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An Ontology-based Approach for Aircraft Maintenance Task Support

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Abstract A relatively low level of digitalization in the maintenance domain, a reliance on legacy, paper-based work processes and systems and a lack of information exchange across stakeholders work together to complicate the consistent execution and record keeping of maintenance tasks. This has a negative effect on the efficiency and costs of product support and phase-out. This paper moves towards a 'push-of-the-button' digital solution for capturing and using aircraft maintenance task knowledge, processes and history to support maintenance execution and prove continued airworthiness compliance. It proposes the use of Enterprise Knowledge Resources – engineering task representations containing the required knowledge, process and outputs for a task – embedded within a semantic context model based on a Product-Process-Resource structure. A proof of concept application has been developed that incorporates a sample EKR within a knowledge management solution to support the capture, use and maintenance of the required elements for executing a specific maintenance task: the modification and detailed inspection of the main track downstop of the leading edge slats of the Boeing B737 aircraft. The developed system has the potential to improve the efficiency of maintenance task execution and record keeping. Future work includes extension of the proof of concept, such that it enables the user to automatically import knowledge from aircraft manufacturers as well as automatically record the results of maintenance task execution.

1. Introduction

Literature for the aircraft maintenance domain tends to focus on performance measurement and optimization of maintenance processes [1] and on the relation between maintenance and safety [2]. In marked contrast to the design and manufacturing phases of the product lifecycle, literature regarding the development and use of advanced information technology (IT) such as Product Lifecycle Management systems (PLM) or Knowledge-Based Systems (KBS) for the maintenance lifecycle phase is very limited. This is supported by Lee *et al.* [3], who note the low adoption of PLM technology in maintenance when compared to other lifecycle phases, as shown in Figure 1 under 'Service'.

A fair representation of current practice in aircraft maintenance is provided by Lampe *et al.* [4] who maintain that aircraft maintenance is currently supported by a mixture of paper and digital documentation as well as tools, materials and parts required for the job. Within aircraft maintenance processes, an increasing number of

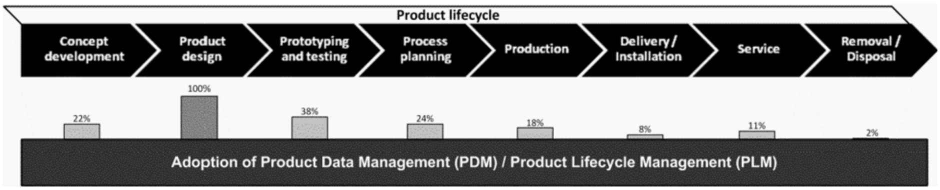


Figure 1: Adoption of PLM in the MRO domain [3]

supporting documentation is offered digitally. This includes the Airplane Maintenance Manual (AMM), Maintenance Planning Document (MPD), Illustrated Parts Catalogue (IPC), Structural Repair Manual (SRM) and Service Bulletins (SB) - all OEM documentation that can be offered through the OEM's web portal (e.g. Baker *et al.* [5]) or as part of OEM software [6].

However, a significant share of aircraft maintenance processes are largely manual [3] and frequently paper-based [2, 7]. Similar findings are reported by Lampe *et al.* [4], who point out the labor intensive manual documentation and check procedures at aircraft maintenance providers. The time associated with searching for appropriate documentation can amount up to 15-20% of the total work time of a mechanic [4]. Consequently, a number of major issues remain to be addressed:

- **Legacy work processes & systems:** the remaining aspects of a paper-based approach to aircraft maintenance lead workers to shortcut the process as it takes too long to collect the relevant documents: safety and efficiency are compromised [2].
- **Information exchange across stakeholders:** various stakeholders hold different information necessary for the successful execution and record keeping of aircraft maintenance tasks. For instance, MyBoeingFleet.com can provide the OEM information, the FAA or EASA holds the regulatory information (Airworthiness Directives), and the airliner holds engineering orders (EO) and maintenance records. This information needs to be exchanged and be available to the end user in an integral way.
- **Maintenance report keeping and data accuracy:** proof-of-concept research regarding the use of RFID tags to support automatic maintenance documentation has been performed [4]. However, recent findings [7] suggest that report keeping is still a manual job that has only partly transferred into digital format. The manual entry of maintenance data is error-prone and may cause issues with data accuracy and completeness.

A more structured approach to data, information and knowledge capture, storage and use in aircraft maintenance processes may resolve these issues while aiding data-driven research and improvement [8].

This paper consequently aims to make a contribution by moving towards a 'push-of-the-button' digital solution for capturing and using aircraft maintenance task knowledge, processes and history to support maintenance execution and prove continued airworthiness compliance. A proof-of-concept solution for the digitalization, use and maintenance of knowledge, processes and reports related to a specific maintenance task has been developed and is discussed as part of this paper. The maintenance task considers wing maintenance for the Boeing B737: modification and detailed inspection of the main track downstop assembly of the leading edge slats [9]. This task is associated with a revised Service Bulletin (SB) issued by the OEM, Boeing [9], and a FAA Airworthiness Directive (AD) [10]. In the remainder of the paper, the theoretical context is discussed first, followed by development of context and task models to represent the engineering task related to the proof-of-concept solution. The implementation of this solution is presented, followed by some conclusions.

2. Theoretical context

The application of knowledge within engineering systems is studied within the field of Knowledge-Based Systems (KBS). KBS are systems that use an acquired set of knowledge to offer problem-solving advice (Expert Systems) or solve tasks directly. KBS are typically comprised of a structured knowledge base containing the required set of knowledge, acquisition mechanisms and inference mechanisms to solve the task(s) at hand, and a user interface [11]. Though KBS have been developed for all phases of the product lifecycle, literature regarding KBS adoption in aerospace and general maintenance, repair and overhaul (MRO) is extremely scarce (save a few exceptions, e.g. Painter *et al.* [12]).

Recent work in the KBS domain has explored an ontology-based approach that uses an engineering task representation as a central aspect in the development of knowledge-based applications [13, 14]. In this work, the concept of a task is defined using Schreiber *et al.* [15]'s description of a task as 'a subpart of a business process that represents a goal-oriented activity adding value to the organization; handles inputs and delivers desired outputs in a structured and controlled way; consumes resources; requires knowledge and other competences; is carried out according to given quality and performance criteria; and is performed by responsible and accountable agents'. As such, an engineering task includes the central aspects of input, activity / process, output and goal. In the ontology-based approach [13, 14], the authors propose the use of an *Enterprise Knowledge Resource (EKR)*: a modular 'container' of knowledge elements, process elements and cases that can be used to represent an engineering task by modelling the task goal(s), inputs and process and capturing the outputs. Besides EKRs, the ontology-based approach rests upon the development of domain-specific metamodels based on the *Product-Process-Resource (PPR)* paradigm [16, 17] to facilitate annotation of the EKRs for improved traceability and use.

The ontology-based approach has the potential to be extended to the maintenance domain. In the following sections, the ontology-based approach is adopted for the development of a KBS for the maintenance engineering task introduced before: modification and detailed inspection of the main track downstop assembly of the leading edge slats of the Boeing 737.

3. Modeling

To prepare the development of a proof-of-concept knowledge-based application for the maintenance engineering task, a number of models are developed based on the knowledge acquired from the Service Bulletin [9] and Airworthiness Directive [10]. Knowledge acquisition consisted of report analysis as well as maintenance engineer interviews at a Dutch MRO provider to provide additional insights into the domain.

Based on the understanding of the relevant concepts and relations, models have been developed. Modeling is discussed in two steps: modeling of the maintenance engineering task using the EKR concept, and modeling of the domain context using the PPR paradigm.

3.1. Modeling the maintenance engineering task using the EKR concept

The modification and inspection task for the B737 slat track main downstop can be described in IDEF0 terms using the inputs in the form of the Service Bulletin [9] and Airworthiness Directive [10], the output – a modified and inspected B737 slat track main downstop assembly – and the controls (Airworthiness Directive) and mechanisms (mechanic, tooling). The AD serves as both input and control to the task: it offers input information such as aircraft type applicability and controls the task, for instance through the mandatory compliance time.

The subtasks are represented in Figure 2 as an A0 IDEF0 diagram, based upon the task description as included in Boeing Service Bulletin 737-57A1302.

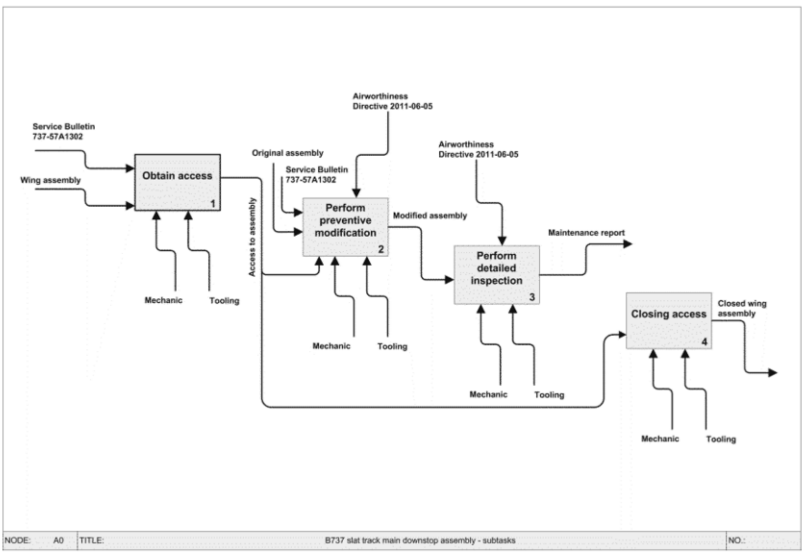


Figure 2: IDEF0 A0 diagram for B737 slat track main downstop subtasks

To model the maintenance task in preparation for development of the proof-of-concept solution, the EKR concept has been used. An EKR class diagram has been modeled for the maintenance domain and related tasks. It is shown in Figure 3 and further explained below.

- **Enterprise Knowledge Resource**: the 'container' level of the EKR contains general attributes such as authorship as well as specific maintenance attributes, including effective date, applicability, subject, unsafe condition and compliance time. These attributes have been identified as common attributes in Airworthiness Directives and Service Bulletins.
- **EKR_Knowledge:** The **EKR_Knowledge** class has general attributes and includes common maintenance attributes (effective date, applicability, subject,

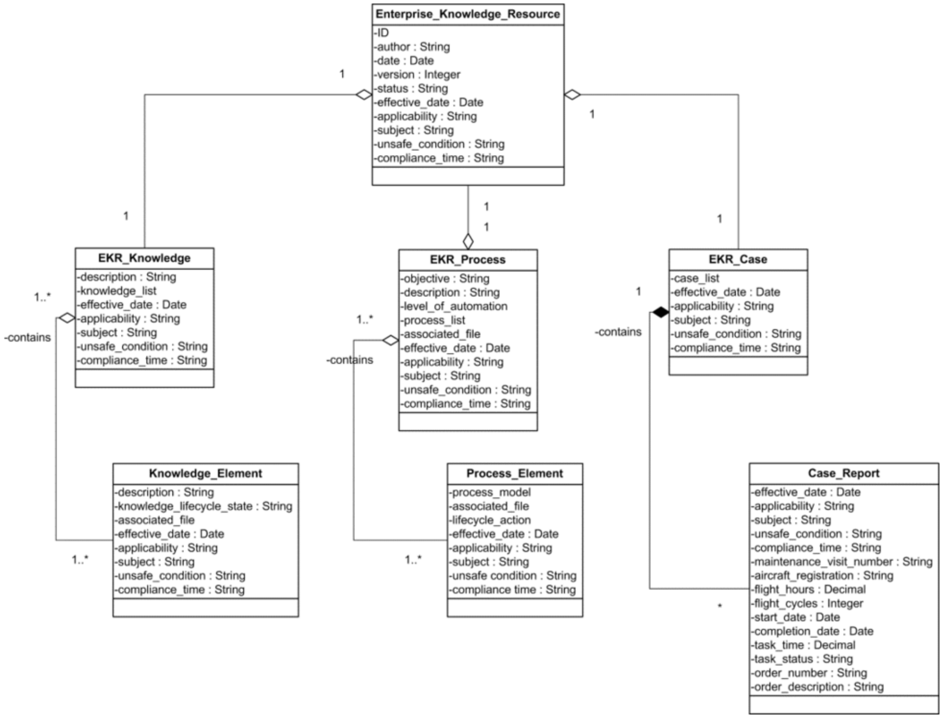


Figure 3: EKR class diagram (UML) for generic maintenance task

unsafe condition, compliance time) as identified from regulatory documents such as ADs and SBs. The **Knowledge_Element** class inherits the same attributes. Instances of this class can be used to capture knowledge related to the problem, mainly product knowledge such as drawings and specifications.

- **EKR_Process:** the EKR uses a process representation for the maintenance activities that must be completed to fulfil a maintenance task and comply with any related ADs or SBs. Figure 2 shows the activities for the specific maintenance task studied in this paper. The individual activities can be modeled using the **Process_Element** class. As for the previous classes, the common maintenance attributes are included into the **EKR_Process** and **Process_Element** classes.
- **EKR_Case:** a central case repository is set up that can hold the results from the modification and inspection task. Individual case reports are filled into the repository. The class for individual reports includes maintenance-specific attributes. Besides the common maintenance attributes previously identified, other report-specific attributes such as the maintenance visit number, aircraft registration, flight hours and flight cycles of the aircraft, start date, completion date, task status, order number and order description are included into the class.

3.2. Modeling the domain context: Domain ontology development

The second step towards the development of a proof-of-concept solution is to provide a knowledge structure that can be used to store the captured knowledge and can serve as the semantic backbone for the knowledge-based application. A domain-specific set of concepts and relationships – a domain ontology – has been developed. To elicit the applicable concepts and relationships for the domain, various sources have been employed. This includes the regulatory and OEM documents [9, 10, 18] as well as literature [1, 3, 4, 7, 8, 19]. The high-level concepts of the PPR paradigm (**Product**, **Process** and **Resource**) have been used as a starting point for domain ontology development. These concepts have been extended into domain-specific class hierarchies. In this section, excerpts of the domain-specific class hierarchies are given to explain how the domain ontology is composed.

First of all, the domain-specific class hierarchy for the **Product** class is shown in Figure 4. The **Part** and **Assembly** classes are critical to represent aircraft products; they can be used to represent the product breakdown structure. Relative to the B737 maintenance task, Figure 4 includes the slat assembly (through aggregation), including the slat track assembly and the slat can (track housing) assembly. The former contains the downstop assembly. These assemblies contain parts. To satisfy the requirements of

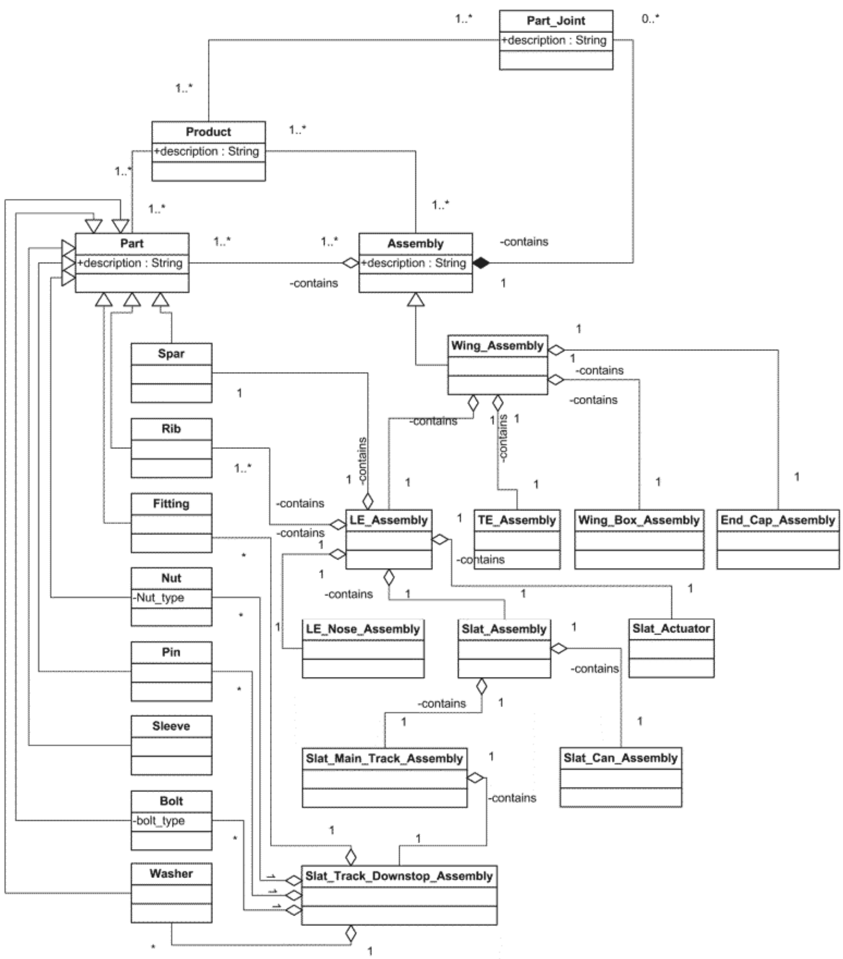


Figure 4: Product class hierarchy

the developed proof-of-concept solution, the parts that make up the downstop assembly have been added to the part hierarchy and the aggregation relationships are shown.

Second, the class hierarchy for the **Process** class relative to the maintenance proof-of-concept development is shown in Figure 5. The **Process** class has been extended to include **Maintenance_Process**, which in turn is a parent for the **Inspection_Process**, **Modification_Process** and **Repair_Process** classes. As these are all subclasses of the parent **Process** class, they inherit the aggregation with the **Activity** class (in other words, all of the process classes contain one or more activities).

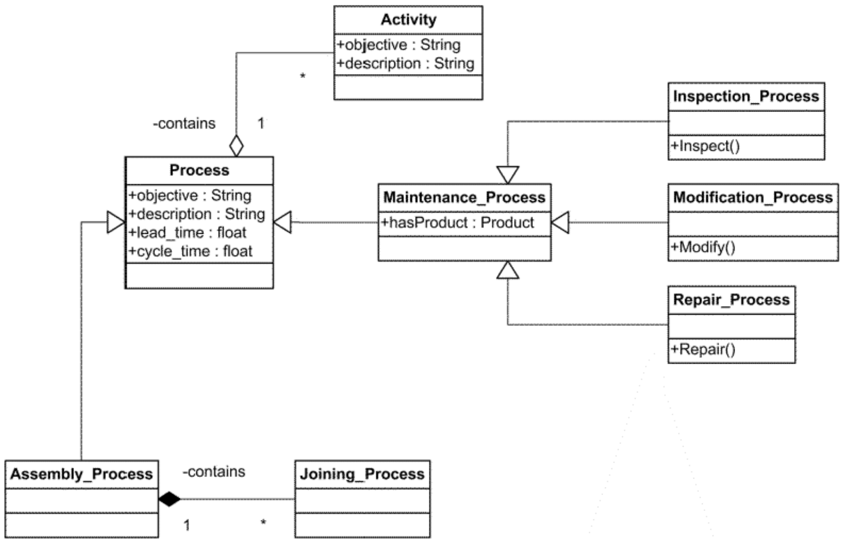


Figure 5: Process class hierarchy

The **Resource** class hierarchy is shown in Figure 6. It contains a number of general resource types, which have been extended using maintenance concepts. In particular, the **Document_Resource** class is of note, as this includes the various document types from the regulator and OEM side.

The maintenance domain ontology has been used to structure the captured knowledge and will be used to annotate (elements of) the developed solution. This is further explained in Section 4.

4. Implementation of a proof-of-concept solution

This section describes the development of a proof-of-concept knowledge-based application for the previously mentioned maintenance task: the modification and detailed inspection of the main track downstop of the leading edge slats of the Boeing B737.

One EKR has been developed and implemented for this maintenance domain proof-of-concept. To implement the EKR and the annotation models presented in the previous section, a solution has been developed on the basis of the Ardans Knowledge Maker (AKM) knowledge management tool [14]. This tool consists of a web-based interface on top of a knowledge base implemented in MySQL. Technological

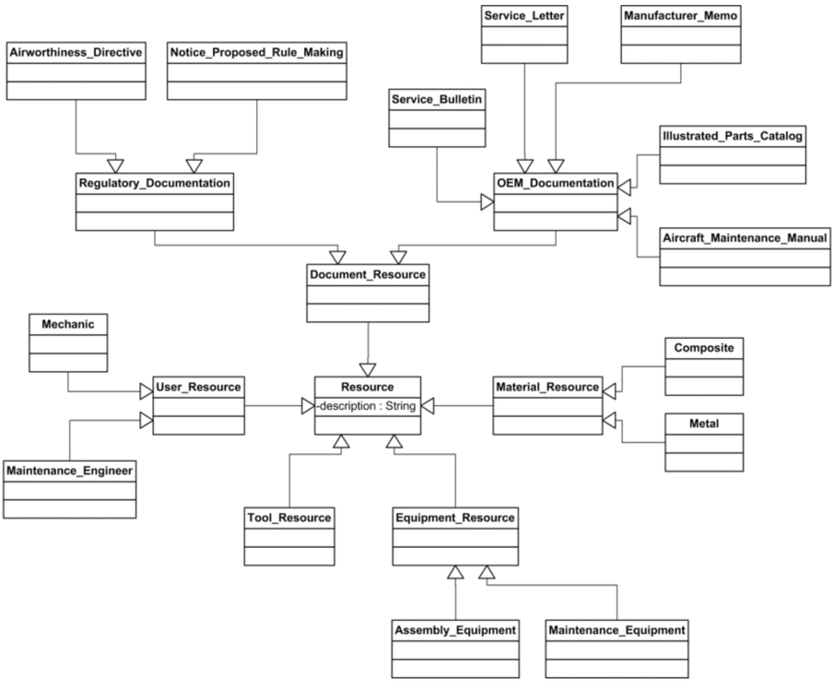


Figure 6: Resource class hierarchy

alternatives include semantic wiki tools such as Confluence [20] and dedicated maintenance management tools (e.g. Maintenix [21]). AKM has been chosen as it offers the possibility to implement semantic structuring and ontology techniques while offering the record keeping facilities necessary in the maintenance domain. The web-based nature of the tool allows for user interaction wherever an internet connection and device is available.

The following implementation architecture has been devised – see Figure 7.

A number of AKM models have been developed for the EKR class and its subsidiary classes (knowledge, knowledge element, process, process element, case and case report). For each class, a single model is made that contains fields. These fields represent the attributes of the classes. The relations between the classes are represented through the addition of direct links between related AKM models. Some automated functionality is added by using the XPATH language to identify and fill model fields. For instance, XPATH expressions are used to let the knowledge, knowledge element, process and process element models inherit the common maintenance attributes (effective date, applicability, subject, unsafe condition, compliance time) from the EKR container class. Furthermore, metadata such as author, date and status is automatically added. XPATH is also used to facilitate the implementation of 'templates' that guarantee a consistent representation of model instances.

The AKM models are used to generate knowledge articles; they are in effect instances of the EKR classes implemented in AKM. The process of creating articles and generating the article content is currently largely manual. Though the AKM models take away much work by offering a consistent representation and filling some article fields automatically, the remaining fields must be filled manually with the appropriate knowledge. The following Figure gives an example of an implemented EKR article.

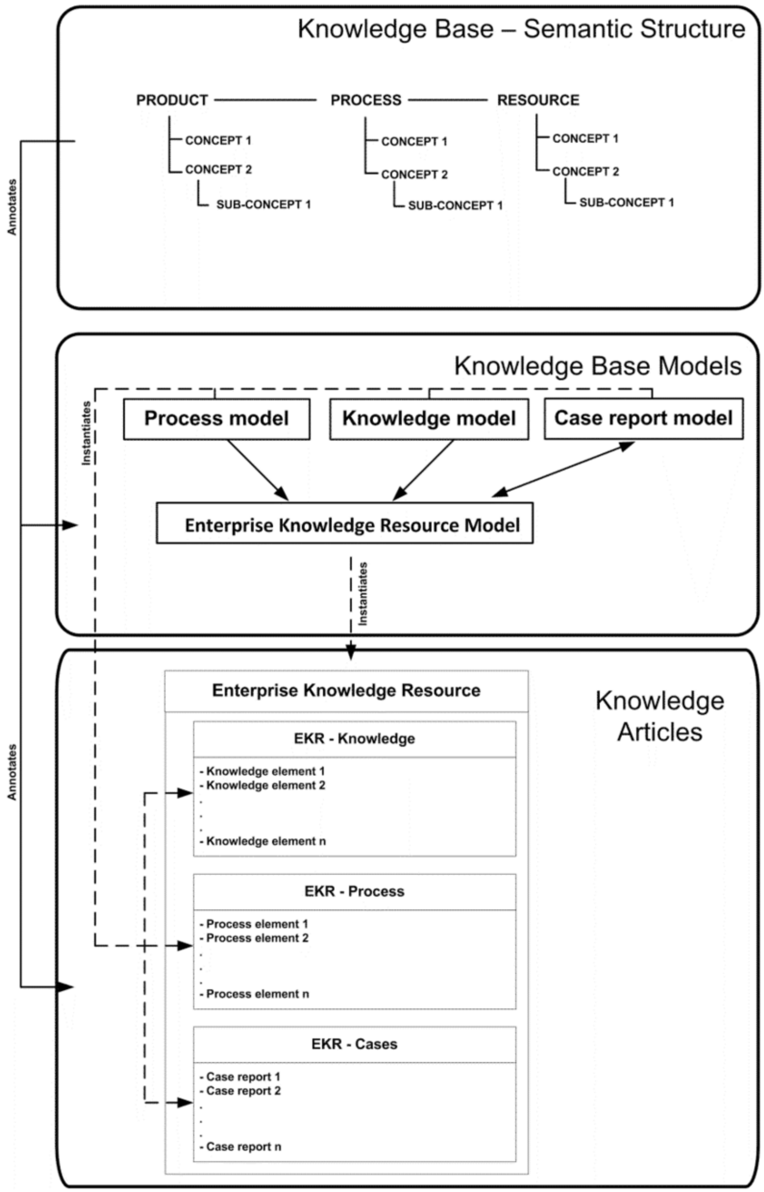
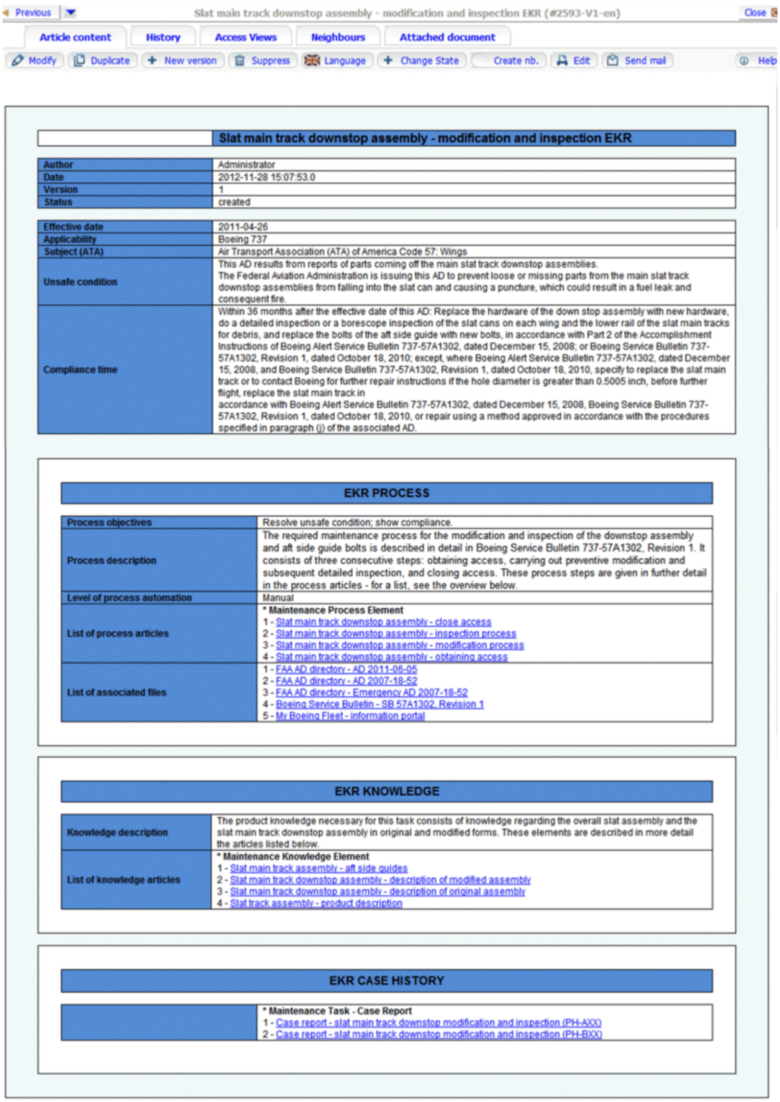


Figure 7: Implementation architecture

As a subsidiary part of the general EKR structure, the case report model and associated articles are particularly important from the perspective of documentation management for maintenance compliance. The format of these case reports can easily be changed to fit company specifications. The AKM tool includes functionality to export articles and article information into Word or Excel directly. This makes it possible to completely digitalize the generation, storage and management of maintenance documentation.



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	Slat main track downstop assembly - modification and inspection EKR
Author	Administrator
Date	2012-11-28 15:07:53.0
Version	1
Status	created

Effective date	2011-04-26
Applicability	Boeing 737
Subject (ATA)	Air Transport Association (ATA) of America Code 57: Wings
Unsafe condition	This AD results from reports of parts coming off the main slat track downstop assemblies. The Federal Aviation Administration is issuing this AD to prevent loose or missing parts from the main slat track downstop assemblies from falling into the slat can and causing a puncture, which could result in a fuel leak and consequent fire.
Compliance time	Within 36 months after the effective date of this AD: Replace the hardware of the down stop assembly with new hardware, do a detailed inspection or a borescope inspection of the slat cans on each wing and the lower rail of the slat main tracks for debris, and replace the bolts of the aft side guide with new bolts, in accordance with Part 2 of the Accomplishment Instructions of Boeing Alert Service Bulletin 737-57A1302, dated December 15, 2008; or Boeing Service Bulletin 737-57A1302, Revision 1, dated October 18, 2010; except, where Boeing Alert Service Bulletin 737-57A1302, dated December 15, 2008, and Boeing Service Bulletin 737-57A1302, Revision 1, dated October 18, 2010, specify to replace the slat main track or to contact Boeing for further repair instructions if the hole diameter is greater than 0.5005 inch, before further flight, replace the slat main track in accordance with Boeing Alert Service Bulletin 737-57A1302, dated December 15, 2008, Boeing Service Bulletin 737-57A1302, Revision 1, dated October 18, 2010, or repair using a method approved in accordance with the procedures specified in paragraph (j) of the associated AD.

EKR PROCESS

Process objectives	Resolve unsafe condition; show compliance.
Process description	The required maintenance process for the modification and inspection of the downstop assembly and aft side guide bolts is described in detail in Boeing Service Bulletin 737-57A1302, Revision 1. It consists of three consecutive steps: obtaining access, carrying out preventive modification and subsequent detailed inspection, and closing access. These process steps are given in further detail in the process articles - for a list, see the overview below.
Level of process automation	Manual
List of process articles	* **Maintenance Process Element** 1 - Slat main track downstop assembly - close access 2 - Slat main track downstop assembly - inspection process 3 - Slat main track downstop assembly - modification process 4 - Slat main track downstop assembly - obtaining access
List of associated files	1 - FAA AD directory - AD 2011-06-05 2 - FAA AD directory - AD 2007-18-52 3 - FAA AD directory - Emergency AD 2007-18-52 4 - Boeing Service Bulletin - SB 57A1302, Revision 1 5 - My Boeing Fleet - information portal

EKR KNOWLEDGE

Knowledge description	The product knowledge necessary for this task consists of knowledge regarding the overall slat assembly and the slat main track downstop assembly in original and modified forms. These elements are described in more detail the articles listed below.
List of knowledge articles	* **Maintenance Knowledge Element** 1 - Slat main track assembly - aft side guides 2 - Slat main track downstop assembly - description of modified assembly 3 - Slat main track downstop assembly - description of original assembly 4 - Slat track assembly - product description

EKR CASE HISTORY

	* **Maintenance Task - Case Report** 1 - Case report - slat main track downstop modification and inspection (PH-AXX) 2 - Case report - slat main track downstop modification and inspection (PH-BXX)

Figure 8: example of EKR article for maintenance case study – slat track downstop assembly modification and inspection EKR

To enable the search and retrieval of EKRs in the maintenance domain, semantic annotation is used. Annotation of EKRs and its subsidiary elements is achieved through applying the PPR maintenance domain ontology concepts and relationships to the EKR classes. An (only partially complete) example for the slat main track downstop assembly EKR is given in Figure 9. In the figure, only the EKR is annotated to maintain clarity. In reality, all classes are annotated. In practice, annotation is achieved through article tags in AKM, which associate an article (be it an EKR article, a knowledge element article, a process element article or a case report) with a number of semantic tags.

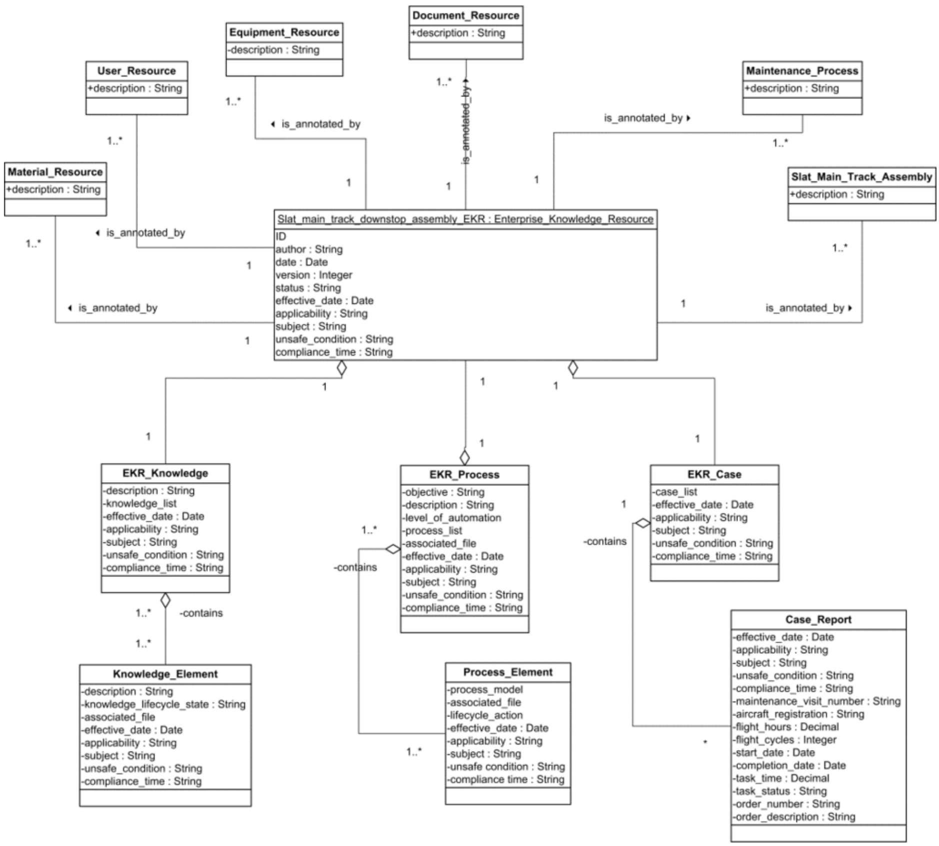

Figure 9: Semantic annotation of EKR

5. Conclusions

With respect to the functionality of the developed proof-of-concept solution relative to the objective (capturing and using aircraft maintenance task knowledge, processes and history to support maintenance execution and prove continued airworthiness compliance), the following observations can be made.

First, the solution provides knowledge life-cycle management through the EKR approach. In particular, the knowledge and process elements can be captured, used, maintained, updated and retired independently of each other. There is also the possibility to track the change of knowledge through the retention of historical knowledge articles.

Second, the solution facilitates knowledge use through the exploitation of model 'templates' that ensure a consistent representation of knowledge, processes and case reports. The web-based character of the AKM tool makes it feasible for end users (e.g. mechanics) to perform a task and immediately fill in a digital report in a consistent way. Furthermore, the use of a dedicated knowledge base, with the associated provisions to ensure the availability of trustworthy knowledge, assures users that the right knowledge is available at the right time. This can also support staff in execution of maintenance processes. It is useful to have discrete process element and knowledge element representations. This allows a mechanic or engineer to find and inspect exactly those elements that he/she needs support on. Finally, the current drawbacks of the paper-based approach are avoided as documentation is stored digitally. With some additional functionality (e.g. electronic signatures), the solution can fairly easily be used to manage airworthiness compliance.

Third, the solution addressed knowledge transparency by including semantic annotation and provision for knowledge explication.

To sum up, the developed solution improves upon the current approach by facilitating a digital approach to maintenance task support and record keeping. Consistency of record keeping is maintained through the application of models within a knowledge base. The contents of reports can be checked manually, with the potential for automatic checks and completion through future extension of the solution (see below). The solution allows for digital data exchange between various stakeholders.

There are a number of disadvantages and challenges related to the currently implemented solution. First of all, the solution requires manual interaction, primarily in setting up EKRs but also in completing maintenance reports. Despite a low time needed to implement a single EKR (up to a few hours per EKR), the sheer amount of ADs and SBs available for the various B737 types (up to 330 per type) indicates a significant investment of resources to set up a complete knowledge base with EKRs for each maintenance task. There is however some potential to automate knowledge article generation by linking AKM with AD and SB information retrieved from myboeingfleet.com and FAA / EASA databases, as information in XML format can be imported to and exported from AKM. The completion of case reports also requires manual input. Similar to the previous point, case report generation is technically feasible by linking AKM with external maintenance programs. These options will be explored in future research.

References

[1] Garg, A. and S.G. Deshmukh, Maintenance management: literature review and directions, *Journal of Quality in Maintenance Engineering* **12** (2006): pp. 205 - 238.

[2] Wartan, S., Sharing Safety Knowledge for Aircraft Maintenance. Delft University of Technology, M.Sc. thesis, (2010).

[3] Lee, S.G., Y.S. Ma, G.L. Thimm, and J. Verstraeten, Product lifecycle management in aviation maintenance, repair and overhaul, *Computers in Industry* **59** (2008): pp. 296-303.

[4] Lampe, M., M. Strassner, and E. Fleisch, A Ubiquitous Computing environment for aircraft maintenance. Proceedings of the 2004 ACM symposium on Applied computing, Nicosia, Cyprus, 2004, ACM.

[5] Baker, M., T. Dowling, W. Martinez, T. Medejski, D. Pedersen, and D. Rockwell, *New Enhanced Service Bulletins*, in *Aero Quarterly*2006, Boeing. p. 12-15.

[6] Airbus. (2012). *AIRMAN*. Retrieved 13-11-2012, from http://www.airbus.com/innovation/proven-concepts/in-fleet-support/airman/.

[7] Burhani, S., Compliance during Aircraft (Component) Redeliveries. Delft University of Technology, M.Sc. thesis, (2012).

[8] Jagtap, S. and A. Johnson, In-service information required by engineering designers, *Research in Engineering Design* **22** (2011): pp. 207-221.

[9] Boeing, *Boeing Service Bulletin 737-57A1302, Revision 1*, 2010.

[10] FAA, *Airworthiness Directive FAA AD 2007-18-52*, 2007.

[11] Studer, R., V.R. Benjamins, and D. Fensel, Knowledge Engineering: Principles and methods, *Data and Knowledge Engineering* **25** (1998): pp. 161-197.

[12] Painter, M.K., M. Erraguntla, G.L. Hogg Jr, and B. Beachkofski, Using simulation, data mining, and knowledge discovery techniques for optimized aircraft engine fleet management. Proceedings of the Winter Simulation Conference (WSC), Monterey, CA, USA, 2006.

[13] Bermell-Garcia, P., W.J.C. Verhagen, S. Astwood, K. Krishnamurthy, J.L. Johnson, D. Ruiz, G. Scott, and R. Curran, A framework for management of Knowledge-Based Engineering applications as software services: Enabling personalization and codification, *Advanced Engineering Informatics* **26** (2012): pp. 219-230.

[14] Verhagen, W.J.C., P. Bermell-Garcia, P. Mariot, J.-P. Cotton, D. Ruiz, R. Redon, and R. Curran, Knowledge-based cost modelling of composite wing structures, *International Journal of Computer Integrated Manufacturing* **25** (2012): pp. 368-383.

[15] Schreiber, G., H. Akkermans, A. Anjewierden, R. de Hoog, N. Shadbolt, W. Van de Velde, and B. Wielinga, *Knowledge engineering and management: the CommonKADS methodology*, MIT Press, Cambridge, MA, 1999.

[16] Butterfield, J., W. McEwan, P. Han, M. Price, D. Soban, and A. Murphy, Digital Methods for Process Development in Manufacturing and Their Relevance to Value Driven Design. Air Transport and Operations - Proceedings of the Second International Air Transport and Operations Symposium 2011, Delft, The Netherlands, 2012, IOS Press.

[17] Curran, R., J. Butterfield, Y. Jin, R. Collins, and R. Burke, Value-Driven Manufacture: Digital Lean Manufacture. R. Blockley and W. Shyy (eds.), *Encyclopedia of Aerospace Engineering*. John Wiley & Sons, Ltd, 2010, pp.

[18] FAA, *Airworthiness Directive FAA AD 2011-06-05*, 2011.

[19] Tsang, A.H.C., Condition-based maintenance: Tools and decision making, *Journal of Quality in Maintenance Engineering* **1** (1995): pp. 3-17.

[20] Confluence. (2013). *Team Collaboration Software - Atlassian Confluence*. Retrieved 07-08-2013, from http://www.atlassian.com/software/confluence/overview/team-collaboration-software.

[21] Mxi Technologies. (2013). *Mxi Technologies - Aviation Maintenance Management Software*. Retrieved 08-07-2013, from http://www.mxi.com/products/maintenix/overview/.