On the Road to Hospital Digital Transformation: Using Conceptual Modeling to Express Domain Ontology

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Abstract: During the COVID-19 pandemic, Israel Aerospace Industries engaged with hospitals with the goal of promoting their effective operation by means of digital transformation, and particularly by designing an information system in support of the hospital operational processes. In this short paper we report our use of conceptual modeling to capture and communicate the organizational and operational ontology of the problem domain, based on a requirements specification for the system. We discuss how the derived ontology relates to metamodeling, and discuss some practical and theoretical implications of using metamodeling to document ontology.

1 INTRODUCTION

Hospitals in Israel are faced with the need to manage their operations and resources more efficiently (Chernichovsky and Kfir, 2019). This has increased due to the COVID-19 pandemic, with the need to treat isolated patients with limited means.

Information Technologies (IT) systems play an enabling role in modern healthcare (Meydan et al., 2015; Topaz et al., 2020) as well as impact its organizational structure (Moreno-Conde et al., 2019). Accordingly, some hospitals expressed interest in promoting their digital transformation for treating COVID-19 patients. Israel Aerospace Industries (IAI) engaged with these hospitals to utilize its technological and engineering knowledge for the development of information systems that may assist the hospitals to operate better.

Information systems rely extensively on data. In order to effectively communicate the data with various stakeholders, to produce insights with respect to the data and to support data-based collaborative work, data should be well structured and clear, preferably standardized (Schulz et al., 2019; Moreno-Conde et al., 2019; Husáková and Bureš, 2020). The use of ontologies in the engineering of systems is an enabler of good knowledge management and is essential to establishing explicit, sharable, reusable and interoperable knowledge representations (Yang et al., 2019; Husáková and Bureš, 2020). Ontologies also contribute to the explainability of machine learning models (Panigutti et al., 2020).

Research efforts has produced a multitude of healthcare related ontologies, such as an ontology for healthcare technology innovation (Moreno-Conde et al., 2019), ontologies describing ubiquitous computing environment for healthcare (Ko et al., 2007; Kim et al., 2014), ontology for health care networks (Dieng-Kuntz et al., 2006) and breast cancer imaging ontology (Hu et al., 2007). While crucial for the organization of knowledge, such research derived ontologies typically remain theoretical. For example, a pertinent ontology for medical services (Zeshan and Mohamad, 2012), which was designated to be used by IT systems, has only been theoretically checked for consistency.

HL7 – a not-for-profit organization – leads a data standardization effort from a practitioners' perspective, and its current "Fast Healthcare Interoperability Resources" (FHIR)[1] specification offers some ontology-related concepts. These, however, are offered from a technical, implementation point of view, requiring significant effort to analyse and review for use; and was deemed inappropriate for addressing the

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[1] http://hl7.org/fhir/toc.html, last accessed: 17/9/2020.

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aforementioned operational challenges rapidly. As an illustration, in FHIR, a patient relation to a doctor ("physician" in FHIR terminology) is not directly expressed but is represented by a relation between a patient and the more generic entity "practitioner," with the doctor being a type of a practitioner. This relation is directional, from the patient to the practitioner; meaning that a stakeholder that wishes to explore the ontological concepts of a doctor as a practitioner cannot identify this relation to a patient without exploring the underlying resource model from a patient perspective (i.e., the doctor and patient relations is not accessible from the doctor perspective). Furthermore, the relations are not graphically depicted, and this hinders the communicability of the ontological concepts.

In this paper we share our experience using conceptual modeling to capture a primal ontology for hospital operations, while developing a prototype for a hospital IT system. We demonstrate a bottom-up approach to defining ontologies, which – we believe – can encourage and promote their practicality. In Section 2 we explain our approach. Then, in Section 3, we introduce the derived ontology of hospital operations. Finally, in Section 4, we reflect on our conceptual model and the represented ontology as well as on the advantages and limitations of our approach, setting the stage for further research.

2 ONTOLOGY DERIVATION APPROACH

We approached the derivation of an ontology for hospital operations primarily by examining a set of requirements and identifying the relevant ontological entities and their relationships within this set. Further details follow.

The requirements set was delivered to us as a preliminary specification for a hospital management IT system. While the requirements specification is considered intellectual property – and therefore cannot be reproduced here – we address some relevant aspects. The specification was in Hebrew, and included three sections: a mission statement, describing the system's objectives and a basic narrative; an illustration referring to the operational scenario; and a list of high level, natural language requirements describing both medical and technical needs.

We – as the development team's systems engineering function – reviewed the specification and attempted to derive relevant domain entities and their relations. This was done in accordance with a model-based design approach, which we assumed for the development of the said information systems. While some entities and relations were mentioned explicitly, others were mentioned implicitly, e.g., by a business process description. Furthermore, during our analysis of the specification we identified some additional gaps, implying that some of the domain knowledge remained tacit, i.e., it was not stated in the requirements. Whenever deemed critical, we filled in the gaps, by suggesting additional entities and relations.

The aforementioned approach was a part of an overall rapid prototyping approach, which we took due to the circumstances in question: urging hospital needs due to the COVID-19 pandemic and the low availability of relevant hospital personnel to provide us feedback on system design documentation drove us to communicate our understanding of the requirements and its solution on the basis of a system prototype artifacts, and specifically using a formal metamodel. We captured the ontology formally using an ECORE metamodel, which is used within the Eclipse Modeling Framework for describing models[2] based on the standard EMOF specification (Object, Management Group, 2016).

3 DERIVED ONTOLOGY

The derived hospital operations ontology is represented in Figure 1, using an ECORE metamodel. This standardized representation shows the ontological entities as box nodes colored either yellow or grey; and their relations using edges between nodes. Relations take various forms: a directed arrow with a diamond source depicts composition, i.e., the source contains the target; a bi-directional arrow depicts a bi-directional relation; and a hollow-headed arrow depicts a "type-of" relationship to depict the source entity is a type of the target entity. For example, many of the entities are – each by itself – a type of a general entity, which is used purely from a modeling perspective to add generic features (e.g., the "name" attribute, contained within the "GeneralEntity" box). Cardinality is marked as a textual tag on the opposing end of the relation edge (for example: doctor relations to multiple patients is denoted

[2]Eclipse Foundation website, https://wiki.eclipse.org/Ecore, last accessed 2020/9/16.

"[0..*] patient"), while the patient's singular location is denoted "[0..1] location" (with no location denoting a location has not been assigned yet).

We identify eight entity types: hospital, location, health indicator, patient, temperature, medical file, doctor, and department. While all of these entities appear explicitly in the requirements specification, some of these appear using redundant terms. Specifically, those redundancies (in Hebrew language) exist in references to the patient (2 terms), location (4 terms) and doctor (2 terms).

The relations between the entities and their cardinalities are not as explicit in the specification as the entities, and specifying many of them involved interpretation of the specification's text. Few exceptions are: 1) temperature is explicitly mentioned as a type of a health indication; 2) location is specifically mentioned in relation with the patient and with the doctor (although the nature of these relations is not explicitly stated); 3) location is specifically mentioned as "inside the hospital," which, implicitly leads to a composition relationship (i.e., the hospital has locations); 4) doctors are implicitly mentioned in one statement as "belonging to the hospital," which, implicitly leads to a composition relationship (i.e., the hospital has doctors); 5) health indictors and patient are explicitly mentioned as a construct state, implying a composition relation, i.e., a patient has health indicators.

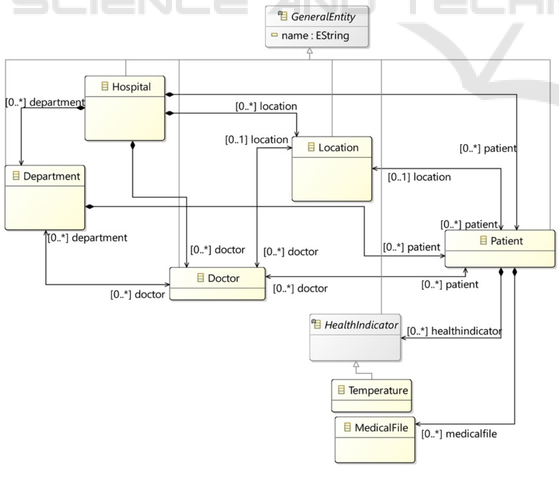

Figure 1: A formal conceptual metamodel representing the derived hospital ontology (in ECORE Tools).

4 DISCUSSION

A formal ontology is crucial to establishing systems and specifically to capturing and communicating related domain knowledge. We used a conceptual model in the form of a metamodel to a capture domain-specific ontology for hospital operations, derived from a requirements specification.

Using a well-defined, standardized conceptual model was shown to contribute to formalizing pertinent knowledge, which is intended for use within an information system. Conceptual entities were identified and reduced from redundant natural language terms to singular ontological entities. Furthermore, relations between entities were both concretized from somewhat implicit definitions, and their cardinality was explicitly state. While the improvement of relationship definitions reflects design decisions and is therefore subjective, it promotes ontology related discussion with stakeholders, specifically with respect to the review, refinement and/or reconsideration of our design. The communication of our design decisions with stakeholders forms a basis not only for the information system specification, but also for understanding and possibly even improving operations. For example, our model depicts a scenario in which the hospital manages its doctors as a common resource (expressed by compositional relation of the hospital in Figure 1) and assigns them (dynamically) to hospital departments (the bi-directional relation between "Department" and "Doctor" in Figure 1). This centralized approach can be contrasted with an alternative approach, in which doctors are a dedicated resource of the department.

The conceptual model is a highly communicable representation of domain knowledge, which can be used to discuss the ontology with multiple, technical and nontechnical stakeholders. Furthermore, its standardized metamodel implementation (using the EMOF compliant ECORE) forms a basis for a rigorous information systems implementation. Our ongoing effort concentrates on developing such an information system (in Eclipse) while elaborating and refining the ontology – as new requirements are specified and analyzed – and by identifying the required dynamic behavior of the entities (e.g., processes).

Our hospital operations ontology – based exclusively on requirements from a practitioner's viewpoint – directly corresponds with the previously conceived, theoretical ontology for medical services (Zeshan and Mohamad, 2012). Specifically the following ontological concepts are common to both ontologies and are termed identically: "doctor," "patient"; and the "health indicator" is also a common concept, termed "vital sign" by the ontology for medical services, with both ontologies describing "temperature" as a type of indicator. Also, both ontologies identify similar relations between the common concepts: a doctor relates to a patient, and a patient has health indicators. The cardinalities of these relations only appears in our ontology.

Furthermore, whereas the ontology for medical services is more comprehensive with respect to the services, our hospital operations ontology includes other hospital organization related concepts (e.g., "location", "department", "hospital" and their relations), corresponding with the need to reflect and impact organizational structure design and resource allocations (as suggested by Moreno-Conde et al. (2019)). The lack in some service related concepts is likely due to the minimal requirements specification, which was designed to support the development of a minimum viable product. We can share that subsequent requirements sets for our designated information system include additional concepts that are common to the ontology for medical services (e.g., "device").

Our approach has several limitations. First, the representation of the ontology using a metamodel only captures direct relations between entities, and does not capture nor communicate implicit ontological relations. Specifically, structural relations (composition) mask possible behavioral interactions between the ontological entities. For example, a particular use case may exist in the form of a doctor examining a patient's temperature, and yet there is no direct relation between "doctor" and "temperature." We note that information system implementations that use our metamodel can support such interactions (and – thereby – the implementation of support for such behavioral use cases), e.g., by allowing a doctor to query all/some of the patient's relations. Regardless, we advise further research to consider enhancing metamodel representations with behavioral related relations, to support a more comprehensive representation of ontologies. Addressing this gap may also facilitate the development of systems based on metamodels, reducing the need in some additional behavioral descriptions – such as sequence diagrams – for basic, ontology-derived functions. A possible approach may be in the form of incorporating explicit ontological relations into a metamodel. For example, an ontological relation between "doctor" and "temperature" may be introduced to the metamodel as a new type of relation. This ontological relation can then be further specified as a composition of several metamodel relations: the bi-directional relation between "doctor" and "patient," the compositional relation between "patient" and "health indicator," and the type relation between the latter and "temperature." This is illustrated in Figure 2, on top of our original metamodel (Figure 1). The "examines" ontological relation (in dashed blue arrow) is added to the metamodel, depicting the doctor ability to examine the temperature. This suggestion also opens up an opportunity for verifying the completeness of the conceptual model based on the ontology. For example, red dashed arrows in Figure 2 denote the relation trajectory that implements the aforementioned "examines" ontological relation: a doctor relates to a patient, which has a health indicator of type temperature. If, hypothetically, one of the concrete metamodel relations was missing, then the composite relation trajectory from "doctor" to "temperature" could not have been realized, indicating a gap in the design of the metamodel.

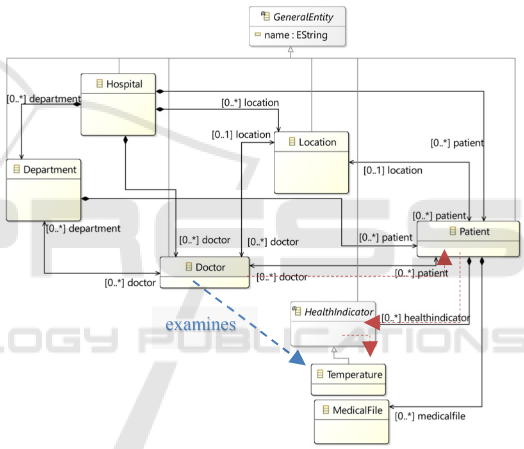

Figure 2: An illustration of using an ontological layer on top of a formal metamodel.

Second, with respect to the derivation of an ontology based on specifications without considering existing ontologies, a critique may be raised claiming our somewhat bottom-up approach can lead to an inflation of domain-specific ontologies. However, in agreement with a grass roots approach to modeling (Sandkuhl et al., 2018), we argue that it is a trade-off to use the ontology and conceptual modeling as a basis for application, even if these are proprietary or redundant with respect to existing ontologies; and that this is preferable to developing applications without establishing clear understanding and formal representation of the pertinent ontology. While existing ontologies may be used as a stepping stone for identifying domain-specific ontology, a full investigation and/or implementation of existing ontologies can be a hurdle in practice; and this should therefore not be a barrier for ontology-based engineering (Hu et al., 2007). In the hospital operations ontology case, for example, the ontological concept of "device" – which exists in the ontology for medical services – was not considered essential for the minimum viable product prototype. Furthermore, from a technical implementation point of view, translation technologies can be used to harmonize different ontologies, and specifically to translate a uniquely defined (proprietary) ontology with a standardized ontology. For example, entities of the hospital operations ontology can be translated to a standard definition (e.g., "health indicator" can be translated to the ontology for medical services' "vital sign"). Particularly, with respect to our Eclipse-based conceptual modeling, the standardized, automatically generated XMI technical representation of our metamodel facilitates such translation capabilities.

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