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Is a top level ontology based digital twin the solution to human-machine interoperability?

Rosario Davide D'Amico[a]*, Sri Addepalli[a], John Ahmet Erkoyuncu[a]

[a]*Centre for Digital Engineering and Manufacturing (CDEM), School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, MK43 0AL, United Kingdom*

*Corresponding author: Rosario Davide D'Amico; *E-mail address:* r.damico@cranfield.ac.uk

Abstract

Over the last decade, life cycle management has made leaps and bounds not just enhancing but also creating newer interactivity with the modelling world. A digital twin (DT) monitors the condition of the mirrored entity through life, providing a holistic overview of both its functionality and operability. Whilst DTs are gaining interest, the current challenge in their efficient utilisation is the interoperability between those different DTs. Today, DTs are being created for domain-specific functionalities (closed architectures), often using proprietary solutions, limiting their interoperability. This paper aims to present a high-level DT framework based on a standard top-level ontology called the Basic Formal Ontology (BFO) as a solution to the integration of twins. BFO is a well-established top-level ontology in the biomedical sector, as it is the core of the Open Biological Ontologies (OBO) Foundry. This paper contains a review of the state-of-the-art DTs based on top-level ontologies and highlights the value of implementing this framework, especially in the maintenance phase. The proposed open framework enables and improves the interoperability of DTs, creating the fundamental infrastructure where DTs can work together in a federation of twins. This research is an attempt to identify the applicability of this fundamental, interdisciplinary, cross-sectoral linkage for digitally enhanced eMaintenance platforms and their effective deployment. The paper thus presents an overview of how a typical BFO based DT would work in the context of a network of twins that targets human-in-the-loop (HITL) and their interoperability establishing a future towards the next industrial revolution: Industry 5.0.

Keywords: Digital twin; ontology; BFO; network of twins; eMaintenance; industry 5.0; industrial ontology foundry (IOF); semantic

1. Introduction

Digital twin (DT), a dynamic digital representation of a real entity, is a way to reach the dynamic optimisation of complex engineering assets. The optimisation is achievable through the interaction between the physical asset and the high-fidelity twin model, which supports the asset throughout the continuous evolution over time [1]. Research in DT is gradually advancing from the high level into the singular aspect such as designing, processing, and maintenance. Nonetheless, the development of DTs is still in the early stage, lacking guidance on modelling through DTs [2].

Complex engineering assets are those assets on which the maintenance phase is the longest-lasting and resource-consuming phase of the lifecycle. One of the main issues concerning complex engineering assets is the interoperability of tools and stakeholders operating around those assets. Developing DTs through the ontology approach enhances the flexibility and extensibility of those systems [3].

It is not just an issue in industries, but also in smart city management as highlighted by Petrova-Antonova et al. [4]. They pointed out how the data is distributed across different organisations and systems *without common semantics and a technology base* [4]. With this condition, there is poor predictability and limited interoperability, mostly when there is the need to link heterogeneous data. In urban management, like in industry, there is the need for a common data semantic that all the stakeholders agree on [4]. A possible solution to address this semantic interoperability issue lays in an ontology approach.

The ontology is *a collection of terms, relational expressions, and definitions, which allows a high-fidelity description of the asset or process of interest and its operation* [5]. Ontology is described by a language called OWL (Web Ontology Language, based on RDF (Resource Description Framework) [6]. To facilitate the reading of ontologies, multiple tools are available that translate the coding from OWL to a graphical representation that is easy to read and to work on. Examples of these are Protégé (popular), Ontolingua, WebOnto, WebODE, OntoEdit, etc. [6].

In general, an ontology is used to provide a standard for information exchange between different systems, and examples of this combined with DTs are described in the following section. Current research suggests that the ontology model can be refined and applied in the industry through a standardisation process of this methodology. Further impact on the lifecycle management can be provided by interconnecting the existing industry models,

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such as MES (Manufacturing Execution Systems), and ERP (Enterprise Resource Planning) with ontology tools, such as Protégé [2].

Madni et al. [7] highlighted the need for the creation of an upper-level ontology to guide, among others, the integration of systems, HITL, and DTs; such ontology can be reused, thus enabling interoperability. They suggested the creation of a formal ontology testbed with essential capabilities to start experimentation with models and algorithms [7].

In fact, the success of the ontological approach has led to a proliferation of different ontologies created from scratch, without following any reference model. This proliferation creates obstacles for the interoperability of those ontologies and hence of the systems [8]. To overcome this incompatibility issue, the top-level ontology (TLO) approach has been introduced. The TLO is an "*ontology that is created to represent the categories that are shared across a maximally broad range of domains*"[1]. In literature, other expressions that might refer to TLO could be the upper-level ontology [4], or the formal ontology [7].

The main contributions of this paper are:

- A TLO that allows cross-domain interoperability of domain-specific ontologies.
- A conceptual maintenance DT framework that uses the TLO approach as a methodology to improve semantic interoperability.

Using ontology as a starting point to develop a flexible framework conceptually has already been established in the literature. For instance, an upper-level ontology has been considered as the starting point to develop an open framework to overcome semantic interoperability issues [4]. However, the lack of standards that regulate and guide the development of these tools, has made the implementation of semantic models prohibitive [9].

The proposed framework aims to support the maintenance management of complex engineering assets. The idea comes from an evolution of what has been introduced by D'Amico et al. [10], regarding the development of a DT to support the maintenance management for complex engineering assets. Interest in DT for maintenance is growing [11] and the use of DT for maintenance management brings benefits such as improved prognosis accuracy [12]. Moreover, this paper introduces a methodology to develop structured DTs using a TLO that has been regulated through the ISO/IEC 21838, making a step towards a standardised DT.

[1] ISO/IEC 21839-1

The rest of this paper contains: i) a literature review section that gathers existing work about DTs using ontology or TLO as reference semantic model for the twin; ii) a methodology section that contains the ontology and in particular the TLO description; iii) a section that contains the conceptual model of the structured maintenance DT for complex engineering assets; iv) and finally a conclusion section that contains the final considerations, limitations and future works.

2. Literature review

In this section, similar works found in the literature related to the use of an ontology to develop DTs are presented.

Research on Scopus (www.scopus.com) regarding the works related to "digital twin" AND "Ontology" (in title, abstract, and keywords), resulted in 73 documents found on 31st of May 2021. The results of the database search in terms of distribution of publications over time and by type are shown in Fig. 1 and Fig. 2. Among the 73 publications, a brief screening has been carried out, resulting in 18 relevant works following described.

- Xu et al. [3] introduced ontology as the methodology to develop their DT model of the robot. This enhances the flexibility and extensibility of the system.

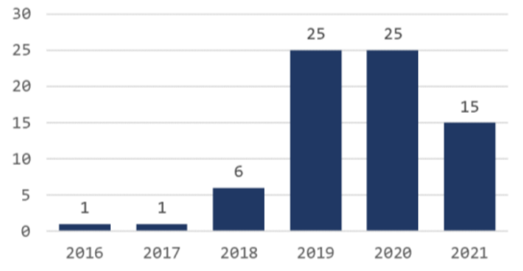

Fig. 1 - Number of publications related to "digital twin" AND "ontology"

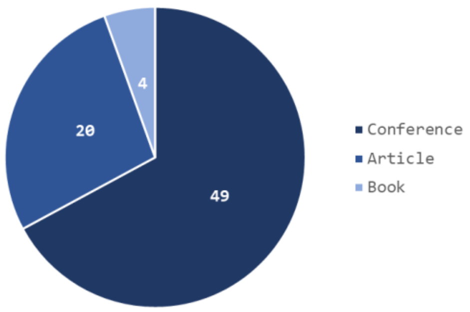

Fig. 2 - Distribution of publications in articles, conference and books.

- Madni et al. [7] proposed formal ontology as the methodology to make modelling more rigorous, facilitate the assessment of model completeness, semantic consistency, synaptic correctness, and traceability.
- Boje et al. [9] pointed out the weak points of the BIM (Building Information Modelling) approach and proposed the semantic/ontological approach as a dynamic and flexible solution. They highlighted how the research still lacks in the usability of RDF/OWL models in the context of HITL and proposed a new framework that considers a user-centric approach.
- Ameri et al. [13] in 2010 identified formal ontologies, or TLOs, as the tool that will represent the digital factories of the future.
- Skobelev et al. [14] used ontology as a fundamental layer for the DT in the field of farming management. Ontology has been used to define the basic classes of concepts and relations, called "explanatory dictionary for agents". Interesting is the structure of the DT ontology, which reminds the TLO approach. The ontology created has a hierarchy, where at the top-level there are the most general and reusable classes, and successively more and more domain-specific ontologies to describe details of the system. This structure facilitates and improves the solution of issues using existing protocols and procedures. Related work in the same field that used a similar ontological approach can be found in M. Pantano et al. [15] and P. Skobelev et al. [16,17].
- Liu et al. [18] used the ontology approach in their DT to overcome the issue of multi-source heterogeneous data fusion for a CNC machine tool.
- Schweiger et al. [19], in the context of DTs that helps companies in the servitisation paradigm, introduced the ontology approach to support and maintain the DT through life.
- Bao et al. [20] provide a seven-step method to develop an ontology for DT, starting from the characterisation of the domain and scope, and successively the possibility of reusing existing ontologies. In the paper, they also consider the recent development of standardised ontologies, without a mention of TLOs.
- Morgado et al. [21] used EMMO (European Materials & Modelling Ontology) as TLO to solve the issue of semantic interoperability in their DT in the mechanical testing field.
- Erkoyuncu et al. [22] adopted the ontology approach in their shared language architecture in the development of adaptive DTs.
- Nordahl et al. [23] in the context of FMI (Functional Mock-up Interface) standard in co-simulations, introduced the key idea of building ontologies based on existing ontologies in a hierarchical structure for their DT.
- Blaj et al. [24] used the ontology approach to simplify the data management and stakeholders interoperability in the scenario of a DT in logistics.
- Cho et al. [25] used ontology as a semantic-driven approach pointing to an efficient integration and management of data for predictive maintenance.
- Longo et al. [26] introduced the concept of "flexible ontology-based knowledge structure" to describe a modular and resilient methodology to develop ontologies that can be reused in several factory DT configurations.
- Zaki et al. [27] used an ontology approach as a starting point for the development of a robot DT used in the field of ORE (Offshore Renewable Energy) sector. This approach gives a potentially significant contribution to autonomous robotic systems.

As can be seen, only limited evidence has been found in literature about DTs and ontologies and specifically on the TLOs approach. Besides, most of them highlighted the need for standardisation, empowering the motivation to present the following conceptual framework of a TLO-based DT.

This work aims to cover the research gaps highlighted above by proposing a structured DT using the TLO approach to enable semantic interoperability.

3. Methodology – TLO approach

TLO has been chosen to develop the structured maintenance DT. Ontology is a "*collection of terms, relational expressions and associated natural-language definitions together with one or more formal theories designed to capture the intended interpretations of these definitions*"[2]. Ontology uses OWL as language, based on RDF. OWL includes descriptive logical semantic primitives for describing and building ontologies [6].

The TLO approach has been selected to improve the interoperability of systems, following the requirements in the ISO/IEC 21838-1. The definition

[2] ISO/IEC 21838-1

of TLO, as mentioned in the introduction section, is: "a domain-neutral ontology that is created to represent the categories that are shared across a maximally broad range of domains"[2]. In this way, starting from a domain-neutral TLO, specific-domain ontologies can be created following the same structure and semantic. A TLO approach works with a hierarchical structure known as the hub and spokes architecture (see Fig. 3), where the domain-neutral TLO acts as the hub of the system and more and more domain-specific ontologies are connected to the hub as spokes. In this way, different assets, based on the relative domain-specific ontologies, can communicate because of the same semantic compatibility with the TLO, thus ensuring the interoperability of different systems within the same ecosystem.

Therefore, creating DTs based on the same TLO solves the issue of semantic interoperability, allowing the interconnection of different twins and enabling the creation of a network of twins. The network of twins could be a powerful sharing knowledge tool to improve the training, the experience and hence the intelligence of each asset. Basic Formal Ontology (BFO) has been chosen as TLO for the creation of the DT, for the following reasons:

- It has been already successful in the biological sector [8];
- It has been adopted as a reference TLO for the Common Core Ontology (CCO) in the defence sector [28];
- It has been adopted as a reference TLO in the Industrial Ontology Foundry (IOF) created in 2016 at NIST for manufacturing purposes [29];
- It is going to be an ISO/IEC standard (ISO/IEC 21838-2).

All these factors increase the confidence in the success of the project, also due to the growing interest from research and industry around BFO and Industrial Ontology Foundry (IOF). Petrova-Antonova et al. [4] highlighted how the upper-level ontology approach (TLO approach) was the starting point in the development of a city DT, overcoming

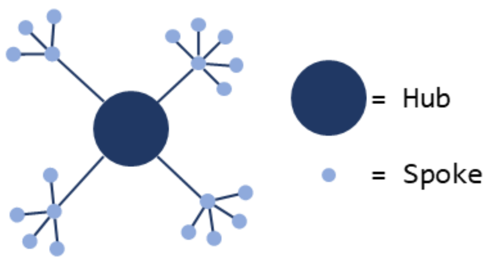

Fig. 3 - Hub and spokes architecture

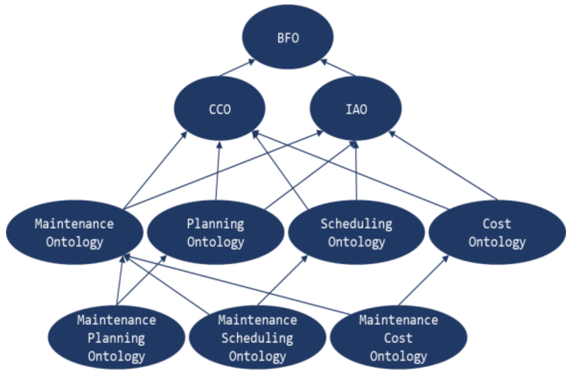

Fig. 4 - A mapping of relationships between BFO-compliant ontologies, highlighting the maintenance path. [Direction of arrows can be read as follow e.g. CCO imports BFO] (IAO - Information Artifact Ontology).
Adapted from Karray et al. [30]

issues like semantic interoperability and data consistency.

The TLO approach consists of developing more and more domain-specific ontologies importing semantic and properties from the domain neutral reference TLO, which in this case is the BFO (see Fig. 4). This is the starting point for the development of the structured DT for maintenance for which the conceptual model is described in the following section.

4. Conceptual model of DT

Fig. 5 illustrates the conceptual model of the structured DT. The diagram is divided into 2 parts, the physical world (light blue on the bottom) and the digital world (dark blue on the top). There is also a connection (in grey) that allows the DT to be connected to other DTs assembling a network of twins, or a federation of twins. The network of twins allows the interoperability of several twins, increasing the training data set available for artificial intelligence algorithms and hence the experience of the systems to provide better predictions over time. The physical world side shows the lifecycle of the physical asset or process of interest and its through-life degradation process. The digital world contains the conceptual model of the DT, an open framework model that constitutes several connected modules.

The 2 blocks in the middle, *data acquisition* and *dynamic adaptiveness*, represent the bidirectional ability of the DT to interact with the real world. The DT will be able to both catch data from the real world and dynamically interact with the physical asset. This dynamic adaptiveness is one of the features that make the DT different from a static model. It will have the capability of dynamically changing the parameters of the asset and provide action plan

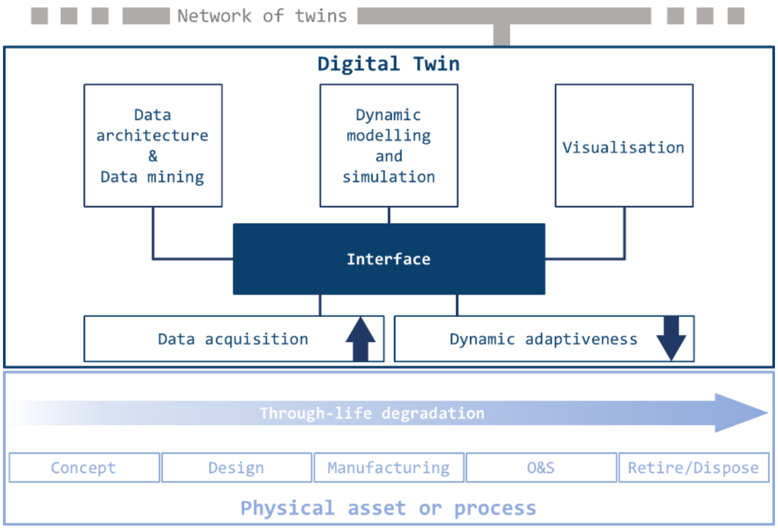

Fig. 5 - Conceptual model of the structured DT

scenarios for decision-makers. The 3 main blocks represented above, are connected through a flexible and reliable interface. They represent the main parts of a DT:

- The *data architecture & data mining* block represents the data allocation and mining strategy of the DT. This will configure the rules that govern which data is collected, and how it is stored, arranged, integrated, and put to use in the DT.
- The *dynamic modelling and simulation* block represents the intelligence of the system in terms of dynamic models and simulation capability. This part will contain the degradation models that can be applied in the DT, as well as simulation features to investigate several real-world scenarios, and artificial intelligence algorithms to perform predictions of remaining useful life.
- The *visualisation* block represents the characteristic of the twin to provide a graphical user interface containing all the information useful to make decisions. The visualisation can be performed through applications, web applications, and eXtended Reality (XR) technologies.

Ideally, the DT will be capable of processing data coming from the physical entity and once elaborated it should adjust parameters to optimise, in real-time, the operation of the asset of interest. Besides, data need to be processed across all the blocks of the DT, with the interfaces enabling interactions between blocks as well as with the physical asset. The interface will be constituted of a flexible messaging protocol capable to receive messages and address them to the right recipient. The architecture of the whole DT will be based on a TLO approach that will ensure the semantic interoperability of the modules.

Fig. 6 represents an example of a network of twins, or a federation of twins. The diagram represents 3 main DTs (DT) that are composed of subsystem DTs (nDT) belonging to 3 different domains (A, B, and C). The 3 domains may refer to 3 different contexts where a similar asset might be installed. For instance, the DT of an engine installed in domain A (e.g., a ship) can be connected to the DT of a similar engine in domain B (e.g., a power plant). All the twins are designed starting with an ontology

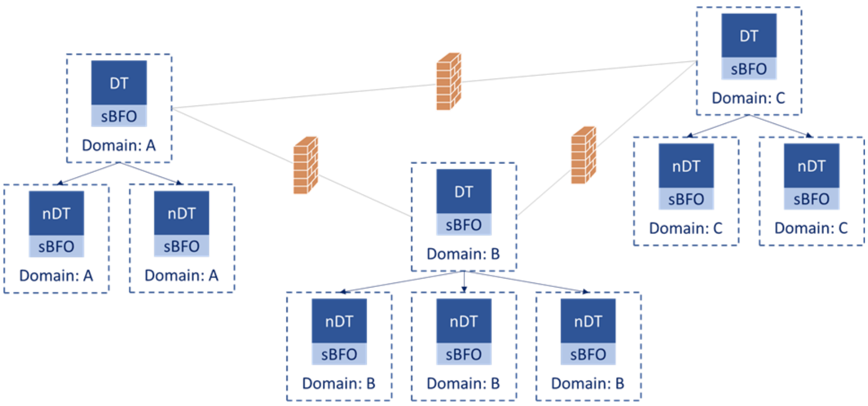

Fig. 6 - Example of representation of a network of twins or federation of twins

that is based on BFO as TLO (sBFO). The twins are connected creating a network of twins, and data can flow through those twins. This interconnection increases the training dataset available and hence the experience, refining the artificial intelligence algorithms to better predict the remaining useful life of the asset. The orange firewalls indicate the capability of the network of twins to filter only relevant data useful to improve the predictions.

5. Conclusion

Designing DTs based on a standardised TLO (ISO/IEC 21838-2) set the basis for a potential standardisable DT. If DTs are standardised, based on the same standardised TLO, the interconnection of those twins is improved, ensuring semantic interoperability. This results in the creation of a network of twins and therefore the ability to share the data across those twins. This knowledge sharing across twins improves the efficiency of the artificial intelligence algorithms optimising maintenance decisions. Moreover, this increase in intelligence leads the DT to better predict the remaining useful life of the asset. In this way, we can move from reactive maintenance to proactive maintenance, avoiding downtimes and optimising maintenance planning, the efficient usage of resources and hence optimising the overall through-life costs (predictive maintenance).

Furthermore, the knowledge gained in the operation and maintenance phase of the lifecycle will be useful to identify the causes and effects of failures, bottlenecks, and anomalies of complex engineering assets. Those are useful pieces of information to be sent as feedback to the earlier phases of the lifecycle, thus improving the conceptual definition and design of future assets, contributing to the overall sustainability.

Saariluoma *et al.* [31] have recently introduced a methodology to build human DTs through the cognitive mimetic approach using ontology as the starting point. That project aimed to bring people's actions and roles inside the overall cyber-physical system to refine the prediction scenarios and improve the decision-making process.

BFO is the reference TLO of the Open Biological and Biomedical Ontology (OBO) Foundry. This means that all the ontologies that belong to the OBO Foundry use BFO as reference TLO, including the Gene Ontology (GO) [8]. GO has been a successful approach in the biological and biomedical industry [32]. It allows finding similarities in different species through the recognition of similar ontology patterns between those different species [32]. For example, similarities between humans and mice, that enable the experimentation on mice for humans' purposes [33,34].

Table 1. advantages and disadvantages of the TLO approach

Advantages	Disadvantages
Overcome the issue of semantic interoperability;	Every stakeholder has to agree to the same TLO;
Ontologies can be reused and adapted to suit other applications;	Starting from a domain neutral TLO might extend preparation time.
Ontology evolves over time following the asset through life.	Needs graphical tool to facilitate the reading.

Through this paper, the authors proposed a structured DT based on the TLO approach solving issues associated with interoperability and the effective deployment of the federated twins' architecture especially the non-compatibility associated with closed architecture DTs. The framework introduces a new methodology to create DTs through the TLO approach. Particularly using BFO as reference TLO for maintenance DTs. This hypothetically means that, following the same methodology, a DT of a human body can be created. Human DT creation can be facilitated since the TLO used to create the human DT is the same TLO used in the biological and biomedical sectors [8]. Therefore, the creation of structured DTs through the methodology presented in this paper shall ease the integration of humans and machines in the system. Additionally, this approach facilitates the interoperability of human DTs in digital societies or smart cities. The need to bring humans into this ecosystem, or human-in-the-loop (HITL), will be the core objective of the industry 5.0 [35].

Possible limitations about this approach lays in the structured approach. According to what has been presented here, if different stakeholders work on the same asset, they have to agree to the same rules, or specifically to the same semantic. This might seem hard to achieve, but similar approaches exist and have already been successful. One of these successful applications is the web. Through the semantic Web, those who want to share data and website on the Web, they have to follow the same structured rules and protocols.

Future works include the development of the ontology for degradation assessment related to BFO as TLO. Successively, the development of the structured DT with particular emphasis on the interface of the DT model will need to be undertaken as well. There is a lack of research and publications on semantic interoperability through BFO in manufacturing and city management. Using the TLO approach may overcome the semantic interoperability issue, particularly using BFO which is the first standardised TLO under the ISO/IEC 21838.

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