Towards Ontologizing a Digital Twin Framework for Manufacturing

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Abstract. This paper presents a timely opportunity for manufacturing researchers to ontologize a digital twin framework for manufacturing by using recently published international standards. An ISO/IEC 21838 series of standards was released recently to address 'top-level' ontologies. These standards have been used by industrial consortia to release standards called 'mid-level' ontologies. One such 'mid-level' ontology standards is the Industrial Ontologies Foundry (IOF) Core. Around the same time, an ISO 23247 series of standards was released to standardize a digital twin framework, specifically for the manufacturing domain. This paper proposes to apply existing top-level and mid-level ontologies to create a 'domain-level' ontology for a digital twin framework for manufacturing. This domain-level ontology can then be used to create a manufacturing sector-specific digital twin ontology, called the 'application-level' ontology. In this paper, that application-level is the biomanufacturing sector. This paper also calls for a collaborative effort to create and deploy these two bottom-level ontologies and the digital twin standards associated with them.

Keywords: ontology, digital twin, framework, standards, manufacturing, biomanufacturing

1 Introduction

The past few years have seen some important advances in the standardization of ontologies, and digital twins are gaining great interest in the manufacturing industry. On the ontological front, a joint effort by ISO (International Organization for Standardization) and IEC (International Electrotechnical Commission) has resulted in the publication of a series of top-level ontology standards [1]. This original series of standards has been picked up by other standards organizations, such as the OAGi (Open Applications Group Inc.). OAGi used these top-level standards as the foundation for building and releasing its own mid-level ontology standard [2] that is meant to benefit primarily the manufacturing industry. In the meantime, ISO has also released a series of standards on a digital twin framework for manufacturing [3].

Both the ontology standards and the digital twin standards are of great interest to the manufacturing sector. As a result, it is natural for the manufacturing industry to inquire what benefits would accrue if these standards were used to ontologize a digital twin framework for manufacturing. This paper examines such benefits and uses them to propose a collaborative research effort to create an ontology-based digital twin framework for manufacturing. If successful, this framework will benefit not only existing manufacturing industries but also many emerging and important manufacturing industries, such as biomanufacturing.

The rest of the paper is organized as follows. Section 2 gives a brief description of the existing top-level and mid-level ontology standards. A similar briefing is given in Section 3 about manufacturing-specific digital twin framework standards. The main task of Section 4 is to propose how the existing domain-independent ontology standards described in Section 2 can be used to create a domain-level ontology for the digital twin framework described in Section 3. In Section 5, application-level ontologies are proposed for emerging and important areas using biomanufacturing as an example. Section 6 provides some concluding remarks.

2 A Hierarchy of Ontologies

The term ‘Ontology’ has a rich and colorful history in the human world, dating back to the development of philosophy, metaphysics, and theology. Since its recent appearance in the computational world, however, the term ‘ontology’ has taken a decisively utilitarian turn. It has a new focus, which is no longer about philosophy, metaphysics, or theology; now it is about using rigorous mathematics and logic to create data-driven *informational terms* and data-driven *relational expressions.* Both live in the digital world, and both are associated with the data being collected in the real world. Those resulting and varied data repositories are now being used across a wide range of scientific and industrial disciplines.

This new ontology-based focus was first triggered by earlier needs in two scientific disciplines: biological sciences and life sciences. The first joint need was a gene ontology. The success of addressing some of those more recent needs for different kinds of bioscience ontologies has, in turn, triggered some serious attempts to define a related ontology hierarchy using a hub-and-spoke approach. That approach is described below.

One of the seminal developments behind this hierarchical approach was the Basic Formal Ontology (BFO), which was soon recognized as one of the Top-Level Ontologies (TLOs), and it provides a basis for other ontologies. In fact, BFO has been used successfully to build several bio-related ontologies. BFO is the first TLO that has been standardized recently by ISO and IEC [1, 4]. Table 1 shows some of the *information terms and relational expressions* formally standardized (that is, with axioms) in BFO. Currently there are a total of 84 terms and relationships in BFO, attesting to the compactness of this TLO. A directed, ontology graph can be created using the terms as the nodes and the relational expressions as the directed arcs.

Table 1. Examples of terms and relational expressions standardized in BFO [1].

Terms	Relational expressions
entity	is a
continuant	continuant part of
occurrent	occurrent part of
spatial region	located in
temporal region	exists at
material entity	
process	
quality	

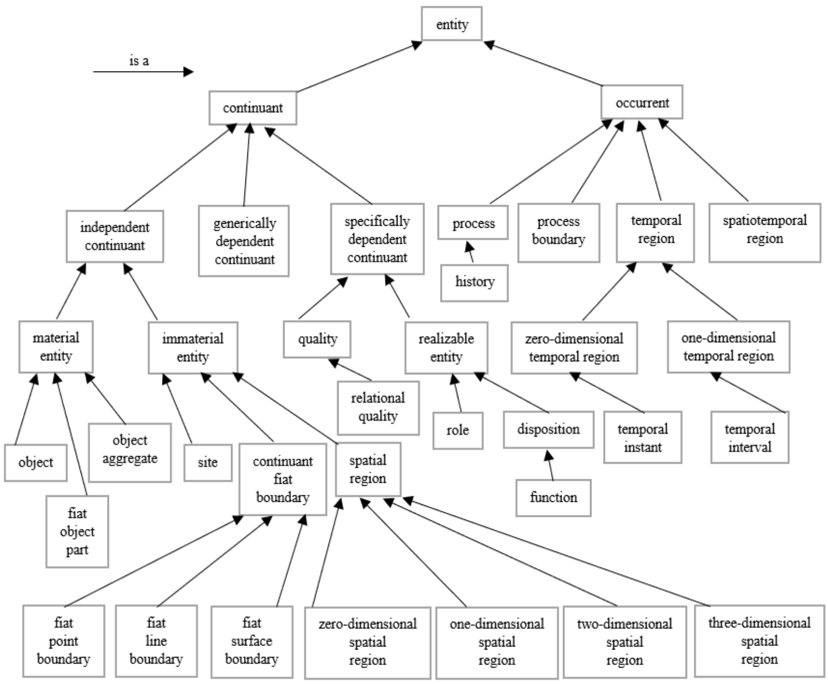

Fig. 1. A BFO hierarchy of terms using the *is a* relationship [1].

At the root of BFO is the informational term 'entity.' Fig. 1 shows how this term is further refined and specialized using the 'is a' relational expression. TLO was followed by the creation of Mid-Level Ontologies (MLOs) built on TLO. Two of the recently developed MLOs are the Common Core Ontologies (CCO) and the Industrial Ontologies Foundry Core (IOF Core) [2], both built on BFO as the TLO. Some of the informational terms and relational expressions that are formally standardized by IOF Core are shown in Table 2. Currently, there are 57 terms and 38 relational expressions in IOF Core, supporting a wide range of industrial (including manufacturing) needs.

Several domain- and application-level ontologies have been built from BFO and IOF Core, using a hierarchical, hub-and-spoke approach. A Supply Chain Reference Ontology (SCRO) is one such domain-level ontology. It defines the terms and relationships for the structure (members and their roles, functions, capabilities, relations, and resources) and operations (processes and flow of material and information) of supply chains. An application-level ontology called the Supply Chain Traceability (SCT) ontology has been created from SCRO. SCT is an ontology for supply chain traceability within a specific, manufacturing supply chain in agriculture.

Table 2. Examples of terms and relational expressions standardized in IOF Core [2].

Terms	Relational expressions
design specification	acts on behalf of at some time
material artifact	satisfies requirement
engineered system	is available to at some time
equipment role	has output
product production process	

3 A Digital Twin Framework for Manufacturing

Around the same time as the ontology standards were released, another ISO series of standards (called the ISO 23247 series) was also released [3, 5]. This series defines a digital twin framework specifically for the manufacturing sector. These newer standards provided both a 'fit-for-purpose' digital representation of each Observable Manufacturing Element (OME) and the temporal synchronization needed between the OME and its digital twin representation. An OME, in this context, is a physical manufacturing element. Fig. 2 shows the interconnected layers of the standardized framework for building digital twins for manufacturing. It should be noted that the ISO 23247 series provides only a framework, a structure if you will, standard. The series currently does not include a standard for modeling the data/information that resides on top of that structure/framework. Such a standard is needed. But first, more about the OMEs.

Observable Manufacturing Elements (OMEs) are classified under eight types, each of which can contain up to seven attributes, as shown in Table 3. It should be noted that each of the OME types in Table 3 is an 'entity' from an ontological perspective. Also, each of the attributes is an entity. In addition, Fig. 2 shows layers that contain 'device communication entity', 'digital twin entity', 'user entity', and 'cross-system entity.' Each of these entities are further broken down into a few sub-entities and functional entities [3, 5]. A comparison of Tables 1, 2, and 3 shows the striking similarity among the terms and relationships defined in the ISO/IEC 21383 series and the IOF Core ontology standards, and those defined in the ISO 23247 series of standards on digital twin framework for manufacturing.

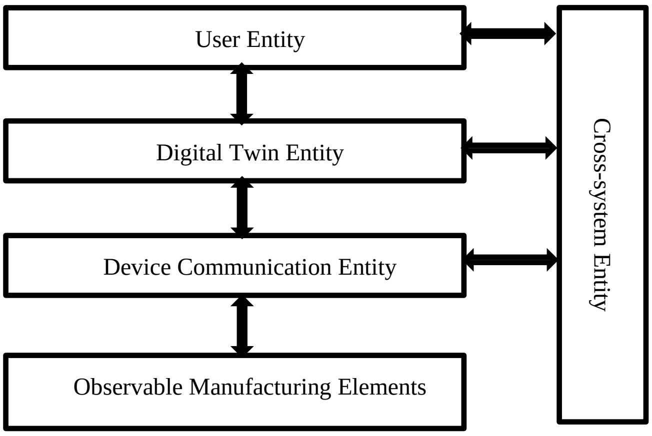

Fig. 2. A standardized digital twin framework for manufacturing [3].

Table 3. Standardized OME types and attributes [3].

Types	Attributes
personnel	identifier (mandatory)
equipment	characteristics
material	schedule
process	status
facility	location
environment	report
product	relationship
supporting document	

As the popularity of digital twins grows and this growth drives the building of several digital twins in manufacturing, an important need for interoperability among them has emerged. An attractive approach to satisfy this need is to use the recently developed top-level and mid-level ontology standards to ontologize the digital twin framework standard for manufacturing. The attractiveness stems from the fact that ontologizing the digital twin could potentially provide (1) logical rigor and thus unambiguity of term definitions, (2) explicit logical connections that permit higher connectivity between various data sources associated with a digital twin, and (3) enable more effective knowledge reuse and sharing. This has been recognized by the broader research community resulting an increasing amount of literature pertaining to utilizing ontologies for digital twin representation and data integration [6-9].

4 A Domain-Level Ontology for Digital Twin Framework for Manufacturing

As described in Section 3, the newly released ISO 23247 series provides a structure for creating, managing, and using digital twins for manufacturing applications. In addition to the structure, the series (1) defines the terms, relationships, components, and processes necessary for developing a digital twin and (2) provides guidelines for their implementation. The intent is that users of this series of standards can be assured that digital twins are consistent, accurate, shareable, and reusable across different organizations and systems. However, at present, there is no formal ontological support for making such an assurance for the ISO 23247 series.

As proposed below, this situation can be remedied by expanding the hierarchy of ontology standards, as described in Section 2, 'downward'. The first downward expansion includes a specific, domain-level (in this case, the physical, manufacturing domain) ontology. The proposed domain-level ontology for manufacturing will include a set of manufacturing-related terms, relationships, and definitions, all of which will be based on the structure and the meaning of the existing digital twin framework. This new ontology could provide a common understanding of the data and information used to create digital twins across the entire manufacturing domain. It could also (1) greatly improve the efficiency and effectiveness of a digital twin development, and (2) ensure that digital twins can be easily integrated and shared between different systems, organizations, and sectors.

The terms and relationships that are already defined in the ISO 23247 series can serve as the starting point for developing such a domain-level ontology. For example, Table 3 lists the terms for eight OMEs, called entities, and seven attributes. As a concrete example, consider the entity 'personnel' from OME list. According to ISO 23247-1 "Personnel in manufacturing generally include those employees who are engaged directly or indirectly in manufacturing." It is a textual definition that clearly indicates that 'personnel' is a person who is also an employee with a role in manufacturing. More generally, 'personnel' could be a contractor employed in a different organization. Since the same term can have two different meanings, formalizing it is important. Such terms can be made more formal using the existing, standardized top-level and mid-level ontologies, as shown in Fig. 3.

In Fig. 3, the top-level is the BFO and the mid-level is the IOF Core. Additionally, Fig. 3 uses color coding to indicate where the various terms originated. Other terms related to OMEs (the types and their attributes) in Table 3 can be ontologized in a similar fashion. Each digital twin can be related to its entity's 'information content', which is already available in IOF Core as shown in Fig. 4. The terms for various components of the digital twin are already defined in the ISO 23247 series and are formally related in Fig. 4 using the indicated relational expressions that are already defined in the BFO/IFO Core standards.

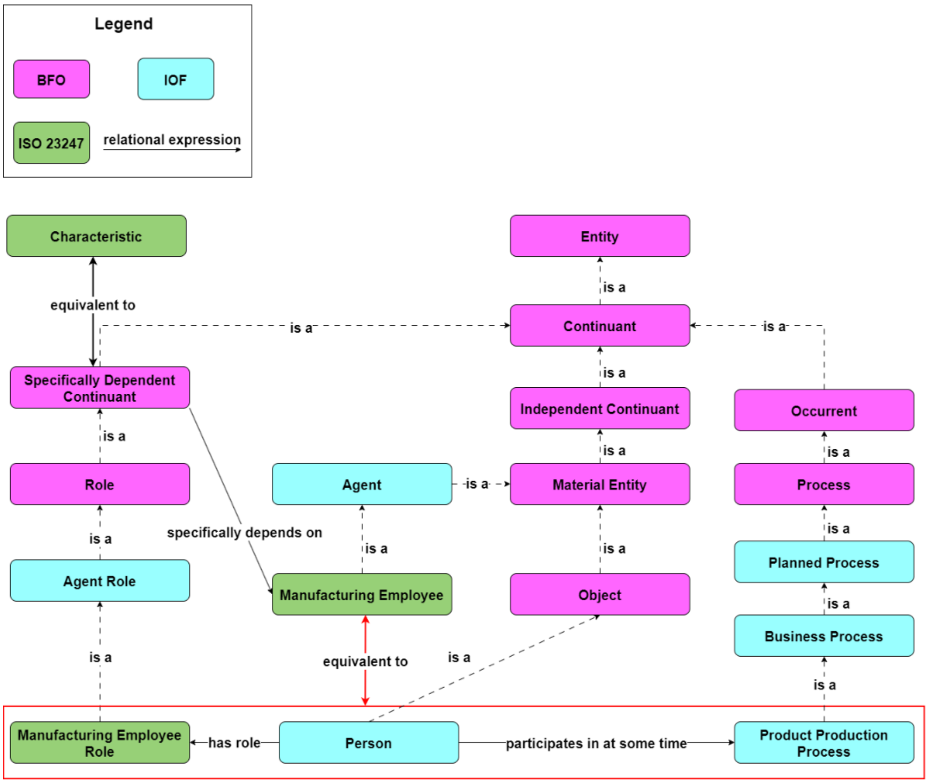

Fig. 3. Introducing the personnel (manufacturing employee) OME into BFO and IOF Core hierarchy.

Another important concept in the digital twin framework is the bidirectional relationship between the OME entities and the digital twin entities. Such bidirectional relationships are critical to maintain the necessary synchronization between both. This synchronization is implemented as the 'device communication' entity layer shown in Fig. 2. In this layer, 'data collection' from the OME is performed by sensors, and the OME is 'controlled' using actuators and controllers. Fig. 5 shows how the collected data can be used to temporally link the OME to its digital twin. Fig. 6 shows how the OME control can be temporally linked to the OME and its digital twin.

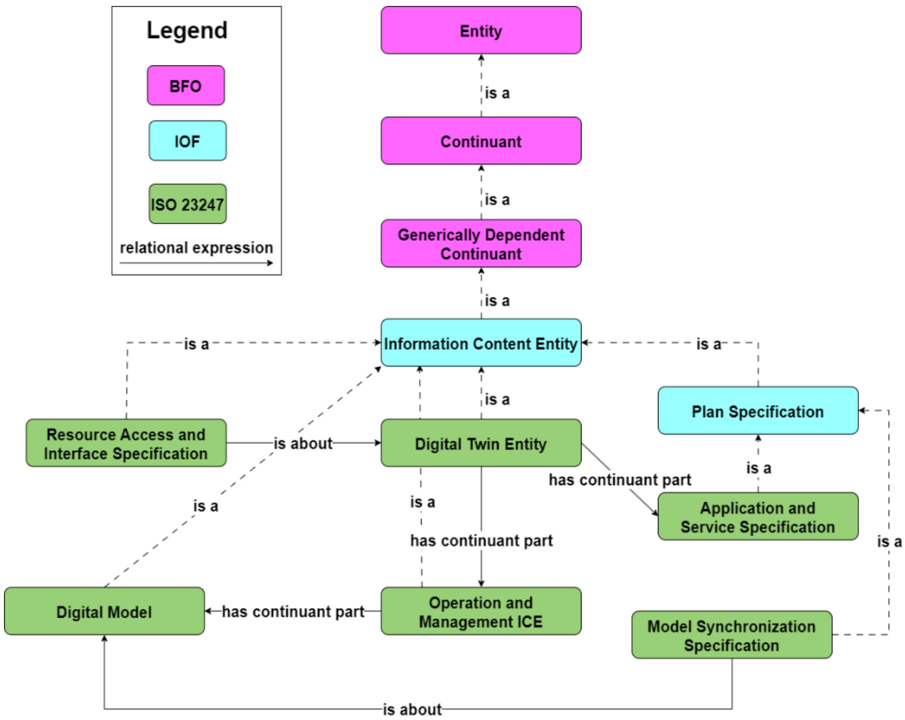

Fig. 4. Introducing digital twin and its components into BFO and IOF Core hierarchy.

The preliminary examples provided in these figures should be viewed only as tentative first steps towards the goal of building the bottom ontology layers of the proposed standardized digital twin framework for manufacturing. More work is needed to (1) cover all the relevant informational terms and relational expressions found in the ISO 23247 series [3] and (2) get their ontologies approved by appropriate standards development organizations and industrial consortia.

To accomplish those two needs, this paper proposes a joint project between ISO/TC 184/SC 4/WG 15 and OAGi IOF Core team. This project will help develop a new standard that is more accurate, consistent, and interoperable than the existing ones. This new standard will pave the way for creating, managing, and using digital twins in the manufacturing industry. In such a joint project, the ISO team will provide the guidelines for creating and using digital twins, while the OAGi team will provide the foundation for representing industrial concepts and relationships. This combination would then enable manufacturers to create digital twins that are based on a common vocabulary and framework. This will make it easier for them to exchange information and collaborate with other organizations. The proposed joint project could also develop software tools and platforms that support the implementation of digital twins.

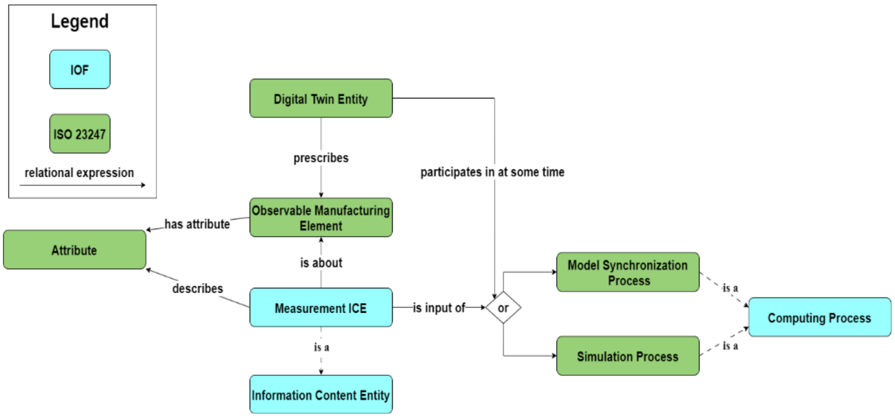

Fig. 5. Data collection is connected to OME and its digital twin using BFO/IOF Core relations.

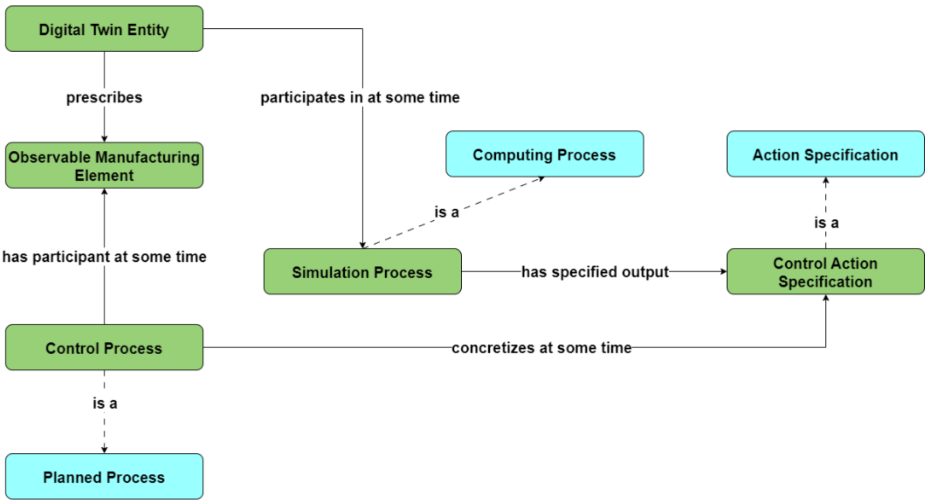

Fig. 6. Control is connected to OME and its digital twin using BFO/IFO Core relations. See Fig. 5 for Legend.

5 An Application-Level Ontology Example – Biomanufacturing

This section will use the ontologies from previous sections to build a biomanufacturing-specific application-level ontology. Biomanufacturing encompasses production processes that utilize living organisms or cell-derived macromolecules (e.g., enzymes) to produce various products (e.g., bioethanol and bioplastics) [10]. Biomanufacturing can be split into three distinct areas: bio-industrial, bio-medical, and agri-food. Compared to traditional manufacturing, biomanufacturing relies more on renewable resources (e.g., biomass, sunlight, CO_2) [11].

Regardless of these potential benefits, market competitiveness within biomanufacturing, as well as with traditional manufacturing processes, mandates the development of production methods that can achieve (1) high yields with minimal manufacturing costs and (2) cost-effective process development. One of the enabling technologies for developing these methods is the concept of digital twins. As described in Section 3, a digital twin transcends the capabilities of traditional models by establishing bidirectional communication with the physical entity it represents [12]. In biomanufacturing, this bidirectionality permits the control of the manufacturing processes in real time and enables updates based on the physical world's feedback.

During their research and development, scientists and engineers can utilize digital twins to gain a dynamic understanding of a process. Such an understanding can help lower the needed experimentation and thus reduce the developmental cost and time [13]. Digital twins also permit the real-time optimization of a process, which is essential for increasing efficiency and maintaining productivity as the bioprocess progresses. Furthermore, digital twins have many process-associated predictive capabilities, such as predicting the equipment failure time [14], key process attributes (e.g., yield, concentration) [15], batch end times [12], and process parameters [16]. These predictive capabilities can inform real-time or offline decision making in all stages of a bioprocess lifecycle [17]. In other words, the dynamic nature of a digital twin and its bidirectional connection with the physical world facilitates an optimized, cost-effective process by (1) providing critical insights to various experts over the entire manufacturing lifecycle and (2) reliably controlling the parameters of a process over prolonged periods.

To gain the full benefit of applying digital twins in biomanufacturing, an application-level ontology for biomanufacturing is desirable. For example, terms such as equipment and process, which are defined in that manufacturing domain ontology, can be further specialized to biomanufacturing terms such as bioreactor, chromatography column, and batch process. It should be noted that for the development and formalization of such biomanufacturing terms, many constructs from other, existing application-level ontologies and standards related to biomanufacturing could also be reused (e.g., ISA-88, Allotrope ontology, OBO Foundry ontologies).

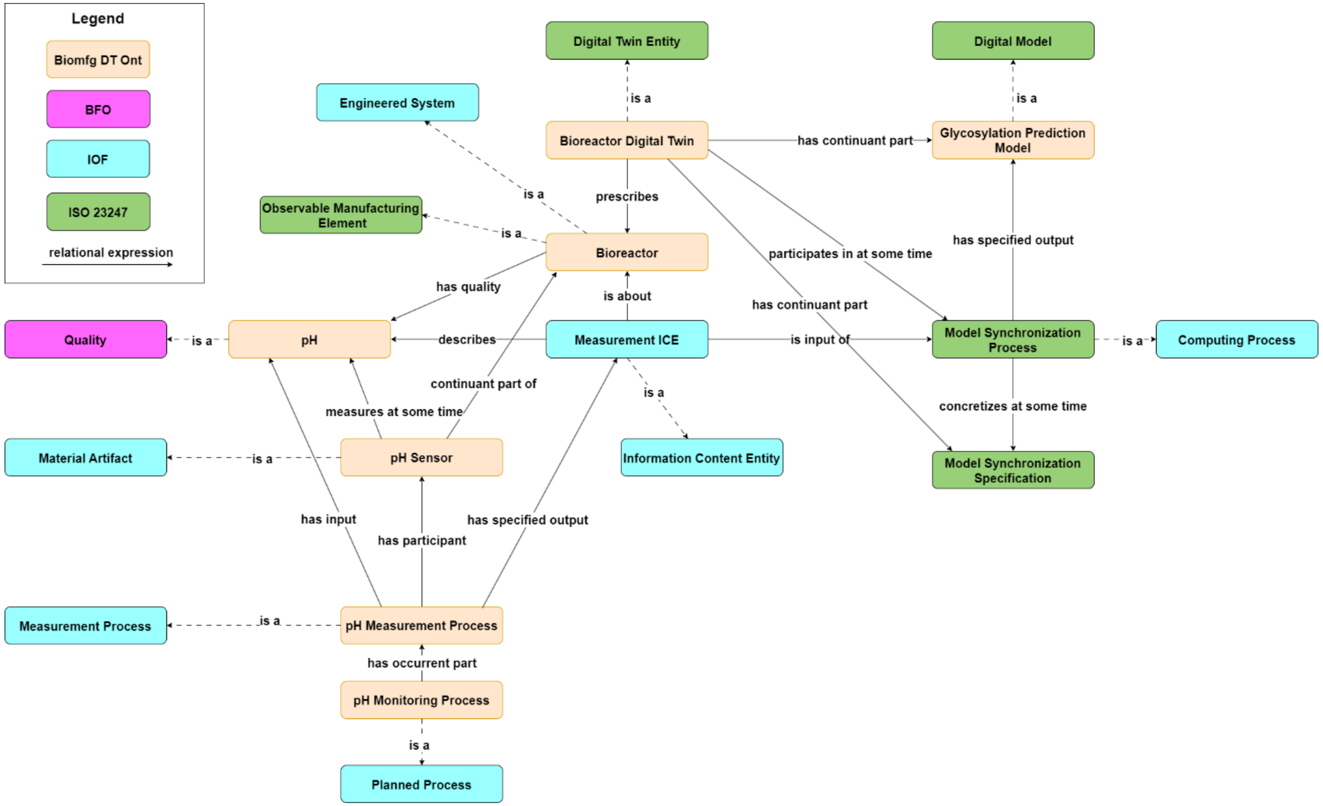

Fig. 7. Example of data collection from a bioreactor to update its digital twin.

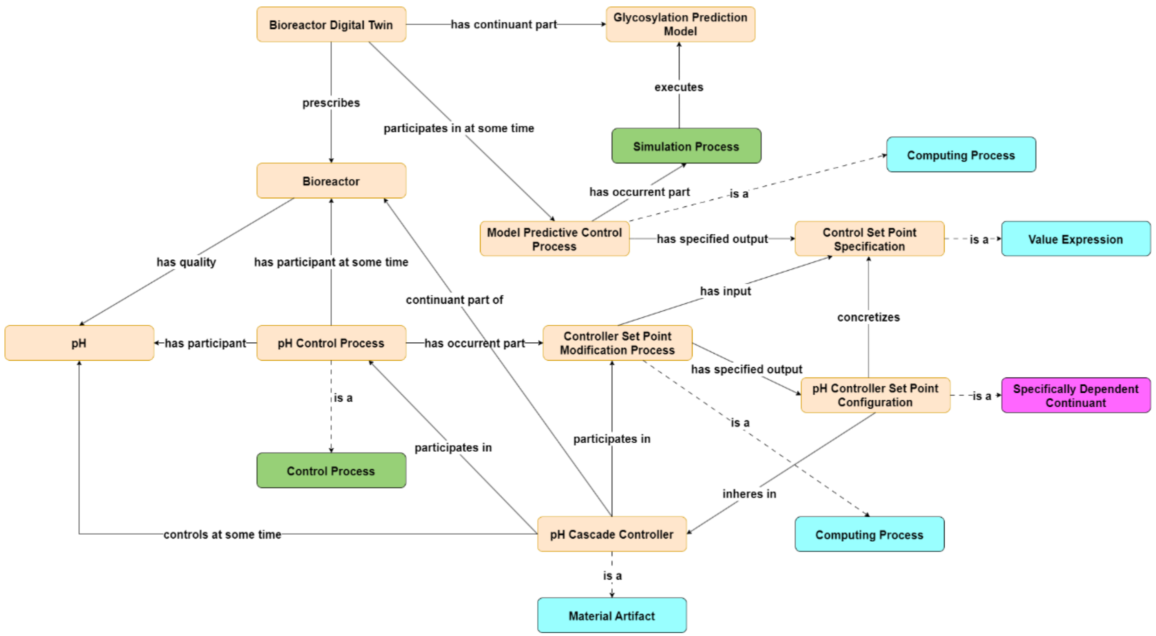

Fig. 8. Example of a bioreactor parameter control based on digital twin simulation results. See Fig. 7 for Legend.

As an example of application-level ontology for biomanufacturing, consider a bioreactor (an essential biomanufacturing equipment) and its digital twin. Fig. 7 represents how the data collected from sensors attached to a bioreactor are used to update the digital twin of the bioreactor. The other direction represents how simulation results from a digital twin of the bioreactor are used to control the parameters of actuators of the bioreactor, as shown in Fig. 8. Data represented using these models enable, for example, comparisons and improvements across predictive models used in the same or similar processes.

6 Concluding Remarks

This paper presented recent advances in the standardization of two important technologies – one is a hierarchy of ontologies to support digital manufacturing and the other is a framework for deploying digital twins in manufacturing. Time is now ripe to combine these two advanced developments in standards, and to undertake a research and development project to ontologize the standardized digital twin framework for manufacturing. This domain-level ontology can then be used to develop application-level ontology for any specific manufacturing sector. This paper focused on one emerging and important manufacturing sector – namely, biomanufacturing. Future work can entail applying the outlined principles to other manufacturing sectors, such as additive manufacturing. Another area of future interest is to utilize the combination of ontologies and digital twins to enhance the understanding of various process parameters on process sustainability. Some initial steps taken in this direction are presented in more detail in [18].

Towards the goal of ontologizing the digital twin framework for manufacturing, this paper has included some preliminary ideas and approaches for an R&D project. This project can be jointly managed and executed by the appropriate standards development organization (SDO) and industrial consortia, both of which have been described in this paper. In addition, IFIP WG 5.7 would be an appropriate community to contribute to this effort. By leveraging their expertise and resources, IFIP WG 5.7 can play three crucial roles: (1) providing technical contributions, (2) performing case studies, and (3) helping industrial adoption. By executing these roles, IFIP WG 5.7 can deliver value to the entire manufacturing community and, more specifically, to the biomanufacturing industry.

Once completed, the new and future ontology-based standards will bring benefits to the bigger manufacturing community. These benefits include advanced knowledge and expertise in the field of digital twins, access to new resources and technologies, improved impacts and outcomes, and opportunities for further collaboration.

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