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DOI
10.1504/IJASM.2017.086159

Publication date
2017

Document Version
Accepted author manuscript

Published in
International journal of Agile Systems and Management

Contextualizing Aircraft Maintenance Documentation

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Abstract
The use of documentation for task support in aircraft line maintenance is still mostly paper-based, which is slow, burdensome and prone to error. This paper provides an overview of the issues associated with the use of paper-based documentation in aircraft maintenance and describes the development of a novel concept for contextualized documentation to address these issues. The developed system features ontology-based data access (OBDA) for improved contextualization and additional flexibility for future integration of other data sources. The ontology is developed in Protégé. The maintenance documents are accessed through the FileTable feature of Microsoft’s SQL Server and is linked to the ontology using Ontop. By inferencing the aircraft manufacturer and family are derived from the registration mark and used as attributes for a Boolean search in the maintenance documentation database.

The OBDA system is able to retrieve relevant documents approximately twice as fast as existing relational database systems and provides support for a wide variety of file types. Limitations of the developed system are software vendor dependency, compatibility issues between integrated software solutions and lack of support for automatic mappings. Nevertheless, the developed system provides a proof of concept for a mobile tool to overcome the weaknesses of maintenance documentation in line maintenance, working towards increased operational efficiency, reduction of human factor induced maintenance errors and reduced paper consumption.

1 Introduction

Commercial air transport is well-known for being a very safe and reliable method of transportation. Its high level of safety has been achieved while the total Revenue Passenger-Kilometres (RPKs), a measure of passenger traffic equal to the number of paying passengers multiplied by the kilometres flown, has near-continuously increased over the past decades, and will continue to do so in the years ahead by an average of 6% for the total market (International Air Transport Association, 2015; International Civil Aviation Organization, 2014). An important contributing factor to the high level of safety is maintenance, but while growing markets are good for business expansion, it also leads to challenges from the maintenance perspective. A growing market requires more aircraft in service to meet the demand and subsequently more maintenance work has to be performed. A first challenging factor is the declining maintenance workforce; experienced technicians are eligible for retirement, new skilled technicians get job opportunities in other industries (International Air Transport Association, 2014) and meanwhile the number of applicants for Aircraft Maintenance Technician (AMT) training programs is declining (Gramopadhye and Drury, 2000; Hampson et al., 2015). Secondly, many new and complex technologies are introduced to create safer and more efficient aircraft, leading to increased knowledge required to adequately perform maintenance. These factors lead to very demanding circumstances for AMTs, both in pressure to perform on time as well as their capability for having the required knowledge at hand. In relation with the previous, AMTs are having trouble to find the required information to perform a task due to the extensive nature of some maintenance documents, cross referencing between documents, the sheer amount of (new) documentation available and the fact that relevant documentation is specific to individual aircraft, due to the aircraft configuration and maintenance history (Taylor, 2008). Because of the weaknesses of maintenance documentation, maintenance technicians waste 15-30% of their time trying to access the right information (European Commission, 2012; Lampe et al., 2004). The weaknesses of aircraft maintenance documentation are also reflected in the operational performance of airline operators by increased turnaround times, maintenance errors that lead to increased maintenance costs (European Commission, 2012), flight schedule disruptions or worse: accidents. Over the past years the issues with maintenance documents are confirmed by several research projects. In 2000, the FAA concluded that failure to comply with maintenance documentation was the main reason for major malfunctions within 90 days of a heavy maintenance check (Johnson and Watson, 2000). More recently the FAA analysed nearly 900 actions taken against AMTs in 2012, showing 36% of the violations were associated with not using technical documentation (Avers et al., 2012).

Looking at aircraft line maintenance specifically the issues are even more critical. Line maintenance is performed on the platform during the turnaround time of the aircraft, which gives AMTs very limited time to perform maintenance, e.g., about 20 mins for Boeing 737 turnaround operations. As an additional complexity, the appearance of unexpected defects during turnaround inspection and maintenance processes may compound time-related stress, as AMTs currently have no direct access to documentation on-board or near the aircraft. Line AMTs are very experienced and might be able to solve most defects without consulting maintenance documentation, but consultation of documentation for task-support is required by aviation authorities. AMTs are however aware of the costly implications of flight disruptions and hence they feel the pressure to perform on time, while respecting the very high safety standards set in aircraft maintenance. As a result, an AMT faces a trade-off with undesired consequences: either get task-support information and risk flight delay, or perform the task without consulting documentation, ignoring regulations and risk maintenance error.

This research project has the objective to improve the access to maintenance documentation and simplify the retrieval of relevant maintenance information, by developing a mobile tool for contextualized documentation and avoid the AMT having to do an unfavourable trade-off. The tool needs to provide quick access to relevant information on-site, not only based on maintenance documentation, but also on the maintenance history and configuration of individual aircraft, providing a single source for task-support information. Such a tool would improve operational efficiency by reducing the turnaround times and minimizing flight disruptions, but also reduce maintenance error by mitigating human factors experienced by AMTs, such as pressure and stress. Furthermore, the switch from a paper-based procedure to a digital one will aid in the realization of sustainable aircraft maintenance.

This paper describes the development of an initial database system to provide a level of contextualization over a set of maintenance documents as a first step to the final research objective. Section 2 starts with a literature review focussing on human factors in aircraft maintenance and solutions developed in both research and industry. Section 3 elaborates on the development of the database system and ontology integration, followed by the results in Chapter 4. The paper ends with a discussion and conclusions in section 5, which also elaborates on directions for future research.

2 Literature review

To provide an efficient solution both the quality of the solution and the end user acceptance of the solution have to be high. Hence, a thorough understanding the problems the end users face is key. This section covers the main findings of the literature review, including an overview of solutions that have been developed in academia and industry.

2.1 Human factors in aircraft maintenance

To better understand how the weaknesses of maintenance documentation lead to problems in the maintenance process, this section elaborates on the human factors in aircraft maintenance. Human factors have been a topic of interest for decades in aviation, but most studies focused on pilot error and cockpit interfaces (Gramopadhye and Drury, 2000) It was not until the Aloha Airlines Flight 243 incident over Hawaii (National Transportation Safety Board, 1989) that the importance of human factors in maintenance was considered relevant in aviation safety. Shortly after, the Federal Aviation Administration FAA started the National Plan for Aviation Human Factors (Shepherd et al., 1991) to establish ground level knowledge on factors affecting maintenance performance: documents, procedures and training, work environment, ergonomics and individual factors such as fatigue, qualifications and skills. From that point onward extensive research in the maintenance field has been done on errors originating from human factors.

Human error has been defined in different ways and they all share the idea that humans are organic mechanisms with failure rates and tolerances similar to hardware and software elements of a system. Furthermore, human error is a negative term for normal human behaviour in less than ideal environments (Latorella and Prabhu, 2000) To find causes for human errors in aviation maintenance several studies developed models to identify the contributing factors, the most well-known being the "Dirty Dozen" (Dupont, 1997) The model is regarded as the foundation for human factors modelling in aviation and identifies 12 factors for human error: lack of communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, pressure, lack of assertiveness, stress, lack of awareness and norms. With the knowledge of the Dirty Dozen and other human factor models, several research projects were performed to understand when human factors occur and how they affect maintenance performance. The Aircraft Dispatch and Maintenance Safety (ADAMS) project (van Avermaete and Hakkeling-Mesland, 2001) was the first European study to focus on human factors in aviation maintenance. The study showed that AMTs have a large commitment to safety, but also deviated from official working standards and procedures. Through surveys and task observations it was found that AMTs used so-called blackbooks with private notes containing useful information about routine tasks, although declared illegal by management. The AMTs gave several reasons for using blackbooks: extraction of the right information from maintenance documentation is difficult due to the level of detail, errors in the manual and poor ergonomic facilitation to review maintenance documents. A problem that specifically occurs at line maintenance is the lack of access to maintenance documents at the platform. AMTs indicated that getting and consulting the maintenance documentation could take up half an hour, a major part of the turnaround time of a mid-size aircraft like the Boeing 737 (Boeing Commercial Airplanes, 2013), which increases the chance of flight disruptions. To overcome these limitations the ADAMS project suggests the use of a portable digital information system which is part of a network controlled by the engineering department. The online Maintenance Assistance Platform (Liang et al., 2010) is an example of a practical solution which reminds technicians to consider the effect of human error on systems and humans, and provides graphic information for specific tasks. During the development, the risks of several human factors were determined and the most important factors leading to error were identified: repetitive and monotonous tasks, work procedures not followed and complacency. Other projects focused on the development of training programs on organizational level to identify and prevent human factor effects such as the Maintenance Resource Management (MRM) training by the FAA (Sian et al., 2000) and the AvSSP Maintenance Human Factors program by the National Aeronautics and Space Administration (NASA) (Darr, 2005).

In 2014, researchers at Airbus and the University of Toulouse have tried to establish why maintenance technicians do not read or use maintenance documents (Zafiharimalala et al., 2014). The study shows that an AMT facing a lack of knowledge 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 task experience, thereby introducing the risk of complacency, but also based on previous experiences with maintenance documentation. Their findings and work of others (Kanki and Hobbs, 2008; Reason and Hobbs, 2003) lead to the conclusion that a substantial number of maintenance error is strongly related to the content and (non-)use of documentation. Zafiharimalala et al. (2014) identified two types of use for maintenance documentation: systematic use where the entire document is read and used, and non-systematic use where only some parts of a document are used. Systematic use is rarely done by AMTs (only 2 of 13 AMTs in the research use this method), because reading all documentation is a very time consuming process. The majority of AMTs use documentation in a non-systematic way and they provided the following reasons to do so:

- Lack of utility: the AMT is self-confident about his/her skills and lack confidence in the maintenance document.
- Lack of usability: the procedure in the document is not easy to follow and not easy to find.
- Lack of compatibility: using the document while performing a task is too devious.

Another factor is the AMTs opinion about the aircraft manufacturer and document author in general, based on the extent to which they are able to provide documentation that is usable and compatible with practical task execution in an operational environment. If the AMT previously found that the author is unable to produce functional documentation, the AMT is less likely to use maintenance documentation of that author later on. These findings illustrate the erratic (human) nature of the decision making process of an AMT to use maintenance documentation. Zafiharimalala et al. (2014) propose a dynamic model to represent the trade-off AMTs make for using documentation or not, which is based on three priorities: safety, legality and efficiency. Within this dynamic model, the cost/benefit trade-off is dependent on the availability and quantity of resources for information. The researchers conclude that a digital, mobile system to support AMTs in task execution may reduce conflicts between the three priorities of the dynamic model by improving the efficiency of acquiring information.

Although human factors research in maintenance has contributed to the overall safety in aviation over the last decades, statistics show the need for continued research. A study in 2012 concluded that risk in aviation substantially decreased since 1962, but the percentage of maintenance related accidents remained constant over the years (Marais and Robichaud, 2012). Moreover, analysis of accidents, incidents and enforcements over the period 1999-2008 showed that accidents caused by maintenance error result in fatalities 6,5 times more often compared to accidents overall, and also increase the number of fatalities for every accident by a factor 3,6. Besides accidents maintenance errors lead to increased cost due to corrective maintenance and flight schedule disruptions, compromising the operational efficiency of airline operators. For example, cancelling a Boeing 747-400 flight will cost the airline operator about $140.000, while an hour of delay at the gate accounts for approximately $17.000 (Hobbs, 2008). Hence, the importance of understanding human factors in aircraft maintenance and mitigating its negative effects to improve operational efficiency and safety is evident.

2.2 Research and industry solutions

Academic research on information retrieval from documents is domain specific, because characteristics and content of the documents heavily affect the success-rate of identification and extraction of relevant information. When scoping down on research papers focussing on the aircraft maintenance domain the contribution is limited. The main problem of aircraft (legacy) maintenance documentation is that the majority is either paper based or a 'paper-on-screen' solution (e.g., Portable Document Format (PDF)), which prevents information from being readily available at the right time and place (Candell and Karim, 2008). To provide the right information to the right user at the right time and place, both content and technology to supply information to the user should be considered (Candell, 2004). For information products, four aspects must be dealt with: time management (when), content management (what), communication management (how) and context management (who) (Haselo, 2005; Heuwinkel et al., 2003). Nicolai et al. (2005) developed and tested a practical solution based on e-Maintenance technologies. In order to improve maintenance efficiency, a wearable information system was developed to assist line AMTs in their tasks. By means of interviews they first established boundaries in the line maintenance process (Nicolai et al., 2005):

- No passengers are allowed in or near the aircraft during maintenance.
- AMTs need up-to-date information on the maintenance task.
- AMTs may work for different airlines with different aircraft tasks.
- Maintenance information is specific for the individual aircraft (registration number).
- AMTs face a wide variety of tasks.
- Data used for maintenance includes routine tasks (planned maintenance), additional tasks (problems reported by cabin/flight crew) and on-board self-diagnostic system information.
- To solve complex problems AMTs require access to technical documentation of the aircraft.
- All performed maintenance tasks have to be documented and provide an important resource for future maintenance tasks.

While modern aircraft have a digital logbook, a troubleshooting manual and printed manuals on-board, AMTs prefer to print relevant pages from electronic manuals from a computer at the hangar or maintenance base, thereby having more time for the actual task at hand instead of searching for relevant information during the turnaround time. An AMT may also contact a colleague with the required expertise to solve the problem, either in person or by phone/radio. To provide an alternative, Nicolai et al. (2005) developed a wearable system that is able to search through manuals, navigate by aircraft structure, provide a part/system location list and classify errors. The system entailed an ontology-based database, a three-part user interface and required the installation of an electronic self-diagnostic system and placement of RFID tags in the aircraft. Implementation of the system would require substantial investments, which may be the reason why the proposed solution never went beyond the conceptual stage.

Operational solutions are available in industry, but getting a complete overview is difficult because most solutions are commercially exploited and vendors rarely share information on the methods and technology used. Both major manufacturers Boeing and Airbus offer their own solutions for managing maintenance documentation in the form of Boeing's Maintenance Performance Toolbox (Boeing, 2015) and AirN@v (Airbus, 2015). Besides being vendor specific, both are not designed for mobile use in line maintenance. Moreover, users indicate performance is slow and search functionality is too limited (e.g., only exact case-sensitive keyword matches). Maintenance, repair and overhaul providers (MROs) like Lufthansa Technik also develop in-house solutions aiming for paperless maintenance operations (Lufthansa Technik, 2015), but focus more on digitalizing future documentation, not on including existing maintenance documents. Another commercial solution is DigiDOC Content Management System (CMS) by Aerosoft Systems Inc., who developed an extensive system to provide "the right form and pieces of information into the right hands, at the right time and place" (Aerosoft Systems Inc., 2015). A limitation of their solution is indicated by "simple navigation to a desired document", which may not be aircraft specific as required. Moreover, finding task-specific information in a single document can still be very time-consuming, as some maintenance documents have hundreds of pages.

3 System development

The previous section showed that there is still need for a system to provide task-specific maintenance information to the line AMT. In this section the development of a novel system for a first level of contextualization will be discussed.

3.1 System framework

The aim of this work is to be able to contextualize maintenance documents, used in their original file format, and filter relevant information based on the context that can be derived from the aircraft registration mark. The ability to provide context by means of the registration mark is considered as essential functionality for an operational solution, because the relevance of maintenance documentation depends on individual aircraft modifications and maintenance history. Individual aircraft are identified by the registration mark or the Manufacturer Serial Number (MSN), but unlike the MSN an AMT can easily find the registration mark on the exterior of the aircraft. With this purpose in mind a framework was established and consists of a database system, an ontology and a query engine (see Figure 1). In the following sections each component of the framework will be discussed in detail.

3.2 Database setup

Due to access restrictions to aircraft maintenance documentation, Airworthiness Directives (ADs) are chosen as the data source for this initial system. Unlike other documents, which are only accessible to manufacturers, MROs, operators and authorities, ADs are available for download as PDF files on the websites of European Aviation Safety Agency (EASA) and the FAA. The aim is to be able to relate these ADs to individual aircraft without the need to further process the documents beforehand. There are currently two methods available to store Binary Large OBjects (BLOBs) like PDF files for use in a relational database system: either store them directly in the database or store them in a separate file system. Research shows that a separate file system provides better performance for larger files (i.e. files over 1MB), but lacks integrated functionality for full-text search which is required to filter relevant maintenance documents (Sears et al., 2006). While ADs usually contain only a couple of pages and require less than 1MB of storage space, other documents, such as the Aircraft Maintenance Manual (AMM), entail hundreds or thousands of pages and are significantly larger in size. To ensure that system performance can be maintained in later project stages, a solution was required that can store the files in a separate file system, but also provides full-text search functionality. Microsoft provides a solution with SQL Server version 2012 or later, which includes the FileTable feature (Microsoft Technet, 2015). This feature accesses files and documents through so-called "FileTables", but are stored in a conventional Windows file folder, and can be opened and modified through Windows explorer. The FileTable feature will automatically detect changes in the specified file folder. The FileTable is a table in the database that represents a hierarchy of directories and files, wherein every row represents a file or directory. Among the benefits of the FileTable feature is the capability to full-text search many different file types, including PDF. Hence, a database was set up based on Microsoft SQL Server 2014, including the FileTable feature and a network file folder containing the ADs. Finally, the database contains a table with the fleet information of an airline operator to be able to relate documents to a registration mark.

3.3 Ontology

A key feature of this system is the integration of an ontology for retrieving task-specific information. An ontology is defined as a specification of a conceptualization, which concerns a description of the concepts and relationships in a domain of knowledge (Gruber, 1992). More specifically, the key role of ontologies in database systems is to specify a data modelling representation at a level of abstraction above specific database designs, so that data can be used across independently developed systems and services (Gruber, 2007). Ontology integration is an increasingly popular method to manage knowledge and provides the following benefits (Noy and McGuinness, 2001):

- 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.
- Analyse domain knowledge; once a specification of terms is established it can be used to reuse the ontology for other domains or expand it.

Using an ontology together with a relational database does not only bring the benefits an ontology provides, but also the robustness, performance, maturity, availability and reliability of the relational database system (Humaira et al., 2015). The two combined therefore provide a powerful platform for context-based querying, known as ontology-based data access (OBDA). OBDA is regarded as a key ingredient of the new generation of information systems. In the OBDA paradigm, an ontology defines a high-level global schema of (already existing) data sources and provides a vocabulary for user queries over databases (Kontchakov et al., 2013). Moreover, the relations and constraints in an ontology can be used for semantic search: by entering a registration mark as the query, the system can determine related aircraft characteristics (e.g., the manufacturer) through the ontology to find relevant maintenance documents.

With no suitable ontology available, a custom ontology has been developed in Protégé. Based on fleet information stored in the SQL database, containing the registration marks and their aircraft models (shown in Table 1), the ontology derives the manufacturer, family and series information from the registration mark and establishes relations by assigning object properties. Figure 2 provides an example for registration mark PH-BVC, a Boeing 777-306, and shows to which ontology classes this aircraft model is assigned in blue. First of all it is assigned to the Commercial Aircraft class like every other aircraft model in the fleet. Then it is assigned to manufacturer Boeing through the object property *hasManufacturer*, to the 777 Family by the object property *hasFamily* and finally to the 300 series through *hasSeries*. The series information (i.e., 306 for the PH-BVC) provides more contextual information about the engine manufacturer (0) and engine model (6) that could be used for further identification of relevant maintenance documents, but analysis of these characteristics showed ambiguity in the engine model numbering. For that reason this contextual information has been left out of the scope of this paper. In a similar fashion the classes and object properties for all the aircraft models in the fleet were added to the ontology. Through the relations in an ontology, the system can infer for example that both the classes Boeing and Airbus have a subclass *hasSeries* 300, but also that the A330 family never *hasManufacturer* Boeing and that manufacturers Airbus and Boeing are disjoint. This explicit definition of relations between classes is one of the key benefits of ontology integration.

3.4 Mappings

Mappings are required to link classes in the ontology with entries in the database. Multiple methods to map ontologies onto relational databases are available, all having specific benefits and drawbacks. A recent survey of the state of the art for automatic and lossless mapping methods shows that available methods still have issues with loss of structure and information or are not fully automatic (Humairaet al., 2015). A new, promising method is provided by Ontop, developed at the Free University of Bozen-Bolzano in Italy. Although the method does not support automatic generation of 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 database and the query engine, Ontop has direct access to the database and the ontology, avoiding loss of metadata and the 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 (Khazalah et al., 2014). Ontop 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 (Rodríguez-Muro et al., 2013).

Using Ontop and its plugin for Protégé, a total of 35 mappings were created to relate the registration marks in the fleet information table in the database to all the respective classes and properties in the ontology, as well as mappings to relate documents linked by the FileTable to the specific aircraft type of a registration mark. A mapping consists of a mapping identifier, a target and a source. The identifier is simply the name given to that mapping, the target states a set of RDF triples and the source refers to specific entries in a database table. A RDF triple states the relationship between resources and always consists of a subject, a predicate and an object. Figure 3 shows an example of a mapping to link registration marks in the fleet information table in the database with manufacturer Airbus to the class Airbus in the ontology, and at the same time linking properties defined in the ontology to the respective entries in the database table. For the Airbus aircraft specified in Table 1 this mapping would result in the RDF triples shown in Table 2.

4 Results

Due to the limited complexity of the system and data structures, direct querying in SQL Server is possible and can be compared with querying using the OBDA method. When the system is extended with more information sources and/or when higher levels of contextualization are desired, querying directly in SQL Server will rapidly become very complex, while the OBDA method will show its true potential for combining data sources.

4.1 Qualitative assessment

First it was verified that the system output, the documents retrieved as relevant for a particular registration mark, is correct. For this, the database containing a small batch of 10 ADs was queried for one registration mark per distinct aircraft model in the fleet, both in SQL Server and using the OBDA method. Manual verification showed that both SQL Server and the OBDA method fail to retrieve all relevant maintenance documents for a given registration mark. Analysis of the documentation led to the discovery that the issue was caused by including the aircraft series information. Two causes could be identified: some documents do not refer to the applicable aircraft series at all or the x00-format is not used. The latter causes problems in combination with the CONTAINS statement that has to be used in combination with the FileTable feature. The CONTAINS statement is a Boolean method and identifies whether an exact keyword match is present or not. In the case of maintenance documents related to Airbus the aircraft type including the engine reference is used, for example A330-321. The CONTAINS statement looks for exact matches and will not return a match for the string ‘300’ when the string ‘321’ is used to refer to a 300 series aircraft. Boeing specific documents often refer to “all the series” of a family without explicitly stating them or use a format like 787-8, also resulting in no matches. This arbitrariness in the specification of series information in documents leads to unwanted exclusion of relevant documents, because documents are only considered relevant to a registration mark if the manufacturer AND the family AND the series are found in the document. If one of these strings is not identified the document will not be returned as relevant.

Both SQL Server and the OBDA method obtain a 100% score for retrieving relevant maintenance documents when the series information is excluded. With the series information included to identify relevant documentation, SQL Server is successful in retrieving the complete set of relevant documents for only 3 out of 9 registration marks, as shown in Table 3. Identical results were obtained with the OBDA method. The consequence of the issues involving the aircraft series information is that for the remainder of the tests the series information is excluded. This leads to false positives because documents that are not relevant for a specific registration mark and its related aircraft family will be returned as relevant (e.g., a document related specifically to a 737-900 will be returned as relevant for a 737-700 as well), but this is preferred over missing relevant documents when the series information is included. As a result the level of contextualization is lowered by relating the registration mark to the aircraft manufacturer and family only.

4.2 Quantitative assessment

The performance of the system is measured in query runtime. For each distinct aircraft model in the fleet a registration mark is selected to measure the query runtime. The database initially contains a batch of 10 documents and after measuring the query runtime a new batch of 10 documents is added. This process is repeated for a total of 5 batches and for 9 registration marks, leading to a total of 45 measurements per batch. For both methods (SQL and OBDA) the query runtime is measured 5 times per batch and then averaged to smooth out erratic behaviour due to background processes running on the test system. Figure 4 shows that SQL Server has steady performance with query runtimes between 0.07 and 0.08 seconds. The OBDA method initially performs a bit slower, but from the second batch onwards the performance increases significantly and outperforms direct querying in SQL Server by a factor over two. This result is somewhat surprising because the OBDA method has to process the mappings before executing the query. Moreover, the developers of OntopPro confirmed that table joins, used in the source of the mappings, and the CONTAINS statement, used for the full-text search, are not fully supported yet. Because the OBDA method requires more information to be processed in a less efficient way due to not fully supported functions, the expectation was that SQL Server would perform better given the limited complexity of the system.

To better understand the differences between the performance of SQL Server and the OBDA method, individual measurements for both methods are analysed. First, Figure 5 shows the individual measurements of the query runtimes for registration mark PH-BFE in SQL Server. Besides the individual measurements and the mean query runtime, the standard deviation with respect to the mean is shown. Overall the standard deviation does not exceed 20%, except in batch 5 where a measurement in run 2 of 0.1248 seconds leads to a relative high standard deviation of 40% while the other measurements for batch 5 are closer to the mean. The high average query runtime of batch 4 is caused by two query runtime measurements of 0.1092 seconds (run 3 and run 5), while the other three measurements for that batch show an average performance, but cannot compensate for the decreased performance in runs 3 and 5. The deviations can only be explained by background processes claiming system resources, as SQL Server consistently shows constant performance when multiple measurements are averaged. The other registration marks show similar behaviour in SQL Server.

For the OBDA method registration mark PH-BXR is analysed in more detail, because it shows a delayed reduction in the query runtime as shown in Figure 6. Where other registration marks immediately show increased performance after batch 1, this increased performance occurs only from batch 3 and onwards for PH-BXR. The standard deviation shows a more erratic behaviour compared to the results in SQL Server. Two exceptionally high first query runtime measurements of 0.203 and 0.15 seconds in batch 1 and 2 lead to a standard deviations from the mean value of around 100%. The later batches show more constant behaviour with reduced variation in the measurements. The other registration marks do not show such extreme deviations in the second measurement of the second batch and therefore immediately show the improved performance after batch 1.

A final test is performed using a larger dataset in order to measure the effect of more data on the performance. The database is filled with 987 maintenance documents having a total size of 148MB. For both methods the following registration marks are queried, representing each aircraft family in the fleet: PH-BFE, PH-AOA, PH-BHC, PH-BXR and PH-BQC. Figure 7 shows the results for the query runtime for 3 consecutive measurements per registration mark. Compared to the previous query runtime measurements on a smaller dataset, the performance of SQL Server has been negatively affected by the increased amount of available maintenance documentation. While the query runtime is fairly constant for all runs, the average query runtime is increased by approximately 33% from 0.075 seconds to 0.1 seconds. The increase in query runtime is unexpected as relational database systems like SQL Server are designed to efficiently deal with large amounts of information. The performance degradation may be explained by the hard- and software used for the test platform, which is based on consumer products. The OBDA method initially shows the weak performance at the first measurement for the first registration mark again, but already performs similar to SQL Server when querying the second registration mark in the first run. The second and third run perform extremely well, showing similar behaviour for later measurements as before. The tests lead to the hypothesis that the increase in performance of the OBDA method in later measurements is caused by an initialization of the mappings when they are first called upon, but are readily available for later queries.

As means of verification the number of documents returned as relevant for each query was checked for both SQL Server and the OBDA method. No deviations between the two methods were found and they both return the same number of relevant maintenance documents:

- PH-BFE Boeing 747 460 documents
- PH-AOA Airbus A330 52 documents
- PH-BHC Boeing 787 28 documents
- PH-BXR Boeing 777 354 documents
- PH-BQC Boeing 737 166 documents

From Figure 7 it can be observed that registration marks with a large amount of relevant maintenance documents and those with a smaller number of relevant maintenance documents show no significant difference in query runtime.

5 Discussion and conclusions

The use of maintenance documentation in aircraft maintenance is currently highly inefficient, due to the limited access and usability of the documents. Especially in line maintenance, remote from the maintenance hangar and with only limited time available, acquiring the right task support information is tedious. As a result the AMT is always faced with a undesirable trade-off: either spend time acquiring task support information and risk delays, or perform maintenance without consulting maintenance documentation, disregard regulation and increase the risk of maintenance error.

To avoid the before mentioned trade-off and overcome its negative effects, this research project aims to deliver the right information to the AMT efficiently and on-site through a mobile device. The AMT should be able to access all sources of maintenance documentation by entering the registration mark of the aircraft (i.e., maintenance documentation is tailored to individual aircraft), because the registration mark is easily identifiable on the exterior of the aircraft. This paper describes the first step of the development and shows a proof of concept for contextualized access to maintenance documentation. A database system was developed to retrieve relevant maintenance documents from the database, using the aircraft registration mark as input only. The core of the database system is Microsoft SQL Server, with the maintenance documents stored in a conventional network file folder that is linked to SQL's FileTable feature for full-text search functionality. An approach for OBDA was pursued to benefit from the high-level conceptual schema and domain knowledge incorporated in an ontology. To implement OBDA, an ontology for the domain of commercial aircraft was developed and integrated by manual mappings using the Ontop plugin for Protégé. With the registration mark as input for a search query, the aircraft manufacturer, family and series information are derived and used as attributes for a Boolean search through all available maintenance documents. It was found that inconsistent use of series information in the documentation, as well as limitations of the full-text search capability of the FileTable feature, led to not retrieving some of the relevant maintenance documents. For this reason, and because including the series information was not deemed necessary for a proof of concept, the series information was omitted in further testing. The measured query runtime, required to retrieve relevant maintenance documents using the only the registration mark as input, was used as the performance indicator. Both direct querying in SQL Server and querying with the OBDA method were assessed. Where SQL Server showed constant averaged performance of approximately 0.1s, the OBDA method only required about half that time to retrieve relevant documents. The OBDA method is initially slower in the first measurement, but consistently outperforms querying in SQL Server in consecutive measurements. Moreover, the performance of the OBDA method is less affected than SQL Server when the amount of available maintenance documents in the database is increased.

The OBDA method contributes to the research field of knowledge management by a novel ontology implementation with SQL Server and its FileTable feature. Although the level of contextualization of the database system is limited to the aircraft manufacturer and family, it provides a functional proof of concept for a novel method to contextualize maintenance documentation. The method can be adapted to other domains facing similar problems with information requests, but that does require replacing the ontology and mappings. Limitations of the developed method are related to the dependency and incompatibility of different software components and the lack of support to automatically create mappings. When more data sources are added to the system to increase the level of achievable contextualization the number of required mappings will grow exponentially, making manual creation of mappings infeasible.

Hence, future development will focus on a new framework for OBDA that is independent of third party software and supports automatic mapping of the ontology onto the database. Next, the research will focus on adding more relevant data sources (e.g., the AMM, the Troubleshooting Manual (TSM) and Service Bulletins (SBs)), classification of information on section level, exploit cross referencing in documents and apply machine learning algorithms for text classification. Currently, the system lacks a graphical user interface and is only used to evaluate text classification accuracy and retrieval times, but future research will also address operational implementation of the system. Several successive prototypes of a mobile tool will be developed for evaluation and validation by the end user (i.e., the AMT). Their expert feedback based on operational use cases will be valuable to the project development, and can provide more insight in used query inputs besides the registration mark (e.g., Air Transport Association (ATA) chapters, Functional Identification Numbers (FINs), part numbers or keyword search) and how to rank the results efficiently. Such a system does not only tackle the limited accessibility for line maintenance technicians, but also improves the usability of maintenance documentation, and could thereby significantly reduce the time currently wasted on acquiring task-specific information. The likelihood of flight schedule disruptions and human factor induced maintenance errors will be reduced, increasing operational efficiency and overall safety of air transport. Finally, it will aid the transition from paper-based to digital operations and avoid the current waste of large amounts of paper in aircraft maintenance.

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Tables, figure captions and figures

Table 1: Example of airline fleet information in the database

Registration mark	Model	Manufacturer	Family	Series
PH-AKA	Airbus A330-303	Airbus	A330	300
PH-AOK	Airbus A330-203	Airbus	A330	200
PH-BGK	Boeing 737-7K2	Boeing	737	700
PH-BVC	Boeing 777-306	Boeing	777	300

Table 2: RDF triples following from a mapping

Subject	Predicate	Object
Reg PH-AKA	hasManufacturer	Airbus
Reg PH-AKA	hasFamily	A330
Reg PH-AKA	hasSeries	300
Reg PH-AOK	hasManufacturer	Airbus
Reg PH-AOK	hasFamily	A330
Reg PH-AOK	hasSeries	200

Table 3: Results of the qualitative assessment

Reg	Model	SQL (series excl.)	OBDA (series excl.)	SQL (series incl.)
PH-AOA	Airbus A330-200	EASA_AD_2014-0148_1 EASA_AD_2014-0248_1	EASA_AD_2014-0148_1 EASA_AD_2014-0248_1	EASA_AD_2014-0148_1 EASA_AD_2014-0248_1
PH-AKA	Airbus A330-300	EASA_AD_2014-0148_1 EASA_AD_2014-0248_1	EASA_AD_2014-0148_1 EASA_AD_2014-0248_1	EASA_AD_2014-0148_1
PH-BGD	Boeing 737-700	EASA_AD_US-84-20-03R1_1 EASA_AD_US-87-02-07_1	EASA_AD_US-84-20-03R1_1 EASA_AD_US-87-02-07_1	
PH-BGC	Boeing 737-800	EASA_AD_US-84-20-03R1_1 EASA_AD_US-87-02-07_1	EASA_AD_US-84-20-03R1_1 EASA_AD_US-87-02-07_1	
PH-BXR	Boeing 737-900	EASA_AD_US-84-20-03R1_1 EASA_AD_US-87-02-07_1	EASA_AD_US-84-20-03R1_1 EASA_AD_US-87-02-07_1	
PH-BFE	Boeing 747-400	EASA_AD_2014-0148_1 EASA_AD_US-84-19-01_1 EASA_AD_US-86-18-01_1	EASA_AD_2014-0148_1 EASA_AD_US-84-19-01_1 EASA_AD_US-86-18-01_1	
PH-BQC	Boeing 777-200	EASA_AD_US-2005-07-02_1 EASA_AD_US-2014-05-03_1	EASA_AD_US-2005-07-02_1 EASA_AD_US-2014-05-03_1	EASA_AD_US-2005-07-02_1 EASA_AD_US-2014-05-03_1
PH-BVG	Boeing 777-300	EASA_AD_US-2005-07-02_1 EASA_AD_US-2014-05-03_1	EASA_AD_US-2005-07-02_1 EASA_AD_US-2014-05-03_1	EASA_AD_US-2005-07-02_1 EASA_AD_US-2014-05-03_1
PH-BHC	Boeing 787-900	EASA_AD_US-2012-24-07_1 EASA_AD_US-2013-02-51_1	EASA_AD_US-2012-24-07_1 EASA_AD_US-2013-02-51_1	

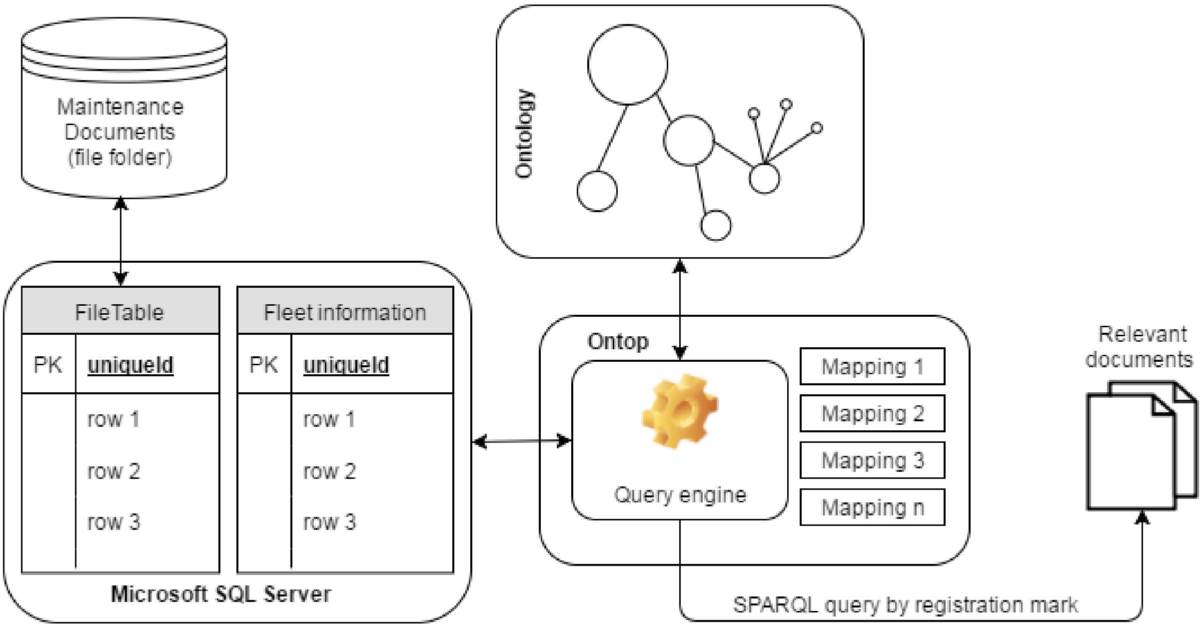

Figure 1: System framework

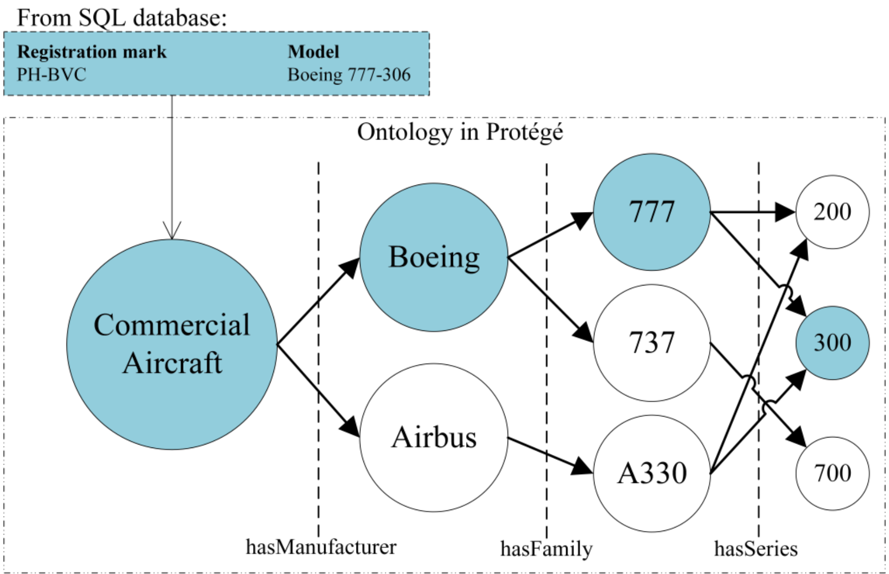

Figure 2: Ontology following from the fleet information

Airbus mapping

```
:{Manufacturer}/{Reg} a :Airbus ; :hasManufacturer {Manufacturer} ; :hasFamily {Family} ; :hasSeries {Series} .
SELECT * FROM FleetInfoKLM WHERE Manufacturer = 'Airbus'
```

Figure 3: Mapping example

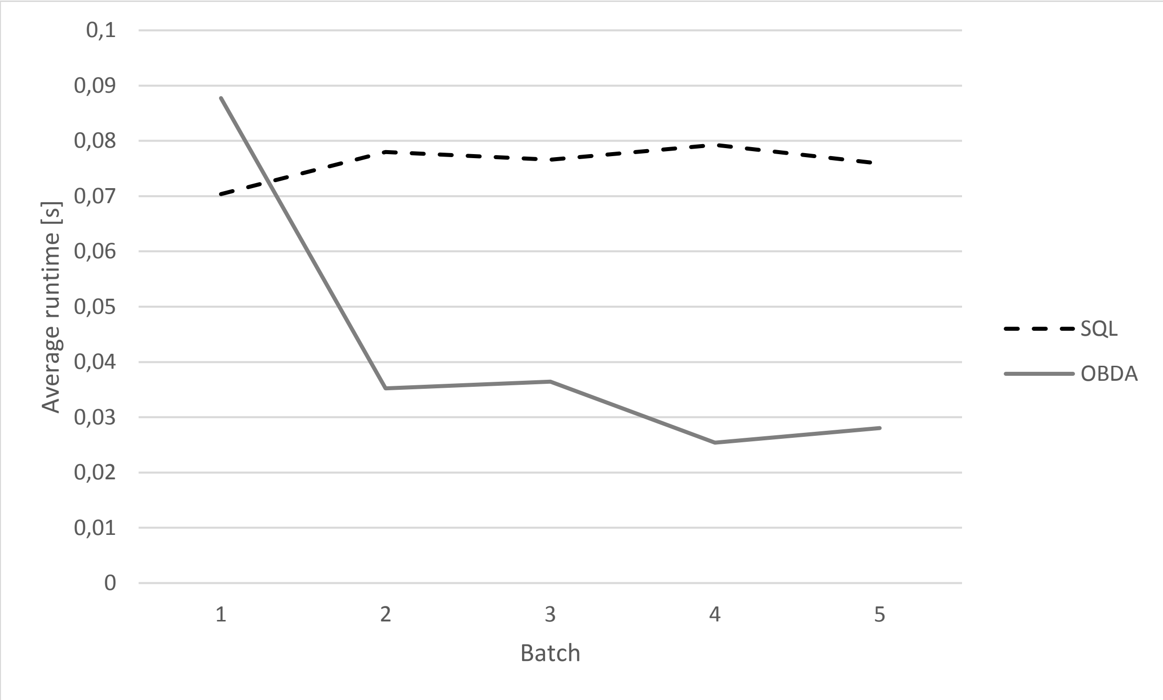

Figure 4: Average query runtime per batch for all registration marks combined

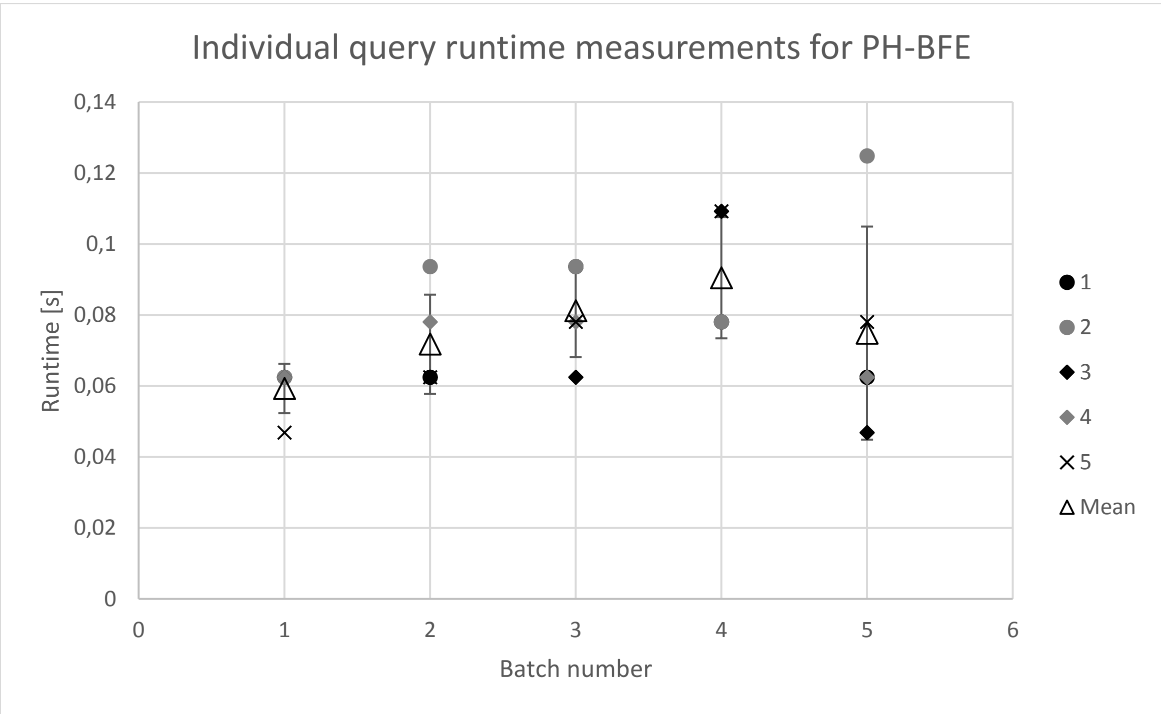

Figure 5: Individual runtime measurements in SQL for PH-BFE with standard deviation

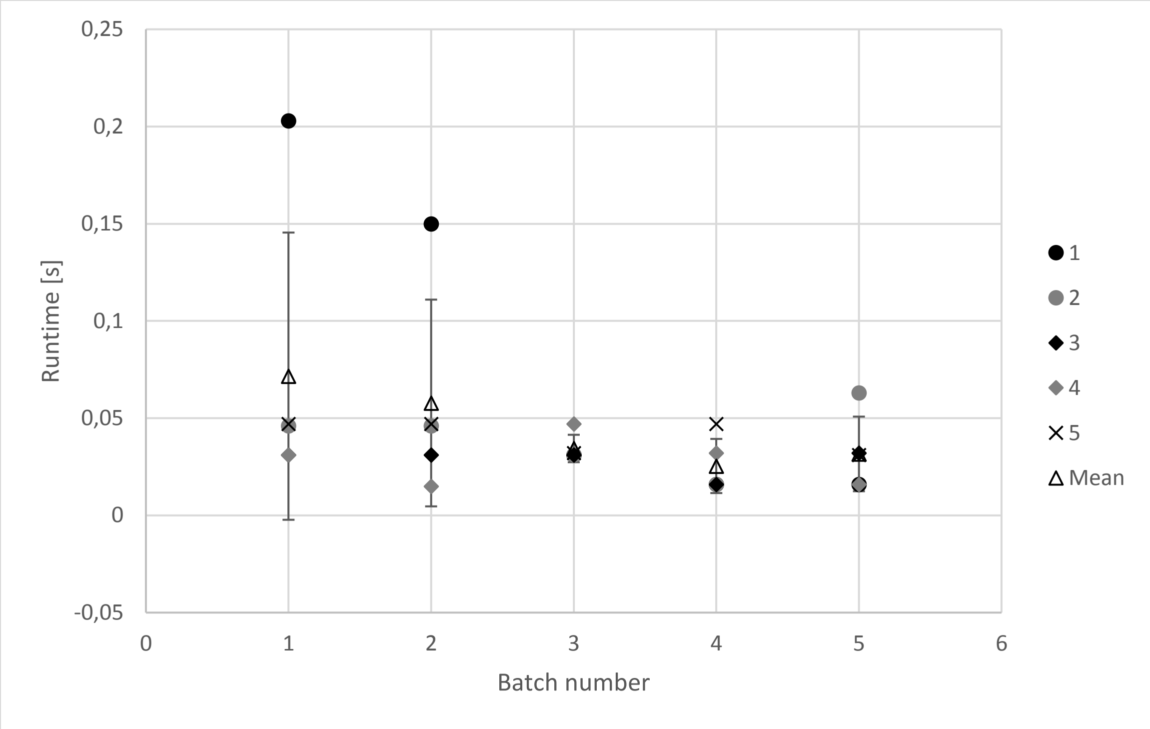

Figure 6: Individual runtime measurements in OBDA for PH-BXR with standard deviation

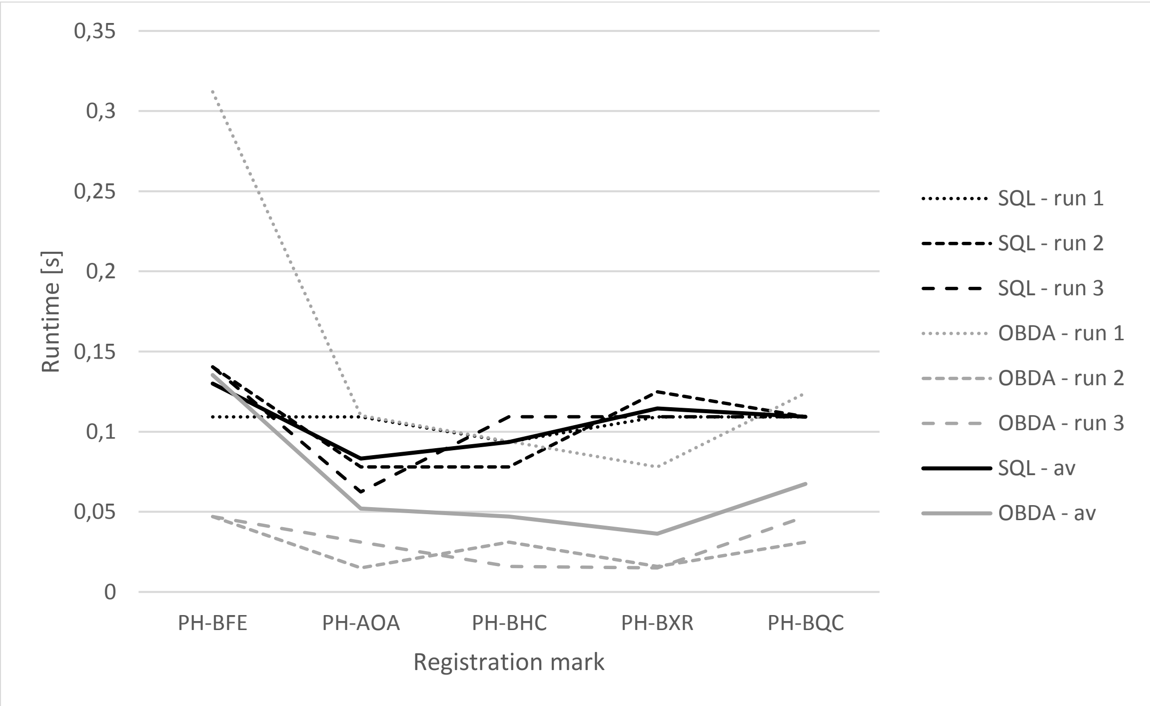

Figure 7: Query runtimes for SQL and OBDA over an extended dataset

Keywords

Aircraft line maintenance, maintenance efficiency, contextualized documentation, ontology-based data access, human factors, paperless