< As1 > is parent of < As2></td></tr>
<tr><td colspan="2">P₂</td><td colspan="3">< Fn > is function of < As ></td></tr>
<tr><td colspan="2">P₃</td><td colspan="3">< Ac > is applicable to < As ></td></tr>
<tr><td colspan="2">P₄</td><td colspan="3">< E > may occur on < As ></td></tr>
<tr><td colspan="2">P₅</td><td colspan="3">< E₁ > may be the cause of < E₂ ></td></tr>
<tr><td colspan="2">P₆</td><td colspan="3">< E₁ > may be the effect of < E₂ ></td></tr>
<tr><td colspan="2">P₇</td><td colspan="3">< Ac > is a suggested action for < E ></td></tr>
<tr><td>B.</td><td colspan="4"><u>M</u>icro Knowledge Propositions</td></tr>
<tr><td colspan="2">"<u>C</u>onfirm" tag</td><td>M_c (Ag , E)</td><td colspan="2">< Ag > Confirmed the occurrence of < E ></td></tr>
<tr><td colspan="2">"<u>I</u>ssue" tag</td><td>M_i (Ag , As)</td><td colspan="2">< Ag > detected unknown Issue on < As ></td></tr>
<tr><td colspan="2">"<u>S</u>chedule" tag</td><td>M_s(Ag , Ac)</td><td colspan="2">< Ag > Scheduled < Ac > for execution</td></tr>
<tr><td colspan="2">"<u>W</u>orking 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">"<u>O</u>bservation" 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 <u>F</u>eedback Proposition</td></tr>
<tr><td colspan="5">F (< textual note>, < numeric value >, < status lock >)
M is reported with note < textual note >, value < numeric value > and at < status lock > state
Micro-knowledge with additional feedback - M^f : $M \cap F$</td></tr>
<tr><td>D.</td><td colspan="4"><u>V</u>ote Proposition</td></tr>
<tr><td colspan="5">V(Ag , M) : < Ag > agrees with M
Micro-knowledge with n votes - $M^{(n)}$: $M \cap V(Ag_1, M) \dots \cap V(Ag_n, M)$</td></tr>
</table>

3.4.2 Maintenance Micro-Knowledge

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 maintenance staff. These propositions describe what has **just now** occurred, manifested, been scheduled or performed on the relevant assets (Table 3.1-B). They do not constitute part of the FMECA model, but instead are tightly coupled with the time context and are a part of the Failure Context. The optional use of tag mini-forms is a feature that contributes to maintenance micro-knowledge scaling. If no specific details are given by the template's description, the mini-form can be used to define (textual note), quantify (numeric value) and validate (state value) a newly well-formed proposition. This mini-form proposition is directly associated with the tag proposition and is modelled as a part of the tag instance (Table 3.1-C). An event proposition can be validated by different users at different times. The simplest way of doing so is through the use of votes whose goal is to refine and rank micro-knowledge. 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 (Table 3.1-D). Consecutive users with similar assessments may add votes to the shared tag instance. The analysis of differently timed annotations with identical semantics, can reveal other aspects and propositions of collaborative diagnostics. Using votes to add more value on the first validation of a micro-knowledge proposition, is a step forward to metadata refinement. However, different analysis expectations and knowledge capturing requirements can dictate different usage policies for tags and votes separately.

Micro-knowledge propositions are defined by tag templates that draw semantics from application-specific reporting and knowledge capturing needs, which in turn are decided by maintenance experts or engineers. The targeted value and the proposition of each tag is explained in the corresponding template's description. Every use of the custom tag validates its proposition and creates the appropriate tag instance. The model's support for user created tag templates translates in the ability to fully customize the micro-knowledge proposition and thus the focus of maintenance metadata. Any initial system set up simply delivers an initial set of tag templates. While this makes the system fully functional upon such a setup, it still leaves room for either a service provider or the actual user to expand or refine the initial set of tags, offering both flexibility and scalability.

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: (i) an early "Issue" tag for the related asset, (ii) an early "Confirm" tag for any of the potential effects; and ends at the exact timing of the failure mode's "Confirm" tag. If the earliest tag is a confirmation of an effect that is either a final result or a functional failure, then that's an indication that important information about the specific failure mode is either missing from FMECA or was not detected.

Studying the validation patterns of multiple sets can provide evidence for re-assessing the validity of the FMECA model propositions: (i) multiple validations of different M_i may reveal a new P_4, (ii) multiple validations of the same M_c validates the corresponding P_4, (iii) sequences of different M_c validations can validate one or more P_5 and P_6, (iv) 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.

3.4.3 Analysis of Maintenance Micro-Knowledge

We now turn our attention to how micro-knowledge can be analyzed to produce results. Expanding on how FMECA revision can be achieved through micro-knowledge analysis, we provide an arbitrary but indicative example. Let's consider all the events that are associated with a single specific failure mode:

- **E_m** : the failure mode event itself

- $\mathbf{E}_{ms(1..n)}$: the 1-to-n events, linked as symptoms (effects) of the specific failure mode
- $\mathbf{E}_{mf(1..n)}$: the 1-to-n events, linked as functional failures (effects) of the specific failure mode
- $\mathbf{E}_{mr(1..n)}$: the 1-to-n events, linked as final results (effects) of the specific failure mode
- $\mathbf{E}_{mc(1..n)}$: the 1-to-n events, linked as causes of the specific failure mode

Using the micro-knowledge propositions of Table 3.1 we can create a truth table that displays the validity of each M_c wfp, whenever $\mathbf{E}_m$ is confirmed. We record which linked events (effects and causes) are confirmed, whenever the occurrence of the failure mode is confirmed (Table 3.2).

Table 3.2. Truth table for the micro-knowledge propositions of a failure mode

# Occur	Micro-Knowledge propositions for failure mode and linked events								
	$M_c(U,\mathbf{E}_m)$	$M_c(U,\mathbf{E}_{ms1})$	$M_c(U,\mathbf{E}_{ms2})$	$M_c(U,\mathbf{E}_{ms3})$	$M_c(U,\mathbf{E}_{mf1})$	$M_c(U,\mathbf{E}_{mr1})$	$M_c(U,\mathbf{E}_{mr2})$	$M_c(U,\mathbf{E}_{mc1})$	$M_c(U,\mathbf{E}_{mc2})$
1	*true*	*true*	*false*	*true*	*true*	*true*	*true*	*true*	*true*
2	*true*	*true*	*true*	*true*	*true*	*true*	*false*	*false*	*true*
3	*true*	*true*	*false*	*true*	*true*	*true*	*false*	*true*	*true*
4	*true*	*true*	*false*	*true*	*true*	*false*	*false*	*false*	*true*
...	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**

A simple overview and study of such a truth table, can reveal informative patterns that are tightly connected with the quality and validity of our current FMECA knowledge:

- ✓ Effects, such as $\mathbf{E}_{ms2}$ that were never recorded in tandem with a specific fault mode instance, should be reviewed for removal from the failure mode's profile.
- ✓ Events such as $\mathbf{E}_{ms3}$ / $\mathbf{E}_{ms1}$ (symptoms) and $\mathbf{E}_{mf1}$ (a functional failure) that were recorded as sole indicators of a fault mode occurrence should be reviewed to be upgraded in terms of importance and even considered as final results.
- ✓ An observation that a specific occurrence of a failure mode was not indicated by any of the recorded final results should alarm that the current profile lacks significant knowledge.

Such insights are valuable for the FMECA review process. Tracking the validity of each proposition in the above table, can eventually lead to the identification of a satisfying model for the failure mode's proposition $M_c(U, \mathbf{E}_m)$. Though we have defined final results as the effects class that can decisively confirm the occurrence of a failure mode, such knowledge is not always available or is not always complete (i.e. 4th occurrence in Table 3.2). In fact, failure modes may manifest themselves in different ways, even for the same asset type, depending on many factors. Therefore propositions aligning failure modes with other entities would in truth be accompanied by a degree of belief/certainty/probability. While the above table can identify the lack of knowledge for the 4th occurrence, it also reveals a pattern where $M_c(U, \mathbf{E}_m)$ **satisfies a set of propositions**. This is equivalent to deciding the validity for the deduction of $M_c(U, \mathbf{E}_m)$ from the concurrent validity of certain propositions. For our example:

$$M_c(U, \mathbf{E}_{ms1}) \cap M_c(U, \mathbf{E}_{ms3}) \cap M_c(U, \mathbf{E}_{mf1}) \cap M_c(U, \mathbf{E}_{mc2}) \Rightarrow M_c(U, \mathbf{E}_m)$$

This brief analysis provides evidence that the metadata layer built by the proposed micro-knowledge model can be a powerful mechanism for capturing, sharing and exploiting maintenance expertise. A gradual accumulation of such evidence offers the means to validate, refine and expand the knowledge contained in an FMECA model. It is a simple method that achieves to create, support and enhance enterprise tacit and explicit knowledge flows.

3.5 Summary

This chapter presented the model that structures and instantiates our system's maintenance information and knowledge. Referencing the analysis of results, from the evaluation of an e-Training platform for maintenance professionals, we explain how the need for swift and concise evaluations of reference knowledge led our research to adopt and study semantic tagging. Then, the core and supporting entities of our FMECA model are documented, pinpointing their functional focus, descriptive goal and cross-linkage. Maintenance Micro-Knowledge is introduced and analyzed next. Maintenance metadata instantiation is discussed, modelling attributes are listed and the default set of maintenance tags is presented and their usage explained. Knowledge formalizations facilitate the process of creating representations for the maintenance knowledge that is embodied in both the FMECA model and maintenance metadata. Important entity relationships of the FMECA model and the semantic tags are mapped to propositions that provide a common understanding for their diagnostics value.

The Failure Context introduces a new knowledge composition that - design-wise - focuses on enabling the following inside the context of maintenance knowledge management, and the FMECA knowledge management in particular:

- ✓ Provide a maintenance context that is not adopting measured parameters of the environment context, but invests in building descriptive and linked knowledge on top of the maintenance service and social context (Figure 2.8).
- ✓ Model the knowledge of failure modes with event profiles that can be easily accessed and consumed by mobile maintenance experts. Link events based on cause and effect relationships, to gradually produce a maintenance map that can support maintenance practice and decision making tasks.
- ✓ Drive maintenance reporting with semantic annotations that reference and enrich FMECA components. Provide an extendable set of tags that can effectively couple with FMECA components to create modular evaluations with a maintenance value proposition.
- ✓ Instantiate the connection between reported evaluations and FMECA knowledge with metadata; a modelling construct that can benefit maintenance knowledge management with features of Linked Data and the Semantic Web.

The above modelling approach offers a set of advantages for e-Maintenance services and their internal functions:

- ➢ The proposed approach does not capitalise on extending maintenance models, but instead addresses the potential of linking and integrating them. Instead of introducing one more schema to comply with, it offers the means to connect, scale and organize failure event with what is already established for their modelling.
- ➢ The instantiation technology will not simply produce more data, neither will it require re-engineering of available models. Maintenance metadata are created to co-exist and enrich FMECA knowledge. Micro-knowledge does not bound knowledge to fixed semantics, but instead unlocks the prospects of creating new maintenance contexts with new and better focused modular annotations.
- ➢ Knowledge building is aimed towards bringing an effective and easy to understand validation loop. The FMECA revision process breaks down into a large number of modular corrections, verifications and change propositions. The impact and value of each such contribution and the knowledge pool of their sum, can be perfectly understood and measured by all roles across the chain of maintenance management and practice.

The design of the overall model was defined to comply with principles of modularity and agile coupling of semantics. It is a model that was structured not aiming towards the performance of executing analytics, but towards the interoperability of a metadata layer that profiles data for them. This work prioritizes the efficiency of linking maintenance events and describing their relevancy to maintenance practice. With its primary modelling construct being a pointer structure itself, knowledge enrichment has a definitive goal to produce more knowledge with less capturing process. Failure contexts are essentially highlighted subgraphs of an FMECA knowledge map, that allow experts to study them on-demand and evaluate or detect existing or new event links, accordingly.

4 System Design and Implementation

4 SYSTEM DESIGN AND IMPLEMENTATION

In this chapter key design and implementation aspects of the final system are discussed, and the decisions made are argued and explained. Initially, a brief description is offered for the system's role in a wider e-Maintenance platform, with a short analysis of this platform's architecture and collaborating components. The system's functional requirements are then discussed, along with the selected provision scheme. The next section provides a study that compares design patterns, appropriate for the development of a maintenance mobile application. Identifying strong points and drawbacks, the efficiency of each pattern is evaluated and linked with specific types of e-Maintenance services, explaining and supporting the decision made for this work. Following this, a detailed analysis of utilized frameworks and technologies is offered, addressing all the aspects of the selected design pattern. Finally, the integration of the final system with other components, of the wider maintenance platform is explained, listing the available exported services and describing their use in cross-component workflows and scenarios.

The FMECA table is the result of a formal and complex engineering study, conducted by engineers at specific time milestones between production cycles. As such, this reference entity, along with its supporting processes positions itself closer to reliability-centred maintenance management. Enterprise and mobile web have emerged to be very effective technologies for supporting such maintenance management tools and applications. The previous chapter described the development of a model that invests and expands on linked maintenance data. On the basis of this model a web-based application, namely IMA-FMECA (Intelligent Maintenance Advisor for FMECA) was designed to enable navigation and annotation of maintenance data and knowledge. The design is tailored for usage via simple touch interfaces, which are available to staff both as fixed-panel display points at the shop floor, as well as portable devices such as tablets.

4.1 WelCOM Platform Architecture

IMA-FMECA has been developed to serve a larger e-Maintenance platform (WelCOM), implementing part of its knowledge management functionality (Pistofidis et al., 2012). The WelCOM architecture is designed to integrate maintenance services that operate at different enterprise application layers, thus vertically integrating maintenance activities. IMA-FMECA serves the management and delivery of FMECA knowledge across platform components. Ranging from Condition Monitoring (CM) to work planning (CMMS), its middleware services offer transparent access to both the FMECA model and maintenance metadata. Its core activities are placed at the 3rd layer of ISA-95(ISA-95), with FMECA enrichment creating an interface between the 3rd and 4th layer (Figure 4.1).

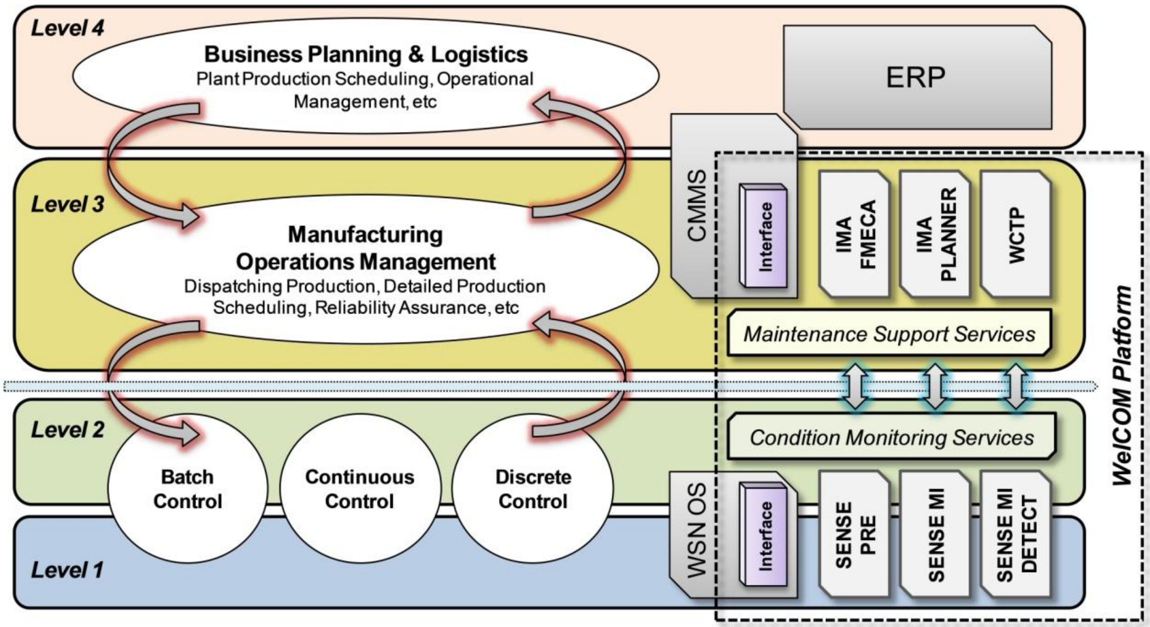

Figure 4.1. The WelCOM component architecture in reference to ISA-95

An important aspect of the WelCOM architecture definition is the specifications of components that stand as mediators for an industrial WSN infrastructure and a knowledge management system. There are two distinct places that interfaces need to be open, namely (a) the interface of all back-end IT level components and sub-systems that may interact with the distributed intelligence elements (DIE) in the periphery, and (b) the interfaces of the DIEs to support intra-DIE interactions. The WelCOM architecture follows a multi-tier design pattern and is organized in several functional blocks. System actors are comprised by maintenance personnel and external systems. The former set is classified, according to their role in maintenance processes, while the later set is populated by systems, such as a CMMS or machinery components that integrate their own operations with WelCOM's components. The platform interfaces with a CMMS to retrieve and enrich information about machinery history, maintenance orders and related data. Furthermore, sensor-monitored machinery assets provide the main and direct source for signal parameters, such as vibration, temperature and acoustic signals. WelCOM users interact with the system, using portal interfaces from desktop or other external systems, such as portable devices.

The WelCOM platform is composed of five (5) design blocks (Figure 4.2):

- The **WCDB** subsystem represents the overall system's data model. This unified model is served by dedicated components (physical databases) appropriately scaled to support each layer/subsystem of the platform's architecture (backend services repository, sensor embedded parameter history, portable device cached data). Its design principles and semantics are described in a maintenance-oriented (MIMOSA compliant) and application-focused schema. Furthermore, the WCDB subsystem includes proper integration mechanisms and interfaces capable of filtering and managing the system's internal and external data flows. IMA-FMECA's model is a part of this block and one tightly connected with FMECA diagnostics and knowledge management workflows.

❖ The **SENSE-MI** subsystem consists of all WSN processing, access and administration components, including the SENSE-NODES embedded logic (novelty detection) and the interfaces/drivers to a prototype optical sensor (WOS - Wireless Optical Sensor). The SENSE-MI block offers the WSNServ interface for the communication with WCIMA and a wireless network service (WSNet) for connection with the peripheral wireless intelligent nodes. This pool of information is the result of a selection process conducted by WCKM, on-demand to aid specific maintenance tasks.

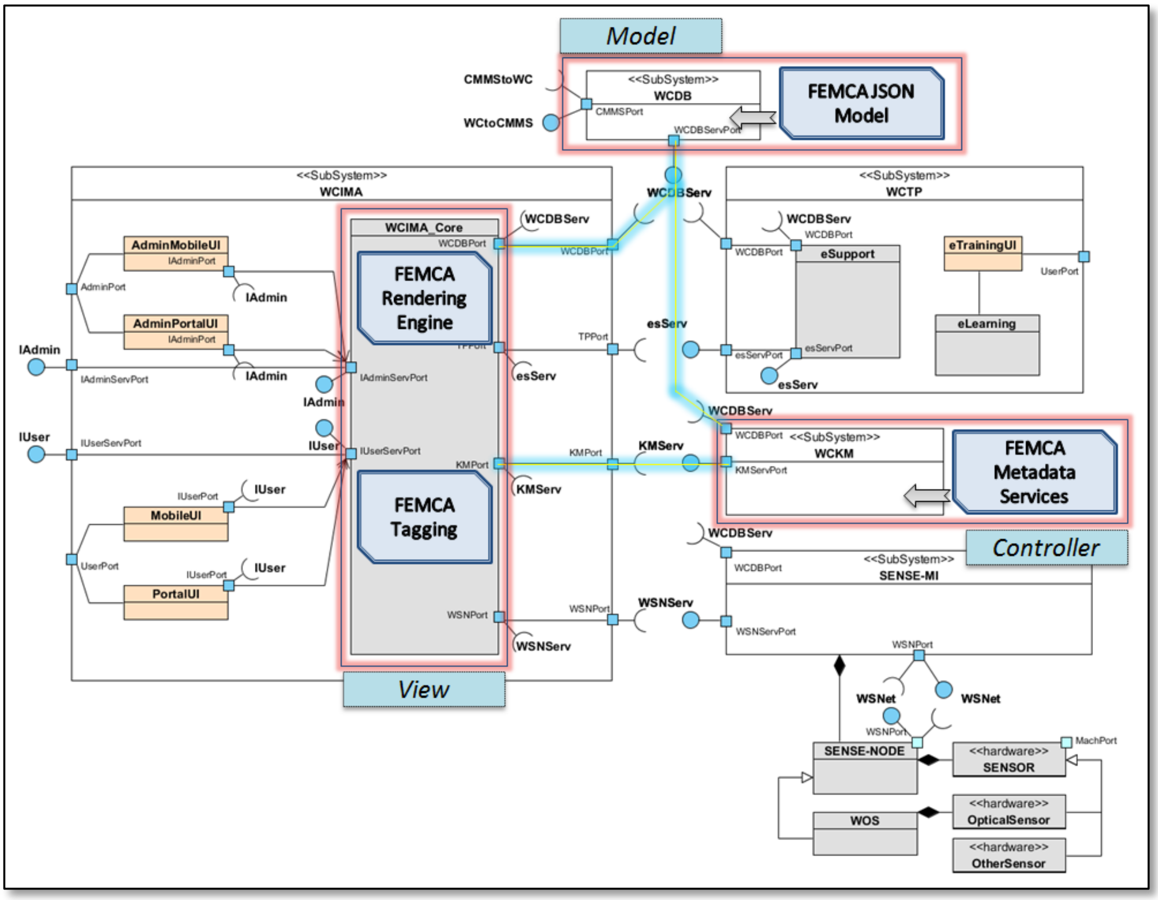

Figure 4.2. IMA-FMECA in WelCOM Architecture

❖ The **WCKM** block stands for a scalable Knowledge Management system. Its role is to drive the semantic enrichment of maintenance data in order to model the knowledge of condition states and then engage in (i) fault diagnostics and (ii) maintenance support. The WCKM block interfaces to the database and the WCIMA block. It collects all the information related to Fault Trees (FT) and Fault Modes, Effects and Criticality Analysis (FMECA) for the WelCOM set of use cases. This block incorporates all the back-end services of IMA-FMECA. These services are focused in managing and enriching the FMECA knowledge.

❖ **WCIMA** is the block responsible for supporting the user's access over all the platforms functionality. As an Intelligent Maintenance Advisor, it incorporates a set of smart interfaces to effectively assist any on-the-spot system action or workflow. WCIMA provides interfaces to all other subsystems and implements the administrative environment. It is also responsible for visualizing knowledge objects and enriched data in flexible views for portable devices. IMA-FMECA's enterprise client is part of the overall WCIMA user experience and one that prioritizes mobility and remote access.

❖ Finally, the **WCTP** subsystem aims to bring an e-Training environment that aids the personnel's fast system familiarization. WCTP also incorporates an e-Support tool capable of backing maintenance staff with technical documentation through portable devices. The WCTP block shares an interface with the WelCOM database for accessing data related to e-support services. Through a second interface (KMServ) WCTP employs WCKM's services to provide a user-adaptive training environment and context-based material for e-support. The e-Training system offers educational material for WelCOM-specific and Condition Monitoring training.

4.2 Functional Requirements and Features

The main workflow of IMA-FMECA's functionality follows two parallel interaction patterns. In the first, the user seeks to find FMECA knowledge that addresses a maintenance issue or task. Following links in FMECA profiles and browsing structured listings of FMECA components, the user navigates between events and assets to reach relevant knowledge. Upon identifying relevant events, the user processes the provided Failure Context and evaluates recommended solutions. Drawing conclusions and processing the available knowledge context, the user moves on to implement the decided maintenance action. The second interaction pattern, serves a different functional goal that recursively leverages the overall tool's value in terms of maintenance knowledge. The goal is to record user findings and evaluations, with minimal overhead on user's mobility and the primary activity of practicing maintenance. Providing on-the-job interaction, this process targets the best circumstances for capturing human expertise and observations at the time and place when it is most contextually relevant. Shop floor experience assists the user to reach content relevancy and at the same time extend relevant content. The user reports back with a few touch-actions. Each tagging action instantiates a simple cross-examination of FMECA knowledge against maintenance practice and real findings. Collecting, sharing and fusing these tags delivers the functionality for the continuous improvement of the FMECA knowledge.

4.2.1 A Multi-User Environment for Accessing FMECA Knowledge

IMA-FMECA constitutes an enterprise application that follows patterns of SOA architectures and invests in providing flexible interfaces and scalable services with backend coordination and frontend contextualization. The client environment is upgraded, both in terms of content visualization and navigation, to accommodate the needs of a mobile shop-floor user. The uniform and instant access pattern of mobile web applications was favoured over the slightly more responsive interaction of native applications, given the sharing focus of the provided service and the structured nature of the knowledge content. Evaluating and referencing FMECA knowledge is a process that can involve staff at multiple levels and roles. It enables contributions by both shop floor staff (technical - providing on-the-job problem solving and observations), as well as engineers and technical managers (engineering and management - obtain an overview of existing and emerging maintenance-related knowledge), who validate, refine and enhance maintenance knowledge or provide feedback to earlier lifecycle phase processes. Sharing tags via a common information pool, creates a bridge of knowledge between field expertise and planning. The targeted functional features are:

- **Access Flexibility to Maintenance Knowledge** - Structured knowledge related to reliability-centred maintenance is made easily accessible at the shop floor by mobile staff. Different users can access the same knowledge from a different point and for a different purpose. While a maintenance technician can make an observation or detect and confirm a symptom at the shop-floor, the final confirmation of a Failure Mode may come from an engineer or technical expert. e-Maintenance mobility is a concept often served by portable devices, and one that can instantly scale sharing efficiency and user participation in multi-user collaborative environments. Additionally, instead of requiring from personnel to carry them, tablets may equally and in some cases more effectively provide support as fixed touch panels. Following the mobile web design pattern allows both industry-provided and personal devices to be used at whatever time and environment context.

- **Personalization and Knowledge Filtering -** IMA-FMECA's functionality handles a balanced FMECA knowledge pool, aligning provided information to user roles. Employing the versatility of the MVC (Model View Controller) pattern, IMA-FMECA uses a controller mechanism that associates maintenance roles with filtered views of the knowledge model. Through this structure, IMA-FMECA is customized to instantiate different interfaces, adapting their content and options according to different roles in the system.
- **Extensible and Configurable Semantics -** FMECA knowledge progressively becomes more and more attuned to the specific practice, industry and maintenance plan or policies. This essentially dictates that specific user roles have the power to edit and configure components of the FMECA knowledge. Managers and engineers are able to functionally extend the semantics that are used for the classification of FMECA knowledge (levels, types and scales). Furthermore, they are able to create, customize and modify the tag templates used by technicians and themselves to annotate and enrich FMECA.
- **User Interaction (UI) Patterns and Linked knowledge -** Balance navigation paths and content provision. Providing efficient mechanisms for quick and on the job-interaction, offers the means that better and more accurately link field experience to referenced knowledge. Interfaces invest on rich and informative profile for assets, events and actions. The client application employs advanced UI components to enable short and fluid navigation paths between connected knowledge. Dynamically scaled directories help user to browse, sort, search, edit and annotate all core FMECA entities. Each single FMECA instance, whether it is an event, or scale, or type, has its own profile that is linked through classified visual elements with all the components that participate in its information context.

Having invested in connecting FMECA as best as possible, we also focused on creating an enrichment process to gradually upgrade the linked profiles with provenance maintenance metadata. The corresponding methodology is discussed next.

4.2.2 A Collaborative Tool for Capturing and Sharing Maintenance Knowledge

Social networks are becoming a powerful platform and a paradigm for the majority of personal and professional collaborative environment. Users, wherever they are, require and extensively use services that support them in sharing concise evaluations of their participating contexts. While such services rapidly evolve and their knowledge value gets validated every day, e-Maintenance systems continue to use exhaustive reports with limited or no integration with linked and contextualized knowledge. Some PLM Tools (TeamCenter[3] for example) have managed to align content views to the user context. However, capturing, managing and fusing user-generated knowledge with established knowledge is weakly supported by existing solutions. The collaborative functionality supported by IMA-FMECA is targeting the following:

- **Easy maintenance reports for knowledge synthesis:** IMA-FMECA proposes and implements a new reference-tag interaction pattern for e-Maintenance systems. The main functional difference of this approach from conventional interaction patterns is that the user is asked to review and annotate a current version of maintenance knowledge, rather than produce it. IMA-FMECA encourages maintenance personnel to save time from reporting symptoms and invest time in processing a timeline of tagged events that describe their

[3] SIEMENS TeamCenter - http://www.plm.automation.siemens.com/en_us/products/teamcenter/

occurrence. In this way the tool supports staff to produce more linked knowledge and spend less time in being disconnected to fill practice forms.

- **Balanced knowledge capturing and staff motivation:** The contextualization of user experience enables maintenance personnel to interact with annotation options that adapt and progressively focus on specific roles and tasks. Balancing contribution between required and optional, leaves sufficient user interaction freedom. Increasing the modularity of a report's content and enhancing its alignment with maintenance contexts, can significantly impact the motivation of the mobile staff that uses them. Such functional features not only challenge users to provide qualitative feedback but also help them value their contribution, thus providing additional motivation for participation. IMA-FMECA adopts the above features and brings a simple reporting methodology based on tag mini forms. The client's functionality is directly aimed at using forms as a secondary medium for capturing knowledge, after the primary use of tags. We treat each maintenance tag as a declarative user action towards a very specific maintenance goal. The completion of the tag's mini-form is optional and allows the user to fill-in a numeric value, a comment and/or a state lock. Two tagging interaction scenarios are offered: (i) the direct tagging and (ii) the mini form tagging. Maintenance managers are offered the functionality to create and edit the tag templates. These templates, define the mini forms content and its interpretation. The use of these forms can fuel a versioning loop that serves the application focus of the available maintenance tags. More importantly, both tag-usage and mini-form feedback offer a valuable knowledge pool for the revision process of the FMECA content itself.
- **Knowledge synthesis through sharing, searching and cross-evaluation:** Whatever context they operate in, mobile actors always favour the timely creation, sharing and consumption of brief and insightful evaluations. In general, users of virtual environments tend to be a lot more motivated when they are not the ones to initiate a feedback discussion or a workflow of constructive comments. In collaborative systems, users are more willing to contribute by commenting upon an opinion/evaluation, rather than initiating or explicitly stating it. User's cross-evaluations formulate a self-evolving social context. IMA-FMECA enables staff to share, search and cross-evaluate existing knowledge, centred around FMECA. Maintenance managers and engineers have made the first step by sharing FMECA, and shop-floor personnel are asked to validate and review it. IMA-FMECA employs votes as a simple and practical method to allow users leverage the value of feedback provided by colleagues. Votes is a very common method that motivates the fusion of user interactions. Votes can be even more popular, if the input is shared amongst team/department members and its value is acknowledged from trusted co-workers. Evaluating how this social context enriches a tagged Failure Mode profile with positive votes, can significantly help its mining for FMECA updates.

4.3 A Mobile Service Provision Scheme

IMA-FMECA is promoting the utilization of solid and non-fragile portable units, capable of operating in harsh industrial environments and by maintenance practicing hands. Introducing state-of-the-art features, such robust tablets can operate as versatile clients and even hosts. Modern units offer impressive durability (aluminium casing, ionized hardened screens and compliance with water and dust resistance specifications) while managing to constantly reduce weight and size. At the same time a large number of application frameworks and operating systems offer the appropriate development tools and infrastructure to create versatile mobile software.

Software engineering practice has introduced new approaches in mobile development and in general portable computing. The primary motivation for building a mobile-supported system is the benefits of experiencing a seamless constant adaptation of the system view. This view can optimally present options that adapt to a traced history, transparently acquired and fused. Supporting such mechanisms, the mobile provision scheme is emerging as a dominant one in many application areas and problem spaces. The majority of web services and multi-user environments receive a significantly influx of users when mobility is supported, and an appropriate client application becomes available. Aligned with these benefits and mainly focusing on availability and scaling, IMA-FMECA targets the following functional features for its current and future mobility:

- ✓ **Portability of users and components** – Each portable device operates as an active mobile system agent that can be easily carried in different shop-floor environments. State-of-the-art hardware configurations and sophisticated operating systems (OS) allow these devices to support the provision of innovative services and applications, while maintaining portability and ease of use. Cross system migration of user sessions and portable data formats allow for a transparent and unified system experience for mobile personnel. Late implementations provide autonomous operation that surpasses the 10 -12 hour limit of event the most heavy-load working shift. The smart energy profile, the robust build and the slim form factor of modern devices gradually transforms them from an intuitive Swiss-knife system to a potent mobile workstation.
- ✓ **Accessibility and reachability** – Mobile networking has been a vital perquisite for high priority tasks that deal with on-site critical events. There are several wireless communication paths that can provide the link between mobile devices and cloud services. The majority of industrial environments that constitute early adopters of modern ICT, currently support wireless connectivity with extended Wi-Fi networks and low powered equivalents for critical and sensitive areas. e-Maintenance knowledge can arrive at the hand of each individual engineer or technician through cellular, Wi-Fi or BT connections. The respective communication routes may include common network devices (access points, routers etc.) or even smart intelligent (on-line or cloud enabled) industrial machinery (Figure 4.3). Such infrastructure enables modern smartphones and tablets to deliver a constantly available and instantly accessible gateway to any form of digital content and remote service.

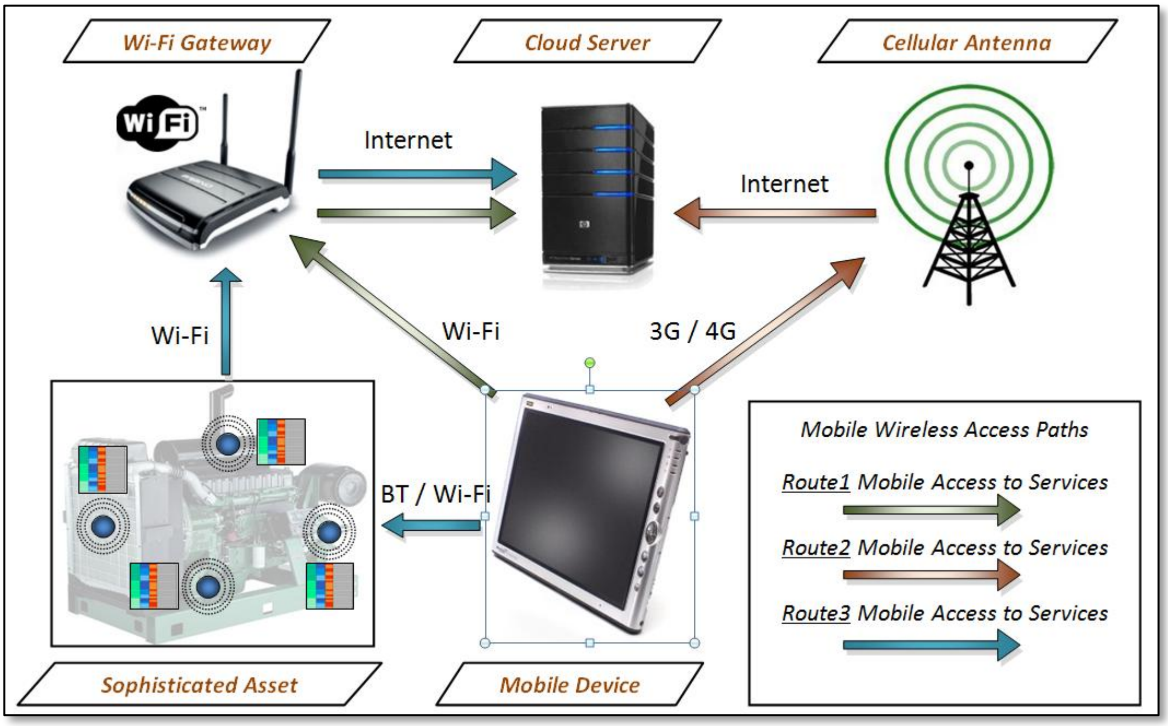

Figure 4.3. Mobile access path to remote services

- ✓ **Advanced tools and UI interfaces –** Last but not least, we consider the presentation potentials offered by the advanced UI features of modern portable devices. The latest smartphones and tablet PCs provide touch-screens, whose size and multi-touch technology can allow them to operate as a highly-efficient reporting tool and tuning dashboards. Modern mobile devices currently host a wide range of client applications and visualize even the most complex web access portals to probe, seek, register and couple with any type of service component, on-demand or in a real-time manner(streams). Mobile applications and mobile web both capitalize in functionality that provides access to multi-user collaborative platforms and media rich shared spaces, rendering them into personalized dashboards. Such implementations of client-server solutions, support the latest integration technologies and allow on-demand participation to larger solution architectures (Figure 4.4).

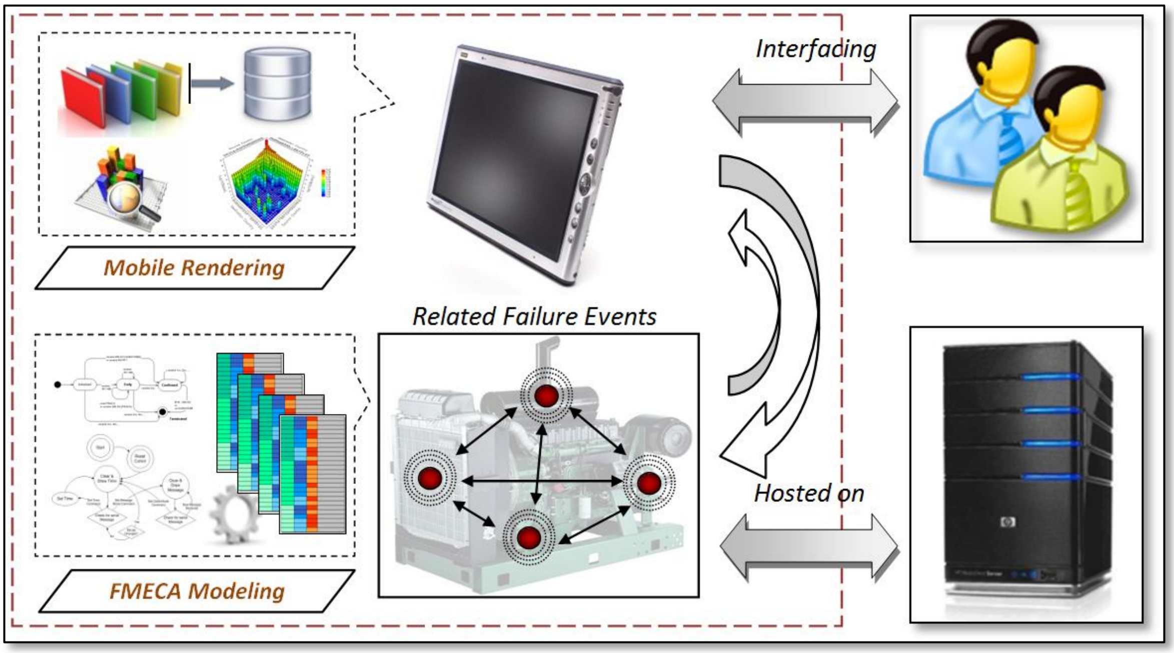

Figure 4.4. Mobile access to FMECA knowledge

4.4 Client - Server Design Pattern

Engineering asset management involves multi-disciplinary teams and decision making processes, with application-focused and field-derived specifications. The corresponding data models and maintenance services require a standardized decentralization of layered and interconnected components. This is a demanding task that web/grid services and rich internet applications have recently efficiently took upon and adequately served. Furthermore, it is a task that portable applications and cloud services come to serve, even more efficiently, due to the native advantage of a context changing user and hosting environment. The question at hand is which design pattern and technology blend can effectively and innovatively address the shop-floor functionality of maintenance and engineering asset management.

To ensure a qualitative result when designing a client-server tool, it is important to determine the depth and range of the parameters that characterize its performance. Exploring these parameters and weighting their importance may reveal new perspectives and more clearly define the specifications of implementation. In the case of IMA-FMECA this process allows our design phase to narrow down the parameters that can leverage reliability in creating and managing rich informative user sessions, while excluding features that can mislead and re-arrange the priority of decisions during the developing phase. To achieve that, we survey and analyze design patterns that couple mobile clients with remote servers for delivering e-Maintenance services. The strengths and weaknesses of each approach is mapped into a vector of adequacy values for system specifications termed as impactful for respective e-Maintenance service. To support our software engineering study we identify the engineering asset management service categories that can benefit from such services and we select a refined set that participates in our implementation. Exploring the specifications for each category of services, we compute and cross-examine the functional requirements vector with the analysis of design patterns. The results drive our conclusions on the decided architecture and implementation options.

4.4.1 Client – Server Design Approach

Focusing on mobile maintenance, portable applications must embody mechanisms that handle requests during failure events and maintenance practice. These requests profile, calibrate and dynamically invoke maintenance reporting, visualization and data modelling services. A set of metrics and specifications have been selected to identify the suitability of well-established design patterns to achieve high availability and enhanced performance for front-end and back-end components. Following domain-generic requirements can lead to acceptable functionality for a wider range of applications; but innovative tools are usually the result of insightful study for field-oriented aspects and details.

The need to balance implementation complexity between portable and server components is crucial and can determine a system prospects very early in its design phase. Table 4.1 provides an analysis of state-of-the-art features that characterise the development of mobile clients and server side components, for modern client-server solutions. Each methodology is evaluated according to a set of widely valued features used as performance metrics.

Table 4.1. Strengths and weak points of client and server design patterns

Front-end Component Metrics	*Native Application*	*Hybrid Application*	*Mobile Web Application*	*Cloud based Services*	*Dedicated Server Services*	*Only Database*	*Back-end Component Metrics*
Application Speed	H	M	M	H	M	M	*Scalability*
Rich Views and Interfaces	H	M	H	H	L	L	*Fault Tolerance/Robustness*
Device Control and Access	H	M	L	H	M	L	*Integration Potentials*
Local History Caching	H	H	L	M	M	L	*Administration Overhead*
Security	H	M	M	H	H	M	*Security*
Cross Platform Operation	-	M	H	L	H	M	*Cost of Infrastructure*
Development Cost	H	M	L	M	H	L	*Development Cost*
Approval Overhead	H	M	-	M	H	L	*Deployment Overhead*

Maintenance Service Categories

Engineering asset management is a multidisciplinary domain, technically supported by IT systems that deliver diverse functionality and focus differently on prioritized tasks. Our study focuses on two service domains and their corresponding tasks. While IMA-FMECA's services exclusively belong in the first domain, studying the second domain was necessary to effectively drive our system's integration inside a larger platform architecture, with other interfacing components. The two domains are as follows:

*A. Maintenance Management Systems (**targeted category for IMA-FMECA**):*

- ✓ (**MM1**) Track, report and handle failure events
- ✓ (**MM2**) Manage resources, assign tasks, and plan maintenance
- ✓ (**MM3**) Reference, share and collectively manage knowledge of diagnostics

B. Condition Monitoring Systems:

- ✓ (**CM1**) Report, visualize and trend condition state parameters
- ✓ (**CM2**) Invoke and visualize findings from novelty detection
- ✓ (**CM3**) Configure and manage monitoring infrastructure

4.4.2 Mapping Maintenance Services to Desired Features

Balancing the traits of a mobile architecture is a challenging issue but an important one, since design decisions allow a small window of options for late modifications in the development strategy. Porting mobile implementation from one platform to another has been an exhaustive task for developers, especially when updates and versioning come in play. Extensive refactoring of middleware components is almost necessary, when dealing with multi-tier applications and services that request direct access to device hardware. In Table 4.2 we analyze the importance of certain features with respect to the functional requirements of each domain and specific maintenance task.

Table 4.2. Analysis of each metric's value for front-end and back-end

<table>
<tr><th>Engineering Asset Management Service</th><th>Application Speed</th><th>Rich Views and Interfaces</th><th>Device Control and Access</th><th>Local History Caching</th><th>Security</th><th>Cross Platform Operation</th><th>Development Cost</th><th>Approval Overhead</th><th>Engineering Asset Management Service</th><th>Scalability</th><th>Fault Tolerance/Robustness</th><th>Integration Potentials</th><th>Administration Overhead</th><th>Security</th><th>Cost of Infrastructure</th><th>Development Time/Cost</th><th>Deployment Overhead</th></tr>
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<tr><td>MM2</td><td>M</td><td>M</td><td>L</td><td>M</td><td>H</td><td>H</td><td>MM2</td><td>M</td><td>H</td><td>M</td><td>H</td></tr>
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<tr><td>Mobile Web Application</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>H</td><td>L</td><td>L</td><td>Cloud based Services</td><td>M</td><td>H</td><td>H</td><td>M</td><td>H</td><td>L</td><td>M</td><td>M</td></tr>
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<tr><td>Native Application</td><td>H</td><td>M</td><td>H</td><td>H</td><td>M</td><td>L</td><td>M</td><td>L</td><td>Cloud Database</td><td>M</td><td>H</td><td>M</td><td>M</td><td>M</td><td>L</td><td>M</td><td>L</td></tr>
</table>

- **Maintenance Management Environment –** The functional specifications of such mobile components indicate that maintenance knowledge management can be better served by a mobile web application. The use of modern HTML, CSS and JavaScript technologies can produce rich application environments that efficiently display structured semantics. Such environments, while providing instant access to a wide range of users and devices, also allow for extensive features for social interactions. Furthermore, web clients and enterprise applications offer fast development cycles, platform independence and controlled complexity. The agile development methodology and the non-existent approval overhead (through a market/app-store) of this design approach allows for frequent updates and thus supports refinement phases, continuous adaptations and consistent performance with evolving services.

  The server side components can effectively deliver knowledge management with cloud services. Shared access to maintenance planning and specific knowledge reference material introduce data mashups that can ensure interoperability and integration performance. A dedicated server may also serve as the secure hosting environment for such services. Nevertheless, even though a dedicated service can provide a more isolated hosting environment, federated cloud services excel in handling the sharing and scaling of a maintenance plan, policies and diagnostic structures. The replication, migration and load balancing mechanisms of cloud services can offer increased availability for critical knowledge, along with the supporting services.
- **Condition Monitoring Console –** Moving to more site-oriented mobile components, a condition monitoring console demands higher responsiveness and simple interfaces. Operating this client in a shop-floor environment and under the pressure of on-spot practice, indicates the significance of highly adaptive and responsive tools. Native applications allow better communication/polling of hardware modules, while also engaging the instant exploitation of every sensor available on the device (voice, light, vibration). Choosing a mobile framework and an operating system is a decision that ensures a certain performance level, but also one that limits access to a very specific class of devices and software features.

  On the server side, a condition monitoring console handles larger volumes of flat data with respect to a demanding set of condition parameters being recorded. Even a small scale history can benefit from federated storage and thus from a cloud approach. Management in terms of a sensor cloud can be delivered by both a cloud database or a set of cloud based services. While the second can offer much more mechanisms for cloud analytics, the first balances complexity and does not overload backend with unnecessary costs for infrastructure and deployment administration.

IMA-FMECA is an e-Maintenance tool that places its functionality in the category of maintenance management services and tasks. FMECA knowledge can leverage its value by coupling its model with condition monitoring parameters, but at its core it represents processed information with higher level semantics and prospects of meta interpretations. IMA-FMECA requires rich visualization capabilities, multiples access points and the means for collective enrichment. To address these requirements our design involved the creation of an enterprise application that provides mobile/web access to cloud services.

4.5 Implementation Technologies and Frameworks

This section discusses implementation decisions for the technologies and frameworks that supported the development of IMA-FMECA. Their selection is linked with certain benefits that impact the performance of the delivered e-Maintenance services. The MVC (Model-View-Controller) design pattern is adopted within IMA-FMECA's implementation (Figure 4.5).

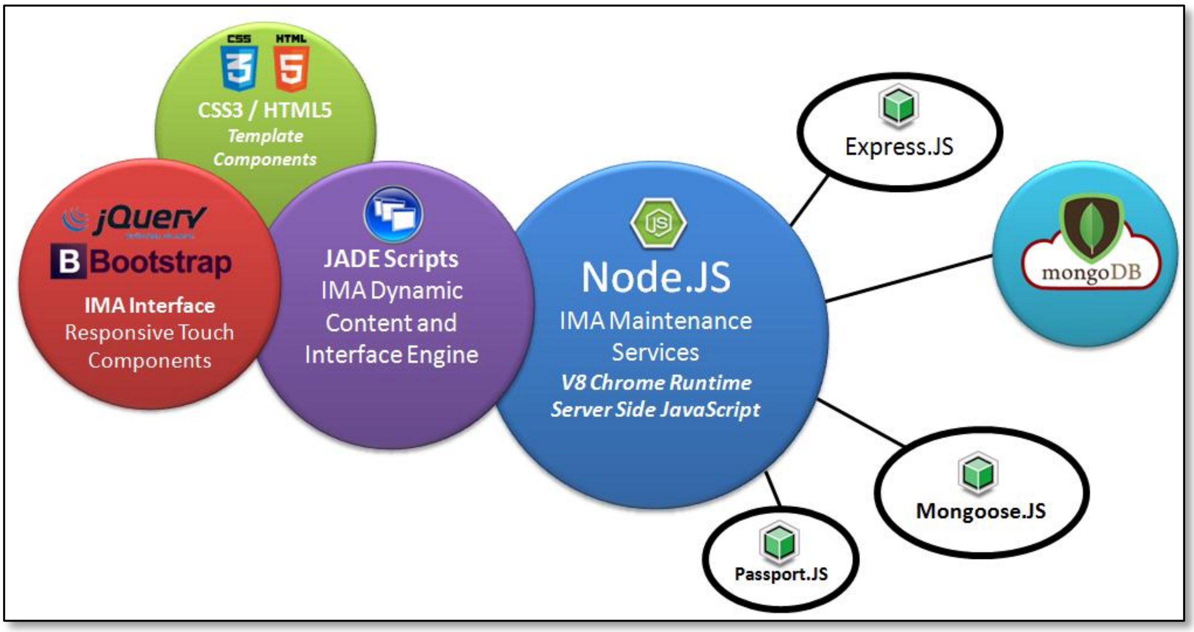


Figure 4.5. IMA-FMECA Implementation Technologies

4.5.1 Data Physical Instance – The Model

Relational databases constitute the most common model instantiation technology, used by the majority of e-maintenance systems. This is mainly attributed to the maturity of the technology, the availability of supporting frameworks and the lack of alternative options, up until recently. XML is adopted for document-based data exchanges in most if not all SOA-based maintenance support systems. Though native XML databases exist, their data handling could by no means match the solidity and efficiency of relational database management systems. MIMOSA`s is a representative example of how modelling technologies have been adopted and used in e-Maintenance. MIMOSA provides an extensive XML schema to accurately map the design of a relational database. The data model of most modern e-Maintenance systems is powered by: (i) relational databases for consistent backend persistency and (ii) XML for versatile frontend handling and presentation. It is a design paradigm that gains from each technology's strong points, but lacks somewhat in integration efficiency.

The emergence of the JSON standardized data interchange format has upgraded the mobility and descriptive nature of structured information. JSON syntax is even more lightweight than XML and can be optimally parsed and processed by any programming language. Its flexibility and rapid adoption has made JSON a reference data exchange format. Initially serving at the front-end of enterprise applications, JSON gradually succeeds XML and has evident potential in e-Maintenance systems. Its support and scalability have reached a maturity level that can empower the effective instantiation and handling of maintenance information that may range from mashups, up to big data. Amongst the most acclaimed advantages of using JSON over XML are the following:

- One of the most easily spotted of these is the considerably less verbose format of JSON over XML. As a direct result of its conciseness, JSON files containing the exact same information as their XML counterparts are always smaller in size, which translates to faster transmission and more efficient parsing for processing. Given the fact that failure mode profiles can scale to be quite structured, readability and efficient exchange are important factors for IMA-FMECA.
- When handled by services and managed by tools, JSON outperforms XML in a number of ways. Benchmarks and studies dictate that JSON can be serialized and desterilized drastically faster, while its processing also exhibits noticeably less resource utilization in CPU. This fact makes JSON a more versatile

format and more suitable for mobile clients and mediating interfaces. While most modern mobile devices currently used in e-Maintenance feature a computation power that can often handle this, the performance of their browsers for rich enterprise applications such as IMA-FMECA can benefit from the performance advantages of JSON objects.

- Another important advantage of JSON is its representation of objects and arrays. It allows for direct mapping onto the corresponding data structures in the host language, such as objects, records, structs, dictionaries, hash tables, keyed lists, and associative arrays for objects, and arrays, vectors, lists, and sequences for arrays. Accurate definition of class semantics is of capital importance for descriptive metadata and knowledge modelling in general.
- JSON supports a more collision free and arguably less troublesome namespacing. In JSON every object has its own namespace following the autonomy that is also used when programming and defining members of different objects. Namespace collisions can prove quite limiting when attempting the integration of FMECA semantics between different industries, standards or even simple asset categories.
- Maybe the most popular advantage of JSON for modern web systems and thus for our application design also, is that JSON is a subset of JavaScript, therefore producing code to parse and package it fits and integrates naturally with JavaScript code. IMA-FMECA uses JSON and JavaScript across all its model design and system components.

Data persistency in IMA-FMECA is powered by MongoDB, a JSON native NoSQL database. NoSQL databases, such as MongoDB[4], are currently adopted by demanding enterprise applications[5] (Wei et al., 2013, Gorton and Klein, 2014), achieving competitive performance while consistently and reliably managing big data. The main advantages of NoSQL include:

- **Made for Big Data -** By design, NoSQL is capable of storing, processing, and managing huge amounts of data and metadata. This not only includes the structured data collected from web reporting forms, but also from text messages, semantic tag-clouds, formatted documents, videos and other forms of unstructured data as well. While RDBMS applications are growing in terms of their ability to handle such capacity, they are largely outclassed and outmatched by NoSQL. Since in IMA-FMECA modularizes feedback into micro-knowledge, its volume will drastically increase, as more tags are applied, FMECA knowledge is expanded and new templates are created. Aiming for managing such pool of information, justifies the use of NoSQL technologies.
- **Seamless Scalability -** NoSQL databases are transparently scalable offering advanced features such as auto sharding, agile sprints, quick iteration, frequent code pushes, automatic replication, integrated caching capability and many more. They follow a scale-out architecture instead of expensive, monolithic architectures. Traditionally, many organizations addressed the need for scaling up by purchasing, commissioning and deploying more assets of infrastructure, both in terms of hardware and software. NoSQL databases are designed with scalability in mind, offering a convenient way for companies to transition to new nodes both on-premise and in the cloud as well, all while maintaining the high level of performance and availability that mission-critical applications require. Scalability is a vital feature for IMA-FMECA not only in terms of data volume, but also for achieving uninterrupted availability for is knowledge sharing environment.

[4] MongoDB - http://www.mongodb.com/

[5] MongoDB Application Cases - http://www.mongodb.com/who-uses-mongodb

Being a document-oriented database, MongoDB can adapt to topology changes (new server or server failure), with dynamic scaling. It can re-balance sharding with automatic configuration and fast deployment.

- **Models are Schemaless -** Schema-less design allows development to freely add fields to JSON documents without having to refactor these changes to existing data. The data's format can be modified at any time, without application disruption. This feature saves development from very long delays imposed by extensive re-engineering, when even a simple model modification can flag multiple problems in most relational databases. The flexibility to revise test and refine the FMECA knowledge model while also following (with no delays) a platform level development plan, had a decisive impact on the quality and performance of IMA-FMEA.

Facilitating the above modelling technologies, IMA-FMECA can effectively handle JSON data that map the whole profile of a Failure Mode. Instead of constantly breaking and joining the components of such a structured profile (records from multiple tables of a relational database), it manages its persistency as a unity. IMA-FMECA can store and retrieve the linked profiles of any FMECA component, and then consume it by its frontend rendering engine. JSON mashups are flexible modules that drive the models of many knowledge management systems. IMA-FMECA invests in creating, handling and consuming FMECA mashups. These are enriched units of structured maintenance data integrated from various structured profiles of diagnostics and destined to be uniformly consumed in a multipurpose manner. This goal and the corresponding modelling technologies allow IMA-FMECA to claim the integration efficiency and the transaction performance of a maintenance system that uses the same powerful modelling technology across all the tiers of its architecture (Model, View, Controller).

4.5.2 Server Side Components – The Controller

These components coordinate the invocation and management of maintenance services. They handle user requests and create appropriate workflows that deliver content and functionality. Controller services are also responsible for data consistency and information security. The flexible Node.js[6] framework was adopted as the platform for the implementation of IMA-FMECA's web services. This decision was based on the following features and advantages:

- **Performance and speed -** Node.js hosts a runtime environment that can execute JavaScript at the back-end of an enterprise application. At the core of Node.js, the V8 Chrome engine assures code performance and efficient scaling. V8 compiles and executes JavaScript at impressive speeds mainly due to the fact that V8 compiles JavaScript into native machine code. Node.js is maturing quickly and is being deployed in more and more mission-critical and revenue-critical systems, such as e-Business and e-Science infrastructures. It's easy to achieve great performance with Node.js, and yet Node.js is deep enough to handle most modern web complexities. IMA-FMECA invested in Node.js to deliver efficiency and fast response for its services execution and its request handling.
- **JavaScript integration efficiency -** This is aligned with the design choice to benefit in performance and integration stability, from the synergy and the uniform facilitation of JSON and JavaScript across all the layers of enterprise components. Using the same language on the backend and frontend breaks down the boundaries between front-end and back-end development. By reusing models, and templates, we managed to reduce the size of IMA-FMECA which reduced complexity and the chance for errors. Matching JSON and traditional front-end JavaScript with Node.js allowed IMA-FMECA to deliver a reliable tool and a fluid experience within the social graph layer of the maintenance shop-floor.

[6] Node.js - http://nodejs.org/

- **Event driven and non-blocking -** Concurrency is a difficult task in many server-side programming languages, and its non-optimal implementation can easily result in poor performance. Node.js is based on an event-driven architecture that achieves non-blocking I/O. It is a feature that can be instantly reflected in application throughput and scalability. Node.js uses an event loop, instead of processes or threads, to scale. In other words, reading and writing to network connections, reading/writing to the file-system, and reading/writing to the database – all very common tasks in web apps – execute very fast in Node. The event based nature of its middleware is a very good fit for real-time applications and data streaming services. Node allowed us to build IMA-FMECA as a scalable network application capable of handling a large number of simultaneous connections with high throughput.
- **Services easy to modify and maintain -** Service development using Node.js is easy because of conventions that have grown and become established practices along with Node's rapid adoption. Creating applications with Node often means that functions are composed from small modules, which are piped together. With Node.js a group of small services is developed instead of one large application, and this enables a change to be made or new functionality to be added without requiring changes to be made deep inside the entire code-base. Over-time the traditional monolithic e-Maintenance applications become rigid and difficult to adapt as new requirements are added, specifications change and workflows of chained user events expand or reduce according to emerging needs. Eventually many such applications begin to creak and underperform under the weight and the stress put on them by the requirements they were not designed for. The orchestration of micro-services was a perfect match for the semantic enrichment and knowledge management services of IMA-FMECA.
- **A rich pool of extension modules -** Fully compliant with the MVC pattern, Node.js was further coupled with the features of widely established libraries and packaged extensions. The Express.js module was used for the design and development of all the basic and advanced services of the IMA-FMECA web infrastructure. Mongoose.js was used to drive the transaction with MongoDB, while Password.js provided the functions for secure access and proper user authentication. Node.js when coupled with Expresss.js, it can virtualize both web application and web server instances. As means of load balancing, it can dynamically instantiate both the web application (software services) and the application server (software infrastructure). This means that IMA-FMECA is able to scale the availability of its services according to user-load and the number of requests. This is one of the many cloud-oriented features that become available when using a solid configuration of well-established Node.js modules.

4.5.3 Frontend UI Interfaces – The View

The technologies and frameworks, employed in the development of IMA-FMECA's frontend, were selected to address two specific goals:

- **A fluid design for user interfaces -** Aiming for the user experience of mobile maintenance staff, IMA-FMECA utilizes technologies that excel in producing mobile optimized web views, namely HTML(5), CSS(3.3) and JavaScript. Focusing on interaction fluidity and usability, IMA-FMECA aimed for a modern touch-oriented environment, equipped with responsive side-panels, top-bar menus and data tables. JavaScript libraries, such as jQuery[7](mobile) and Bootstrap[8] offered a wide range of customizable design components that populated the tool views, and helped to achieve balance between options and content size.

[7] jQuery Mobile - http://jquerymobile.com/
[8] Bootstrap - http://getbootstrap.com/

- **A capable rendering engine for dynamic knowledge views -** IMA-FMECA employs JADE[9], as its template engine. A template engine is a library or a framework that uses rules/scripts to interpret data and render views. In the case of web applications, views are HTML pages (or parts of them), but they can also be JSON or XML files, or, in case of desktop programs, GUIs. JADE is designed primarily for server side templating in Node.js, and is capable of creating highly configurable dynamic views and multi-layered interfaces. Supporting internal routines(mixins) and scaled templating, JADE supported the swift and responsive rendering of IMA-FMECA's knowledge profiles, dashboard widgets and metadata catalogs. JADE's selection is also aligned with the design decision to use JavaScript-powered technologies across all IMA-FMECA components.

4.6 Integration of Maintenance Knowledge and Workflows

In this section we list and describe the purpose of exported services that were developed to test and evaluate the integration of IMA-FMECA with other WelCOM subsystems and platform components. These services are classified into three categories, according to the type of access they provide or the nature of the retrieved data. For each service we provide a short description of its function, and in some case samples of the returned data are also offered.

4.6.1 Exported Services

Exported service for accessing FMECA knowledge:

- /getAssetList

This service returns the list of assets that currently populate the FMECA Table. The request response includes the asset type and criticality for each distinct Asset.


```
...
{
  "_id": "5312548aab585fa01e000008",
  "name": "Test Lift",
  "as_type_code": {
    "_id": "531250cdab585fa01e000005",
    "name": " Lift"
  },
  "cs_type_code": {
    "_id": "52834a40357de8e00800001a",
    "name": "Scale from 1 to 10",
    "max_value": 10,
    "min_value": 1
  },
  "criticality": 8,
  "long_description": "A reference deployment serving as a testbed for
benchmark simulation of failures and further analysis of asset behavior
under specific operation profiles.",
  "active": true
 },
...
```


[9] Jade Template Engine - http://jade-lang.com/

- /getAssetFModes-:id

This service returns a list of all the Failure Modes, currently recorded in the FMECA Table, for a specific asset. The Asset is specified by referencing its :id as a request parameter. The request response includes the event type and severity for each distinct Failure Mode.


```
...
 {
  "_id": "5314c1068255157c0d000001",
  "asset_id": "5312548aab585fa01e000008",
  "event_type_code": {
   "_id": "53122e71ab585fa01e000001",
   "name": "Failure Mode"
  },
  "name": "Final failure at the drive sheaves bearing",
  "severity_lev_type_code": {
   "_id": "5312486aab585fa01e000004",
   "name": "Very High",
   "severity_scale": 9
  }
 },
...
```


- /getFMode-effect_symptoms-:id

This service returns a list of all the Symptoms(Events) for a specific Failure Mode. The Failure Mode(Event) is specified by referencing its :id as a request parameter. The request response includes the event type and severity for each distinct Symptom.

- /getFMode-effect_final_res-:id

This service returns a list of all the Final Results(Events) for a specific Failure Mode. The Failure Mode(Event) is specified by referencing its :id as a request parameter. The request response includes the event type and severity for each distinct Final Result.

- /getFMode-effect_func_fail-:id

This service returns a list of all the Functional Failures(Events) for a specific Failure Mode. The Failure Mode(Event) is specified by referencing its :id as a request parameter. The request response includes the event type and severity for each distinct Functional Failures.

- /getFMode-cause_direct-:id

This service returns a list of all the Causes(Events) for a specific Failure Mode. The Failure Mode (Event) is specified by referencing its :id as a request parameter. The request response includes the event type and severity for each distinct Cause.

- /getFMode-sol_package_id-:id

This service returns a list of all the recommended Maintenance Actions for a specific Failure Mode. The Failure Mode (Event) is specified by referencing its :id as a request parameter. The request response includes the action type and priority for each distinct Action.


```
...
 {
  "_id": "531389df2b3a17e41a000004",
  "name": "Replacement of Drive Sheave's bearing",
  "priority_lev_type_code": {
   "_id": "52834b90357de8e008000026",
   "name": "Low",
   "priority_scale": 2
  },
  "sol_type_code": {
   "_id": "528349ad357de8e008000017",
   "name": "Corrective"
  },
  "asset_id": {
   "_id": "5312548aab585fa01e000008",
   "name": "Test Lift"
  }
 }
...
```


Exported Services for accessing Maintenance Metadata:

- /getAssetLastIssue-:id

This service returns the last use of the tag "Issue" to annotate a specific Asset. Through this service, an external system can retrieve information about the last time an Asset displayed abnormal behaviour or suffered a failure. The Asset is specified by referencing its :id as a request parameter. The response includes the tag category, the annotation action's timestamp and the respective user_id. The response will also include the addition input, provided by the user via the tag's mini-form, along with available votes and voters.


```
{
 "_id": "54a29adbea5d24dc1d000001",
 "tag_code": {
  "_id": "53a96ce0e78506a80b000001",
  "name": "Issue",
  "tag_type": "Diagnostics"
 },
 "user_id": {
  "_id": "52d3c912fa0507ac17000001",
  "username": "Technician-A"
 },
 "instance_id": "5312548aab585fa01e000008",
 "entity_code": 13,
 "timestamp": 1419942619343,
```

```
 "tag_text": "Vibration and unstable movement when cabin reduces speed
and stops.",
 "active": true,
 "__v": 1,
 "votes": 1,
 "voters": [
  "Engineer-C"
 ]
}
```


- /getEventLastConf-:id

This service returns the last use of the tag "Confirm" to annotate a specific Event. Through this service, an external system can retrieve information about the last time an FMECA Event was detected and confirmed. The Event is specified by referencing its :id as a request parameter. The response includes the tag category, the annotation action's timestamp and the respective user_id. The response will also include the addition input, provided by the user via the tag's mini-form, along with available votes and voters.

- /getAssetFModeLastConf-:id

This service returns the last use of the tag "Confirm" to annotate a Failure Mode of a specific Asset. Through this service, an external system can retrieve information about the last time an Asset had one of its recorded Failure Modes detected and confirmed. The Asset is specified by referencing its :id as a request parameter. The response includes the same information retrieved by the *getEventLastConf* service, with the addition of the confirmed Failure Mode's instance_id, name, type and severity.


```
{
 "_id": "544bd3a9d9f12e181d000003",
 "tag_code": {
  "_id": "533ebd3e19c212840e000001",
  "name": "Confirm",
  "tag_type": "Diagnostics"
 },
 "user_id": {
  "_id": "52d3c912fa0507ac17000001",
  "username": " Technician-A "
 },
 "instance_id": {
  "_id": "5314c1068255157c0d000001",
  "name": "Final failure of Drive Sheave's bearing",
  "severity_lev_type_code": {
   "_id": "5312486aab585fa01e000004",
   "name": "Very Hight",
   "severity_scale": 9
  }
 },
 "timestamp": 1414255529768,
 "active": true
```

}

- /getActLastPlan-:id

This service returns the last use of the tag "Schedule" to annotate a specific Action. Through this service, an external system can retrieve information about the last time an Action was scheduled for execution. The Action is specified by referencing its :id as a request parameter. The response includes the tag category, the annotation action's timestamp and the respective user_id. The response will also include the addition input, provided by the user via the tag's mini-form, along with available votes and voters.


```
{
  "_id": "543018c54aa081a81b000001",
  "tag_code": {
    "_id": "53a96dade78506a80b000002",
    "name": "Schedule",
    "tag_type": "Practice"
  },
  "user_id": {
    "_id": "52d3fb7eead6ea1018000002",
    "username": " Engineer-A"
  },
  "timestamp": 1412438213111,
  "active": true
}
```


Exported services annotating FMECA knowledge:

- /directTag-issue-asset-:id

This service allows for the direct annotation of a specific Asset, with the "Issue" tag. Through this service, an external system can flag (inside IMA-FMECA) the detection of an issue for an Asset. The Asset is specified by referencing its :id as a request parameter.

- /directTag-confirm-as_hyp_event-:id

This service allows for the direct annotation of a specific Event, with the "Confirm" tag. Through this service, an external system can confirm (inside IMA-FMECA) the occurrence of an Event. The Event is specified by referencing its :id as a request parameter.

- /directTag-schedule-solution_package-:id

This service allows for the direct annotation of a specific Action, with the "Schedule" tag. Through this service, an external system can schedule (inside IMA-FMECA) the execution of an Action. The Action is specified by referencing its :id as a request parameter.

- /plusTag-:id

This service allows for the annotation of a specific tag instance, with one positive vote. Through this service, an external system that has obtained a session through authentication, can vote and rank the knowledge value of a tag instance. The tag instance is specified by referencing its :id as a request parameter.

4.6.2 Integration Scenarios with CM and CMMS

Having explained the type, the invocation syntax and the purpose of each available exported service, we now use them to build and serve scenarios that describe the integration of IMA-FMECA with other WelCOM subsystems, and its participation to larger functional workflows. Scenario descriptions maintain a technical abstraction that helps the understanding of the end goal, while also following the coupling between systems. Focusing on the role of IMA-FMECA, we only refer to "service polling" when addressing the invocation of external services. In practice, IMA-FMECA can utilize any specific handshake to effectively connect with other systems' exported services.

A. SENSE-MI detects and flags an Asset issue in IMA-FMECA

The following scenario features the collaboration of SENSE-MI, SENSE-MI-Detect and IMA-FMECA:

1. The wireless sensor network collects and processes a series of samples. SENSE-MI-Detect identifies a pattern of parameter values that indicates abnormal behaviour for the monitored asset.
2. SENSE-MI invokes *getAssetLastIssue* to receive from IMA-FMECA the last tag instance that reported an Issue for the specific Asset:
    - In case the tag instance does not exist or features a very old timestamp, SENSE-MI uses *directTag-issue-asset* to tag and report the new issue in IMA-FMECA.
    - In case the tag instance exists, SENSE-MI uses *plusTag* to add a positive vote in IMA-FMECA.
3. In case the detected pattern has already been linked to a specific FMECA Event, SENSE-MI invokes *getEventLastConf* and checks when this Event was last confirmed:
    - In case the tag instance does not exist or features a very old timestamp, SENSE-MI uses *directTag-confirm-as_hyp_event* to tag and confirm it in IMA-FMECA.
    - In case the tag instance exists, SENSE-MI uses *plusTag* to add a positive vote in IMA-FMECA.

B. IMA-Planner schedules an action for execution in IMA-FMECA and assigns orders

The following scenario features the collaboration of IMA-Planner and IMA-FMECA:

1. IMA-Planner invokes *getAssetFModeLastConf* periodically and continuously prompts IMA-FMECA. Essentially, it uses the service to monitor IMA-FMECA and capture the potential confirmation of a Failure Mode for a critical Asset.
2. At some point, a maintenance engineer uses IMA-FMECA to tag and confirm a Failure Mode for the Test Lift.
3. IMA-Planner receives the new tag instance from its continuous polling and invokes internal services that assign orders for visual inspection and failure verification by the supervising engineer.
4. The supervising engineer audits the Asset and uses IMA-FMECA to vote for the Failure Modes confirmation.
5. IMA-Planner, which continues to poll the service, receives the updated tag instance with the vote of the supervising engineer. IMA-Planner now invokes *getFMode-sol_package_id* to receive the recommended Actions for the specific Failure Mode from IMA-FMECA.
6. Using the *getActLastPlan* service IMA-Planner starts to continuously poll IMA-FMECA for all recommended Actions. It essentially monitors IMA-FMECA, to capture which recommended Action gets scheduled for execution.
7. The supervising engineer, having evaluated all recommended solutions, uses IMA-FMECA to tag and schedule the appropriate Action.

8. IMA-Planner captures the scheduling of the Action, and invokes internal services to assign orders for its execution by maintenance technicians.

4.7 Summary

In this chapter the overall architecture of the WelCOM project has been introduced. IMA-FMECA is part of WelCOM e-Maintenance platform and participates with components in two of its major blocks: (i - services) WCKM, the knowledge management sub-system and (ii - client) WCIMA, the Intelligent Maintenance Advisor. The functional requirements of IMA-FMECA were discussed afterwards, placing its aimed and delivered functionality upon two distinct pillars of features; the multi-user knowledge management environment and the collective enrichment process for knowledge capture. The mobile provision scheme was analyzed then for its desired benefits and its general adoption by modern IT solutions. Following this, the design pattern and the implementation technologies of IMA-FMECA were examined in terms of their benefits and suitability for specific system needs and design specifications. The chapter concluded with a catalogue of exported services that facilitate the integration of IMA-FMECA with other WelCOM components or external systems.

This chapter provides a better understanding of what were the core functional features of IMA-FMECA, as a system and a tool. The analysis in this chapter presents a design configuration and a compilation of technologies that have not been used before to drive FMECA-based services. Both the design and the implementation choices align with very recent and modern IT approaches for delivering mobile clients and cloud services. Their applicability and suitability for IMA-FMECA made them important pillars of our research. One of the most challenging tasks during the design phase of our system was weighing carefully how model views, service calls and functionality could be coordinated and delivered, so as to create an engaging experience for our new reporting paradigm. It was important for IMA-FMECA and WelCOM platform as a whole, to approach shop-floor mobile personnel in a way that does not impose its presence but rather transparently blends into the maintenance work space.

5 Application Case Study and Results Discussion

5 APPLICATION CASE STUDY AND RESULTS DISCUSSION

This chapter presents a case study of IMA-FMECA piloting in the context of a real industrial environment. The piloting took place at KLEEMANN Lifts, a large enterprise with global presence in the lifts industry, currently holding more than 3% of the global market. The pilot methodology (Figure 5.1) is first discussed and then further described with detail in dedicated sections. The pilot definition and planning details are explained, presenting all the specifications that were decided for the pilot study. Three machinery assets were selected to drive the application case of IMA-FMECA. An FMECA study was conducted to record knowledge of their operational behaviour and failure profile. In a separate sections, all the specific steps that were followed to conduct the study are analysed, discussing the methodology applied, the goals set and the leads for software integration. This initial knowledge provided the starting knowledge base for the use of the system by the end user's personnel.

For training purposes a set of use case scenarios was produced, so as to cover basic and advanced features of the final system. For each scenario, the prospects and benefits of the presented function are briefly discussed. To better elaborate in our piloting and the system's usage, we analyze a specific application case for one of the selected assets. We follow the process of a failure instance occurrence, from its first detection to the application of an adequate remedy. The products of the systems knowledge capturing process are presented and discussed. Finally this chapter addresses the system's evaluation and its results. Staff participating in IMA-FMECA piloting were asked to offer their feedback completing an evaluation questionnaire. The obtained responses covered all aspects of the IMA-FMECA tool’s usage. We examine the collected evaluations and extract useful insights.

5.1 Pilot Methodology

The followed methodology is aligned with the research questions and provides a framework that builds a practical solution to address them. Figure 5.1 offers an overview of this methodology, displaying the backbone of the research plan along with the separate tasks that comprised each step. As a whole, the research plan was targeted towards three major objectives:

- Compose a framework and a design approach that can produce answers for our research questions.

- Develop a system tool, produce initial knowledge and attune the industrial context for a practical solution that instantiates the framework, incorporates the answers and adopts the design specifications.
- Pilot test the solution and evaluate how system functionality, knowledge quality and user experience attest the delivery of comparable advantages and benefits.

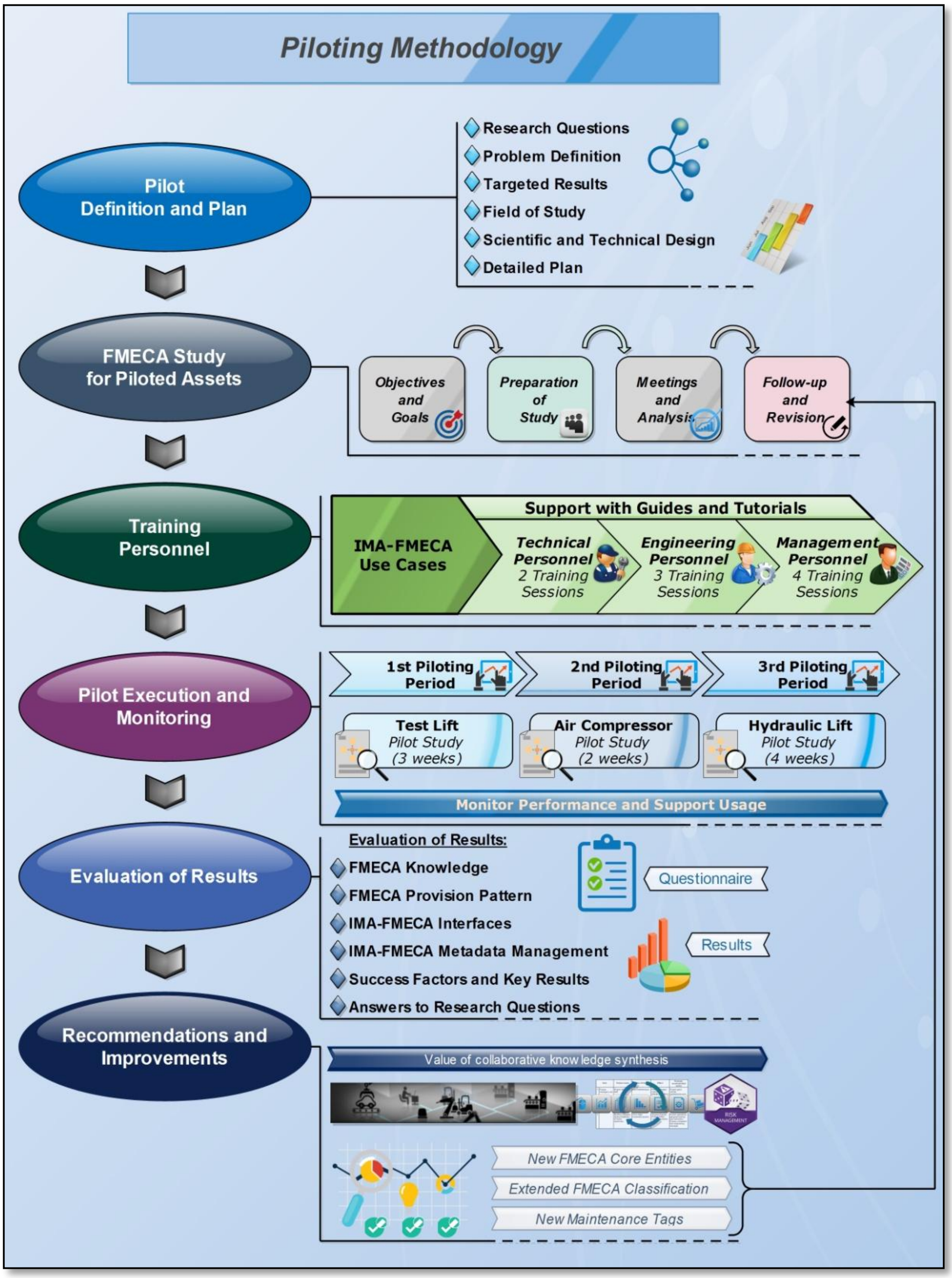


Figure 5.1. Research methodology major phases and internal tasks

The operational objectives of the pilot case study will serve in answering our research questions and act as milestones for the applicability of our methodology in a real industrial environment and a real maintenance process. In this context the targeted goals are more practical and attuned with end user expectations:

- ✓ **Produce the FMECA study to support the maintenance practice of a lift manufacturing industry**

  Assess the FMECA specifications of the specific industry and integrate them while performing the phases of a complete FMECA study. Populate the FMECA model with all produced knowledge and results. Provide remote access to maintenance experts and monitor how FMECA knowledge improves their ability to detect, diagnose and address recorded failure modes.

- ✓ **Collectively enrich and manage FMECA knowledge**

  Make IMA-FMECA available to all the roles and members of the maintenance department. Explain the role and function of maintenance tags, and illustrate how each tag and input connects with FMECA to support its quality management. Utilise maintenance planning and exploit emerging failures to drive the experience of sharing relevant evaluations and collaboratively addressing failure modes.

- ✓ **Engage lift maintenance experts and motivate their FMECA contribution**

  Introduce IMA-FMECA and help maintenance staff adopt its use, as a maintenance support tool. Create use cases and training scenarios that effectively describe the quick and accurate use of maintenance tags. Challenge experts and engineers to use IMA-FMECA's configurability and custom tags to review and improve the FMECA knowledge.

- ✓ **Translate enriched FMECA to a new version**

  Collect tags that imprint knowledge for new failure events and maintenance actions. Collective tags with additional feedback and valid knowledge propositions. Support the fast and qualitative update of FMECA knowledge by the appropriate team, offering them access to these collections. Record changes and additions, along with the required time to identify and decide them.

- ✓ **Evaluate the enrichment process and its role in prospect analytics**

  Study the FMECA components that received the most maintenance tags. Discuss possible connection between the category of tag, the type of component and the context of its use. Extract pointers for new tag templates and possible FMECA extensions.

A piloting methodology was defined, to evaluate the use of IMA-FMECA and measure its success in serving the maintenance needs of the end user's industrial field. This methodology was decided in collaboration with key members of the maintenance department and the IMA-FMECA support team. The stages of our piloting have as follows:

1. **Define and plan the pilot case study -** Decide the number and type of studied assets, examining both the end product and the manufacturing process. Select the roles and members that will participate, supervise and coordinate the FMECA study and the piloting process. Produce a schedule for meetings, tutorials and piloting periods.
2. **Conduct the study -** Collaborate and work to produce the first version of the FMECA study and enter it to IMA-FMECA. Follow the methodology of FMECA practice and go through all the stages of collecting, processing and structuring the appropriate information. Coordinate the team to utilize legacy systems and internal resources for the best possible first version of FMECA. Discuss and record pointers for potential improvements early-on.
3. **Train personnel -** Provide hands-on tutorials and schedule piloting sessions for IMA-FMECA's usage. Compose descriptive guides and representative use cases to achieve the best possible adoption from the piloting team. Create training content for both tutorials and guides with two major focus points: referencing and annotating FMECA.

4. **Perform, monitor and support the case study -** Follow the IMA-FMECA's usage and record how the system function's support staff to perform tasks, during piloting periods. Continuously advise personnel and address any difficulties related with the tool's usage. Provide helpful tips and recommendations for the use of advanced features for knowledge discovery(metadata filtering) and knowledge extension(new tags and FMECA content).
5. **Evaluate pilot results –** Use an evaluation questionnaire and perform interviews to record feedback and discuss results. Map the experience of each different role and measure the level of appreciation for certain core features of IMA-FMECA. Prompt for the overall stance and the specific insights of key maintenance personnel towards the provision pattern, the tagging paradigm and the knowledge management.
6. **Produce recommendations and make improvements -** Use IMA-FMECA findings to review and improve FMECA knowledge. Extract pointers and hints on how to enhance the service parameters of FMECA access and tag-based reporting. Mine evaluation feedback and discuss identified prospects for desired extensions or additional functions. Examine how application-focused or case-locked are the findings and approach them with system abstractions.

5.2 Pilot Definition and Planning

The definition and planning of the pilot study is discussed here in detail.

5.2.1 Problem definition

Validate, use and enrich reference FMECA knowledge for a lift industry. Introduce an effective capturing approach for the field expertise of a respective shop-floor, and encourage a more participatory role of relevant staff. In our focused industrial environment of lift manufacturing, the management and diffusion of knowledge produced by maintenance tasks require an upgrade. The knowledge produced when an event is detected, a diagnosis is reached or a solution is decided, is not captured or shared and the person attaining and holding this knowledge is not timely engaged.

5.2.2 Targeted Results

In the specific industrial context, the pilot should demonstrate the ability of IMA-FMECA to upscale both maintenance efficiency for shop floor practice and knowledge enrichment for the FMECA versioning. These should be verified by its use for real assets and while experienced maintenance personnel deal with real faults. The recorded usage, should be able to provide evidence that:

- ✓ Maintenance personnel do reference the provided FMECA knowledge in everyday tasks. Mobile staff make more confident and faster assessments when referencing FMECA knowledge.
- ✓ Maintenance tags are being collected from a large pool of maintenance roles and service contexts. Maintenance experts use the appropriate maintenance tag to serve each of their reporting or decision sharing needs.
- ✓ Maintenance engineers and technicians use tags to produce more evaluations and better timed observations. Maintenance experts reference and vote maintenance tags that introduce value to FMECA. Collected tags are accompanied by additional feedback with useful insights.
- ✓ The collected metadata support a faster and more qualitative FMECA revision. The revision process can be more frequent and essentially streamlined. The collected maintenance tags report uncharted events, linking

or diversifying them from recorded ones. The collected tags propose alternate solutions to failures, or better steps when performing a suggested one.

- ✓ Enough tags are provided by maintenance personnel to help analysts and engineers identify interesting patterns. Collected tags formulate a well-structured knowledge pool properly formatted for cloud analytics. The available metadata can produce human readable FMECA mashups that present the versioning history of FMECA.

To assess the extent at which the above have been reached or achieved, a structured questionnaire was authored and completed by personnel participating to the pilot. The completed questionnaires were analyzed and studied to drive our conclusion for the system's performance.

5.2.3 Field of study

The pilot case involved experienced maintenance staff and selected engineering assets. The latter included both production machinery as well as actual products, i.e. lifts. During the piloting, IMA-FMECA was called to support the maintenance process for key assets. Each asset was picked as a reference unit to test the tool's ability to serve a different set of existing and prospect maintenance needs. Three specific assets were selected for more in depth focus:

- **An Electrical Testing Lift -** An asset tightly connected to the final product. The goal is to identify the added value that IMA-FMECA can bring as a service to installation partners and maintenance service providers. FMECA will be centrally hosted as an industry-shared knowledge asset, and the partner's maintenance teams will reference it to properly execute maintenance and diagnostics. Their tagging feedback will function as a fast and efficient service logger of installation events and an independently scaled resource of maintenance application knowledge.
- **Air Compressor -** A typical asset of generic usage in industry, it signifies not only the application-specific value of the tool, but also its general applicability. Its wide use and participation in industrial environments and manufacturing lines, makes it a good reference machinery unit.
- **A Hydraulic Lift -** A personnel office lift with heavy usage and an operation profile that makes it a valid reference asset for identifying new potential failures and measuring maintenance efficiency. It is a type of lift with wide residential and office installation base, and the specific unit has exhibited a rich and interesting operation and maintenance history. It was the asset that would most probably provide us with valid, common and actionable faults during our piloting periods.

While the test lift offers a more controlled environment to assess the piloted system in predefined scenarios, conditions and faults, the hydraulic lift allows a real application to drive and trigger the piloted functions and services. Piloting on a reference test asset can provide better insight for the potential integration of the system into existing infrastructure and platforms (CM and CMMS). It can also become very useful, for evaluating interoperability and performance when the piloted functions serve internal process workflows (maintenance plan). On the other hand, piloting on a real running installation allows better feedback on how the system performs as an additional service or component. A system development loop for fixes and improvements is always more effective when linked with metrics and results recorded from real deployments and user experiences. Finally, an asset type typically present in industrial environments, such as an air-compressor, can play a key role in assessing applicability, ease of use and scaling efficiency. While improved performance for unique or specialised assets is desirable, creating an overly complex system that cannot effectively address the needs of more typical assets can often create more problems than the ones it solves.

While our pilot objectives focus on FMECA, knowledge management is a common challenge for most industries. It is a standard practice in industry, to employ enterprise systems and collect or capture knowledge with no specific plan for its use. It is also common to produce and manage knowledge assets that are not properly disseminated, shared and maintained by the proper staff or services. While our research focuses on validating FMECA, there is an increasing number of maintenance knowledge assets that modern industry is currently producing and hosting in enterprise systems (policies, strategies and plans). These assets are often not shared across the layers of the industrial process structure (from shop-floor to management) and are not updated frequently enough to support critical tasks and experts. This typically leads to problems of inconsistent knowledge preservation and incorrect management of available knowledge flows.

Experienced technical staff can very easily understand how to handle and act upon domain-specific knowledge. Providing themselves actionable knowledge as input, is where system adoption and knowledge contribution becomes a challenge. Their predisposition towards any system that "manages knowledge" is often negative, unless they have adequate control and freedom over what is captured and how it is used. This cannot be achieved if the piloted system and cases do not reduce complexity, provide transparency and allow traceability. Our piloted cases and hands-on tutorials, were defined so that all maintenance staff would be more than capable to understand the functional role of tags and their sharing purpose. It was important that they could first experience the support from FMECA knowledge and then care to enrich and validate it. Allowing them to do so by reviewing FMECA through tags, and not by producing it from zero level, achieved a well-balanced participatory role. Our evaluation questionnaire was structured with questions that prompted staff to assess if this balance was achieved.

Senior staff from management and R&D were our targeted early adopters and the most consistent knowledge contributors. They have extensive experience with enterprise systems and are able to understand services that offer functional shortcuts and performance enhancements in knowledge management. Their active involvement in the pilot preparation, coordination and execution was a key enabler for its success and the quality of recorded results. From the early stages of deciding assets, team members and use cases, they provided advice and constant support, having a clear picture of the prospects and benefits for each piloted function and task.

Maintenance engineers played an important role in unlocking access to certain resources, mediating for participating personnel and generally following the quality of the piloting process. They were able to translate specific piloting goals and many times convey better the targeted benefits to their team. Their ability to understand the piloting objectives, allowed them to effectively drive the tasks and motivate the teams they were involved in. The director of technical services provided continuous support for the coordination of actions and the interfacing with higher management. His decisions and actions had definitive impact on the progress of the pilot planning and execution. His availability and timely feedback allowed the pilot to overcome all issues and difficulties. He was a catalyst that managed to enhance the collaborative work in every FMECA meeting and every piloting session.

5.2.4 Scientific and technical design of the study

The application use of IMA-FMECA was designed to include piloting scenarios that drive the understanding of its functions and workflows. The scenarios employed for the system's piloting, were comprised by use cases that target the following expectations:

- ✓ Users should be able to obtain a very good understanding of the navigation routes that deliver IMA-FMECA's functionality. The use cases must test their ability to arrive fast at the desired information or function component.
- ✓ Users should be able to easily populate, edit and extend the FMECA model. They should obtain a good concept of the available FMECA information without the need to know the model and its structure.
- ✓ Users should be able to learn how to decode and facilitate the annotation purpose of each maintenance tag. They should also be able to test the usage of tag mini-forms to provide additional feedback and summarize/quantify their evaluations.
- ✓ Users should be able to understand how they can scan through the failure mode profiles and swiftly reconstruct the failure context from last annotations. They should gradually be able to understand, weight and process each associated tag, event or action in the failure modes profile.
- ✓ Users should be able to use the dashboard filtering widgets to create and consume useful timelines of annotations. The use cases must test their ability to produce and interpret meaningful metadata timelines, from the available history of maintenance annotations.
- ✓ Users should be able to easily materialize their ideas for new annotations with custom maintenance tags. The simple process of creating a custom tag and its instant availability for use, should motivate them to experiment with new semantics of maintenance feedback.

After the pilot use of the system, maintenance staff were prompted for feedback and asked to complete an evaluation questionnaire. The questionnaire was structured to capture the personnel's view on the following aspects:

- ➢ **Question Group I** ***(3 questions)***: Targeting the level of familiarity with portable devices and touch interfaces, both inside and outside maintenance practice. These set was aimed to assess how accustomed and motivated each staff member was, when using portable systems.
- ➢ **Question Group II** ***(6 questions)***: Targeting the access and availability of FMECA knowledge during maintenance practice. This set included questions measure how maintenance personnel valued the support from FMECA knowledge and what were their preferences for an appropriate provision pattern. They were asked for the referencing frequency and the extent of available FMECA content in technical manuals, to measure their stance towards their adequacy. They were also prompted to rate the knowledge value of each specific FMECA component, as offered by the IMA-FMECA's model structure. Finally, maintenance staff were asked to evaluate the contribution of their shop-floor expertise, supporting an FMECA engineering study.
- ➢ **Question Group III** ***(15 questions)***: IMA-FMECA's interface design, usability and service performance were assessed in this set. Navigation efficiency when browsing FMECA, was measured with ratings for the time-to-reach desired information. Failure Event content quantity and quality were rated, to measure the coverage of maintenance knowledge. The response time and efficiency of IMA-FMECA's functions were evaluated, prompting for the benefits of specific maintenance tags in corresponding tasks. Finally, the users were asked for contributing in improvements, by proposing extensibility options and suggesting new templates for maintenance tags.

The pilot study involved participatory roles with different levels of expertise and responsibilities. IMA-FMECA's services were developed to enhance and support the effective function of such personnel as members of either the shop-floor maintenance force, or the back-office team which may deal with FMECA. Therefore, our pilot's measurable outcomes are tightly connected to their experience of participation and their perception of the system's functionality and results. Our piloting process was designed to follow and record their experience, adapting functions and offering access that target each group's area of responsibility. This allowed us to provide better support and monitor more effectively how FMECA knowledge was utilized to aid the tasks of each distinct maintenance role.

The pilot was designed to study a human-contributed knowledge flow in the maintenance context. As such our evaluations were driven by results that indicate how this flow was produced, captured and managed by IMA-FMECA. Our piloting team was the primary source for evidence that indicated how we could better refine, modify and extend the mechanisms that serve the above. More importantly, the piloting was planned and executed in a way that enabled us to later interpret the user experience and the level of appreciation, to identify possible improvements and extract new desired features. The piloting evaluation managed to fuel an analysis that pointed us to the right direction, in order to upgrade IMA-FMECA both as an FMECA model and as a metadata management system.

5.2.5 Detailed plan for the study

The piloting plan was produced in close collaboration with the end user's maintenance department. It was elaborated by managerial personnel, and many details were discussed and defined by the director of technical services. The contribution of engineers and R&D personnel was also vital in collecting and organizing the available information and material for background diagnostics. Given the fact that most assets and skilled personnel were following a heavy duty assignment profile, availability and accessibility were planned to integrate well with their operation profiles and scheduled tasks, accordingly. Throughout the whole process of defining the details and schedule of the pilot study, the end user's company structure coupled very efficiently with the WelCOM's project management team and the IMA-FMECA's development team (Pistofidis et al., 2014). It is worth mentioning that both maintenance technicians and engineers exhibited a positive stance and a good predisposition towards their participation in the pilot plan. This was a direct result from them understanding that the piloted system would allow them to contribute, consume and manage knowledge, in ways that were not possible before.

Access to IMA-FMECA's enterprise application was made available to the industrial end user personnel, with two distinctly planned deployments: (i) a local deployment, at the offices of Kleemann's maintenance department and (ii) a remote deployment, at the server room of the ATHENA Research Centre facilities. This deployment plan facilitated the validation of the systems' performance and response time both as a local and a cloud service. The first deployment will target the evaluation of system services as part of an indoor private cloud. For such a deployment, IMA-FMECA will be piloted as an internal tool aimed to serve Kleemann's maintenance department. The second deployment will pilot IMA-FMECA's efficiency as a remotely accessed cloud service. It is a deployment plan that better maps how this tool would serve external contractors such as installers and maintenance vendors.

The pilot's 16 participants belong to one or more of the following groups or roles:

- **Director of technical services and maintenance managers (3 participants)**

  This group is often comprised by maintenance directors and members of the company's management hierarchy. Their participation involved the use of IMA-FMECA as a tool for maintenance knowledge management and dissemination. Participants of this group targeted the filtering of maintenance metadata to assess how the maintenance strategy was captured by FMECA and how the feedback policy was served by the maintenance tags.

- **Design engineers (4 participants)**

  This is a crucial role for the quality of FMECA knowledge. Participants from this group monitored how FMECA knowledge was accessed and consumed by maintenance engineers and technicians. They were responsible for filtering and studying how maintenance metadata were clustered around certain FMECA events and assets. They voted tags to pinpoint actionable knowledge for the versioning of FMECA, and to denote additional feedback that led to FMECA improvements.

- **Maintenance process engineers (3 participants)**

  This is a group that was mainly focused on monitoring the timelines of tagged actions and tagged events. Mostly voting tagged solutions, they were responsible to act as an interface to invoke processes outside IMA-FMECA that required its input. Usually these processes had administrative purposes and served diverse functional flows. They would often act as means of exporting FMECA evaluations and employing them into hardcopy reports and maintenance orders.

- **Maintenance engineers (7 participants)**

  This is a large group that includes personnel that range from shop-floor supervisors to maintenance experts. Their role involved the tagging and voting of failure modes and their solutions, while actively monitoring and interpreting the latest annotations for critical assets and severe events. They constituted the more active and populated user group, contributing the most additional feedback and utilizing optimally the semantics of tags. Their support for the FMECA review process was also vital, as many of them were summoned during FMECA meetings to ensure accurate interpretation of clustered metadata for assets and events that they tagged.

- **Maintenance technicians (5 participants)**

  This is commonly the second largest group in a maintenance department and includes personnel with significant presence on the shop-floor, and the first to detect symptoms and signs of abnormal asset behaviour. Their responsibilities in the piloting were to timely confirm events and report their diversification from the FMECA reference with additional feedback. The ability to access the profiles of high risk failure modes and track their confirmation by engineers, motivated them to maintain long sessions in the tool. They saw, in IMA-FMECA, the opportunity to access and process shared filed expertise that could upscale their own background knowledge.

- **Research and Development (3 participants)**

  R&D was a very small and focused group that would only participate as a consumer of the collected metadata. Their role in our pilot was less active and more supervisory. They would periodically assess the amount and type of metadata that were produced by each piloted failure mode. Their interaction was reserved to vote tags that were also voted by Design engineers, to rank them as metadata capable of providing useful improvements for the FMECA knowledge or the tool itself. Their role was very important during the piloting evaluation, discussing the pilot results and providing qualitative pointers for future actions and potential analytics.

While the execution of the IMA-FMECA workflow was presented to all personnel, the hands on experience focused attention on relevant cases, for each different maintenance role. The training of participants was coordinated to gradually create a collaborative environment between them. This environment would host a small virtual community that allowed its members to experience the sharing and cross-examination of FMECA as a virtual map of possible events. Having this as a common goal, the training sessions were then evolved independently adapting to the needs and roles of the targeted group of trainees. In greater detail:

- Maintenance technicians participated in the piloting process with sessions that focused on their familiarization with FMECA browsing and maintenance tagging. Their ability to quickly arrive at the desired FMECA content and tag the detected events was our primary learning goal. The training sessions invested on the timely nature of their evaluations and their ability to effortlessly utilize tag mini forms. Interface design and its visual elements for FMECA linkage were addressed repeatedly, to upgrade the technicians navigation efficiency. It was important to seamlessly drive their training sessions deeper into FMECA knowledge, allowing them to produce more evaluations about events. Also important was their ability to track scheduled solutions and easily follow the provided steps.
- For maintenance engineers, the IMA-FMECA's piloting was extended to longer sessions of hands-on use. During these sessions, engineers received training on all functional aspects of FMECA's knowledge management and maintenance tag templates. Filtering metadata to produce meaningful timelines was a priority here. Quickly accessing the latest annotations for critical assets and severe events in their area of responsibility, was the primary goal. Their training was balanced to facilitate their awareness of the produced metadata for emerging failure modes. Their ability to effectively understand and consume the failure context as displayed by the tool's interfaces, was essential. Last but not least, design and process engineers were also trained to implement the versioning and upscaling of IMA-FMECA's, by editing and expanding FMECA knowledge, or creating new templates for maintenance tags.
- R&D engineers and the director of technical services were interviewed separately with dedicated system presentations. These presentations piloted the full scope of IMA-FMECA's features and capabilities, while also offering an overview of the system's design, architecture and integration prospects. Their training was implemented as crash courses, given their increased familiarity with enterprise systems and knowledge management. Apart from core IMA-FMECA functions, these presentations were followed by discussion that served two important goals: (i) converge on targeted knowledge and the rate/quality of its capturing, and (ii) receive advice and schedule improvements for the on-going training or the planned piloting of other groups.

To support the above training sessions and provide a reliable point of reference, extensive user guides were authored and produced with visual aids and tips. These guides could be accessed at any time through IMA-FMECA's main menu. Their content was composed to be rendered on portable devices, allowing a touch optimized browsing experience.

The pilot study timetable was decided based on the maintenance plan and centred around the emerging needs of the end user. Piloting periods were intentionally scheduled between and after the execution of important maintenance workflows that served preventive or corrective plans. The overall timeline of the key phases and tasks were planned as follows:

I. **Phase**: FMECA Study

   Process Steps:

   - ✓ 4 meeting at Kleemann's Headquarters
   - ✓ 5 net meetings with design and process engineers
   - ✓ 2 net meetings with external advisors and maintenance consultants

   Duration: 2 months and 2 weeks

II. **Phase**: IMA-FMECA Training

Process Steps:

- ✓ 2 training sessions for maintenance technicians
- ✓ 3 training sessions for maintenance engineers
- ✓ 4 training sessions and discussions with the director of technical services and R&D

Duration: 2 months and 1 week

III. **Phase**: 1st IMA-FMECA's Piloting Period

Process Specifications:

- ✓ Monitoring focused on Test Lift
- ✓ Includes usage before and after scheduled maintenance
- ✓ Evaluation by director and R&D at its end

Duration: 3 weeks

IV. **Phase**: 2nd IMA-FMECA's Piloting Period

Process Specifications:

- ✓ Monitoring focused on Air Compressor
- ✓ Includes usage before and after scheduled maintenance
- ✓ Evaluation by director and R&D at its end

Duration: 2 weeks

V. **Phase**: 3rd IMA-FMECA's Piloting Period

Process Specifications:

- ✓ Monitoring focused on Hydraulic Lift
- ✓ Includes usage before and after scheduled maintenance
- ✓ Evaluation by director and R&D at its end

Duration: 4 weeks

VI. **Phase**: FMECA Review

Process Steps:

- ✓ Analyze collected metadata
- ✓ (FMECA Improvements) Add and update events and actions
- ✓ (FMECA Extensions) Create new classification entities
- ✓ (FMECA Extensions) Create new maintenance tags
- ✓ Evaluation by director, design engineers and R&D

Duration: 1 month

VII. **Phase**: IMA-FMECA Evaluation and Results Discussion

Process Steps:

- ✓ Evaluation questionnaire for all participants
- ✓ Interview with R&D and director
- ✓ (IMA-FMECA Improvement) Improve interfaces and service
- ✓ (IMA-FMECA Integration) Discuss next steps

Duration: 4 weeks

The pilot study was monitored and coordinated by the collaborative effort of WelCOM's project management team and Kleemann's director of technical services. While the first ensured a qualitative system deployment and constant piloting support, the later facilitated access to core maintenance processes during critical phases of the company's maintenance plan. Any emerging difficulties were redirected and effectively addressed by one of the two supervising teams. Unknown or obscure terminology, inability to properly use technology, or even negative stance towards embracing the use of the tool, were all handled by the joined effort of both teams to provide the best possible training environment, piloting process and system experience.

5.3 FMECA Study for Pilot Assets

In order to populate the system's model and produce a qualitative starting knowledge, we planned and conducted a FMECA engineering study for a specific number and types of Kleemann's assets. This study followed a formal methodology and included various steps and phases.

5.3.1 FMECA Study Objectives

The first action in our FMECA plan was to define a set of objectives and goals. These objectives are aligned with best practices and constitute well-established indicators for the effectiveness of an FMECA study:

- **Process Improvements -** The FMECA should drive product design or process improvements as the primary objective. Our FMECA study focused on producing knowledge that could indicate improvements on both a testing reference (lift) and a final product installed in a heavy usage environment. Furthermore, the delivered study was contextually adapted to be consumed, reviewed and validated by the full range of roles in the maintenance process.
- **High Risk Failure Modes -** The FMECA should address high-risk failure modes with effective solutions and executable action plans. Towards this goal our study progressed with a direct aim to investigate, record and deliver well-structured solutions and alternative action paths for all high-risk failures.
- **Interfaces -** The FMECA scope should include failure modes that progress and emerge at points of asset or process integration. This essentially states the need to study failures that affect the interfaces that couple asset components or link collaborating assets. Our study incorporated a significant pool of failure events tightly associated with mechanisms of asset hierarchy or asset function flows.
- **Lessons Learned -** The FMECA study should consider all major "lessons learned" as input from various knowledge and event capturing sources. Both our system and our study were implemented with a clear goal to facilitate a validation loop between failure mode identification and established knowledge of diagnostics. The FMECA study was conducted in a way that creates modular knowledge and promotes its enhancement through independent sources of feedback.
- **Level of Analysis -** The FMECA should offer the correct level of detail in order to balance effective use with information quality. Reaching the appropriate depth of analysis has a direct impact on the size and complexity of content produced from the FMECA study. Even though our model can support longer causality paths, our study invested on a large number of short paths. This design decision would later facilitate the efficient browsing and referencing of the FMECA study by maintenance shop-floor personnel.
- **Timing -** The FMECA should be conducted or revised during the "window of opportunity" whence it can most effectively influence the supported process. Our FMECA study was completed right before the implementation of a major maintenance action plan, scheduled by Kleemann. This timing allowed us to

evaluate the delivered FMECA study shortly after it was concluded for the specific assets. It also provided a sufficient period of validation through feedback collected from our system.

- **Team -** The right people have to be adequately trained in the procedure and participate on the FMECA team throughout the analysis. Team composition is crucial for gathering the required knowledge of failure modes. Collecting knowledge from the right personnel at the right stage of the FMECA study, was a process that required a preparation and availability plan from Kleemann. Their collaborative spirit and consistent support provided us access to key maintenance staff that were able to offer their insight when it was most needed.
- **Documentation -** The deliverables of the FMECA study should be documented in a format that can be referenced and consumed to serve its process goals. In our case the produced FMECA table was initially structured in a spreadsheet file that facilitated its sharing, review and collaborative editing. To evaluate its practical benefits in the maintenance process, this information was then input in our system and served as a digital FMECA reference model.
- **Time Usage -** Time spent by the FMECA team to familiarize itself with the concepts, the methodology and the usage of the FMECA study is an effective and efficient use of time with a value added result. The quality of the final study should reflect the time invested by the team.

5.3.2 FMECA Study Preparation

Before proceeding with the required meetings of the FMECA study, a number of preparation steps can be made to define a guiding context. These steps helped both us and Kleemann's personnel to have a better overview of the overall study timetable, the specifications of each stage and the value of the prospect results. The steps where successfully concluded with the support of two important contributors: (i) a maintenance advisor from a company that offers maintenance consultancy and e-Maintenance solutions and (ii) Kleemann's director of technical services. In greater detail these steps included the following:

1. Determine the Scope of Kleemann's Study

Starting from the director of technical services and taking advice from the maintenance consultant we defined the scope of the FMECA study in terms of asset range and depth of analysis. Asset participation was evaluated and discussed using various metrics. Subsets of these metrics were employed to estimate asset criticality and decide its suitability for the FMECA study.

Towards this goal Reliability Critical Items (RCI) were identified using the following criteria:

- ✓ Unproven service history and reliability level
- ✓ Novel use of existing equipment/technology
- ✓ Safety critical
- ✓ Failure leading to expensive maintenance
- ✓ Failure occurrence without prior warning ie. no gradual degradation
- ✓ Item has a life limitation which decisively affects cost of ownership/availability
- ✓ Items with long procurement lead times for components of the item itself

Similarly, it was possible to study assets that participated in company processes deemed as Reliability Critical Processes (RCP) according to criteria such as:

- ✓ Unknown Right First Time record
- ✓ Involves technology unproven in company
- ✓ Involves novel use of existing equipment/technology

- ✓ Poor maintenance history
- ✓ Breakdown immediately stops production
- ✓ Difficult/expensive to identify/rectify problems
- ✓ Difficult/expensive to rectify problems if found in subsequent processes

2. Decide Application Areas and Visual Delivered Results

An FMECA study can expand on various areas bringing different benefits to each. A strategic decision to limit its focus can result in a study with upgraded value and more important impact. For our study, each application area was separately discussed to assess the potential added value of the inputs, outputs and interfaces:

- ➢ *Design engineering* - The FMECA study can be used to identify and correct potential design related problems. Specifically, pin-point design flaws of the final Kleemann product and create shorter revision loops for testing various compilations of lift features.
- ➢ *Manufacturing* -The FMECA study may be used as input to optimize production and acceptance testing. The FMECA study was able to strengthen the reliability of Kleemann's manufacturing processes and streamline their expected level of performance.
- ➢ *Maintenance planning* - The FMECA study is used as an important input to maintenance planning, and for our system, as part of reliability centred maintenance (RCM). Maintenance problems related with management or practice, may be identified and corrected.

3. Assemble the Right Team Members

The correct team had to be identified, trained and empowered to work on the FMECA study. While a design FMECA is often initiated by the design engineer, the system/process FMECA should be initiated by the systems engineer. The following roles were involved in various stages of the study, gathering information, reviewing and validating the FMECA:

- ➢ Project manager
- ➢ Director of Technical Services
- ➢ Design engineer
- ➢ Maintenance and process administrator
- ➢ Maintenance engineer
- ➢ Maintenance technician
- ➢ External maintenance consultant
- ➢ FMECA Facilitator

Our role as FMECA Facilitators was to coordinate actions, support process flow, intercept issues and provide interfacing knowledge, so groups were able to function effectively and make high quality decisions. This is a role that mainly acts as a helper and enabler, whose goal is to support key team members to achieve FMECA sub-goals within agreed specifications and at a desired level of performance.

4. Gather Information and Data

At this last preparation stage, all information that could and did support the compilation of FMECA knowledge was gathered and made easily available to the team. During this phase both the director of technical services and the group of maintenance engineers coordinated a survey of all hardcopy and digital material that recorded information about failure modes for the studied assets. The final material collected by Kleemann included the following:

- Technical sheets and maintenance manuals
- Exported maintenance history from e-Maintenance services
- Maintenance management action plans
- Company maintenance policy

5.3.3 FMECA Study Meetings

Having finished the preparation steps, we then created a plan for conducting the FMECA team meetings. The sequence and scheduling of these meetings had to comply with member availability and task completion time frames. Spanning across many meetings we followed a workflow of tasks that could eventually provide us with the desired outcome. These tasks were completed for each of the selected assets and had the following order:

1. Determine the failure modes
2. Assess the severity of failure mode
3. Impact to operations profile and specific functions
4. Identify and classify the effects of failure mode
5. Assess the severity of effects
6. Identify causes of failure mode
7. Assess the severity of causes
8. Discuss current prevention controls and assess probability of occurrence
9. Discuss current detection controls and assess the probability of detection
10. Decide the recommended actions for preventive or corrective maintenance

To complete the above tasks, the discussion evolved around a specific set of questions. These questions were often posed to design and maintenance engineers and the answers were reviewed and refined by the technical director, the project manager and the maintenance expert:

Table 5.1. FMECA study questions

Phase	Tasks	Questions	Output - Answers
Identify	1	What can go wrong?	Failure descriptions
	3, 4	How will it go wrong?	Failure modes → Effects
	6	Why will it go wrong?	Causes → Failure modes
Analyse	2, 5, 7	How serious is it going to be?	Severity of Failure Mode, Causes, Effects
	8	How likely is a failure?	Level of occurrence
	9	Will we be able to intercept or detect it?	Level of detection
Act	10	What can be done?	Solutions and action plans
		How can we eliminate the causes?	Manufacturing changes, test plans, error proofing, monitoring techniques (preventive actions)
		How can we reduce the severity?	
		How can we deal with the consequences?	Maintenance techniques, practise steps, logistics (corrective actions)

Asset behaviour and operational profile can significantly vary during the progression of a failure. Asset condition status may exhibit a totally different range of effects during the early stage of a failure, in comparison to the ones manifested towards its middle phase progression or its final impact. To map this diversity the maintenance expert and design engineers were able to provide a complete profile separately for the (i) early stage, (ii) advanced stage and the (iii) the final stage of specific failure modes. Separating them in such a way, also using unique failure descriptions, allowed us to compose a more structured and well-organized FMECA study. The appropriate use of this methodology helped Kleemann engineers to discuss and analyze the failure modes more efficiently, effectively compartmentalizing their field experience. Furthermore, the modularity of FMECA knowledge was a desired aspect of our final system's model and a functional requirement.

The result of our meetings with Kleemann professionals led to the collection of FMECA knowledge that could provide a solid starting point for our study, model and system use:

Table 5.2. FMECA study size in numbers

FMECA Study Component	# of unique instances
Assets and Asset Components	9
Failure Modes	26
Failure Events (Causes and Effect)	125
Solution Packages - Actions	26

5.3.4 FMECA Study Follow-up and Revision Process

The FMECA study is a repeated process that employs feedback from long or short periods of monitoring its use and effectiveness. Its revision process can include reviewing processes from several factors (management, expert audits, personnel feedback). This knowledge loop, along with the major steps of the FMECA study can be viewed in Figure 5.2. During each stage, software such as our system can facilitate the performance of capturing, organizing and enriching the appropriate inputs and outputs.

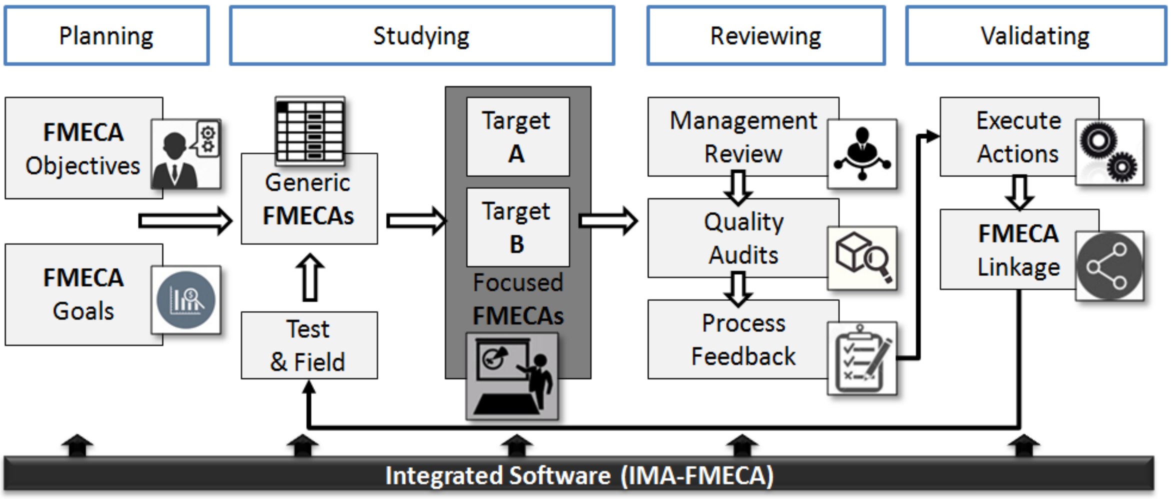


Figure 5.2. FMECA revision process and software integration

The displayed integration couples with activities that often succeed or interface with the FMECA process, and can really benefit from its output. For our study, Kleemann used the delivered results to fuel processes and groups supporting the following actions:

- ❖ Develop and Implement Corrective Actions – Developing new corrective actions, using the full range of available quality and reliability tools. (***Supported by our system***)
- ❖ Review High Risk with Management – Update risk assessments by reviewing all high risk issues with maintenance management and understanding better the handling of related resources and maintenance execution strategies. (***Supported by the integration of our system with CMMS***)

- Audit FMECA Effectiveness – Monitor if and how FMECA meets all quality objectives and record utilization and feedback from associated staff. (***Supported by our system***)
- Link FMECA to Test/Control/Monitoring Plans – Linking FMECA to test and control plans leverages the integration of its knowledge with condition monitoring systems. (***Supported by the integration of our system with WSN monitoring client***)
- Update FMECA with Lessons Learned – FMECA will need to be updated with subsequent test and field failures to create a reliable validation loop that constantly enriches FMECA content with new and contextually relevant failure modes. (***Supported by our system***)

5.4 Pilot Training with Representative Use Cases

The sections that follow, present and describe representative use cases that were used during the IMA-FMECA piloting training and hands-on tutorials.

5.4.1 Confirm a Malfunction in FMECA

This is the most direct and simple use of IMA-FMECA. Its success-end condition is the creation of maintenance metadata from timed confirmation of FMECA events.

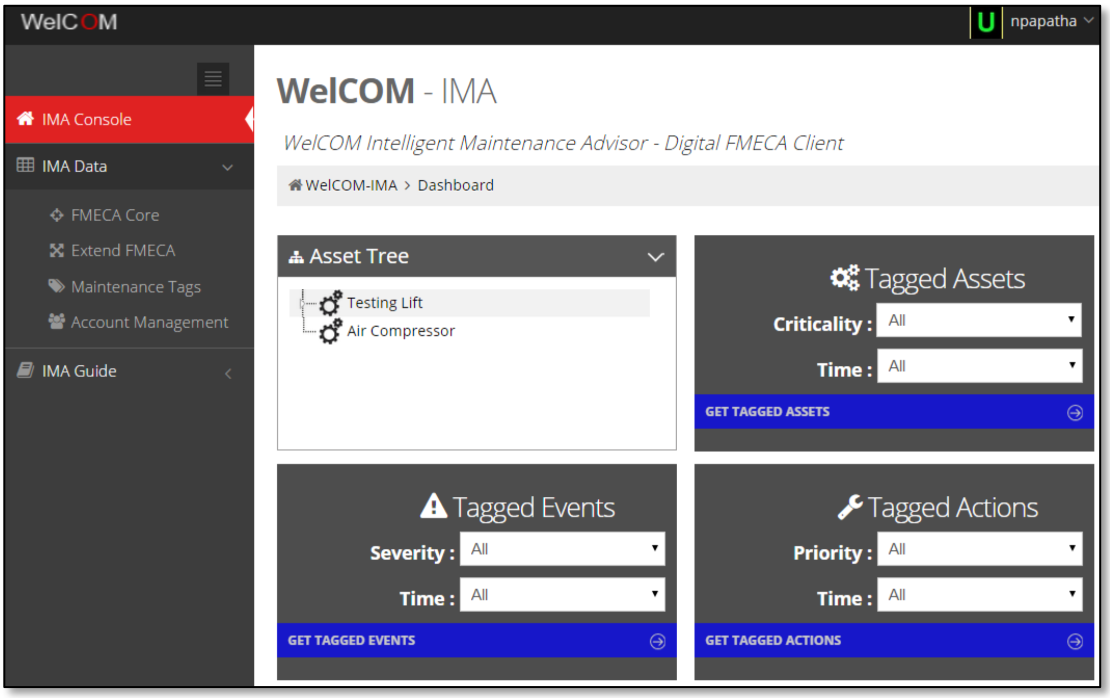


Figure 5.3. IMA-FMECA Dashboard Environment

A noise event is recorded. This can be the result of a monitoring system alarm, or a technician's observation. Experience and closer inspection points at the Lift's Drive Sheave, as the source of the noise. Closer inspection reveals increased vibration. Using a tablet, a technician accesses the IMA-FMECA portal to report the findings. Successful authentication creates a new user-session and renders the IMA-FMECA dashboard environment (Figure 5.3). This interface constitutes IMA-FMECA's starting page and provides access to a few useful widgets: (i) an Asset Tree structure widget for immediate browsing and access to all asset profiles, (ii) three search widgets that support customized filtering of maintenance tags applied to Assets, Event and Actions respectively. The technician uses the Asset Tree and navigates from the Testing Lift to the profile of its Drive Sheave component. From the Drive Sheave's profile the technician has access to related Events and Actions. Two dropdown menus provide access to all different types of Events and Actions. In our case, the technician uses the Events dropdown menu and selects to view the related Malfunction (Figure 5.4). A table of results appear, listing the Drive Sheave's Malfunctions currently present in the system's FMECA knowledge. Upon finding the Events that document Noise and Vibration, the technician uses the "Confirm" direct-tag button to report the current observation (Figure 5.5). The tagging is timestamped and stored as maintenance metadata.

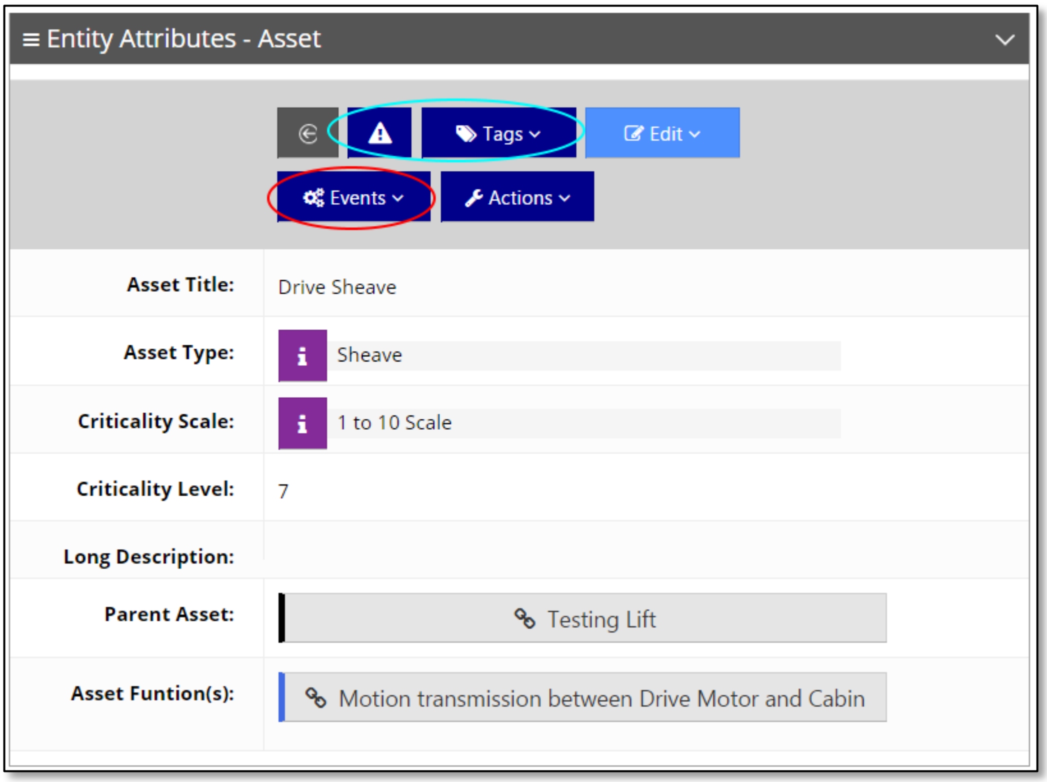


Figure 5.4. Asset profile actions

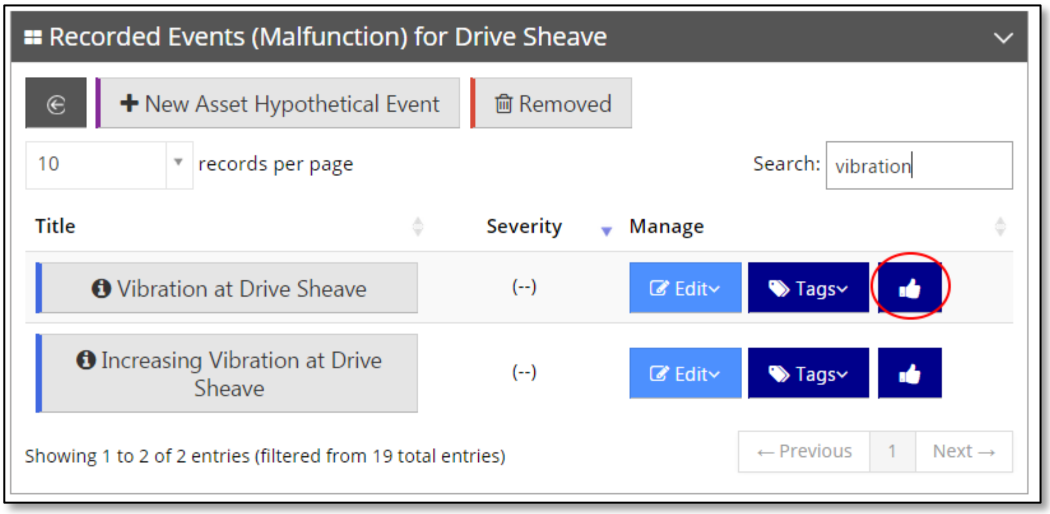


Figure 5.5. Filter and confirm malfunctions

5.4.2 Enter an Observation for a non-recorded Malfunction

In this scenario we present a case where the user does not find the desired information inside IMA-FMECA. The user can handle such a situation, by employing the maintenance tags' mini-forms. Whenever available FMECA knowledge appears not to contain sufficient relevant knowledge, rather than prompting for direct editing by shop-floor personnel, the usage pattern involves minimal user input, as a means for collecting additional insight. Post processing upon collective user contributions will lead to FMECA knowledge enrichment, during its scheduled review.

A technician logs-into IMA-FMECA at the beginning of a shift. At the dashboard interface, the technician uses the appropriate widget to search for recent Tagged Events. The search widget offers the option to define a specific time window, along with a 3-tier (low, medium, high) scale for the severity of the tagged event. The corresponding field in the Tagged Assets and Tagged Actions widget, addresses the criticality and priority level respectively. In this scenario the technician only uses the timeframe option and proceeds with the query. The system presents the requested results as a sorted table (Figure 5.6). Each entry provides information about the applied maintenance tag and the annotated FMECA event. The table is sorted in descending order, according to the annotation time, forming a timeline of maintenance tags. In practice the technician simply gains access to the most contextually relevant information: the recent confirmation of noise and vibration at the Drive Sheave, and decides to take a closer look.

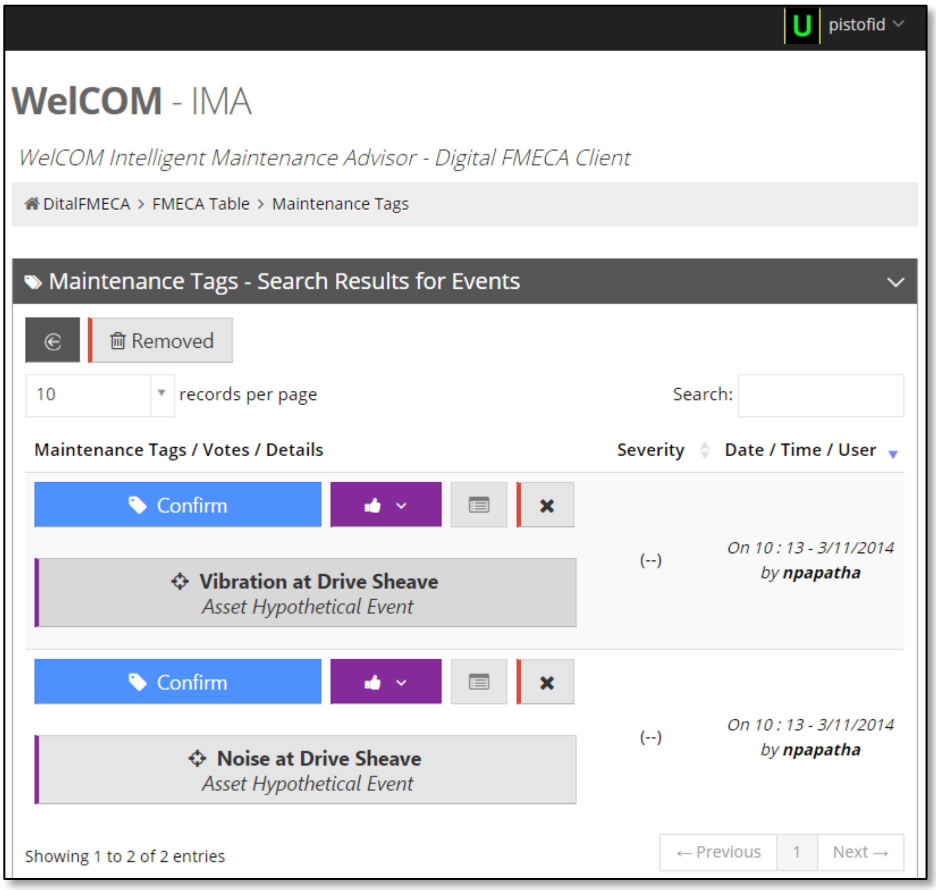


Figure 5.6. Results from searching recently tagged events

The technician observes irregular lift traction. Having become aware of the reported malfunction at the lift's motor drive sheave, the technician uses IMA-FMECA to report the new observation. The technician retrieves a table with all Drive Sheave's Malfunctions currently in FMECA. There are no Malfunctions that refer to traction issues. The technician decides to report this as a new Drive Sheave issue. Using the Asset Tree widget, the technician arrives at the Drive Sheaves profile and applies the "Issue" tag. This only reports the presence of an issue but the technician wants to provide further details. The "Tags" menu, at the Drive Sheave's profile has a "New" option (Figure 5.4). This renders an interface with all available tags and their mini-forms, for annotating the corresponding FMECA entity (Asset). The technician uses the "Issue" tag's mini-form to enter a brief note with his evaluation: "Irregular traction" and then applies the tag (Figure 5.7).

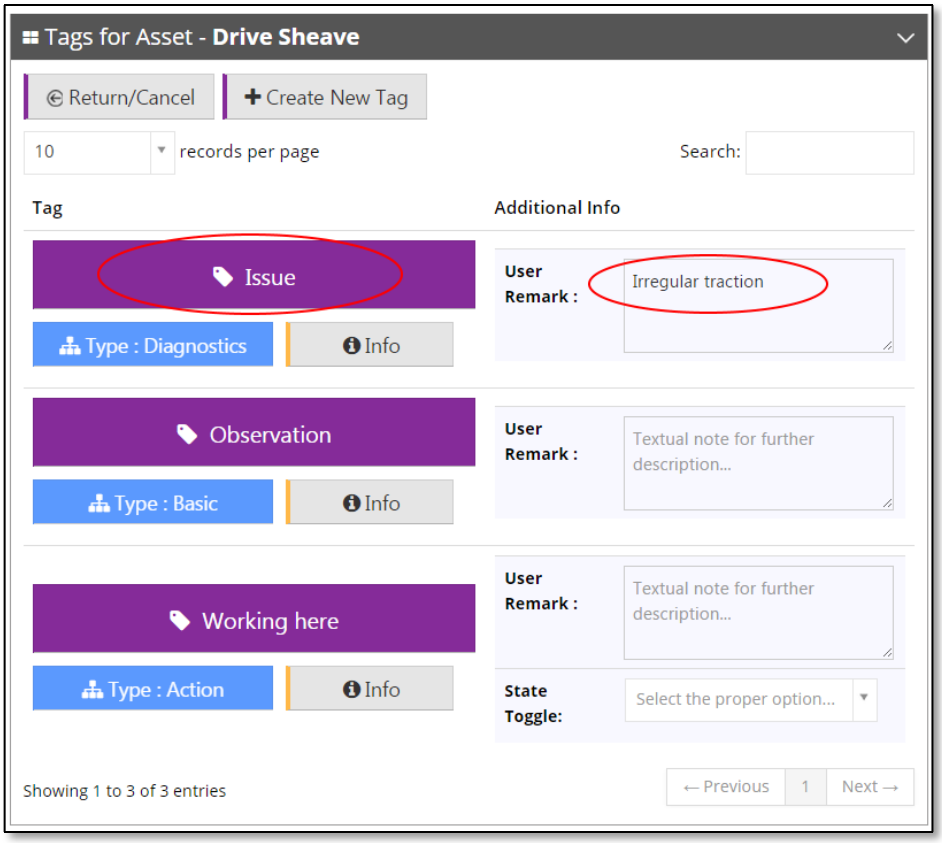


Figure 5.7. Tagging and "Issue" with the use of mini-forms

5.4.3 Processing Failure Context and Failure Mode Confirmation

This scenario presents a typical usage example for the IMA-FMECA's Failure Context. A key context parameter is Time. The faster a user reports a shop-floor event, the more accurate and effective successive evaluations can be. Each confirmed event's value, in the Failure Context, is dynamically weighted by supervising staff expertise and perception. The time distance, the severity and the type of the event, support reaching an informed decision.

Continuing from the previous scenario, the next day the technical supervisor checks which events have been tagged. Using the dashboard widget, the supervisor finds out about the confirmed noise and vibration at the Drive Sheave. To collect more information about the Drive Sheave's history, the engineer uses the "History" option of the "Tags" menu. The supervisor spots that the last "Issue" tag was applied by the second technician and consults the tagging. Checking to see if there is a bigger issue, the supervisor selects the "Failure Mode" option from the "Events" menu of Drive Sheave's profile. A sorted (by severity) table with all related Failure Modes is rendered by IMA-FMECA. While scanning the profile of each Failure Mode, the supervisor is alarmed by the profile of "Drive Sheave's bearing fault", at Severity scale "Very High". Processing this profile reveals the following (Figure 5.8): (i) both noise and vibrations are recently confirmed symptoms, (ii) the effect "Wear at the Drive Sheave's grooves" was confirmed last week by an engineer, (iii) the issue "Irregular lift function" was entered the previous day by a technician, (iv) the effect "Rope deflection" is tightly related with irregular traction (reported at the "Issue" tag) and should be averted at all costs. The engineer inspects the Drive Sheave's bearings and finds evidence of advanced wear. The event is reported by the supervisor, who uses the direct confirm button at the "Drive Sheave's bearing fault" profile (Figure 5.9).

Though "Wear at the Drive Sheave's grooves" was tagged last week, it constitutes a Drive Sheave's Failure Mode and thus contains elevated diagnostic value. Furthermore, the causality link between the two Failure Modes documents IMA-FMECA's ability to generate a graph of events that can support Fault Tree Analysis (FTA).

The above scenario illustrates the way an IMA-FMECA user can traverse, process and enrich the failure context. It comprises a number of steps, each of which somehow facilitates or builds upon certain context aspects (Figure 2.8) properly adapted to describe and support maintenance practice:

- Search and list other user's maintenance tags (social context), relevant to events and assets that belong in the users responsibility domain (user context)
- Search, list and navigate through the links of the failure mode profiles relevant to the alarming tags. Process each profile and interpret its history of tagged linked events (service context)
- Review shared user's findings (social context) and evaluate their importance to assess the need for further action (service context)
- Diagnose the occurrence of a failure mode (service context) and confirm with maintenance tags, to share this decision and invoke appropriate action (social context).

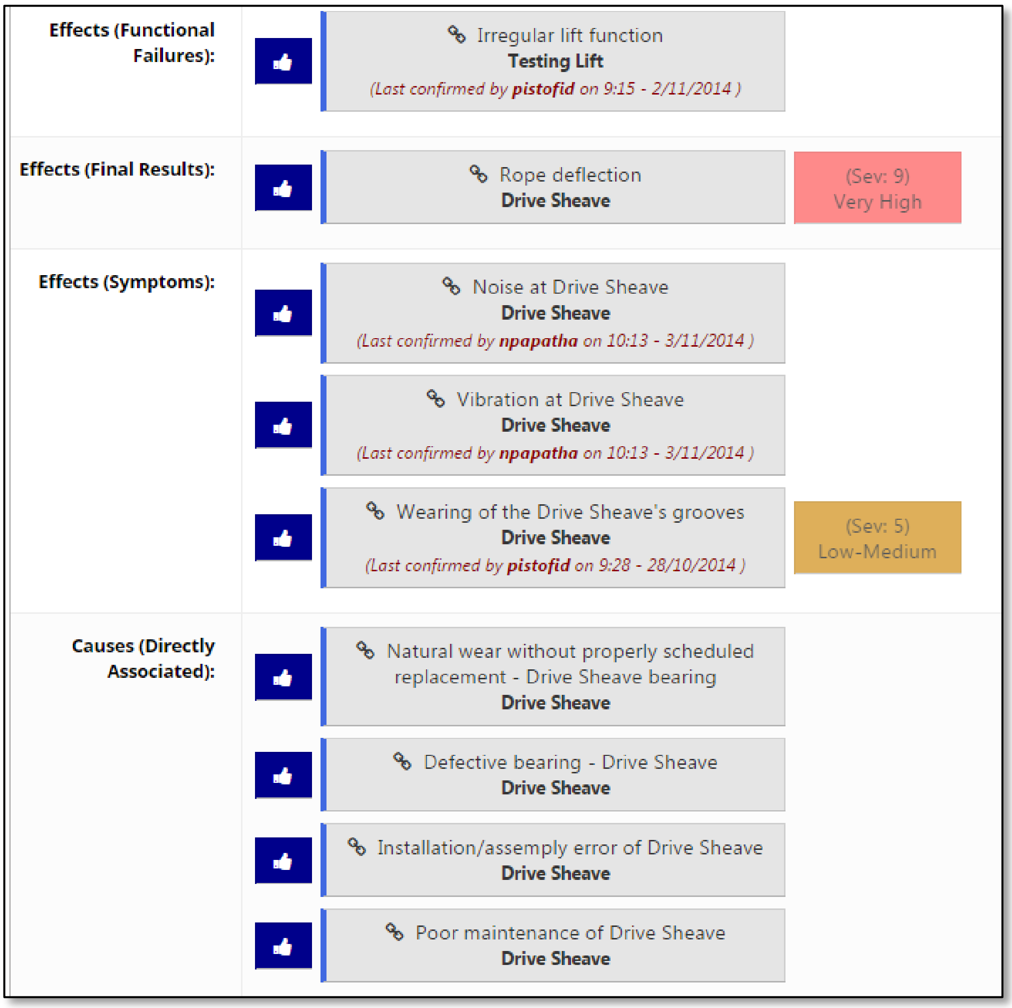


Figure 5.8. Failure mode profile - Failure Context

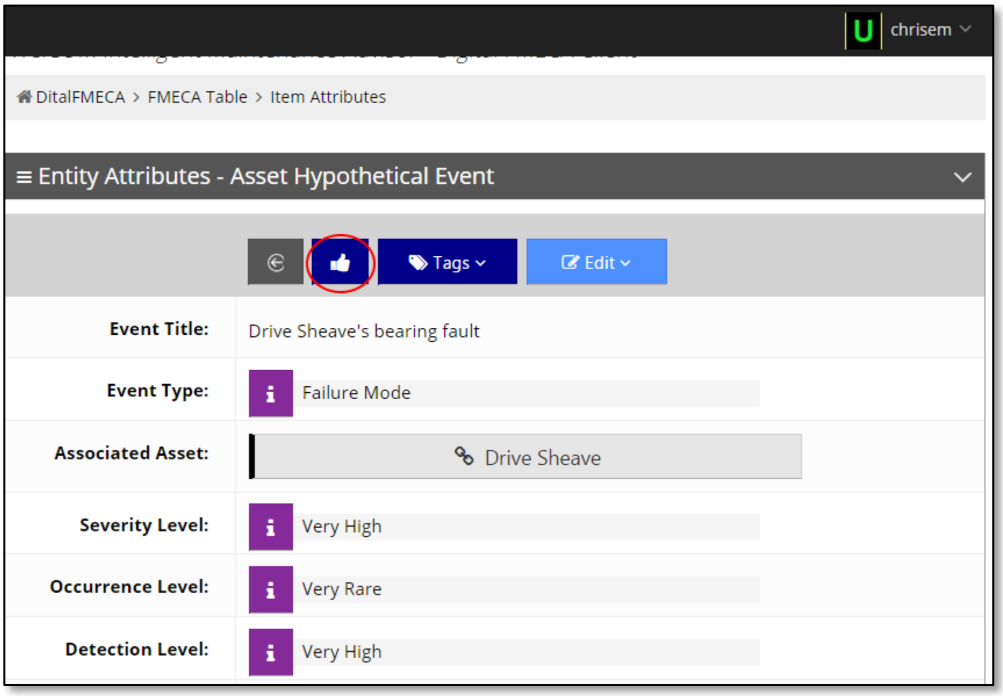


Figure 5.9. Confirmation of a Failure Mode (Hypothetical Event) profile

5.4.4 Cross-examination and Voting - Maintenance Action

A Vote is a simple and direct method to state a consensus upon an evaluation. It can reduce the amount of similar/identical tags and helps IMA-FMECA to rank-up the maintenance value of single tags.

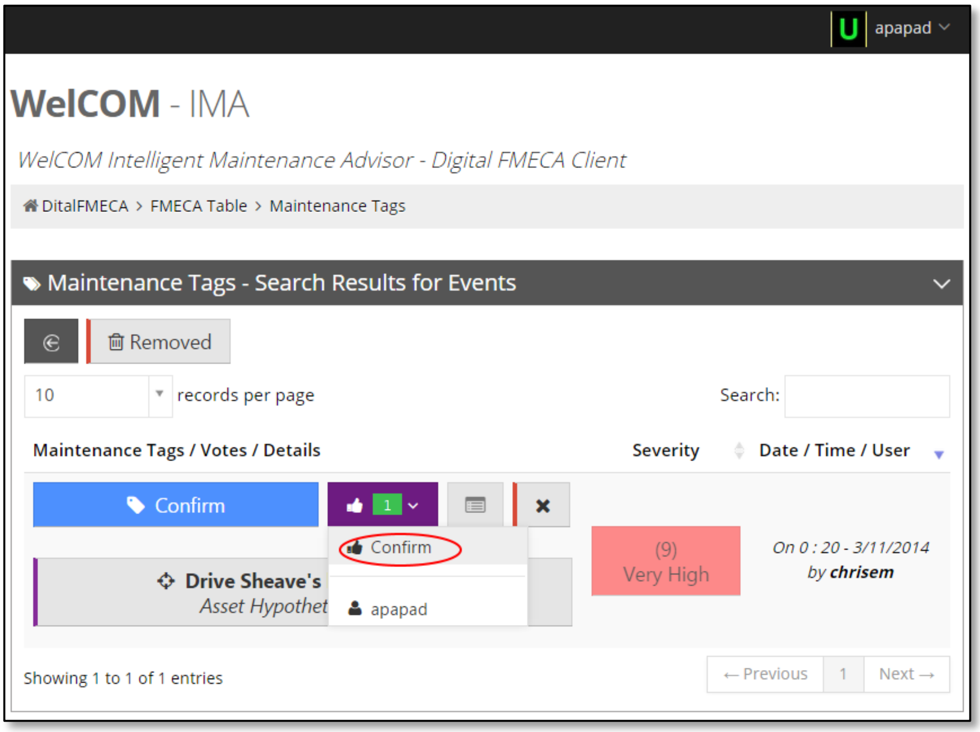


Figure 5.10. Positive votes for applied maintenance tags

Having to meet with external contractors and suppliers, the director of technical services spends the day outside the industrial compound. Employing a tablet checks only for tags that need immediate attention, Tagged Assets and Tagged Events widgets are both used through the Dashboard. The corresponding queries prompt for tags applied to high criticality Assets and high severity Events, during the last day. The Failure Mode confirmation by the supervisor is spotted, along with the issue note of the second technician. Processing again the Failure Modes profile, the manager agrees with the immediate reporting and votes positively the corresponding confirmation tag (Figure 5.10). A positive vote is also placed at the technicians Issue tag. Checking the proposed maintenance actions, at the Failure Mode's profile, the manager uses the appropriate direct tag button to "Schedule" the Drive Sheave's bearing replacement (Figure 5.11).

The use of "Schedule" tag and votes, are presented here. "Schedule" is available for direct tagging, at Event profiles with a button next to each suggested maintenance action. Using "Tags"→"New", from the Action's profile, allows the user to access the mini-form of "Schedule" (or any other supported maintenance tag).

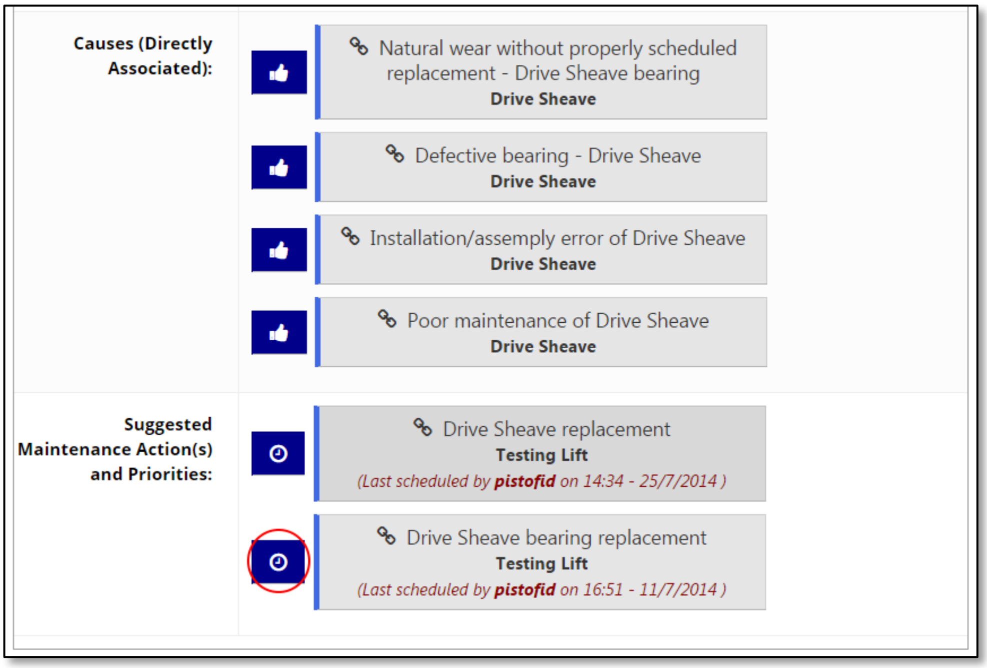


Figure 5.11. Use of "Schedule" tag for proposed actions

5.4.5 Update FMECA - Create new Maintenance Tags

The last usage scenario presents how the collected maintenance metadata can be processed and consumed to upgrade both FMECA knowledge and system functionality. The results of a simple tag history mining, can easily lead to insight that may benefit FMECA coverage validation and refinement.

The time for a planned FMECA revision has been reached. Senior staff gather to evaluate the tagging history of each critical asset and failure mode. They find out that traction issues have been repeatedly reported for the lift, along with Drive Sheave issues. In all cases, the "Issue" tag mini-form was used to describe the traction issue. Given that specific Drive Sheave's Failure Modes were confirmed right after such tags, the FMECA review group decides to include lift traction issues in FMECA knowledge. The appropriate Event is created and linked to the mentioned Failure Modes. The group also detects a common action pattern of "Replace a part or equipment" inside FMECA. While such actions are very rarely scheduled for large assets, they seem quite common for smaller equipment and parts. They decide to start the pilot use of a new "Replace" tag. It can be applied to Asset components and will support textual note for additional feedback. The collected tag timelines can offer insight for both maintenance and logistics and act as a triggering mechanism for services of the later.

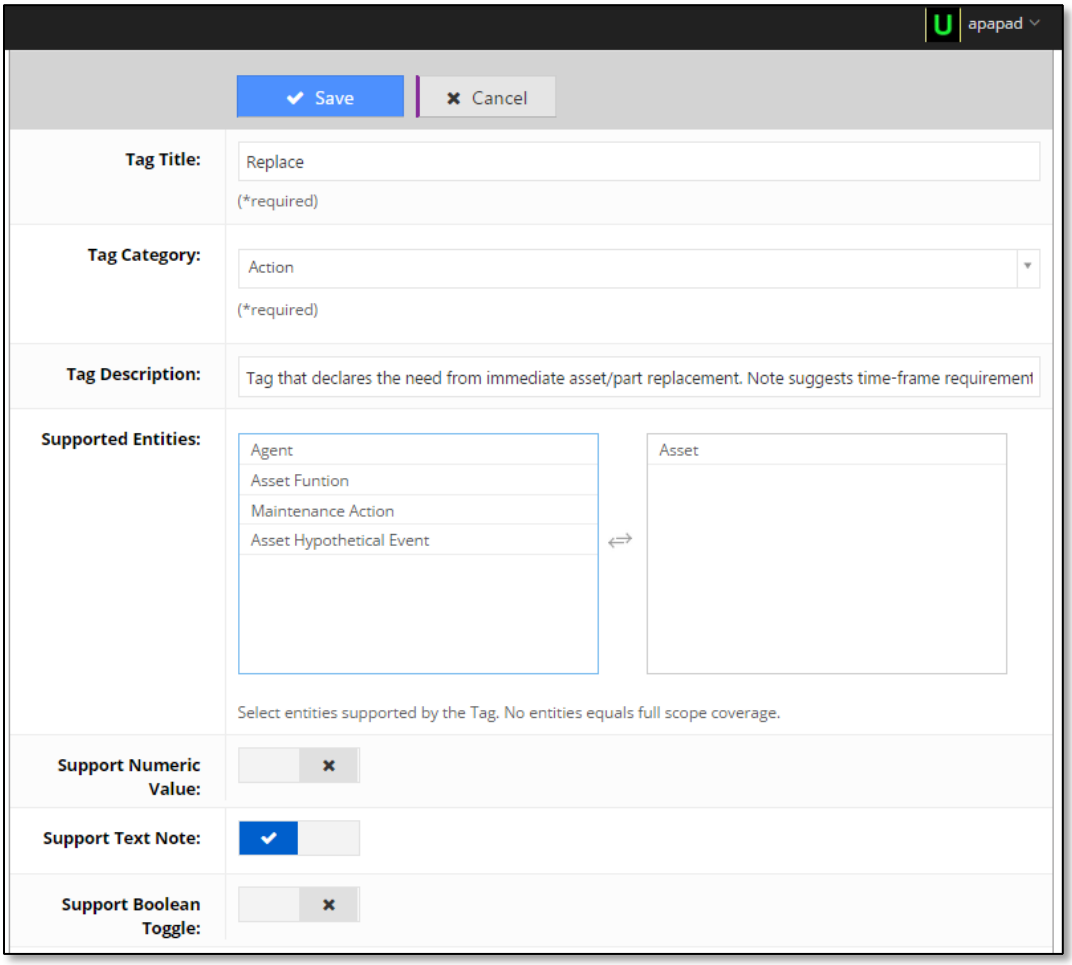


Figure 5.12. Creating the template for a new "Replace" tag

5.5 Pilot Case Study - Hydraulic Lift

During IMA-FMECA's application time-window, on the industrial field, the system supported personnel in documenting asset conditions and relevant to them actions. Experiments were performed on several assets, including a 15-storey building test lift. To explain system usage, we have chosen to focus on a representative case of a hydraulic lift, as this lift type has a very wide residential and office installation base. The lift, operating for approximately 10 years at Kleemann offices, has a cabin move distance of 6610mm, 600kg of load carriage capacity and a typically slow movement of 0.5m/sec, involving three stops. Preventive maintenance is performed on monthly basis. In parallel with IMA-FMECA piloting, a prototype monitoring system was used. Vibration was monitored via an accelerometer positioned at the cabins' roller wheels aimed at detecting deviation from expected operation patterns (Katsouros et al., 2015).

5.5.1 Piloting Case Process Flow

Figure 5.13 displays a process flow that describes the IMA-FMECA usage during piloting. The case developed as follows:

1. Using IMA-FMECA tool a maintenance engineer has entered initial FMECA information for the lift.
2. A maintenance technician detects a subtle but distinct noise inside the cabin. Not being able to find an FMECA event that accurately mapped the observed noise, the technician tagged the hydraulic lift with an *issue* and a *textual note* describing the sound.

3. The monitoring system records higher vibrations(Figure 5.14) 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. It was clearly an effect of poor movement of the cabin on the guides. The corresponding FMECA events were tagged as *confirmed*.
5. A maintenance expert, having viewed the three tags, suspected a problem with the roller wheels and ordered a closer inspection. The lift has a glass exterior and is exposed to sun-heat and dust (environment conditions). The dirt on the roller gradually damaged the rubber of two wheels. The respective FMECA events were tagged by an expert, *confirming* wear on the roller wheel rubber (failure mode), alerting the maintenance supervisor.
6. The maintenance supervisor, having access to the previous tags, *schedules* a recommended action for wheels replacement. Using the tag *mini-form*, the supervisor labels the action to be of moderate urgency and thus scheduled together with the next lift maintenance. *Votes* were applied to key assessments.
7. The next scheduled maintenance was 6 days later. Thanks to the confirmed tagging, the team was ready with all necessary spare parts to replace the roller wheels, which are normally only replaced after a few years of operation. Thus, IMA-FMECA increased the efficiency of maintenance.
8. The monitoring system records lower vibration levels (Figure 5.14).
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, thus supporting enhancement of relevant knowledge.

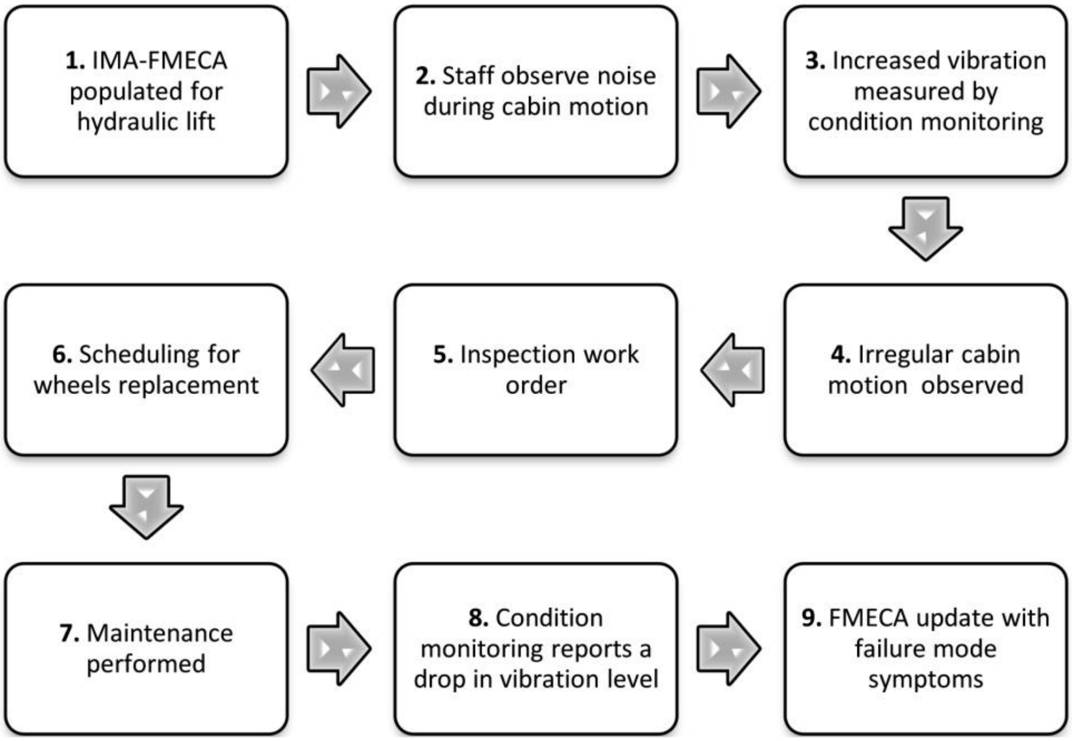


Figure 5.13. Application Case Process Flow (Pistofidis et al., 2014)

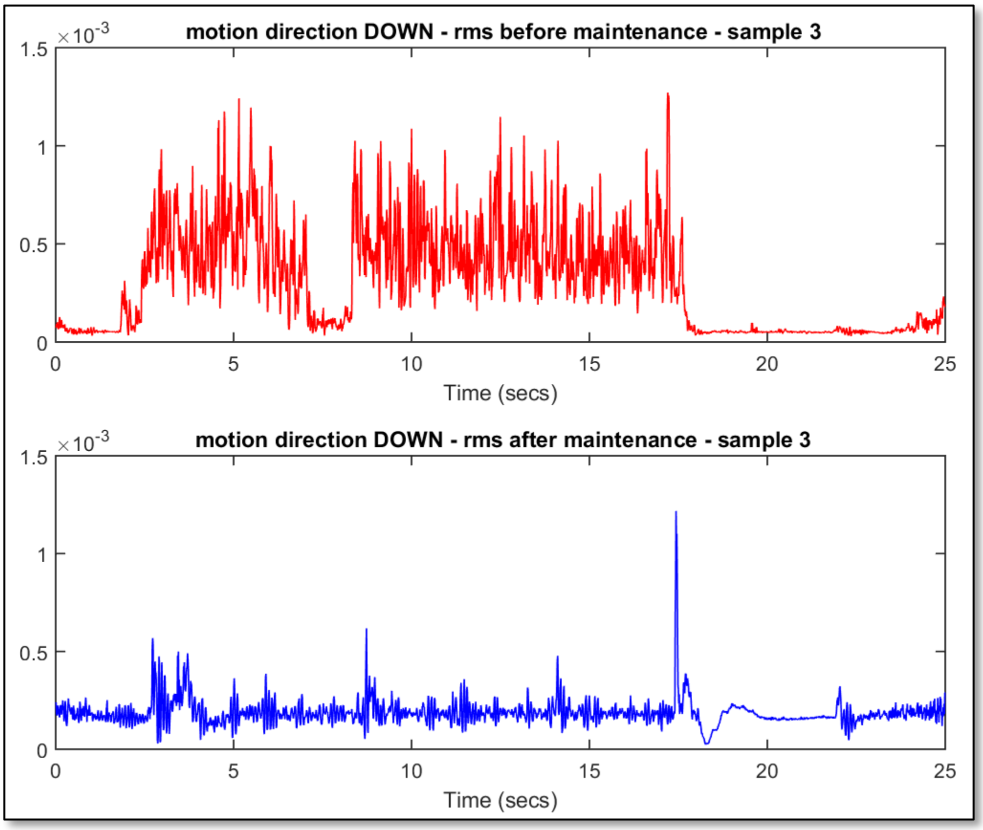


Figure 5.14. Symptoms Identification (Katsouros et al., 2015)

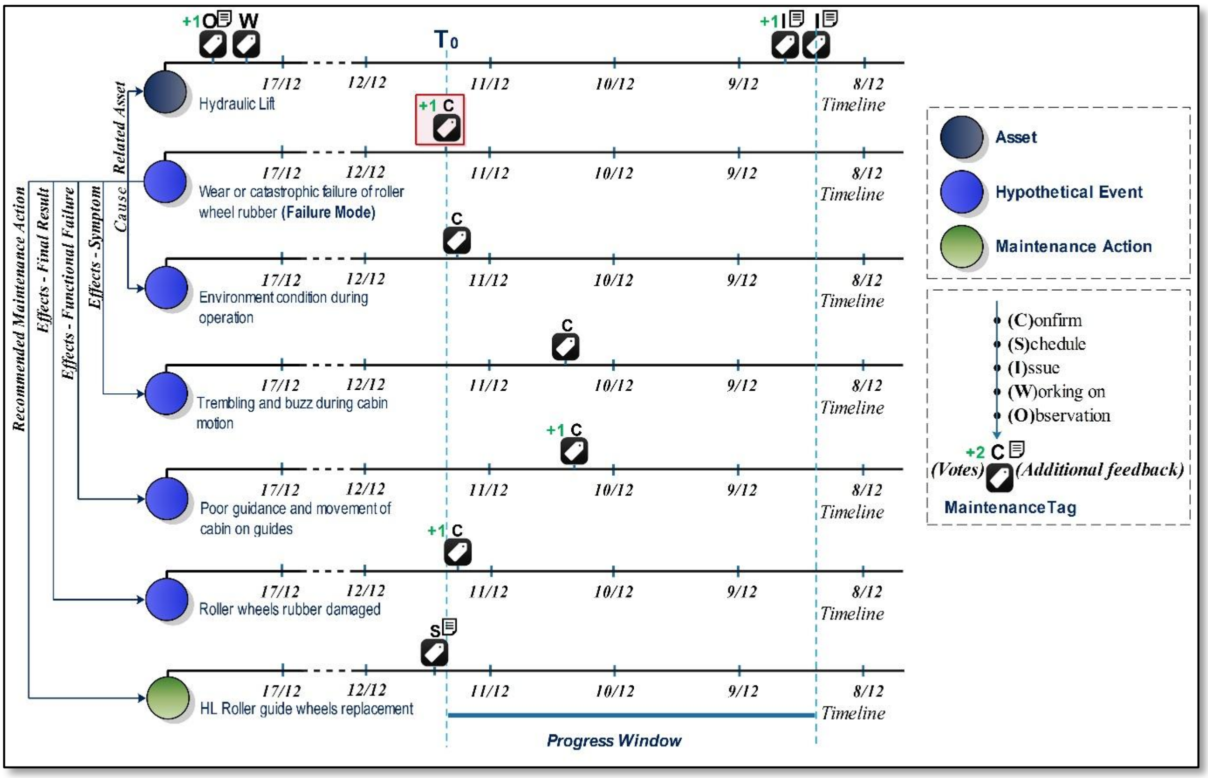


Figure 5.15. Application case micro-knowledge timelines

Each step involves evaluations and decisions that are reported through the use of tags. The respective timeline of actions is visualized in Figure 5.15, presenting the scenario's progress and tagging timestamps. Figure 5.16 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.

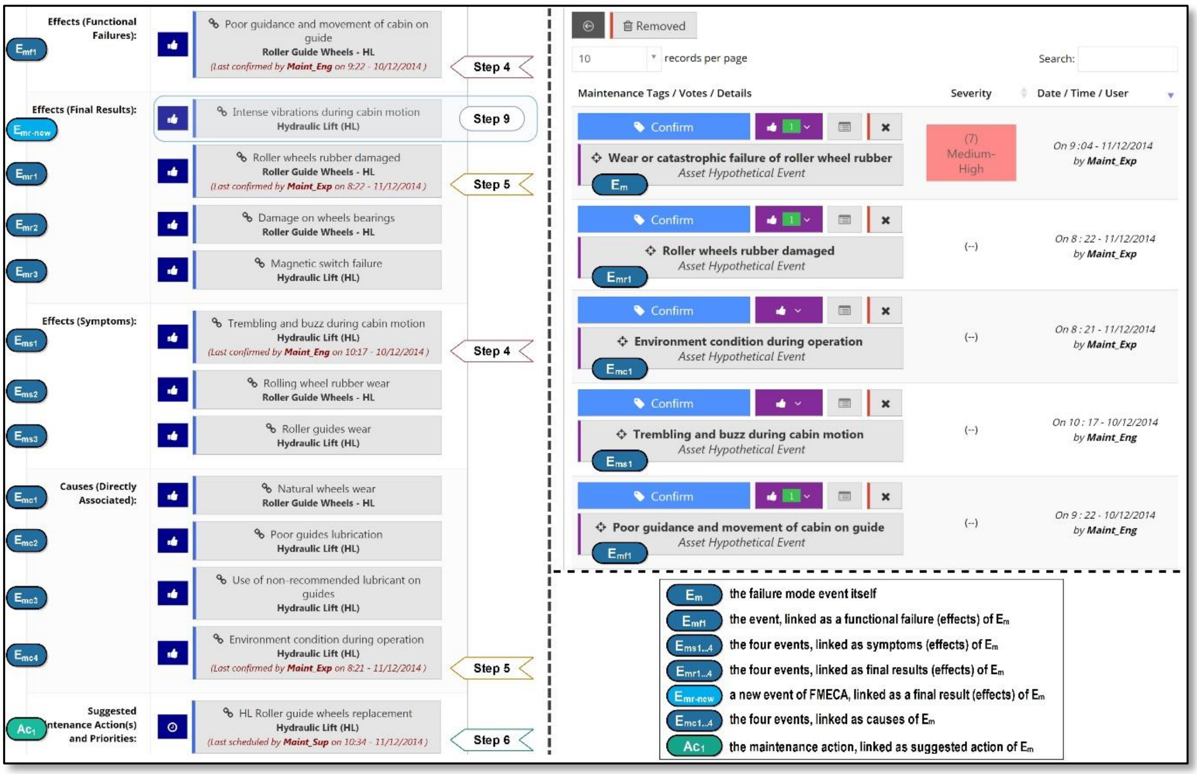


Figure 5.16. Hydraulic lift's (HL) failure mode profile and tagging/voting timeline

5.5.2 Piloting Case Analysis

Table 5.3 tracks all the micro-knowledge validated in the scenario. Expanding on our analysis from the arbitrary example of chapter 3, we now study all the produced micro-knowledge for FMECA content, linked with the profile of the confirmed failure mode $\mathbf{E_m}$. This extended truth table now also contains micro-knowledge produced though the tagging of assets and maintenance actions relevant to the confirmed failure mode. For each micro-knowledge entity the validated proposition is recorded. 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.

Votes constitute a good example of how meta-knowledge can be captured with simple semantic mechanisms. Table 5.3 also records the voting propositions for our application scenario. The list presents votes relevant to the specific failure context. Analysis of these propositions can reveal: (i) if and how much additional feedback is appreciated when provided; (ii) which type of micro-knowledge is voted more, both in terms of specific tags or specific FMECA content; (iii) what is the average time-locality of voted micro-knowledge, and many more. Such simple metrics can help experts to balance and estimate the knowledge value of each tag and annotated FMECA content.

Table 5.3. Truth table for the propositions and votes

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

Micro-knowledge propositions are produced using the formalizations introduced in Chapter 3. Table 5.4 provides the full text description for representative micro-knowledge propositions of our presented case.

Table 5.4. Translating micro-knowledge propositions

(Maint_Tech, As)	(M) Maintenance technician detected unknown issue on hydraulic lift **And** (F) He detects a subtle but distinct noise from inside the cabin **And** (V) Maintenance supervisor aggress with this assessment.
(Maint_Exp, E_{mr1})	(M) Maintenance expert confirmed the occurrence of worn roller wheels rubber **And** (V) Maintenance supervisor aggress with this assessment.
(Maint_ Tech, As)	(M) Maintenance technician is working on the hydraulic lift **And** (F) Performing scheduled maintenance, replacing damaged roller guide wheels
(Maint_Sup, Ac)	(M) Maintenance supervisor scheduled HL roller wheels replacement **And** (F) Action of moderate urgency be performed during next regular lift maintenance

Table 5.3 is an example of how knowledge can be incrementally captured for a failure mode. Each new failure mode occurrence can be recorded with additional micro-knowledge. Moreover, each new custom tag template can expand the table's knowledge capacity with additional possible propositions. The number of votes and the sequence of each tag are indicators of the proposition's ranking and maintenance value inside the failure context. Studying the failure mode occurrences' records, we may identify a pattern where $M_c(U, \mathbf{E_m})$ *satisfies a set of propositions*. This is equivalent to deciding the validity for the deduction of $M_c(U, \mathbf{E_m})$ from the concurrent validity of propositions. For the studied case:

$$M_c(U, \mathbf{E_{mf1}}) \cap M_c(U, \mathbf{E_{mr1}}) \cap M_c(U, \mathbf{E_{ms1}}) \cap M_c(U, \mathbf{E_{mc4}}) \Rightarrow M_c(U, \mathbf{E_m})$$

The information of Table 5.3, along with the annotation timelines of Figure 5.16, form a knowledge overview that enables maintenance staff to review and study the failure context's provenance. While the knowledge and micro-knowledge handling functionality is undertaken by the tool, the results are eventually presented to the users via simple and intuitive interfaces, enabling a quick understanding of the failure context and empowering them to act upon it.

5.6 Pilot Evaluation and Results Discussion

This section documents the findings and results of IMA-FMECA's evaluation. We discuss important comments and evaluation points that helped us understand how to enhance the usability of our system and perceive prospects for its use and further development. The industrial end user staff that participated in the piloting offered a first real indicative assessment of the tool's usability and value. Overall 16 staff members participated and completed evaluation questionnaires through interviews.

5.6.1 Evaluating the IMA-FMECA Provision Pattern

The majority of Kleemann's maintenance personnel reported a high level of familiarity with portable devices, both inside and outside maintenance practice. All agreed that reference knowledge of failure modes and suggested actions, is highly appreciated, when provided on-the-job and through portable devices. Mobile access to e-Maintenance services was clearly favoured over the use of desktop applications and complex software suites. The rating gap shows that maintenance personnel has a positive attitude towards e-Maintenance mobility. Smart-phone ratings were very close to tablet's, since most staff were also users of smart-phones that featured five to six inch displays. Fixed access points with wireless tablets were considered as a more practical alternative for staff with situational needs for the tools functionality. Such access points can support the progressive use of IMA-FMECA, from shop-floor personnel that need not carry a device but can benefit from the provided knowledge.

5.6.2 Evaluating the FMECA Knowledge

Kleemann's maintenance staff all agreed that shop-floor expertise can decisively contribute to the quality of FMECA knowledge. Most stated that during their everyday tasks, they reference and receive diagnostics advice and support, from machine manuals and other hardcopy material. They also stated that the provided FMECA knowledge from such material is limited to a simple association between brief event descriptions and single maintenance actions. Allowing them to rate the maintenance value for each component of IMA-FMECA's failure mode profile, we measured how they prioritize the related knowledge. Combining the results with interview remarks and comments we recorded the following:

- The knowledge of failure effects constitutes the most valued component of IMA-FMECA's failure mode profile. Engineers pinpointed that available resources for diagnostics lack the organized knowledge of how certain effects and events participate in more complicated failures. Both maintenance engineers and technicians stated that small and medium sized failures can be detected with almost no support, since the related effects and behaviours can be perceived by personnel either from manual referencing or from basic shop-floor experience. What cannot be easily detected, is how each different failure or effect contributes in slow-progressing failure modes that are not well-recorded in manuals and are tightly related to the specific machinery deployment/installation. 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. This is the kind of information that results from a carefully planned FMECA study and populates profiles such as the one's available in IMA-FMECA.

- The second most valued component of IMA-FMECA's Failure Mode profile is the suggested actions. Though maintenance staff acknowledge the convenient use of manuals that draw direct connections between specific events and appropriate actions, they also require the scaling of such information and the power to do so themselves. FMECA at shop-floor was reported as a great reference for alternative solutions, providing also more depth (action steps) and sequence support (action priority) in maintenance practice. Referencing the work-steps from a CMMS generated work order, maintenance technicians identified IMA-FMECA's benefits from allowing similarly structured maintenance actions to participate in Failure Mode's profile.
- The third most valued component is the IMA-FMECA's feature to allow extension of FMECA semantics. Customizability was right from the start appreciated by engineers and technicians. Allowing access to editing severity, criticality and priority scales was welcomed but not facilitated during the piloted use. Both technicians and engineers decided to maintain and adapt to the levels defined by the conducted FMECA study. Event, asset and action taxonomy is where engineers were initially most interested in. After IMA-FMECA's first piloted week, Kleemann's engineers created new types of events, assets and actions that best suited their needs. During the second piloting week and an extensive usage of maintenance tags, engineers showed increasing interest in organizing their own custom tag templates with more tag categories. This indicates how customizability motivates experts to offer their own additional insight.
- The failure mode's causes, were rated as the fourth most useful FMECA knowledge component. Causes provide a path for back-tracking the causality of events. The causes in a failure mode's profile, can be perceived as links to events that reference this failure mode as an effect in their own profile. Though it contributes in IMA-FMECA's prospects for supporting FTA and RCA (Root Cause Analysis), it is not always a standard component of FMECA and its effect-reversed semantics can be sometimes misinterpreted by maintenance technicians. While R&D engineers understood and discussed the prospects of cause semantics, shop-floor engineers could not find significant value in everyday practice.

5.6.3 Evaluating the IMA-FMECA Interfaces

Testing the functionality of IMA-FMECA's enterprise application, Kleemann's staff evaluated its appearance, usability and responsiveness (Figure 5.17). Appearance and usability were rated "Very Good", with maintenance engineers appreciating the balanced content per view and the intuitive interface design. Responsiveness was overall rated as "Good" with small network delays when accessing remote services and/or the remote database deployments. The final user-experience was a result of design adaptations that had already been implemented and incorporated, after an early evaluation from the director of technical services. These adaptations pointed us to downgrade the complexity of certain interfaces, to simplify interactivity and help the technicians better understand the functional context and their available options. Although we hypothesized that direct tagging and short navigation paths would be more easily accepted by users, we initially left these features unaddressed. Related feedback, from the director of technical services, pinpointed their importance, and they were later introduced into IMA-FMECA. Since timing and usability were top in IMA-FMECA's priority list, the appropriate interfaces and service were updated to provide a faster tagging functionality. Both maintenance technicians and engineers positively appreciated the overall look-and-feel of their browsing experience, acknowledging the usability of touch-optimized layouts (i.e. the application theme) with responsive components (i.e. automatic filtering search fields).

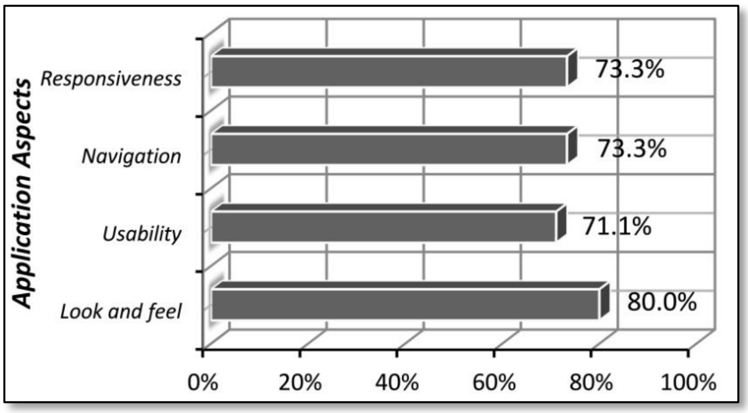


Figure 5.17. Average user rating for IMA-FMECA tool

Assessing the ability of IMA-FMECA to provide qualitative FMECA content, Kleemann's staff were asked to rate and comment upon the time-to-reach the desired knowledge and the failure mode's profile coverage(Figure 5.18). The time-to-reach was rated overall "Good", and the profile's coverage for appropriate knowledge was rated "Very Good". Maintenance technicians appreciated the detailed information presented in a failure mode's profile, but needed more time to get accustomed to browsing FMECA through tablets. On the other hand, maintenance engineers had no problem while navigating FMECA, and even provided useful feedback on how IMA-FMECA's rendering engine could better prioritize the displaying sequence of failure mode's information, for quicker consumption by the user. Though dense linkage of profiles was comprehensible and exploitable by engineers, technicians found it less useful and sometimes confusing. When discussed during the interviews, it was clear that visually uniform links were creating some confusion or distraction. This sometimes resulted in the delayed arrival to desired knowledge and its tagging. Customizing the rendering engine, a visual classification of links was made so that each of them was easier to perceive and distinguish.

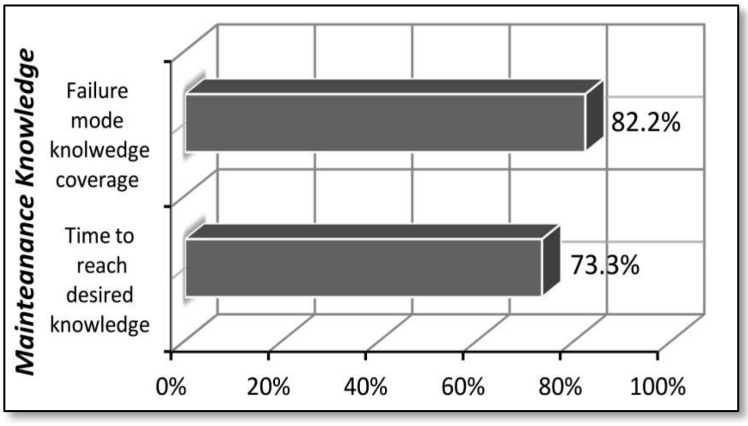


Figure 5.18. Average rating for knowledge features

5.6.4 Evaluating the IMA-FMECA Metadata Management

Technicians and engineers understood how IMA-FMECA's capitalizes in the time dimension of the Failure Context. IMA-FMECA helped them understand the FMECA value and how maintenance tags implement the instantiation of their reports. Both appreciated(Figure 5.19) the direct reporting via tags and the direct connection of their remarks with representative FMECA knowledge. Technicians valued this approach, and stated that many maintenance supporting software systems still require a lot of off-duty data entry. The lack of mechanisms to record timely input and the disconnected diagnostics mindset of the maintenance user, were stated by engineers as important factors behind the empty forms of such IT systems. Maintenance engineers almost instantly identified the potential of maintenance tags in streamlining the reporting process. They appreciated the automated clustering of maintenance feedback around FMECA and its classification based on the well-defined tag semantics from the maintenance function. Right from the start they understood how each default maintenance tag could benefit the corresponding maintenance task or analysis: (i) "Issue" tags as a direct alert for Assets, (ii) "Confirm" tags as the milestone of the Failure Context timelines and (iii) "Schedule" tags as the timely decision for maintenance action. Having used the dashboard's widgets to work and interpret timelines of maintenance tags, technical staff was aligned with IMA-FMECA's targeted functionality and R&D engineers could visualize the prospects of performing analytics.

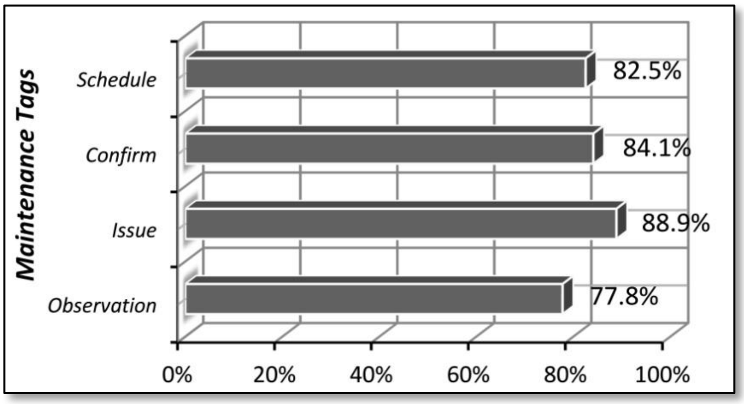


Figure 5.19. Average rating for tag's knowledge value

The field application, provided evidence of how IMA-FMECA can streamline maintenance feedback and support, especially demonstrated on the application case of the hydraulic lift. Technicians and engineers were able to tag FMECA content, while explicit evaluations/notes were provided only when there was something more to report. 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.

5.6.5 Evaluating IMA-FMECA Success Factors and Key Results

The results of our pilot study are directly attributed to a set of essential contributing factors. All the participants from Kleemann's maintenance department actively contributed with their field knowledge, analytic skills or administrative actions. The piloting schedule was effectively planned and attuned with a Kleemann's major maintenance program. Our piloting periods were effectively supported by WelCOM's condition monitoring equipment and tools (wireless sensor networks). Appropriate technology infrastructure and connectivity, was available to support the IMA-FMECA provision pattern and deployments. Finally, the FMECA team had access to adequate material to properly extract and process the targeted knowledge for Kleemann's asset diagnostics.

From the first introduction of the tagging methodology, engineers and R&D staff discussed the ability to expand functionality with more tag templates. While testing the use of tags, engineers proposed new template descriptions that specified a more focused use for the tag's mini-forms. After the first piloting session, the "Working on" tag template description was updated, so that the additional note can reflect the status of the maintenance task and the numeric value can provide an estimation for the completion percentage(function context). The "Schedule" template's description was also updated, so that the additional note can provide a specific date and/or time for the requested maintenance action(time context).

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 linked data between two important maintenance knowledge sources: FMECA and maintenance practice. The pilot case demonstrated how a metadata management system can effectively bridge and improve such knowledge, and do 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.

5.7 Summary

The purpose of this chapter was to map and document all the stages of our system's application case. Starting with explaining all the aspects of our pilot methodology and definition, a detailed plan is then offered for the FMECA study that was conducted in order to accurately analyze their failure modes. For each asset a representative set of failure modes were profiled with the help of Kleemann's maintenance and design engineers. Related to that effort, it became necessary to understanding specific FMECA process steps, priorities and revision policies. It was important to develop a knowledge pool with the potential for encompassing the totality of the agreed FMECA diagnostics. This goal was accomplished with the support and valuable insight of maintenance experts, along with the vital coordination of WelCOM's project manager and Kleemann's director of technical services.

Once the fundamental stages of the FMECA study were completed, the produced information table was digitally stored in the system's model. The populated system was then piloted during various sessions, by different roles of maintenance personnel. Initially a set of representative use case scenarios allowed technical personnel and engineers to familiarize themselves with the system functionality and its interfaces. Kleemann's maintenance department was then able to use the system in real scenarios, allowing its staff to reference, extent and tag the FMECA content. One such scenario is discussed in great detail, explaining all the steps that validate the system's ability to offer FMECA advise services, a tag-oriented reporting tool and constant knowledge enrichment.

Both pilot testing and application usage were followed by an evaluation process that was comprised by a questionnaire for the maintenance and design engineers, complemented by interviews for the director and maintenance experts. The evaluation results and their extensive discussion was provided at the final section of this chapter.

In conclusion, the performed piloting described in this chapter involved maintenance personnel that already had extensive experience with e-Maintenance support systems. Taking into account their feedback during the design, implementation and piloting phase, the following contribution from the use of the IMA-FMECA system, has been recorded:

- ✓ The FMECA model attains increased shop floor relevance, by functionally and semantically moving it closer to maintenance practice. Maintenance staff could easily comprehend, use and enrich the relevant knowledge pool by accessing on-demand context-depended information views, through the use of tablets. Appreciating the immediacy of their involvement and the potential impact of their contribution, mobile maintenance staff were motivated to engage in what is essentially a collective knowledge fusion process. Maintenance managers considered FMECA as a more successful knowledge asset, when validated and upgraded by shop-floor expertise. Thus, IMA-FMECA becomes a tool that facilitates a shop-floor validated <u>knowledge support</u>.
- ✓ Maintenance tags have been a welcomed commenting shortcut for maintenance personnel that function on the shop-floor and on-the-move. The annotation process is simple and involves the mere flagging of FMECA content with predefined comments, thus easing their contribution. Maintenance engineers perceived maintenance metadata as a method to track how often reference diagnostics apply to real practice. Since the collected history of tags was instantly updated and available to them through a richer event profile (the failure context), engineers were able to produce many and interesting ideas on how tag semantics could better fit their everyday shop-floor needs. In this way, IMA-FMECA becomes a tool that facilitates relevant shop floor maintenance <u>knowledge capturing</u>.
- ✓ During the piloting of IMA-FMECA maintenance engineers updated the FMECA model with event types that were very common and informative of their daily diagnostics. As a result, a considerable number of tags were applied upon content that was just introduced through the extension of FMECA. Extensibility and user-control are important elements to motivate greater participation. Maintenance staff found it very useful to search, browse and filter the collected tags. Having their feedback being driven with predefined semantics and a relatively simple FMECA model, allowed them to understand the prospects of analytics. Their tags were automatically clustered around the FMECA knowledge and were classified by the tag semantics. Being able to produce timelines of provenance metadata, maintenance engineers and research staff became interested on how these could be analyzed to create elevated knowledge that answers more demanding questions. Thus IMA-FMECA plays an important <u>knowledge synthesis</u> support role, which may drive consequent maintenance planning, management and strategy decisions.

6

Conclusions and Future Work

6 CONCLUSIONS AND FUTURE WORK

This chapter offers the conclusions of this work, and examines how the achieved results address the research questions and fulfil the research objectives. Furthermore, this chapter discusses possible next steps that could extend this work and facilitate its results towards new and challenging research directions and application uses.

6.1 Conclusions

This thesis introduces a novel way for capturing and handling maintenance knowledge from shop-floor expertise. To that end, the relevant literature was assessed, so as to reveal the state of the art in maintenance knowledge modelling and e-Maintenance services. According to the literature, the process of maintenance knowledge management is disconnected from maintenance practice and the shop-floor experts it aims to support. The research of this thesis proposes a methodology that differs from the more conventional pattern, where maintenance experts are directly prompt to produce the required knowledge with weak or no connection to an already available knowledge pool. Starting from an extended FMECA model, as a solid initial knowledge pool, this methodology uses maintenance focused semantic annotations to enable staff to channel their maintenance experience in a straightforward and practical way. Instead of maintenance reports and system forms, maintenance metadata are created through the use of maintenance tags, a feedback methodology that minimizes interaction time and maximizes knowledge value.

The implemented IMA-FMECA system recruits the features of modern enterprise technologies to offer a collaborative tool which enhances maintenance knowledge management. Users can directly map their shop-floor experience, findings and evaluations by commenting on and tagging the FMECA model with customizable maintenance tags. The collected metadata create timelines of evaluations that link FMECA with maintenance practice. IMA-FMECA has the ability to render a rich profile for each maintenance event, fusing maintenance data and metadata in a single view. Access to such profiles allows experts to understand the relevant failure context in order to drive correct maintenance decisions.

To address the thesis research questions, specific answers or solutions were provided by this work. Revisiting each one of them, the following connections can be made with specific research conclusions and results:

Q1: *How can an FMECA model be extended, so that it balances its knowledge complexity between what shop-floor engineers can reference and benefit from, and what analysts can study and use for better knowledge management?*

To address this question, this work studied, designed and implemented an FMECA model that provides:

- ❖ More depth and ranking for semantics that address the **causality of failure events**. Sub-classing effects allowed for faster and more efficient evaluation of Failure Mode profiles. Offering a greater range of effects, empowered maintenance personnel to gradually assimilate and own this knowledge.
- ❖ Concise **steps and alternative solutions** for maintenance actions. Prioritized solution steps inspired the confidence of a well-documented process and ensured effectiveness. Alternative course of action helped maintenance personnel better understand how each Failure Mode can be dealt with, at various stages and under different circumstances.
- ❖ Extendable scales for Severity, Detectability and Occurrence, facilitate an **RPN-based evaluation**. It is a model that invests in a risk-analysis indicator, using parameters that can benefit shop-floor practice.

Balancing the complexity of the FMECA model required the continuous feedback and advice from maintenance experts and engineers. The model design brought more details and better structure for failure profiles that otherwise would never be available for access by shop-floor personnel. Maintenance technicians and machinery operators were more than qualified to understand, process and evaluate the ranked cause-effect relationships between events or even failure modes. This allowed them to identify greater risks and offered them the background knowledge to expand their own expertise and skills for accurate diagnostics. The availability of knowledge for causes and effects, allowed them to comprehend the scaling and progression of failures that were previously hidden from their radar and everyday audits. Furthermore, offering a range of alternative solutions to a fully developed failure mode, placed engineers at a more responsible position, where they had to evaluate and interpret the failure context in order to decide the correct action. Upgrading their access from problem-solution tables to better linked diagnostics, helped shop-floor personnel feel more trusted by the industry and better connected with maintenance management. Their elevated access to a failure context that significantly outlasts their shift and spans in weeks or even months, allowed maintenance technicians to feel more invested in assimilating and expanding upon the FMECA knowledge for machinery under their domain of responsibility. For some senior engineers and technicians FMECA knowledge presented a new challenge; a reference that could verify and test their own background experience. The overall appreciation of the FMECA model was even better recorded by the discussion it invoked between maintenance managers and shop-floor experts. During the whole FMECA study, all the piloting session and the final evaluation of IMA-FMECA, these two parties found in IMA-FMECA the opportunity to use a common knowledge model to share, validate and relate their experience with each other.

Q2: *How can the FMECA knowledge enrichment process be collectively driven and not only centrally managed? How can such a process be continuous and transparent, allowing its mechanisms to be easily understood and adopted by maintenance experts?*

To answer this question, this research:

- ❖ Introduces an enrichment methodology that is **easy to adopt and based on familiar mechanisms**. The functions of tagging and annotation were known to most users, being accustomed to the use of other social tools.

- ❖ Invests in collecting and managing **a large number of small contributions,** and does not opt for a small number of large contributions. Embedding the enrichment process in a reporting paradigm targeting everyday use, allowed it to be **equally continuous and consistent**.
- ❖ Delivers a system, whose provision scheme and design pattern achieves to **approach and connect all the roles and staff** of a maintenance department. The transparency of the annotation process was supported by the inherent **sharing features** of semantic tags.

To make FMECA knowledge enrichment a collectively driven process, this work had to create a collaborative multi-user environment. IMA-FMECA was designed specifically to engage as much personnel as possible and make their access as easy as possible. Offering a mobile optimized web application ensured access from any point inside and outside of the industry, with FMECA enrichment being only one system-login away. No requirements for application installations, for specific infrastructure or specific devices. The piloting access-logs revealed that maintenance engineers and supervisors made several connections to IMA-FMECA from outside the industry, from their home or while on the move. Early on, the hands on tutorials revealed that maintenance personnel was quite accustomed with tagging and the concept of semantic annotations. Having already used the same concept on various other on-line environments, they were able to instantly understand how their contribution could enrich and validate FMECA. Both the tagging mechanisms and the voting option felt familiar to personnel that participate in other social enterprise applications. This sense of familiar mechanics helped IMA-FMECA to gain their increased participation and investment. Finally, the ability to instantly see their tags and votes in event profiles and metadata timelines, allowed maintenance experts to understand the transparency of the system. There was not one single contribution that was not instantly shared. Many maintenance experts reported that knowing their input is intended for creating industrial business intelligence becomes a lot less of an intimidating process, as long as they can understand, share and benefit from the knowledge management approach.

Q3: *How can maintenance experts be motivated to contribute in a knowledge capturing process? How can they be encouraged to invest in and use the knowledge enrichment process for FMECA?*

In order to motivate participation and stimulate a contributing mindset, this research:

- ❖ Allows maintenance personnel to **access and cross examine a well-established knowledge asset.** FMECA becomes a part of a decision support system, and thus shifts its focus towards the needs of shop-floor actions. As a result, FMECA becomes a knowledge asset that maintenance personnel now care more, for its validity and enrichment.
- ❖ Challenges maintenance staff to identify and report if, how and when FMECA knowledge is aligned with shop-floor events and maintenance practice. Maintenance tags provided the means for **a knowledge validation loop,** were all staff members could function as FMECA evaluators and reviewers.

Starting from perceiving IMA-FMECA as the integration of a reporting system with a maintenance support reference, engineers managed to gradually appreciate the knowledge value of the collected feedback when they begun filtering and processing the history of available maintenance metadata. Being able to view the detected milestones of an impactful failure mode and its early solution or even prevention, helped technicians and operators understand how each maintenance tag contributes in the composition of the respective timeline. IMA-FMECA maintenance tags purposely carry flexible semantics so that users can use mini-forms to report verbally or with a percentage, the level of certainty or belief for an event confirmation, an asset issue or a decided solution. These options allowed experts to map the confidence of their feedback and thus transform many of their evaluations into hints, observations and suggestions. This flexibility allowed IMA-FMECA to collect a significant pool of feedback and tags, and create a rich knowledge infrastructure that roles with more confidence and responsibility later used to verify with votes or asserted with more definitive evaluation tags. Furthermore, the ability to access and process metadata timelines allowed experts to connect specific FMECA updates with their own maintenance tags. Being able to track how clustered maintenance tags lead to FMECA updates was a very rewarding experience for the maintenance personnel that participated in the piloting sessions. While data provenance was not a concept that maintenance experts could initially apprehend, after witnessing how their evaluations contributed in the FMECA versioning process, it became a process domain and a topic that they actively wanted to invest in and gain knowledge for.

Q4: *How can maintenance linked data support the FMECA revision and provide evidence for the identification of gaps, mismatches and errors?*

To address this question, the presented research:

- ❖ Facilitates **semantic structures and mechanisms** to create and manage linked data for FMECA knowledge. Established methods(semantic annotation) and components(tags and metadata) are used to evaluate how contextually relevant, and thus useful and valid the current version of FMECA is.
- ❖ Manages to capture the **critical stance that experts engage while referencing FMECA.** Using metadata, this reviewing process is imprinted into small units of field expertise (micro-knowledge) that can be easily mined and analyzed for FMECA gaps and corrections.

Maintenance metadata managed to offer an easily compiled maintenance report with strategic value. Their timeline was essentially introduced as a new form of the overview provided by most common maintenance report systems. Instead of feedback with fluctuating content and quality, the tags offered a streamlined series of evaluations with clear focus and self-declarative knowledge value. The pre-defined nature of tags and the brief and normative content of additional feedback required significantly less sophisticated analysis to deliver results. In this context, the prime principles and benefits of metadata, as a knowledge modelling construct, were directly inherited by all the processes that produced and handled them. More specifically, the descriptive focus and the human readable content of metadata are traits that deeply affected IMA-FMECA's role, both as a system and as a platform component. They are features that allowed maintenance experts to essentially become the front line of analysis in terms of text mining, feature extraction and detecting new correlations between data. The ability to effectively filter and selectively visualize the metadata history for each FMECA component, allowed maintenance experts to record, discuss, and assess a much more extended set of possible meta-interpretations. IME-FMECA managed to critically reduce the time of identifying "*What must be updated?*", during the FMECA revision, and at the same time offer a rich informative timeline of valid point towards "*Why to update?*" and "*How to update?*". One of the most important benefits of IMA-FMECA is its ability to manage a maintenance knowledge context that can be enriched by experts as easily and naturally as it can be processed and be consumed by them.

Q5: *How can the enrichment of FMECA knowledge support maintenance analytics? Can semantic enrichment lead to better understanding of maintenance knowledge?*

To answer this question, this research:

- ❖ Produces **highly formalised knowledge for FMECA and maintenance evaluations**. The employed formalisations enable the effective analysis of the corresponding knowledge, first and foremost, **by the maintenance personnel**. Their processing capacity and analytic skills are quite sufficient to extract useful insights and identify informative patterns from the descriptive timelines that represent how maintenance knowledge evolved through versioning and connected with practice.

- ❖ Maintains a backlog of failures, recorded as a series of annotations that can be instantly classified and clustered by their type, referenced entity, number of votes and additional feedback. This translates in a **state of structural readiness that is compatible with available cloud analytics**, either as a stream of maintenance metadata or a collection of maintenance mashups.
- ❖ Provides a systems that instantly shares each contribution and allows all users to understand how knowledge from a large pool of small contributions can scale to reveal important insights for the failure context. That is **the same failure context available and destined to support them** during shop-floor maintenance practice, or deciding the next version of FMECA.

Delivering an FMECA knowledge management tool, with the features and the functionality mentioned above, was a challenge both for its efficiency in linking knowledge and its ability to promote the use and extension of maintenance tags. IMA-FMECA is not a tool that introduces another approach for highly focused analytics. It is also not a reasoning tool based on the very definitive semantics of an ontology. Several similar approaches failed to deliver the desired or expected results, simply because the employed semantics did not originally emerge from the targeted user-group and the processes. In order to design and create knowledge with purpose, an industry must first capture and refine the semantics that outline and drive the targeted processes, and in the case of this research the maintenance processes. IMA-FMECA is a tool that, through the use of customizable semantic tags and an FMECA knowledge model, enabled an industry to guide, track and capture the maintenance knowledge that its experts carry and are willing to share. This research claims that capturing these semantics is a crucial precursor for the development of an ontology that can accurately map the desired knowledge and drive inference that brings added value. This research also claims that capturing these semantics is an important step prior to analytics in order to successfully select the methods and the features that drive them. Evaluating this research, the knowledge acquired from the industrial piloting has already provided newer versions of FMECA. These knowledge iterations and updates, can now lead towards a refined set of semantics for an FMECA ontology that effectively maps the specific industry's needs. Concluding this work, FMECA semantics for applying meaningful analytics on the collected metadata, are now more clearly identified. Most importantly, these semantics have been captured, decoded and validated by the maintenance experts of the industry itself. Moving towards building a inference or an analytics extension of IMA-FMECA is a step that the author of this thesis and the collaborating industry are now more confident to make with success.

6.2 Future Work

The main focus of the presented research was to bring both technical staff and experts into the enrichment loop of a well-established maintenance knowledge model; the FMECA study. They both can and should actively participate in knowledge management processes that extract and define practical maintenance knowledge. The semantics of such knowledge can be used in modern cloud platforms for: (i) the preparation and profiling of data before analytics, (ii) communicating and exchanging knowledge between interoperable system and services. Maintenance metadata embody great scalability and can effectively map the above processes through their native support for linked data.

Successful maintenance knowledge validation, capturing and synthesis may open new ways for advancing maintenance practice to achieve stated objectives. The industrial piloting case study involved staff with experience in maintenance support systems, which evaluated IMA-FMECA's 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 versions. This incentivized them to propose new and better means to support their role in the enrichment process:

- ✓ Upgrading features of tag-template management, were proposed to allow more depth on the availability and usage **of special-purpose tags**.
- ✓ Extended **tag management** was requested to allow for more diverse timelines and a greater focus, when clustering maintenance evaluations around FMECA components.
- ✓ **Tagging options** were requested to be available at almost any possible view and interface of the delivered web applications.
- ✓ Experts prompted for the exploration and testing of more **annotation semantics for maintenance metadata**. This essentially means that maintenance experts want to have more options to rank maintenance evaluations, apart from the currently available positive votes.

Such extensions can fuel a whole different context of semantics that can capture how the social and the function context can fuse and create several layers of enriched shared expertise. It is a knowledge capturing concept that starts to become more distant from the platform of a reference knowledge and unlocks the infinite enrichment loop of evaluating an evaluation. The loop of capturing, interpreting and then driving the context semantics of such a “**discussion**” is one of the most challenging and active domain of knowledge management and one currently heavily invested in social enterprise networks and collaborative environments.

Expanding IMA-FMECA with exporting services for direct connection with **cloud analytics**, is a natural next step. Linking and semantically enriching data with relevant metadata is a natural precursor to applying cloud analytics. Maintenance 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 to further expand its value adding role in the industry: (i) the use of IMA-FMECA’s enrichment methodology for the collaborative evaluation of other shared knowledge assets, directly (program or plan) or indirectly (policy or strategic objectives) associated with the maintenance process; and (ii) 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, IMA-FMECA can evolve into an interoperable plug-in component that easily couples with third party software, simply by acting as an external module that provides management and usage of maintenance tags on top of different maintenance data models. Both the model design and the implementation technologies ensure the fast and efficient deployment of such a module on various enterprise systems and services. The tagging services are already being gradually ported as an autonomous modularized API, whose components are easy to invoke and integrate. As a first such integration we aim to study the connection of IMA-FMECA with a condition monitoring infrastructure. It is a project that will link FMECA knowledge with condition state parameters and sensor embedded novelty detection. In this context, experts will be able to use maintenance tags to associate FMECA knowledge with vectors of samples representative of the asset's condition and deemed as "novel" by sensor intelligence. Allowing IMA-FMECA to serve diverse maintenance models and industrial applications will extend its tagging semantics to adopt, configure and describe a wider range of maintenance knowledge. This will help tag categories to evolve into tag super classes and thus provided meta-contexts for the metadata. It constitutes a methodology that will allow IMA-FMECA to scale into a metadata management system that can reference, annotate and organize distributed heterogeneous maintenance data and services. This path can serve the integration of ubiquitous maintenance resources and will bring e-Maintenance closer to the standardization of an e-Maintenance metadata schema for linked maintenance data.

Annex

IMA-FMECA
Evaluation Questionnaire
English Version

Questionnaire ***Web Application*** ***FMECA Services*** *(Failure Modes, Effects and Criticality Analysis)*	Date: __/__/____ Name/Surname (*optional*): .... Maintenance role *(e.g. Engineer, Technician, Operator, other)*: .... Years of experience in Maintenance: ....

I. Questions assessing familiarity with portable devices and IT solutions:

1	**How often do you use portable devices with touch screens?**				
	Very rarely ❑	*Rarely* ❑	*When needed* ❑	*Often* ❑	*Very often* ❑

2	**How often are your everyday tasks supported by a computing device?**				
	Very rarely ❑	*Rarely* ❑	*When needed* ❑	*Often* ❑	*Very often* ❑

3	**How often do you facilitate a portable device to conclude a work task?**				
	Very rarely ❑	*Rarely* ❑	*When needed* ❑	*Often* ❑	*Very often* ❑

II. Questions assessing access and availability of FMECA knowledge:

4	**How often do you receive on-the-job support by machinery manuals that list potential failures and advise on appropriate maintenance actions?**				
	Very rarely ❑	*Rarely* ❑	*When needed* ❑	*Often* ❑	*Very often* ❑

5	**Can shop-floor experience and field practice enrich the knowledge included and provided by the manufacturer's manual?**				
	Strongly disagree ❑	*Disagree* ❑	*Neither agree nor disagree* ❑	*Agree* ❑	*Strongly agree* ❑

6	**Which of the following more accurately describes the extent of knowledge commonly provided by maintenance/operation manuals?**
	Failure description / Recommended solution *Failure description / Effects / Recommended solution* *Failure description / Effects / Causes / Recommended solution* *No such information*

7	**Do you find it useful to receive on-the-job maintenance support, through portable devices, about potential failures and recommended actions?**				
	Strongly disagree	*Disagree*	*Neither agree nor disagree*	*Agree*	*Strongly agree*
	❑	❑	❑	❑	❑

8	**Please rate the diagnostics value of the following knowledge components.** *Use the scale:* ***1.*** *None* ***2.*** *Insignificant* ***3.*** *Of low importance* ***4.*** *Indifferent* ***5.*** *Important* ***6.*** *Very important* ***7.*** *Crucial*	
		Failure quantification to better convey the severity, frequency, and detectability of the problem.
		A descriptive list of probable effects (symptoms, functional failures or final results) that are results of the failure's occurrence.
		A list of probable causes of a specific failure to support prevention or detection.
		Steps for recommended actions

9	**Please rate the following IT access devices based on their ability to offer FMECA knowledge as part of maintenance support services.** *Use the scale:* ***1.*** *Least suitable medium* ***2.*** *Minor suitability* ***3.*** *Suitable but lacking key features* ***4.*** *Indifferent* ***5.*** *Suitable featuring key features* ***6.*** *Promising suitability* ***7.*** *Optimal medium*	
		Work Station - Desktop Computer.
		Portable Computer - Laptop
		Portable Device - Tablet
		Portable Device - Smartphone

III. Questions for the evaluation of IMA-FMECA:

10	**The general look and feel of the application**				
	Very bad ❑	*Bad* ❑	*Satisfactory* ❑	*Good* ❑	*Very Good* ❑

11	**The usability of the application**				
	Very bad ❑	*Bad* ❑	*Satisfactory* ❑	*Good* ❑	*Very Good* ❑

12	**The navigation efficiency of the application**				
	Very bad ❑	*Bad* ❑	*Satisfactory* ❑	*Good* ❑	*Very Good* ❑

13	**The application responsiveness**				
	Very bad ❑	*Bad* ❑	*Satisfactory* ❑	*Good* ❑	*Very Good* ❑

14	**The time-to-reach desired content or knowledge**				
	Very bad ❑	*Bad* ❑	*Satisfactory* ❑	*Good* ❑	*Very Good* ❑

15	**The knowledge provided by a failure mode's profiles is**				
	Very bad ❑	*Bad* ❑	*Satisfactory* ❑	*Good* ❑	*Very Good* ❑

16	**What is your stance on the following statements**				
	The use of maintenance tags helps the timely input of observations.				
	Strongly disagree ❑	*Disagree* ❑	*Neither agree nor disagree* ❑	*Agree* ❑	*Strongly agree* ❑
	The "Issue" maintenance tag supports the early detection of a failure.				
	Strongly disagree ❑	*Disagree* ❑	*Neither agree nor disagree* ❑	*Agree* ❑	*Strongly agree* ❑
	The "Confirm" maintenance tag allow the efficient reporting and capturing of events.				
	Strongly disagree ❑	*Disagree* ❑	*Neither agree nor disagree* ❑	*Agree* ❑	*Strongly agree* ❑
	The "Schedule" maintenance tag allow fast response to confirmed failures.				
	Strongly	*Disagree*	*Neither agree*	*Agree*	*Strongly*

disagree		*nor disagree*		*agree*
❑	❑	❑	❑	❑

Maintenance tag templates offer customization options that help configure and leverage the application's use and support value.

Strongly disagree	*Disagree*	*Neither agree nor disagree*	*Agree*	*Strongly agree*
❑	❑	❑	❑	❑

17 Suggest appropriate keywords for new Maintenance Tags templates that support the annotation of...

a. Assets:

b. Hypothetical Events:

c. Maintenance Actions:

18 How likely is it to use IMA-FMECA again in the near future?

Not likely at all	*Not likely*	*If needed*	*Quite likely*	*Very likely*
❑	❑	❑	❑	❑

19 How likely is it to recommend the use of IMA-FMECA to others?

Not likely at all	*Not likely*	*If needed*	*Quite likely*	*Very likely*
❑	❑	❑	❑	❑

20 Comments and suggestions for system improvements?

IMA-FMECA
Ερωτηματολόγιο Αξιολόγησης
Ελληνική Εκδοχή

Ερωτηματολόγιο ***Διαδικτυακών Υπηρεσιών*** ***Εργαλείου FMECA*** *(Failure Modes, Effects and Criticality Analysis)*	Ημερομηνία: __/__/____ Όνομα/Επώνυμο (*προαιρετικά*): .... Ρόλος στις διαδικασίες συντήρησης (*π.χ. Μηχανικός, Τεχνικός, Χειριστής*): .... Έτη απασχόλησης στη Συντήρηση: ....

I. Ερωτήσεις σχετικές με το βαθμό εξοικείωσης και χρήσης φορητών συσκευών και ηλεκτρονικών υπολογιστών:

1	**Πόσο συχνά χρησιμοποιείτε φορητές συσκευές που διαθέτουν οθόνη αφής;**				
	Πολύ σπάνια ❑	*Σπάνια* ❑	*Όποτε χρειαστεί* ❑	*Συχνά* ❑	*Πολύ συχνά* ❑

2	**Πόσο συχνά χρησιμοποιείτε υπολογιστή για την υποστήριξη των εργασιών σας;**				
	Πολύ σπάνια ❑	*Σπάνια* ❑	*Όποτε χρειαστεί* ❑	*Συχνά* ❑	*Πολύ συχνά* ❑

3	**Πόσο συχνά χρησιμοποιείτε φορητές συσκευές για την υποστήριξη των εργασιών σας;**				
	Πολύ σπάνια ❑	*Σπάνια* ❑	*Όποτε χρειαστεί* ❑	*Συχνά* ❑	*Πολύ συχνά* ❑

II. Ερωτήσεις σχετικές με πρόσβαση σε πληροφορία FMECA:

4	**Πόσο συχνά χρησιμοποιείτε και συμβουλεύεστε έντυπα ή εγχειρίδια που αντιστοιχούν πιθανές βλάβες με προτεινόμενες λύσεις;**				
	Πολύ σπάνια ❑	*Σπάνια* ❑	*Όποτε χρειαστεί* ❑	*Συχνά* ❑	*Πολύ συχνά* ❑

5	**Η πρακτική εμπειρία από την εφαρμογή της συντήρησης μπορεί να εμπλουτίσει τη γνώση που προσφέρεται από τα εργοστασιακά εγχειρίδια;**				
	Διαφωνώ πολύ ❑	*Διαφωνώ* ❑	*Ούτε διαφωνώ ούτε συμφωνώ* ❑	*Συμφωνώ* ❑	*Συμφωνώ πολύ* ❑

6	**Ποιο από τα παρακάτω βρίσκεται πιο συχνά διαθέσιμο στα εγχειρίδια χειρισμού/συντήρησης μιας μηχανής;**
	1) *Περιγραφή Βλάβης / Ενδεδειγμένη Λύση* 2) *Περιγραφή Βλάβης / Συμπτώματα / Ενδεδειγμένη Λύση* 3) *Περιγραφή Βλάβης / Συμπτώματα / Πιθανά Αίτια / Ενδεδειγμένη Λύση* 4) *Δεν υπάρχει πληροφορία βλαβών*

7	**Κατά τη συντήρηση είναι χρήσιμο να έχω πρόσβαση από φορητή συσκευή σε πληροφορίες για βλάβες και προτεινόμενες ενέργειες συντήρησης.**				
	Διαφωνώ πολύ	*Διαφωνώ*	*Ούτε διαφωνώ ούτε συμφωνώ*	*Συμφωνώ*	*Συμφωνώ πολύ*
	❑	❑	❑	❑	❑

8	**Αξιολογήστε την σημασία που έχει η πρόσβαση στην παρακάτω πληροφορία.** *Χρησιμοποιήστε την ακόλουθη κλίμακα:* **1.** *Καθόλου* **2.** *Ελάχιστη* **3.** *Σχετικά χαμηλή* **4.** *Ουδέτερο (ούτε λίγη, ούτε πολύ)* **5.** *Σχετικά υψηλή* **6.** *Πολύ υψηλή* **7.** *Εξαιρετική*	
		Περιγραφή μιας βλάβης με κλίμακες/επίπεδα, που βοηθούν στην κατανόηση της σοβαρότητάς της, την συχνότητα εμφάνισης και την ευκολία ανίχνευσης.
		Περιγραφή των πιθανών συμπτωμάτων/αποτελεσμάτων μιας βλάβης, για την υποστήριξη της ανίχνευσής της.
		Περιγραφή πιθανών αιτιών βλαβών για καλύτερη πρόληψη / αντιμετώπιση.
		Περιγραφή των βημάτων μιας προτεινόμενης ενέργειας συντήρησης, για την υποστήριξης της εκτέλεσής της.

9	**Αριθμήστε τα παρακάτω ψηφιακά μέσα, αξιολογώντας την καταλληλότητα τους για την υποστήριξη των εργασιών συντήρησης με πληροφορία FMECA.** *Χρησιμοποιήστε την ακόλουθη κλίμακα:* **1.** *Καθόλου* **2.** *Ελάχιστη* **3.** *Σχετικά χαμηλή* **4.** *Ουδέτερο (ούτε λίγη, ούτε πολύ)* **5.** *Σχετικά υψηλή* **6.** *Πολύ υψηλή* **7.** *Εξαιρετική*	
		Σταθμός εργασίας - Υπολογιστής γραφείου.
		Φορητός υπολογιστής - Λαπτοπ
		Φορητή Συσκευή - Ταμπλέτα (Tablet)
		Φορητή Συσκευή - Έξυπνο Κινητό (Smartphone)

III. Ερωτήσεις σχετικές με το εργαλείο IMA-FMECA:

10	**Η γενική εμφάνιση στην εφαρμογή είναι**				
	Πολύ Κακή ❑	*Κακή* ❑	*Ικανοποιητική* ❑	*Καλή* ❑	*Πολύ Καλή* ❑

11	**Η γενικότερη ευχρηστία του συστήματος είναι**				
	Πολύ Κακή ❑	*Κακή* ❑	*Ικανοποιητική* ❑	*Καλή* ❑	*Πολύ Καλή* ❑

12	**Η γενικότερη ευκολία πλοήγησης το συστήματος είναι**				
	Πολύ Κακή ❑	*Κακή* ❑	*Ικανοποιητική* ❑	*Καλή* ❑	*Πολύ Καλή* ❑

13	**Η γενικότερη ταχύτητα απόκρισης του συστήματος είναι**				
	Πολύ Κακή ❑	*Κακή* ❑	*Ικανοποιητική* ❑	*Καλή* ❑	*Πολύ Καλή* ❑

14	**Η ταχύτητα εύρεσης επιθυμητής πληροφορίας είναι**				
	Πολύ Κακή ❑	*Κακή* ❑	*Ικανοποιητική* ❑	*Καλή* ❑	*Πολύ Καλή* ❑

15	**Η πληροφορία που παρέχεται για έναν τύπο Αστοχίας είναι**				
	Πολύ Λίγη ❑	*Λίγη* ❑	*Επαρκής* ❑	*Καλή* ❑	*Πολύ Καλή* ❑

16	**Πόσο συμφωνείτε με τις παρακάτω διαπιστώσεις;**				
	Η χρήση των Tags συντήρησης βοηθάει στη γρήγορη αποτύπωση παρατηρήσεων.				
	Συμφωνώ Πολύ ❑	*Συμφωνώ* ❑	*Ούτε συμφωνώ ούτε διαφωνώ* ❑	*Διαφωνώ* ❑	*Διαφωνώ Πολύ* ❑
	Το Tag Συντήρησης "Πρόβλημα" βοηθάει στην γρήγορη και εύκολη αναφορά μιας πιθανής βλάβης.				
	Συμφωνώ Πολύ ❑	*Συμφωνώ* ❑	*Ούτε συμφωνώ ούτε διαφωνώ* ❑	*Διαφωνώ* ❑	*Διαφωνώ Πολύ* ❑
	Το Tag Συντήρησης "Επιβεβαίωση" βοηθάει στην συγκέντρωση ιστορικού συμβάντων αστοχίας.				
	Συμφωνώ Πολύ ❑	*Συμφωνώ* ❑	*Ούτε συμφωνώ ούτε διαφωνώ* ❑	*Διαφωνώ* ❑	*Διαφωνώ Πολύ* ❑
	Το Tag Συντήρησης "Προγραμματισμός" βοηθάει στην υποστήριξη της αντιμετώπιση μιας βλάβης.				

Συμφωνώ Πολύ	*Συμφωνώ*	*Ούτε συμφωνώ ούτε διαφωνώ*	*Διαφωνώ*	*Διαφωνώ Πολύ*
❑	❑	❑	❑	❑

Η επέκταση των Tag Συντήρησης, με την χρήση Tag Προτύπων, βοηθάει στην προσαρμογή της λειτουργίας και τη σταδιακή βελτίωση του συστήματος.

Συμφωνώ Πολύ	*Συμφωνώ*	*Ούτε συμφωνώ ούτε διαφωνώ*	*Διαφωνώ*	*Διαφωνώ Πολύ*
❑	❑	❑	❑	❑

17 Προτείνετε κωδικο-λέξεις συντήρησης, που μπορούν να χρησιμοποιηθούν ως νέα Tags Συντήρησης για να χαρακτηρίσουν ένα...

α. Πάγιο: ……………………………………

……………………………………

β. Συμβάν Βλάβης: ……………………………………

……………………………………

γ. Ενέργεια Συντήρησης: ……………………………………

……………………………………

……………………………………

18 Πόσο πιθανό θεωρείτε να χρησιμοποιήσετε ξανά το σύστημα;

Πολύ λίγο πιθανό	*Λίγο πιθανό*	*Αν χρειαστεί*	*Αρκετά πιθανό*	*Πολύ πιθανό*
❑	❑	❑	❑	❑

19 Πόσο πιθανό είναι να προτείνετε τη χρήση του συστήματος σε άλλους;

Πολύ λίγο πιθανό	*Λίγο πιθανό*	*Αν χρειαστεί*	*Αρκετά πιθανό*	*Πολύ πιθανό*
❑	❑	❑	❑	❑

20 Σχόλια και προτάσεις για την βελτίωση του συστήματος;

……………………………………

……………………………………

……………………………………

……………………………………

……………………………………

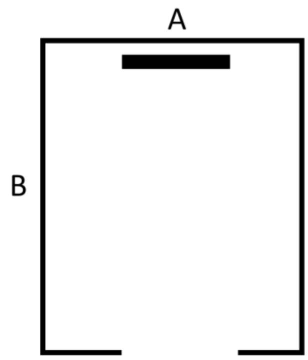
……………………………………

……………………………………

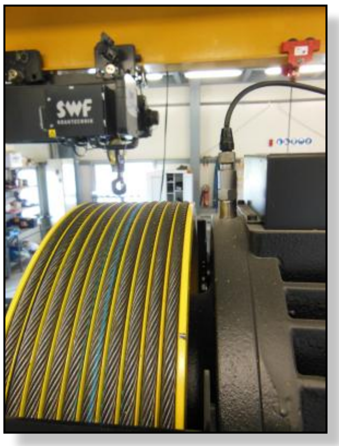
Asset Technical Data

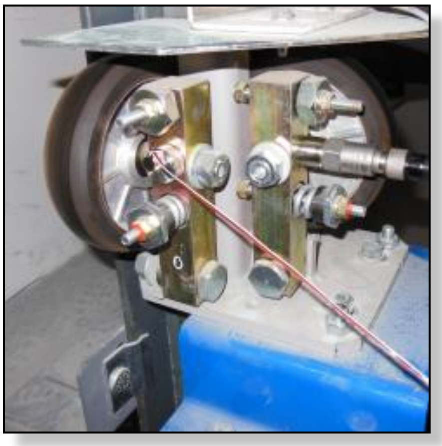
I. Electric Testing Lift

Technical Details	
Cabin Move Distance	43400 mm
Load Carriage Capacity	1275 kg
Movement Speed	3.0 m/sec
Number of Stops	15
Shaft Size A	3000 mm
Shaft Size B	2205 mm



Related Photos





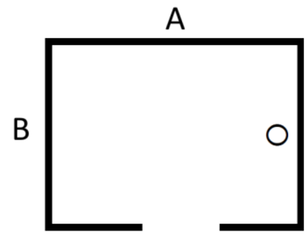
II. Air Compressor

Technical Details	
Rated Capacity	74 kW
Engine RPM	3000 rpm
Air Compressor RPM	5592 rpm
Output	10 ... 50 m^3/min
Type	rotary screw, liquid

Related Photos

III. Hydraulic Lift

Technical Details	
Cabin Move Distance	6610 mm
Load Carriage Capacity	600 kg
Movement Speed	0.5 m/sec
Number of Stops	3
Shaft Size A	1800 mm
Shaft Size B	1500 mm



Related Photos

Glossary

List of Acronyms

BD	Big Data
CM	Condition Monitoring
CMMS	Computerized Maintenance Management Systems
CSS	Cascading Style Sheets
DM	Data Mining
ERP	Enterprise Resource Planning
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FTA	Failure Tree Analysis
GUI	Graphical User Interface
HTML	HyperText Markup Language
IaaS	Infrastructure as a Service
IoT	Internet of Things
JSON	JavaScript Object Notation
JSON LD	JavaScript Object Notation for Linked Data
KDD	Knowledge Discovery from Databases
LD	Linked Data
MMS	Metadata Management Systems
MVC	Model View Controller pattern
PLM	Product Lifecycle Management
RCM	Reliability Centred Maintenance
RDFa	Resource Description Framework in Attributes
RCA	Root Cause Analysis
SOA	Service Oriented Architecture
UI	User Interface
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
XML	eXtensive Markup Language

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