The Case for Contextualized Knowledge Graphs in Air Traffic Management

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Abstract. Knowledge graphs represent real-world entities and their relationships with each other, with a broad range of applications in various domains. In this paper, we argue that contextualized knowledge graphs fit naturally with air traffic management, which heavily depends on the timely flow of required information. In particular, we illustrate how the temporality concept of the Aeronautical Information Exchange Model is represented using contextualized knowledge graphs with a temporal dimension. We further explain what spatial, provenance, and other semantic dimensions of context are relevant for air traffic management. We draw from experience with past research projects on the benefits of employing semantic web technologies for air traffic management.

Keywords: Resource Description Framework · Aeronautical Information Exchange Model · ATM knowledge graphs · Temporal context.

1 Introduction

For various applications, organizations now employ knowledge graphs. A knowledge graph (KG) comprises knowledge about real-word entities and their relationships with each other (see [6] for further information). KGs mainly focus on ABox (instance) rather than TBox (schema) knowledge, although ontologies may serve to organize KGs and infer knowledge (see [14]). Hence, a KG consists of statements about the real world, typically covering multiple topics [14]. These statements are often to be interpreted in a particular temporal, spatial, or other semantic context. For example, the statement "Vienna airport's 16/34 runway is closed" likely refers to a particular temporal context, e.g., a specific date, unless the runway is permanently closed. For the semantic web, numerous approaches to context exist. Contextualized knowledge repositories [16], for example, serve as formal framework for the representation of context, with a knowledge propagation mechanism from more general to more specific context.

Modern air traffic management (ATM) relies heavily on the timely flow of relevant information. Industry and academia display a growing interest in employing semantic web technologies for ATM (see [8]). Semantic web technologies promise to improve management and processing of ATM information, e.g., by facilitating intelligent filtering and annotation of notifications in air traffic operations [18]. For ATM in general, information/knowledge about infrastructure, aircraft, flight plans, weather, etc. is relevant. In the specific case, however, e.g., an individual flight, what constitutes the valid, relevant information/knowledge depends on the context. In this regard, various dimensions of context come into play, mostly temporal and spatial but also other types of context such as importance and provenance. For example, the valid, relevant knowledge for a pilot to safely operate a flight depends, among other things, on the date (temporal context) and route (spatial context).

In this paper, we propose the use of contextualized knowledge graphs for ATM in order to organize relevant ATM information/knowledge for different applications. For representing such *contextualized ATM knowledge graphs*, we adapt the concept of *semantic container* [7, 13] as developed in the course of the BEST project[5] within the SESAR Joint Undertaking of the European Union's Horizon 2020 program. A semantic container is a package of data items which has a semantic description of the container contents. The semantic description can be regarded as a context which the semantic container contains all the relevant information for. The remainder of this paper is organized as follows. In Sect. 2, we briefly present information (exchange) models for ATM. In Sect. 3, we introduce contextualized ATM knowledge graphs. We conclude with a brief discussion, a presentation of related work, and an outlook on future work.

2 Information Models for Air Traffic Management

ATM employs multiple information (exchange) models for various different purposes. The Aeronautical Information Exchange Model (AIXM [1]), for example, serves to exchange information about aeronautical features, e.g., characteristics of navigation aids and runways, as well as temporary changes thereof. Similarly, the ICAO Meteorological Information Exchange Model (IWXXM) and the Flight Information Exchange Model (FIXM) serve to exchange information about weather and flight plans, respectively. The ATM Information Reference Model (AIRM), on the other hand, incorporates concepts from various information (exchange) models, acting as common reference model (see [21] for further information).

The AIXM Temporality Concept [19] allows for the definition of "deltas" with respect to the baseline information, indicating temporary changes to the state of the world, e.g., a temporarily closed runway. In this regard, the notion of *time slice* is central: Each aeronautical feature, in a given time interval – the time slice – has a state (or none at all). AIXM distinguishes between baseline and tempdelta as well as snapshot time slices. The baseline consists of the regular

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[5] http://project-best.eu/

Listing 1. An example DNOTAM in XML notifying of airport closure due to snow

```
1  ⊟ <notamMessage:AIXMBasicMessage>
2    ⊟ <notamMessage:hasMember>
3      ⊟ <AirportHeliport gml:id="VIE1">
4        ⊟ <timeSlice>
5          ⊟ <AirportHeliportTimeSlice gml:id="VIE1_TS1">
6            ⊟ <gml:validTime>
7              ⊟ <gml:TimeInstant gml:id="VIE1_TS1_TI">
8                ⊟ <gml:timePosition>2018-06-08T08:00:00
9            ⊟ <interpretation>SNAPSHOT
10           ⊟ <locationIndicatorICAO>LOWW
11       ⊟ <timeSlice>
12         ⊟ <AirportHeliportTimeSlice gml:id="VIE1_TS2">
13           ⊟ <gml:validTime>
14             ⊟ <gml:TimePeriod gml:id="VIE1_TS2_TP">
15               ⊟ <gml:beginPosition>2018-06-08T08:00:00
16               ⊟ <gml:endPosition>2018-06-09T08:00:00
17             ⊟ <interpretation>TEMPDELTA
18           ⊟ <availability>
19             ⊟ <AirportHeliportAvailability gml:id="VIE1_AV1">
20               ⊟ <operationalStatus>CLOSED
21               ⊟ <annotation>
22                 ⊟ <Note gml:id="VIE1_NT1">
23                   ⊟ <propertyName>operationalStatus
24                   ⊟ <purpose>REMARK
25                   ⊟ <note lang="eng">DUE TO SNOW
```

feature values (which may change) whereas the tempdelta defines overriding temporary feature values. Snapshot refers to the current feature values when considering both baseline and tempdelta time slices. Listing 1 shows the XML representation of a Digital Notice to Airmen (DNOTAM) according to AIXM, a message that notifies of a temporary change of the baseline information regarding an airport's operational status. The time slice with id "VIE1_TS1" (Lines 5-10) shows the current state of Vienna airport with respect to its ICAO location indicator. The time slice with id "VIE1_TS2" (Lines 11-25) defines a tempdelta for the 24-hour period beginning at 8:00 a.m. on 8th June 2018, indicating a closure of Vienna airport due to snow.

AIXM describes a comprehensive conceptual model in UML, which along with IWXXM and FIXM may be used to represent the state of the world (as relevant for the aeronautical domain) and construct an ATM KG. Although XML serves as the representation format of DNOTAMs in AIXM, AIXM builds on the Geography Markup Language (GML), which itself was heavily influenced by RDF [11, p. 20]. Hence, RDF is a natural fit for the representation of AIXM and the construction of KGs based upon it. Existing ATM ontologies may also serve to construct ATM KGs. For example, in the BEST project, we developed an

AIRM ontology [20] which may act as starting point to define further background knowledge. The NASA ATM Ontology [9] also allows for the representation of similar ATM information/knowledge.

3 Contextualized ATM Knowledge Graphs

Context serves to structure ATM knowledge graphs in order to accommodate for the different information needs of different applications. The context determines which information/knowledge is valid or relevant. Contextualized KGs explicitly represent the context and thus facilitate selection of valid and relevant information/knowledge. In the following, we illustrate the representation of context in AIXM, particularly temporal context.

A context is characterized by a dimensional vector consisting of concepts from different ontologies, one for each context dimension. The dimensional vectors serve to determine coverage relationships between contexts. More specifically, subsumption or other relationships between concepts in the ontologies determine the coverage relationships between contexts. Consider, for example, the context with knowledge relevant in the year 2018 for the entirety of Europe, which covers the context with knowledge relevant in January 2018 for the route from Vienna to Frankfurt. We say that when a context c covers a context c', the context c' is narrower than c. Conversely, we say that c is broader than c'.

The coverage relationship between contexts is important for knowledge propagation. Specifically, the broader contexts propagate their knowledge to the covered, narrower contexts. We refer to related work on contextualized knowledge repositories [16, 3] for further information on such knowledge propagation mechanism for contexts.

Context information often derives directly from the model elements. The AIXM time slices, for example, serve to associate statements with contexts along a temporal dimension. Figure 1 shows a contextualized RDF representation of the DNOTAM information from Listing 1. Metadata and general information such as the definition of the VIE1 individual as an instance of AirportHeliport with ICAO location indicator “LOWW” are associated with a temporal context characterized by All-TemporalEntity rather than any particular time instant or interval. The All-TemporalEntity concept serves as the single top concept of the temporal dimension; any time instant or interval is subsumed by that top concept. Then, another context characterized by the particular time interval from 8th to 9th June 2018 at 8:00 a.m. – which is narrower than the first context – comprises the statements indicating temporary changes to the baseline data, namely the closure of VIE1 airport due to snow.

The AIXM Temporal Concept specifies that tempdelta property values override values from the baseline context. For example, some features such as navigation aids operate on a schedule which might change temporarily. To enable such an override mechanism in knowledge propagation, an additional context dimension captures the time slice interpretation. Each context either consists of baseline, tempdelta, or snapshot information as per the AIXM definition.

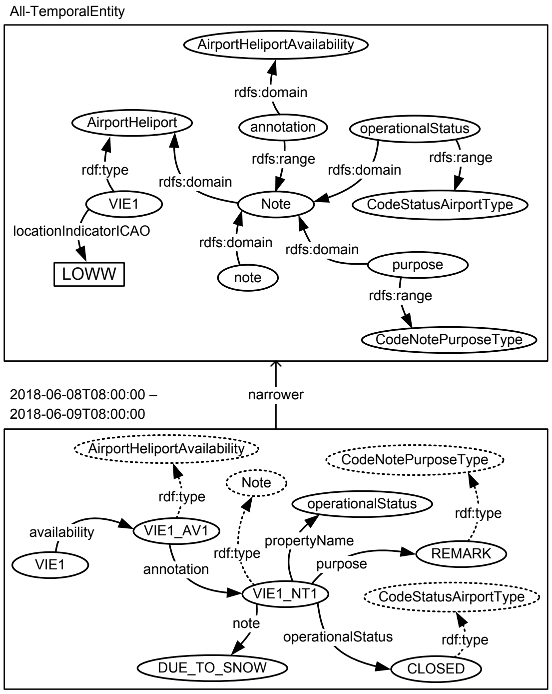

Fig. 1. Contextualized ATM knowledge graph which contains the DNOTAM information from Listing 1. Dotted lines indicate inferred triples. The broader context defines schema information (TBox) as well as general knowledge, which serve to define and infer knowledge in the narrower context.

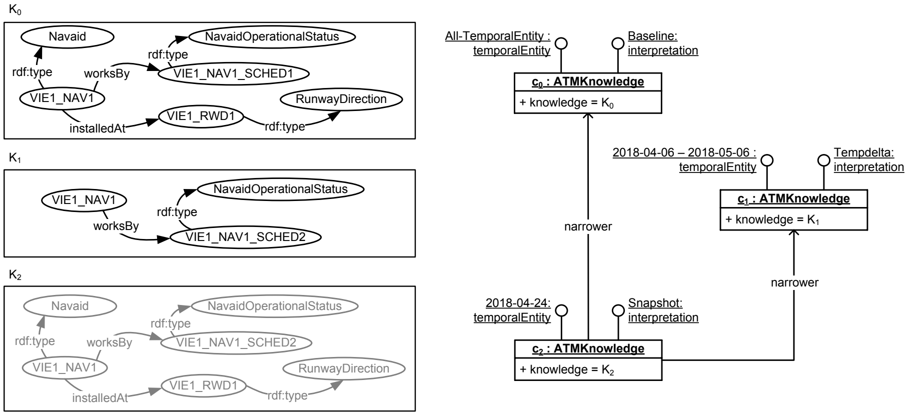

Fig. 2. Knowledge propagation with override. The right-hand side shows the different contexts. The left-hand side shows the RDF triples associated with the different contexts. The gray triples are inherited knowledge from the broader contexts.

A snapshot combines baseline and tempdelta information; snapshot contexts inherit from both the baseline and tempdelta contexts. Figure 2 illustrates the introduction of such an interpretation dimension along with the override mechanism. The context c_0 contains baseline knowledge valid in the general case. The navigation aid VIE1_NAV1, installed at the VIE1_RWD1 runway direction works by the VIE1_NAV1_SCHED1 schedule. A tempdelta time slice c_1 introduces the VIE1_NAV1_SCHED2 schedule for the VIE1_NAV1 navigation aid in effect in the time interval from 6^{th} April to 6^{th} May 2018. The snapshot context c_2 for 24^{th} June 2018 inherits the knowledge from c_0 and c_1, with properties from the tempdelta context overriding property values from the baseline context.

In terms of semantic containers [7], the broader contexts are composite containers which comprise the subsumed narrower contexts as component containers. The narrower contexts – the component containers – "inherit" the knowledge that the subsuming broader context – the composite container – explicitly associates: The knowledge propagates from the broader context to the narrower contexts. Specific merge operations may serve to combine the knowledge from various different contexts.

Different ontologies may serve to define the context dimensions. In the previous examples we adopted the concept TemporalEntity from the OWL-Time ontology [5] in order to describe values in the temporal dimension. Here, the various temporal relationships may serve to determine coverage relationships between contexts. For example, we might define coverage in such a temporal dimension to be based on the intervalDuring property. Note that we employ the OWL-Time ontology as vocabulary for expressing intervals and instants in the temporal dimension and the schedule knowledge. Furthermore, to support merge operations with unions of non-overlapping intervals – the result of which is not an interval – our approach would benefit from an extension of OWL-Time with a temporal element as a finite union of intervals (see [17]).

Contexts may also capture geographic relevance of knowledge. Geographic locations may be represented using GeoSPARQL [15] vocabulary and concepts derived thereof. For example, flight routes could be defined as geographic concepts spanning a certain area on the map, based on coordinates defined using the GeoSPARQL vocabulary. Then, a context may contain all the relevant knowledge for a specific flight route, possibly in combination with a temporal dimension.

Importance is another dimension of context. Different knowledge may have different importances (see [18] for DNOTAM importance). For example, a non-operational navigation aid may be a potential hazard while an airport closure is flight critical. The importance dimension will typically have to be paired with other context dimensions in order to capture, e.g., the importance of knowledge for a particular flight when in a certain geographic location.

Context may also capture the provenance of knowledge, thus facilitating the accurate assessment of the reliability of the knowledge. In ATM, capturing provenance is also important for auditability purposes in case of accidents. In the System Wide Information Management (SWIM) concept, SWIM information services produce and process ATM information/knowledge. In previous work [7], we propose a model for capturing provenance in the spirit of the PROV-O ontology [12]. Likewise, a provenance context may capture which SWIM information service the context's knowledge originates from.

Along with the ABox statements, TBox statements may also be stored in the contexts. The example in Fig. 1 contains only simple RDF Schema statements (domain and range). More complex ontologies could also be employed in contextualized ATM KGs. Existing ATM ontologies are modular (cf. [20, 9]). A topic dimension could then serve to associate contexts with topics according to the ATM ontology modules.

4 Discussion, Related Work, and Outlook

In this paper, we have argued for contextualized KGs in ATM. We have illustrated how the idea of contextualization fits naturally with the information requirements of modern ATM. Different applications have different information needs at different points in time. Contextualization allows for the convenient representation of ATM information/knowledge along temporal, spatial, or other semantic dimensions. Applications may then select the appropriate knowledge for their tasks from the available contexts, using the context dimensions to merge the knowledge from these contexts.

The aeronautical domain is increasingly becoming aware of the benefits of semantic web technologies (see [8]). In particular, semantic web technologies have been employed for data integration [10], and we expect contextualization to similarly facilitate the data integration task. The overriding propagation of knowledge as required by AIXM could be expressed using exceptions [2]. Furthermore, contextualized rule repositories [4] may complement the static information/knowledge with active rules.

Contextualized ATM knowledge graphs may serve different types of applications: operational and analytical. Both types of applications have different requirements regarding the context dimensions. In particular, the analysis of events in air traffic flow and capacity management (ATFCM) may benefit from more homogeneous context dimensions in the spirit of data warehouses, e.g., a fixed granularity of the temporal dimension. Future work will introduce a framework for management and querying of contextualized KGs.

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