

## Aircraft Disposal and Recycle Cost Estimation

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# Automating Contextualized Maintenance Documentation

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**Abstract.** Currently, task-specific support information in aircraft maintenance is mostly provided using paper-based solutions, which are burdensome, slow and prone to error. Next to these issues, Aircraft Maintenance Technicians (AMTs) have very limited on-site access to support information. This leads to 15-30% of hands-on-aircraft time being wasted on acquiring the right information or not using maintenance documentation for task support at all, risking maintenance error. The decision by the AMT to use or not use maintenance documentation is also affected by human factors, such as time pressure and complacency, and poses an additional risk for the number one priority in aviation: safety. To overcome the weaknesses of maintenance documentation and mitigate the related human factor effects, a mobile tool will be developed to provide direct access to task-specific information. With such a system the AMT will have on-site access to the right information, spend less time on retrieving the right information and therefore will be able to make well-informed decisions under less pressure, reducing maintenance errors. This paper describes the development of a system for a first level of contextualization of maintenance documentation. Combining a tailor-made ontology for the aerospace domain with a relational database system for Ontology-Based Data Access (OBDA), maintenance documents relevant to a specific aircraft registration mark can be identified. The system contributes to the research field of knowledge management by using OBDA for selecting relevant maintenance documents stored in a regular file folder and provides a promising start in the development of a mobile contextualized documentation tool to improve operational efficiency in the (line) maintenance environment. Future work includes advanced methods for contextualization, integration of semantic search capabilities, exploiting document referencing, implementation of end-user feedback and preferences, machine learning and verification and validation of a prototype in an operational environment.

**Keywords.** Aircraft maintenance, maintenance efficiency, contextualized documentation, ontology-based data access, human factors, mobile tools

## Introduction

Air transport is well-known for being a very safe and reliable method of transportation. The high level of safety in air transport is achieved while Revenue Passenger-Kilometers (RPKs) have continuously been increasing over the last decade; a trend which is expected

to continue at an average rate of approximately 6% a year [1]. One of the most important factors contributing to safety is maintenance, which is based on strict schedules that originated during the development of the Boeing 747. This eventually led to the MSG-3 maintenance approach, now used for all commercial aircraft [2].

While a growing market is good for business, it creates challenges from the maintenance perspective. It leads to more required maintenance work, yet currently the maintenance workforce is declining [3]. Simultaneously, AMTs require more knowledge to adequately perform maintenance on new and complex systems. When an AMT does need task-support information for task execution, acquiring it is difficult because aircraft maintenance documentation is notoriously extensive, containing a lot of information not directly relevant to execute a task [4], and because the information has to be gathered from multiple sources. AMTs also face very limited access to task-support information; maintenance documentation is usually accessed through fixed workstations (i.e. desktop computers), which are available in the back-offices of the maintenance organization, but not in the direct vicinity of the AMT's workplace. This is especially problematic for line AMTs, as the distance from the platform to a workstation can be significant [5]. These weaknesses of maintenance documentation lead to 15-30% of hands-on-aircraft time being wasted on acquiring the right information [6] and negatively affects the operational performance of airline operators by increased turnaround times (TAT), maintenance errors [7] that lead to increased maintenance costs [8], flight schedule disruptions, major malfunctions [9] and in some cases accidents.

As part of the European Union's Clean Sky 2 research programme, the Airline Maintenance Operations implementation of an E2E Maintenance Service Architecture and its enablers (AIRMES) project aims to develop multiple Integrated Mobile Tools to support the AMT during maintenance tasks. Such tools will improve maintenance execution efficiency, reduce turnaround times and can lead to cost reductions that are estimated at 195 to 395 M€ annually [10]. Within the scope of the AIRMES project, a mobile tool for contextualized documentation will be developed to address the weaknesses of maintenance documentation and mitigate implications on operational efficiency and safety.

This paper describes the development of a database system to provide initial contextualization over sets of maintenance documents. The database system uses Ontology-Based Data Access (OBDA) to search and select various types of maintenance documents and is based on a relational database system, a tailor-made, domain-specific ontology and an integrated software platform to query the database. Using the registration mark of an aircraft as input, the database system returns the relevant maintenance documents, based on the contextual information that can be derived from the registration mark (e.g. aircraft manufacturer, family). Qualitative and quantitative assessment of the database system show very accurate results in retrieving relevant maintenance documents with excellent performance. In the remainder of the paper, human factors in aircraft maintenance are discussed first, followed by the development of the system and a discussion of the results obtained. Finally, conclusions are drawn and future research is identified.

## **1. Human factors in aircraft maintenance**

To start understanding the use of maintenance documentation by AMTs, knowledge of the human factors involved is required. Human error has been defined in different ways and all share the idea that, for one, humans are organic mechanisms with failure rates and tolerances similar to hardware and software elements of a system, and secondly, human error is a negative term for normal human behavior in less than ideal environments [11]. To find causes for human errors in aviation maintenance several studies developed models to identify the contributing factors. The most well-known model for human factors that lead to error was developed in 1993 by Gordon Dupont and is known as the “Dirty Dozen” [12].

In 2008, Hobbs investigated the conditions in which AMTs work and identified resulting physical (e.g. omissions, precision) and psychological (e.g. memory lapses, wrong assumptions) actions that lead to error [13]. AMTs are confronted with exceptional circumstances; adverse weather, working at heights, hard to reach and confined spaces and the unique sense of stress because the work performed can influence the lives of flight crew and passengers in the future. Line maintenance is performed within the flight schedule and creates an increased sense of pressure on the AMT to fulfill maintenance tasks on time to avoid flight disruptions. Time pressure typically increases the chance of individual errors as result of memory lapses and procedural violations. Poor maintenance procedures and documentation can also lead to errors. The FAA found that AMTs spend 25-40% of their time dealing with maintenance documentation, including administrative work [13; 14]. Procedures and manuals are often impractical to use; prescribed procedures are not in agreement with the way an AMT performs a task and manuals are written with extensive use of warnings, complicating extraction of useful information. Limited access to maintenance documentation is also a problem, especially for line AMTs working on the platform. During a research project [5] AMTs indicated that getting access to maintenance documentation could take up to half an hour, depending on the layout of the airport. All these issues with maintenance documentation result in a continuous trade-off being made by AMTs when they need to consult task-specific information [15]. A study showed that the AMT will only look for the required information if the benefit or value of that information exceeds the cost (e.g. time, effort) to acquire it. The AMT individually determines the added value of the documentation based on experience (risking complacency), but also based on previous experience with maintenance documentation [16]. These findings, together with the strong relation between aviation maintenance errors and the content and (non-)use of maintenance documentation [7; 9], show the importance of using correct, complete and relevant maintenance documentation during task execution.

## **2. Development of a proof of concept for contextualized documentation**

To address the weaknesses of maintenance documentation and its implications on operational efficiency and safety, this work introduces a proof of concept approach to contextualize and provide maintenance documentation. This is driven by the need of the

AMT to obtain on-site access to task-specific information and the developed system includes a tailor-made ontology, a relational database system to search and manage maintenance documentation as well as the airline fleet information and a software solution to integrate the ontology for Ontology-Based Data Access (OBDA).

### 2.1 Ontology development

The database system uses a concept developed in previous work by Lattner and Apitz [17], which uses metadata captured in ontologies to contextualize information. The use of an ontology to structure and classify information in a database system has several benefits [18]:

- Share common understanding of the structure of information among people or software agents
- Enabling reuse of domain knowledge; existing ontologies can be reused in other domains or used to expand other ontologies
- Make domain assumptions explicit; assumptions can easily be changed when knowledge about the domain changes
- Separate domain knowledge from operational knowledge
- Analyze domain knowledge; once a specification of terms is established it can be used to reuse the ontology for other domains or expand it

Especially in an innovative industry like aviation, where new knowledge continuously becomes available, the benefit of using an ontology to describe the domain (e.g. aircraft models, engines, modifications) is evident. To be able to establish relations between the registration marks in a fleet and the maintenance documents related to it, an ontology representing the aircraft models in the fleet is required. With no ontology readily available, an ontology was developed based on the fleet of KLM Royal Dutch Airlines using Stanford's open-source ontology editor Protégé. Table 1 shows a sample of KLM's fleet information, with the registration mark (Reg) and aircraft type (Aircraft Type) as relevant information for the ontology.

**Table 1.** A sample of KLM's fleet information

Reg	Aircraft Type	Aircraft Name	Age
PH-AKA	Airbus A330-303	Times Square - New York	3.5 Years
PH-AKB	Airbus A330-303	Piazza Navona - Roma	3.5 Years
PH-BGN	Boeing 737-7K2 NG	Jan van Gent / Gannet	4.4 Years
PH-BGO	Boeing 737-7K2 NG	Paradijsvogel / Bird of Paradise	4.4 Years

From the aircraft type contextual information for the retrieval of relevant maintenance documentation can be derived. Airbus and Boeing have slightly different approaches, but the manufacturer, family and series information can be derived for both in a similar way. Taking registration mark PH-AKA as an example, the manufacturer (Airbus), family (A330) and the aircraft series (303) can be derived from the aircraft type. The last two digits in the aircraft type for Airbus refer to the engine manufacturer and model, where the last characters in the Boeing aircraft type refer to the customer and aircraft variant. Because of the different approaches for the naming of the aircraft types by Boeing and

Airbus, the proof of concept is limited to include the manufacturer, family and series information. Based on this information a tailor-made ontology was created in Protégé. A visual representation of a part of this ontology is shown in Figure 1, which shows the relation between aircraft type “Airbus A330-303” and its related classes: “Airbus” (hasManufacturer), “A330” (hasFamily) and “300 series” (hasSeries).

## 2.2 Database development

With the ontology available, a database for the maintenance documents was set up. As most maintenance documents are available in the Portable Document Format (PDF), the goal was to use a system that can directly use this file format. Database systems can work with Binary Large Objects (BLOBS) like PDF files in two ways: store them directly in the database, which can cause performance issues with larger files [19], or store them in a separate file system. A separate file system provides good performance, also for large files such as Aircraft Maintenance Manuals (AMMs), but generally lacks the integration of essential functionality for the task at hand, namely full-text search. Currently, the only solution available to work with a separate file system and have full-text search functionality is provided by the FileTable feature in Microsoft’s SQL Server (2012 and later). The FileTable feature can access and search the maintenance documents, stored in a regular (network) file folder, in their unstructured, original file format. Hence, a Microsoft (MS) SQL Server with the FileTable feature enabled was set up with access to a set of maintenance documents in a network file folder.

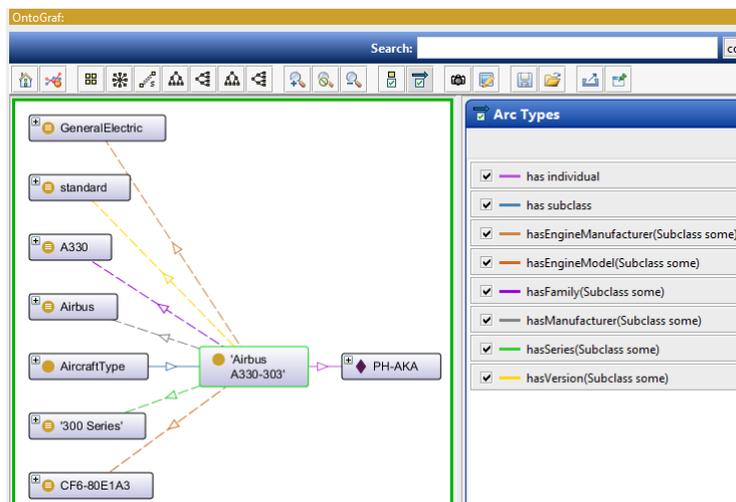


Figure 1. Graphical representation of the aircraft type ontology in Protégé

Next to the maintenance documents, a table with the fleet information was imported into the database in order to link registration marks from the fleet to aircraft type classes in the ontology. The registration marks could be included in the ontology directly, but this is deliberately avoided to keep the ontology independent from the airline the system is used for. This way, the ontology can be used for any fleet that is imported into the database, provided all the aircraft types in the fleet are described in the ontology. Using

a script, distinct columns for the aircraft manufacturer, family and series were automatically added to the fleet information table to be able to establish links with the corresponding classes in the ontology. The resulting SQL database table is shown in Figure 2.

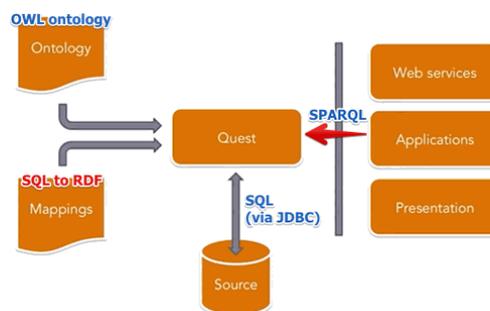
	reg	Aircraft Type	Aircraft Name	Age	Manufacturer	Family	Series	Model
1	PH-AKA	Airbus A330-303	Times Square - New York	3.5 Years	Airbus	A330	300	Airbus A330-300
2	PH-AKB	Airbus A330-303	Piazza Navona - Roma	3.5 Years	Airbus	A330	300	Airbus A330-300
3	PH-AKD	Airbus A330-303	Plaza de la Cathedral - Habana	3.4 Years	Airbus	A330	300	Airbus A330-300
4	PH-AKE	Airbus A330-303	Praça de Rossio - Lisboa	2.6 Years	Airbus	A330	300	Airbus A330-300
5	PH-AKF	Airbus A330-303	Hofplein - Rotterdam	0.8 Years	Airbus	A330	300	Airbus A330-300

**Figure 2.** Sample of the modified KLM fleet information in the database

With separate columns for the manufacturer, family and series information, links with the related classes in the ontology can be made by using so-called mappings.

### 2.3 Linking the ontology to the database for OBDA

Multiple methods for mapping of ontologies onto relational databases are available, all having specific benefits and drawbacks. A recent survey of state-of-the-art methods for automatic and lossless mapping of ontologies onto relational databases shows that the several available methods still have issues with loss of structure, loss of information or are not fully automatic [20]. A new, promising method is provided by Ontop, an approach developed at the Free University of Bozen-Bolzano in Italy. Although the method does not support automatic mappings, it proves to be one of the best approaches for OBDA. Unlike other methods, which have the ontology as a virtual layer between the source database and the query engine, Ontop provides direct access to the sources, the ontology and the mappings (Figure 3), avoiding loss of metadata and performance or memory issues the other approaches have. Ontop is provided as a plugin for Protégé and consists of a tool for creating mappings as well as a reasoner/query engine, enabling on-the-fly querying of the underlying database using the SPARQL query language [21]. Quest has superior SPARQL-to-SQL translations compared to other systems and outperforms any other known methods for OBDA, such as Virtuoso RDF Views and D2RQ [22].



**Figure 3.** The Ontop framework

Using Ontop and its plugin for Protégé, mappings for the database system were created. A mapping consists of a mapping identifier, a target and a source. The source refers to

specific information in a database table, the target states a set of RDF triples and the identifier is simply used to name the mapping. RDF triples state relationships between resources and always consist of a subject, a predicate and an object.

```

Manufacturer-Airbus
{:Manufacturer}{Reg} a :Airbus ; :hasModel {Model} ; :hasManufacturer {Manufacturer} ; :hasFamily {Family} ;
:hasSeries {Series} ; :namedType {AircraftType} ; :name {AircraftName} ; :age {Age} .
SELECT * FROM FleetInfoKLM WHERE Manufacturer = 'Airbus'

```

**Figure 4.** Manufacturer mapping for Airbus

Figure 4 shows an example of a mapping to link registration marks in the database table having manufacturer Airbus to the class Airbus in the ontology. Similarly, mappings were made to link all relevant columns in the database table to classes in the ontology. The final mappings establish a link between a specific aircraft model and its related maintenance documents, of which an example is shown in Figure 5. The target relates the subject, a registration mark, to an aircraft class and its related documents. Relevant documents are identified in the source of the mapping, where information from the fleet information database table is joined with information in the maintenance document FileTable, under the condition that specific keywords are found in the document (i.e. defined in the WHERE statement).

```

A330-303-Docs
{:Model}{Manufacturer}{Family}{Series}{Reg} a :A330-303 ; :docName {name} .
SELECT FleetInfoKLM.Reg, FleetInfoKLM.Model, FleetInfoKLM.Manufacturer, FleetInfoKLM.Family, FleetInfoKLM.Series,
MaintenanceDocumentation.name, MaintenanceDocumentation.path_locator FROM MaintenanceDocumentation
JOIN FleetInfoKLM
ON FleetInfoKLM.Manufacturer = 'Airbus' AND FleetInfoKLM.Family = 'A330' AND FleetInfoKLM.Series = '300'
WHERE (CONTAINS(file_stream, 'Airbus') AND CONTAINS(file_stream, 'A330'));

```

**Figure 5.** Mapping to relate the aircraft model A330-303 to its related documents

With all required mappings available, relevant maintenance documents in the database can be identified by entering a registration mark in the SPARQL query engine. From the registration mark contextual information about the manufacturer, family and series is obtained to full-text search maintenance documents for the associated keywords with the FileTable feature. When the keywords are identified in a maintenance document, the document is returned as relevant. The result of a query for registration mark “PH-AKA” is shown in Figure 6.

Registration	Name	Model
:Airbus%20A330-300/Airbus/A330/300/PH-AKA	"EASA_AD_2014-0148_1.pdf"	<Airbus A330-300>
:Airbus%20A330-300/Airbus/A330/300/PH-AKA	"EASA_AD_2014-0248_1.pdf"	<Airbus A330-300>

**Figure 6.** Result for relevant maintenance documents for PH-AKA

### 3. System results

The developed database system was assessed with regard to quality and performance, using freely available Airworthiness Directives (ADs). For each of the distinct aircraft families in the KLM fleet, being Boeing 737/747/777/787 and the Airbus A330, 2 ADs are added to the database per batch, after which the respective tests are performed.

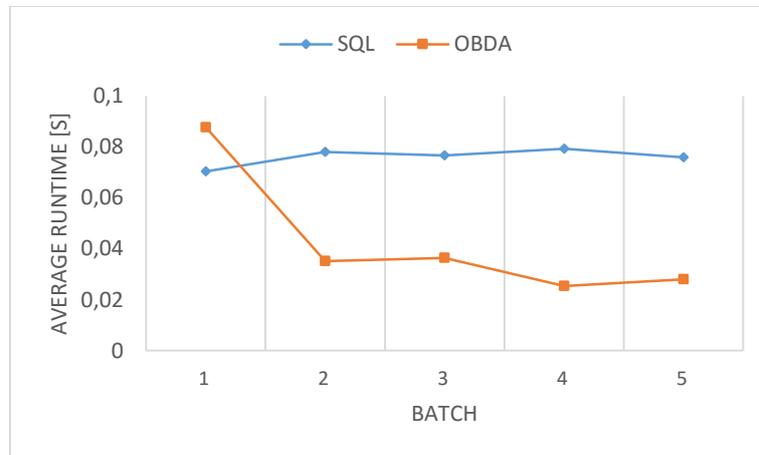
### *3.1 Qualitative assessment*

To test if the system returns the correct relevant maintenance documents, a qualitative assessment was performed over the first batch of 10 ADs. For this, results of the full-text search function of the FileTable were compared with a manual search through the documents to verify that the keywords for manufacturer, family and series information of an aircraft registration mark are correctly identified in the documents. The test was performed without implementation of the ontology, because the OBDA method also uses the FileTable full-text search functionality. The qualitative assessment showed that inclusion of the series information leads to unreliable results. This is caused by two factors. Firstly, the command used by the FileTable feature searches documents for exact keyword matches; when an AD refers to an Airbus A330-201, the FileTable keyword search will not match the specified 200 series format with the 201 series identifier of this specific aircraft type. This is beneficial to avoid false positives based on other information containing the x00 format for aircraft series identification (e.g. the year 2006), but also excludes relevant series information in other formats. Secondly, the series information is not always stated in the AD. Documents may refer to all series of a family, and thus a keyword for to identify the series cannot be found. More advanced methods for the full-text search implementation may be developed to overcome these issues, but since a proof of concept can be achieved without the contextual information about the aircraft series, the aircraft series information was omitted in further assessments.

### *3.2 Performance assessment*

The assessment was continued with a focus on the performance by determining the impact on query execution speed when the number of available maintenance documents in the database is gradually increased by batches of 10 ADs. Starting with a batch of 10 documents, one registration mark for each distinct aircraft model in KLM's fleet is used as input to query the database for relevant maintenance documentation. The performance is measured by the query runtime, defined as the time from initiating the query until displaying the result, and is measured five times per batch per registration mark. By adding 5 batches of maintenance documents a total of 45 measurements per batch were recorded and then averaged.

Query times were measured for a method with and without OBDA integration (referred to as OBDA and SQL, respectively) to be able to assess the effect of using an ontology on system performance. Querying the database without OBDA implementation is possible because the current database structure is still relatively simple. Once the complexity increases, for example when engine model data is added, the benefits of OBDA (i.e. having a high-level, easily adaptable structure independent from the database structure) become more evident. The results are plotted in Figure 7, with on the horizontal axis the batch number and on the vertical axis the average query runtime of 45 measurements per method. It shows that the OBDA method initially has lower performance than the SQL method, but from batch 2 onwards consistently outperforms the SQL method by approximately a factor 2.



**Figure 7.** Average query runtime per batch for SQL and OBDA

The results are remarkable considering that the developers of Ontop confirmed that table joins in the source of the mappings, as well as the CONTAINS statement used for the full-text search in the FileTable feature, are not fully supported. Moreover, the OBDA method requires extra processing to link the database with the ontology through mappings. Further tests showed similar behavior and more research is required to determine the cause.

#### 4. Conclusions

A database system was developed to retrieve relevant maintenance documents from the database, using the aircraft registration mark as input. The core of the database system is Microsoft SQL Server and the maintenance documentation stored in a FileTable with full-text search functionality. An approach for OBDA was pursued to benefit from the high-level conceptual schema, relations and domain knowledge of an ontology. To implement OBDA, an ontology for the domain of commercial aircraft was developed and integrated using the Ontop plugin for Protégé.

Qualitative and quantitative assessment showed that fast and reliable results are obtained when the series information is discarded. After initialization, the OBDA approach retrieves relevant maintenance documents approximately twice as fast as SQL.

The OBDA method contributes to the research field of knowledge management by providing OBDA for unstructured data, such as maintenance documents in their original file format, by using the FileTable feature of Microsoft SQL Server in combination with Ontop for ontology integration. While the level of contextualization of the database system is limited, it provides a functional proof of concept for contextualization of maintenance documentation. The methodology can be applied to other domains by substituting the ontology and alter the mappings accordingly. Current disadvantages of the developed system are the dependency on the FileTable feature, incompatibilities with Ontop and the lack of automatic generation of mappings. Future development of the mobile tool will focus on the level of contextualization, exploit document cross

referencing, semantic search functions and machine learning techniques. Such a system does not only tackle the limited accessibility for line maintenance technicians, but also improves the usability of maintenance documentation, and could significantly reduce the time currently wasted on acquiring task-specific information. The likelihood of both flight schedule disruptions and maintenance error will be reduced, thereby increasing the operational efficiency and overall safety of air transport.

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