Analyzing the Usefulness of ThingFO as a Foundational Ontology for Sciences

Luis Olsina
GIDIS_Web, Facultad de Ingeniería, UNLPam, General Pico, LP, Argentina
olsinal@ing.unlpam.edu.ar

Abstract. This work specifies and defines all terms, properties and relationships of ThingFO –which stands for *Thing Foundational Ontology*. ThingFO is an ontology for particular and universal Things and Assertions placed at the foundational level in the context of a four-layered ontological architecture called FCD-OntoArch. This is a four-layered ontological architecture, which considers foundational, core, domain and instance levels. In turn, the domain level is split down into two sub-levels, namely: top-domain and low-domain. Ontologies at the same level can be related to each other, except for the foundational level where only the ThingFO ontology is. Additionally, ontologies' terms, properties and relationships at lower levels can be semantically enriched by ontologies' terms properties and relationships from the higher levels. Since ThingFO is at the highest level, ontologies at lower levels benefit from reusing and extending its concepts. To illustrate the usefulness of ThingFO, we primarily analyze enriched terms of a couple of ontologies at the core level such as ProcessCO and SituationCO, among others, in which their concepts are cross-cutting concerns for many domain terminologies from diverse sciences.

Keywords: Thing Ontology, Foundational Ontology, Core Ontology, Domain Ontology, Ontological Architecture.

1 Introduction

A foundational ontology (also known in the literature as upper, or top-level ontology) is found at the highest level of reference conceptualizations independent of any domain. Even core ontologies such as project, process, goal, situation, or context, among others, are domain-independent reference conceptualizations, but they generally semantically extend or reuse foundational terms, properties and relationships. Furthermore, domain-dependent ontologies are the most common and massive conceptualizations built to date, such as for the health domain, for software requirements, development and testing, for building construction, for measurement and evaluation in various domains, among many others. However, in much of the current work, they are not based on core and/or foundational conceptualizations. Or, if they do, there is often no clear separation of concerns considering ontological levels [22].

Foundational and core ontologies are becoming increasingly important for integrating heterogeneous knowledge bases coming from different sources and domains. As indicated in [13], they can be used by different parties involved in a process of integration and exchange of knowledge as a reference, as a common terminological model of the reality represented.

The underlying rationale to adopt or create a foundational ontology is to have a minimum set of particular and universal semantic concepts of the world, that is, key terms, properties and relationships (and possible axioms) that describe the world so that they can be reused and extended, and ultimately useful and easy to adopt across all domains. In short, the aim is to have a large number of lower-level ontologies accessible under the umbrella of a given foundational ontology.

As Schneider [20] pointed out, most knowledge engineers are unaware of the challenges of building a foundational ontology. It involves challenges that are unusual for the practice of representing concrete knowledge for specific domains. Also, he indicates that though its "starting point is the set of common-sense intuitions that make up the human conceptualization of reality, they ultimately aim at describing the categorical structure of the world as a whole".

Therefore, to build a foundational ontology requires a transdisciplinary knowledge not only in various areas of Information Systems Engineering and Artificial Intelligence, but also grounds in Philosophy and Cognitive Science.

As a matter of fact, while thousands of domain and instance ontologies have been built so far, only less than a dozen well-known foundational ontologies have been built in the past three decades. Among them, we can quote BFO [1], PROTON [6], UFO [10], GFO [11], Cyc [12], DOLCE [14], SUMO [19], and Sowa [21], which are the most referenced within the research community.

The current paper specifies and analyzes ThingFO, which is a foundational ontology for particular and universal Things and Assertions placed at the highest level in the context of a proposed four-layered ontological architecture called FCD-OntoArch (*Foundational, Core, Domain, and instance Ontological Architecture for Sciences*). It also justifies why another foundational ontology is needed considering our aim. In the sequel, a brief story and motivation for this endeavor follows.

In the last two decades, we have developed a family of evaluation strategies that help achieve different goal purposes [17]. We are currently developing testing strategies. A strategy is an organizational resource that specifies what to do and how to do it. Consequently, strategies should integrate process specifications, method specifications, and a robust domain conceptual base. These three capabilities promote, therefore, knowing what activities are involved, and how to perform them through methods in the context of a common conceptual framework. This conceptual framework was built on vocabularies, which were structured in ontologies. We have already developed over the years, ontologies for non-functional requirements, context, measurement (metrics) and evaluation (indicators) [18], goal, functional requirements, project [4], process [5], and testing [23].

In the long process of development of these ontologies, we were realizing that they were not on the same ontological level. For instance, non-functional requirements, measurement and evaluation ones are at the domain level. While process and project are at the core level, since process and project terms can enrich the terms of the quoted domain ontologies, and many others as well. Furthermore, we also found in that process that some terms used in measurement and evaluation since early 2000, such as Entity or Entity Category, were probably even at a higher level than at the core or domain level.

As a result, we conceived not only the Thing ontology at the foundational level [15], but also FCD-OntoArch to place ontologies in the corresponding layer and thus harmonize terms, properties and relationships between them.

In summary, as a contribution, this paper documents and analyzes the ThingFO ontology in the context of the four-layered ontological architecture. Additionally, we illustrate the usefulness of ThingFO for enriching terms of a couple of ontologies at the core level such as ProcessCO and SituationCO, as well as one at the top-domain level such as the TestTDO ontology.

The rest of the paper is organized as follows. Section 2 provides an overview of FCD-OntoArch, which includes ontologies such as ThingFO, ProcessCO, SituationCO, TestTDO, among others above mentioned. Section 3 discusses the main terms, properties and relationships of ThingFO. Section 4 illustrates the usefulness of ThingFO for enriching terms of a couple of lower-level ontologies. Section 5 provides a summary of related work on foundational ontologies. Finally, Section 6 summarizes conclusions and future work.

2 ThingFO in the Context of FCD-OntoArch

As previously commented, ThingFO is placed at the foundational level into FCD-OntoArch. This is a four-layered ontological architecture, which considers foundational, core, domain and instance levels. In turn, the domain ontological level is split down into two sub-levels, namely: Top-domain and Low-domain.

As depicted in Fig. 1, ontologies at the same level can be related to each other, except for the foundational ontological level where only the ThingFO ontology is. Additionally, ontologies' terms, properties and relationships at lower levels can be semantically enriched by ontologies' terms properties and relationships from higher levels.

Since ThingFO is at the highest level, ontologies at lower levels benefit from reusing and extending its concepts. ThingFO has terms such as Thing, Thing Category and Assertion that semantically enrich terms of components at lower levels. For example, TestTDO, a software testing ontology placed at the top-domain ontological sub-level is enriched by concepts of the SituationCO [16] and ProcessCO [5] ontologies placed at the core ontological level. In turn, both are enriched by the abovementioned terms of ThingFO.

Looking at Fig. 1, we place ThingFO at the foundational level whose terms are independent of any domain, as we analyze them thoroughly in the next Section. From top to bottom, the next level is called Core Ontological Level. In this level, we place ontologies such as ProcessCO, GoalCO, SituationCO, ContextCO, ProjectCO, among others that are not shown in the figure, such as ProductCO, ServiceCO and ResourceCO. Their terms are also independent of any domain, but they are closer to diverse domains, since, for example, the term Task in ProcessCO is specialized in each domain at hand. In this way, we have specific-domain tasks for measurement, testing, software development or building construction. On the other hand, ProcessCO includes terms with semantic of Thing such as Work Entity (Work Process, Activity, Task), Work Product (Artifact, Outcome), and Work Resource such as Agent, Method, Strategy, Tool, among others.

It is important to note that conceptual components at the same level may reuse terms with each other entirely. For example, SituationCO includes terms borrowed from other core components, such as Goal, Human Agent, Organization, Context, and Project, as we analyze in Section 4.

Looking at Fig. 1, the next level is called Domain Ontological Level, which is split down into two sub-levels. At the Top-domain Ontological Level, we place ontologies such as TestTDO, FRsTDO (FRs stands for Functional Requirements), NFRsTDO (NFRs stands for Non-Functional Requirements), and MEvalTDO (MEval stands for Measurement and Evaluation), among others that are not shown in the figure. Note that the terminological coverage of a top-domain ontology can serve as the basis for the development of low-level (more specific) domain ontologies. Therefore, at the Low-domain Ontological Level, we show the MetricsLDO and IndicatorsLDO conceptual components, but as the reader may conjecture, many others can be conceived at this sub-level.

Lastly, at the Instance Ontological Level, we can place ontologies for instances, such as instances of Units (of measures), instances of Quality Characteristics, among many others.

Ultimately, the presented multilayer ontological architecture promotes a clear separation of concerns by considering ontological levels and assigning conceptual components in the right place. This also favors the modularity, extensibility and reuse of ontological elements throughout the levels.

Note that most elements of the conceptual components in Fig. 1, that is, definitions of their terms, properties, relationships, and in some cases axioms are available at http://bit.ly/TestTDOv1-0_Doc. Some other ontologies are documented in the quoted literature in the Introduction Section.

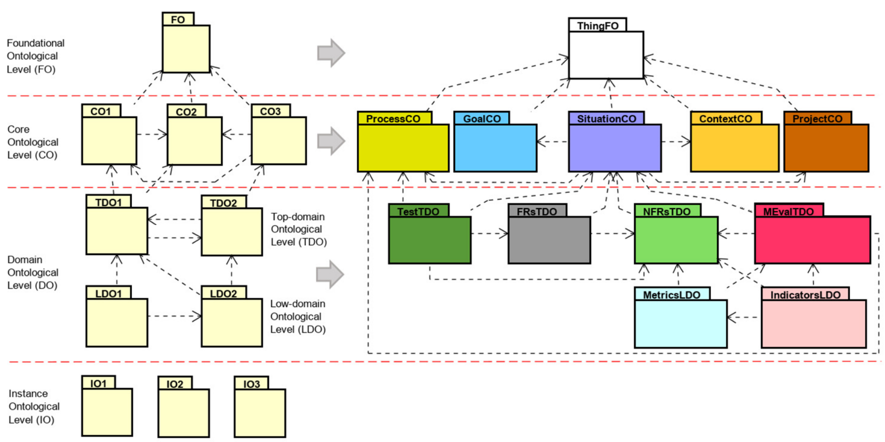

Fig. 1. Four-layered ontological architecture, which considers Foundational, Core, Domain and Instance levels. Also, some conceptual components are shown at the corresponding ontological level. Note that NFRs stands for Non-Functional Requirements, FRs stands for Functional Requirements, and MEval for Measurement and Evaluation.

3 ThingFO: A Foundational Ontology for Things

As commented in the Introduction Section, to build a foundational ontology requires a transdisciplinary knowledge. This is so because we are dealing with mental representations of subjects (i.e., human agents), who explicitly make assertions about the essentials of things and their invisible links between them in particular and universal situations of the world. To put it elegantly, one can grasp and understand the essentials with the eyes of the mind rather than with the eyes of the body. Hence, the eyes of the mind must be at the highest level in order to represent a foundational ontology.

The construction of a foundational ontology entails challenges that are unusual to common knowledge representation practice [20]. On the one hand, the need for descriptive adequacy requires a considerable subtlety of conceptual analysis based on sound philosophical and cognitive backgrounds. On the other hand, the usefulness of foundational ontologies depends on the greatest possible formal simplicity and transparency, as well as on the completeness and, at the same time, the conciseness of the elements included.

Foundational ontologies are representations about domain-independent top-level primitive constructs such as thing or object, property, power, relations, thing categories, and assertions that deal with them. Therefore, the primary aim (and requirement) to conceive a foundational ontology is to have a minimum set of particular and universal semantic concepts of the world, that is, key terms, properties and relationships (and possible axioms) that describe the world so that they can be reused and extended, and ultimately be useful and easy to adopt across all domains of different sciences.

In the sequel, in sub-section 3.1, we first describe and discuss the Thing, Property and Power terms and their relationships. Then, in sub-section 3.2, we describe and analyze the concept of Thing Category, which predicates on related particular objects. Lastly, in sub-section 3.3, we describe and discuss the concepts of Assertion on Particulars and Universals, and a set of specific types of Assertions that an agent can formulate about things and categories.

Note also that we describe the ThingFO v1.0 conceptualization shown in Fig. 2 following the text convention: ontology terms begin with capital letters, properties are italicized, and relationships are underlined. In addition, Tables 1, 2 and 3 contain the definitions of all terms, main properties and non-taxonomic relationships, respectively.

3.1 Things, Properties and Powers

Thing represents a particular, tangible or intangible object of a given particular world, but not a universal category, which is modeled by the term Thing Category. A particular object or entity represents and implies unique individuals or instances. Therefore, a particular Thing generates instances, whereas a universal Thing (Thing Category) does not generate instances.

A Thing is not a particular object (Thing) without its Properties and its Powers, so "things, properties and powers all emerge simultaneously to form a unity" […] "Things, properties and powers are necessary and sufficient for the existence of this unity" [8]. Moreover, a Thing cannot exist or be in spatiotemporal isolation from other Things. This principle of non-isolation is represented among Things (Fig. 2) through the relationship <u>relates with</u>, in which the cardinality is at least one.

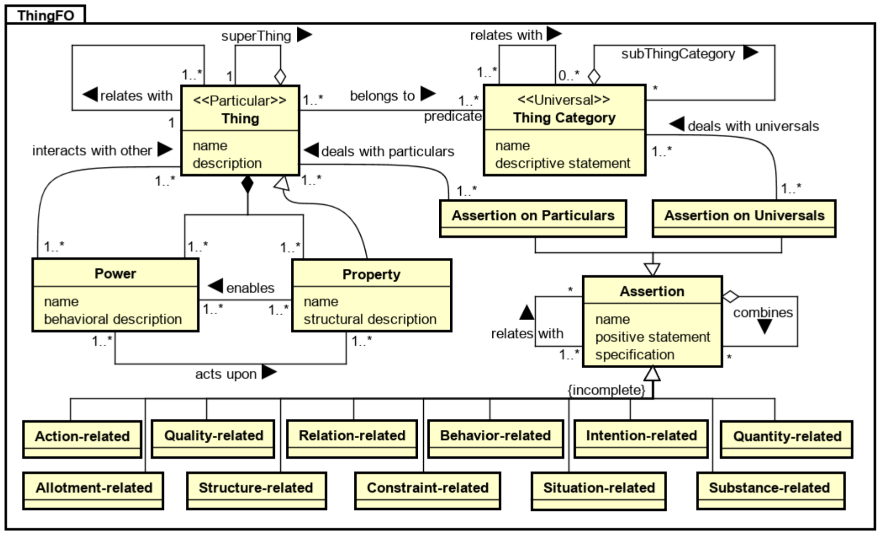

Fig. 2. Main terms, properties and relationships of the ThingFO v1.0 ontology.

So, in a particular world and situation, a Thing (or many) in the role of the `target` is always surrounded by other Things in the role of the `environment`. This aspect is modeled in SituationCO by including the terms Target Entity and Context Entity, as we exemplify later on. Note, however, under the principles of simplicity and conciseness, we try to delegate some responsibilities to core ontologies so as not to overload ThingFO.

Property has a *structural description* that refers to the intrinsic constitution, structure, or parts of a particular Thing, whereas Power has a *behavioral description* that refers to what a particular Thing does, can do or behave. In Table 3, the *behavioral description* is defined as "An unambiguous textual statement describing the Power of a Thing in terms of responsibilities, operations or actions".

According to Fleetwood: "Powers are the way of acting of a things' properties; powers are a things' properties in action" [8]. Also, he states that "Things have properties, these properties instantiate […] acting powers, and this ensemble of things, properties and powers cause any events that might occur". These Fleetwood's statements are specified in the following relationships. One or more Properties enable one or more Powers. In turn, Powers act upon Properties, as well as can interact with other Things.

Powers and Properties are two members of the triad that conform the particular entity named Thing. Consequently, for instance, there is no Power or energy alone floating in the air that can be dissociated from a Thing. It is important to highlight that a Property, which is one member of the triad that conforms a particular Thing is another particular Thing with its own Properties and Powers. "The moment a thing emerges from other things (with their own properties and powers), so too do its properties and powers" [8]. On the other hand, a Thing is part of a whole in the role of a superThing.

We can conclude that the biggest and the smallest Things of a particular world are beyond the reach and understanding of human beings.

Table 1. Definitions of ThingFO v1.0's terms shown in Fig. 2

Term	Definition
Thing (synonym: Entity, Object, Particular, Instance)	It represents a particular or concrete, tangible or intangible object of a given particular world. Note: A particular object represents and implies unique individuals or instances, not a universal category. Therefore, a particular Thing generates instances, whereas a universal thing (Thing Category) does not generate instances, at least with valuable meaning of individual.
Property	It refers to the intrinsic constitution, structure, or parts of a particular Thing.
Power	It refers to what a particular Thing does, can do or behave.
Thing Category (synonym: Entity Category, Universal)	It represents a universal of concrete Things conceived by the human being's mind for abstraction and classification purposes. Note: A Thing Category does not exist, is or can be in a given particular world as a Thing does.
Assertion	A positive and explicit statement that somebody makes about something concerning Things, their categories, contexts or situations based on thoughts, perceptions, facts, intuitions, intentions, and/or beliefs that is conceived with an attempt at furnishing current or subsequent evidence. Note: The part of the previous phrase that indicates "…*about something concerning Things…*" means, for example, about the substance, structure, quantity, quality, amongst other aspects of Things and Thing Categories.
Assertion on Particulars	It is an Assertion that somebody makes about something of one or more particular Things.
Assertion on Universals	It is an Assertion that somebody makes about something of one or more Thing Categories.
Action-related Assertion	It is an Assertion related to the interaction and happening of Things since acting Powers cause any events that might occur.
Allotment-related Assertion	It is an Assertion related to the assignment of something, which implies the assignment of a Thing to itself or to other Things.
Behavior-related Assertion	It is an Assertion related to the Power, which represents the capability and responsibility that a Thing has and/or exhibits.
Constraint-related Assertion	It is an Assertion related to the specification of restrictions or conditions imposed to things, properties, relationships, interactions or thing categories that must be satisfied or evaluated to true in given situations or events.
Intention-related Assertion	It is an Assertion related to the aim to be achieved by some agent. Note: The statement of an Intention-related Assertion considers the propositional content of a goal purpose in a given time frame.
Quality-related Assertion	It is an Assertion related to the requirements and constraints to be specified regarding the quality (distinguishing characteristic, property or attribute) for a Thing and possibly related entities, which may be evaluable.
Quantity-related Assertion	It is an Assertion related to the countable, measurable and evaluable aspect of a Thing and possibly related entities, which can be specified by means of symbolic or numerical expressions.
Relation-related Assertion	It is an Assertion related to logical or natural associations between two or more Things and their categories. Note: A Thing cannot exist or be in spatiotemporal isolation from other Things in a given particular world. Therefore, a Thing is related to another Things.
Situation-related Assertion	It is an Assertion related to the combination of circumstances, episodes, and relationships/events between target Things and context entities that surround them, or their categories, which is of interest or meaningful to be represented or modeled for an intended agent.
Structure-related Assertion	It is an Assertion related to the Property, which represents the intrinsic constitution, structure, or parts of a Thing.
Substance-related Assertion	It is an Assertion related to the ontological significance and essential import of a Thing as a whole entity, or a set of Things.

Table 2. Definitions of main properties of the ThingFO v1.0's terms shown in Fig. 2

Term	Property	Definition
Thing	*description*	An unambiguous textual statement describing a particular Thing.
Property	*structural description*	An unambiguous textual statement describing the Property of a Thing in terms of its constituents, structure, or parts.
Power	*behavioral description*	An unambiguous textual statement describing the Power of a Thing in terms of responsibilities, operations or actions.
Thing Category	*descriptive statement*	An unambiguous textual description of the category aim as universal.
Assertion	*positive statement*	An explicit declaration of the Assertion to be defined. Note 1: Regarding a particular Thing or category, a positive statement refers to what it is, was, or will be, and contains no indication of approval or disapproval. Note 2: A positive statement should be based on current or subsequent empirical evidence.
	specification	The explicit and detailed representation or model of the Assertion in a given language. Note 1: Assertions can be modeled by means of informal, semiformal or formal specification languages. Note 2: A specification can include text in natural language, mathematical and/or logical expressions, sketches, well-formed models and diagrams, multimedia resources, among other representations.

Table 3. Definitions of ThingFO v1.0's non-taxonomic relationships shown in Fig. 2

Relationship	Definition
acts upon	A Power acts upon one or more Properties, so it can look at them or update the status of the Thing's properties.
belongs to	Particulars Things may belong to one or more Thing Categories. Note: In other words, a Thing Category predicates about a set of Particulars and their instances.
deals with particulars	An Assertion on Particulars deals with Things.
deals with universals	An Assertion on Universals deals with Thing Categories.
enables	A Property enables the Powers of a Thing. Note: Because the Properties of a Thing are there, the Entity behavior can be enabled and manifested.
interacts with other	Due to the Power of a Thing, Things interact with each other.
relates with (x3)	A Thing relates to other particular Things.
	A Thing Category relates to other universal Things.
	An Assertion relates to other Assertions.

3.2 Thing Categories

Thing Category represents a universal of particular Things conceived by the human being's mind for abstraction and classification purposes. While a Thing represents a concrete object or entity, which may imply unique instances, a Thing Category represents an abstract or universal entity in which the instances may not have valuable meaning. As indicated in the note in Table 1, a Thing Category does not exist, is or can be in a given particular world as a Thing does. On the contrary, it can only be mentally formed or developed by human beings as an abstract or generic construct, which in turn, hierarchies of sub-categories can be developed.

Hence, a Thing Category predicates on related particular objects. That is, it predicates on the common essence of Things which, therefore, belong to the intended Category of Thing.

For the sake of exemplification, the common names of Entity (Thing) Categories of interest documented in various scientific disciplines are Organization Category, Project Category, Resource Category, Process Category, Product Category, Service Category, System Category, among others. Furthermore, each category can be sub-categorized according to the abstraction purpose given by an agent. Consider, for example, the System Category. A particular Thing or entity that belongs to it –or that belongs to the Smartphone Mobile Application sub-category- can be "Social Network Mobile Application". Then, we can evaluate the quality of unique instances such as "LinkedIn mobile app version x.x", "Instagram mobile app version y.z", and so forth.

3.3 Assertions on Particulars and Universals

Assertion is a key term in ThingFO that has a great conceptual impact when someone intentionally represents and models particular and universal Things and situations of the world in question. Table 1 defines Assertion as "A positive and explicit statement that somebody makes about something concerning Things, their categories, contexts or situations based on thoughts, perceptions, facts, intuitions, intentions, and/or beliefs that is conceived with an attempt at furnishing current or subsequent evidence". Regarding a particular Thing or category, a *positive statement* refers to what it is, was, or will be. Hence, it contains no indication of approval (e.g. I like it) or disapproval (e.g. I dislike it). Assertions are conceptualized consequences of persons' mental models of the represented world, phenomenon, situation, or event at hand.

To be valuable, actionable and ultimately useful for any science, an Assertion should largely be verified and/or validated by theoretical and/or empirical evidence. Assertions can be represented by informal, semiformal or formal specification languages. Thus, a *specification* can include text in natural language, mathematical and/or logical expressions, sketches, well-formed models and diagrams, multimedia resources, among other representations.

There are Assertion on Particulars for Thing, and Assertion on Universals for Thing Category. Assertion on Particulars deals with particulars (Things), whereas Assertion on Universals deals with universals (Thing Categories).

Concerning Things and categories, by means of assertions, we can specify aspects of substance, situation, relations, structure, behavior, intention, quantity and quality, among others. In the sequel, we describe the types of Assertions shown in Fig. 2. However, additional types of Assertions could be conceived.

An Action-related Assertion is related to the interaction and happening of Things since acting Powers cause any events that might occur. That is, particular Things can interact to each other, just as a Thing can act upon itself. Interrelated Things interact to each other conforming particular situations, i.e., specific circumstances, episodes and events that are of interest to an intended agent. Interactions among particular Things both target entities and context entities in particular situations can be abstracted in general situations.

An Allotment-related Assertion is related to the assignment of something, which implies the assignment of a Thing to itself or to other Things. For example, a particular resource (method, tool, person, etc.) is assigned to a task in a particular situation. Or, the specific amount of time a person gives him/herself to do an assignment. Or, the specific amount of time a professor gives their students to take a test.

A Behavior-related Assertion is related to the Power, which represents the capability and responsibility that a Thing has and/or exhibits. It can be specified for Particulars and also be abstracted for Universals.

A Constraint-related Assertion is related to the specification of restrictions or conditions imposed to Things, Properties, relationships, interactions or Thing Categories that must be satisfied or evaluated to true in given situations or events. It can be specified for both Particulars and Universals.

An Intention-related Assertion is related to the aim to be achieved by some agent. The statement of an Intention-related Assertion considers the propositional content of a goal purpose in a given time frame. It can be specified for both Particulars and Universals.

A Quality-related Assertion is related to the requirements and constraints to be specified regarding the quality (distinguishing characteristic, Property or attribute) for a Thing and possibly related entities, which may be evaluable. Quality requirements and constraints can be specified for a particular Thing in terms of its Properties or Powers, or in terms of both as a whole. Quality requirements and constraints can be specified for Particulars and also be abstracted for Universals.

A Quantity-related Assertion is related to the countable, measurable and evaluable aspect of a Thing and possibly related entities, which can be specified by means of symbolic or numerical expressions. Qualities of Things can be measured, evaluated and analyzed by specifying Quantity-related Assertions and strategies. A quantity or a relationship between quantities can be formalized, for instance, by mathematical, statistical or logical expressions. Also, it can be specified for both Particulars and Universals.

A Relation-related Assertion is related to logical or natural associations between two or more Things and their categories. As abovementioned, a Thing cannot exist or be in spatiotemporal isolation from other Things in a given particular world. Therefore, a Thing is related to other Things. Also, it can be specified for Particulars and also be represented for Thing Categories

A Situation-related Assertion is related to the combination of circumstances, episodes, and relationships/events between target Things and context entities that surround them, or their categories, which is of interest or meaningful to be represented or modeled for an intended agent. A Situation can be represented statically or dynamically depending on the intention of the agent. It can be specified for Particulars and also be generalized for Universals.

A Structure-related Assertion is related to the Property, which represents the intrinsic constitution, structure, or parts of a Thing. Structural aspects can be specified for Particulars and also be abstracted for Universals.

Finally, a Substance-related Assertion is related to the ontological significance and essential import of a Thing as a whole entity, or a set of Things. Substance aspects can be specified for Particulars and also be abstracted for Universals.

4 Analyzing the Usefulness of ThingFO

To analyze the usefulness of ThingFO, we mainly illustrate enriched terms of a couple of ontologies at the core level such as ProcessCO and SituationCO, where their concepts are themselves cross-cutting concerns primarily for domain terminologies of any Science. To this end, we showcase the applicability of ThingFO in conjunction with these two core ontologies, to enrich not only terms but also to reuse some of their properties and relationships by TestTDO. Additionally, we also reuse or mirror some conceptual blocks or patterns as we address later on.

It is important to note that we use stereotypes as a particular mechanism to semantically enrich terms. Regarding the procedural way to enrich a given term from a higher-level term, we have argued in [5] that stereotypes are, at least to our aim and context, a more suitable mechanism that inheritance relationships, since it generates a loose coupling between a lower-level component and a higher-level component. Conversely, in some cases, defining a term as a specialization (inheritance relationship) of less specific terms can minimize the reuse of, for instance, a domain ontology, in addition to promoting tight coupling between components. Furthermore, stereotypes can reduce the complexity of the model, also promoting comprehensibility and communicability.

In the sequel, in sub-section 4.1, we describe how some ThingFO terms are stereotyped in ProcessCO to semantically enrich their terms, in addition to highlighting how some ThingFO properties and relationships are reused in ProcessCO. Similarly, in sub-section 4.2, we do an analogous description and analysis for SituationCO. Then, in sub-section 4.3, we address how these foundational and core concepts are semantically extended or reused by TestTDO, a top-domain ontology for software testing. Finally, in sub-section 4.4, we perform an abridged discussion.

It is important to note that we are not going to emphasize and discuss the content of the ProcessCO, SituationCO and TestTDO ontologies, but rather the enrichment and reuse mechanism of terms, properties and relationships. The reader interested in these ontologies can look further at the references.

4.1 ThingFO semantically enriches to ProcessCO

Fig. 3 depicts a fragment of the ProcessCO ontology with some terms, properties and relationships enriched or reused from ThingFO. ProcessCO is placed at the Core Ontological Level as commented in Section 2 and represented in Fig. 1. This ontology, which is primarily concerned with human work processes rather than natural processes, was first developed in the late 1990s, then improved in 2014 [5], and recently updated [2] to harmonize its concepts primarily with ThingFO in the context of FCD-OntoArch.

The term Thing enriches, for example, the term Work Entity and, consequently, Work Process, Activity, and Task (the latter not shown in the fragment). In addition, we can say that the term Work Product has semantics of Thing, the same as Artifact and Outcome.

The term Thing Category enriches the term Product Category, so Product Entities belong to this category –where this underlined relationship is reused entirely from the ThingFO one.

The term Constraint-related Assertion enriches the term Condition, while the term Assertion on Particulars enriches the term Process Perspective.

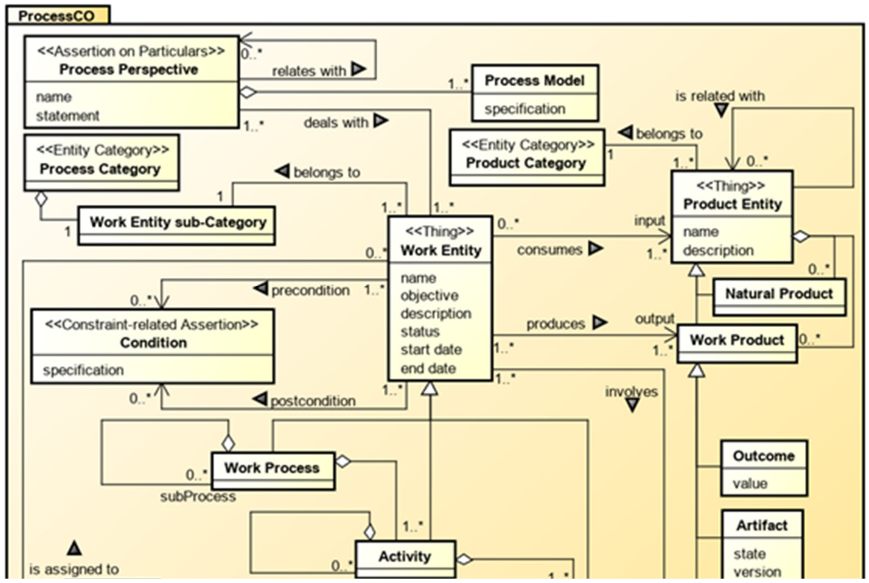

Fig. 3. Fragment of the ProcessCO diagram with some terms, properties and relationships enriched from ThingFO.

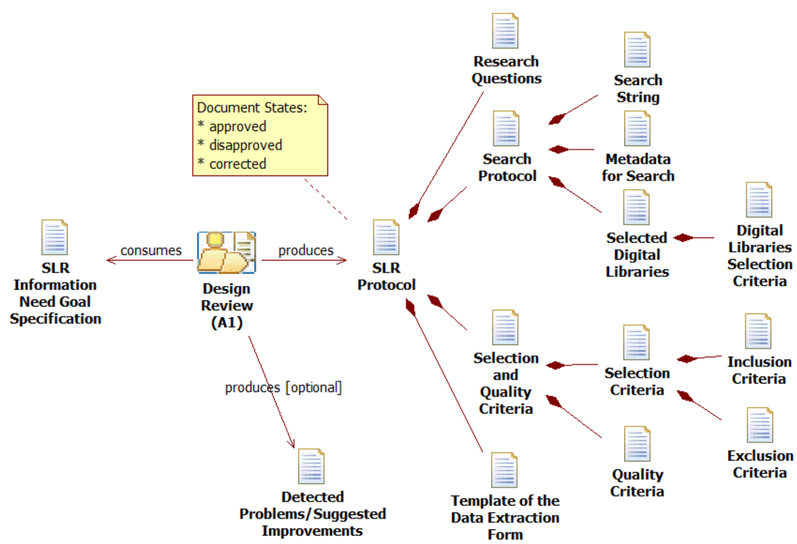

Fig. 4. Informational perspective for the Design Review (A1) activity in the context of a Systematic Literature Review (SLR) process.

We would like to illustrate in the sequel the concept of Process Perspective, which is an Assertion on Particulars that specifies the functional, behavioral, informational, methodological, or organizational perspective (or view) for Work Entities and related concepts.

A work process commonly can be modeled taking into account five perspectives [3]: i) functional that includes the Work Entities' structure, Work Products as inputs and outputs, etc.; ii) informational that includes the structure and interrelationships among Work Products produced or consumed by Work Entities; iii) behavioral that models the dynamic view of Work Entities, including Conditions; iv) organizational that deals with Agents and Roles; and, v) methodological that is used to represent the process constructors (i.e., Methods) that can be applied to different descriptions of Work Entities.

Therefore, a Process Perspective is an Assertion on Particulars, which depending on the situation at hand may be a Behavior-related Assertion, an Action-related Assertion, or some other type of Assertion specified in sub-section 3.3 for ThingFO. For example, the informational view is a Structure-related Assertion, and the organizational view is an Allotment-related Assertion. Fig. 4 models the Informational Perspective for the Design Review (A1) activity in the context of a Systematic Literature Review (SLR) process. In [3], we have specified four process perspectives for this SLR process.

Furthermore, Fig. 3 shows that a Process Perspective is represented by a Process Model *specification*. Note that *specification* is part of the Assertion term in ThingFO. As a consequence, each Assertion can be represented by at least a model in a given language. Fig. 4 represents thus a concrete model using the UML language.

Ultimately, a Process Model, a Situation Model (term included in Fig. 5), a Quality Model (term included in the NFRsTDO component), or any model made by a human being under the sun, has semantics of Artifact. The *specification* of an Assertion –initially conceived in a person's mental model- can be materialized in a model (the produced artifact) of utility in a certain scientific problem/situation.

4.2 ThingFO semantically enriches to SituationCO

Fig. 5 depicts a fragment of the SituationCO ontology with some terms, properties and relationships enriched or reused from ThingFO. SituationCO is also placed at the Core Ontological Level in the context of FCD-OntoArch. This ontology, which mainly deals with particular and universal situations in a given problem at hand, was developed in mid-2019 [16]. Its concepts primarily extend from ThingFO, and it also borrows some core concepts from ProjectCO, GoalCO, ContextCO and ProcessCO.

The term Thing enriches, for example, the terms Target Entity and the terms reused from the abovementioned core components such as Project, Organization, Context Entity, and Human Agent, respectively.

The term Thing Category enriches the term Entity Category and Context Category. So particular Target Entities belong to the Entity Category, whereas Context Entities belong to the Context Category, as depicted in Fig. 5.

The term Situation has semantics of Situation-related Assertion and applies to both Particulars and Universals. Also, Goal (term reused from GoalCO) has semantics of Intention-related Assertion.

For the sake of a summary, a Human Agent/Organization conceives/establishes Goals that are operationalized by Projects. A Goal implies a Situation, which can be specified by a Situation Model [25]. A Particular Situation is a Situation-related Assertion on Particulars that explicitly states and specifies the combination of particular circumstances, episodes and relationships/events embracing Target Entities and their surrounding Context Entities, which is of interest and relevant to be represented.

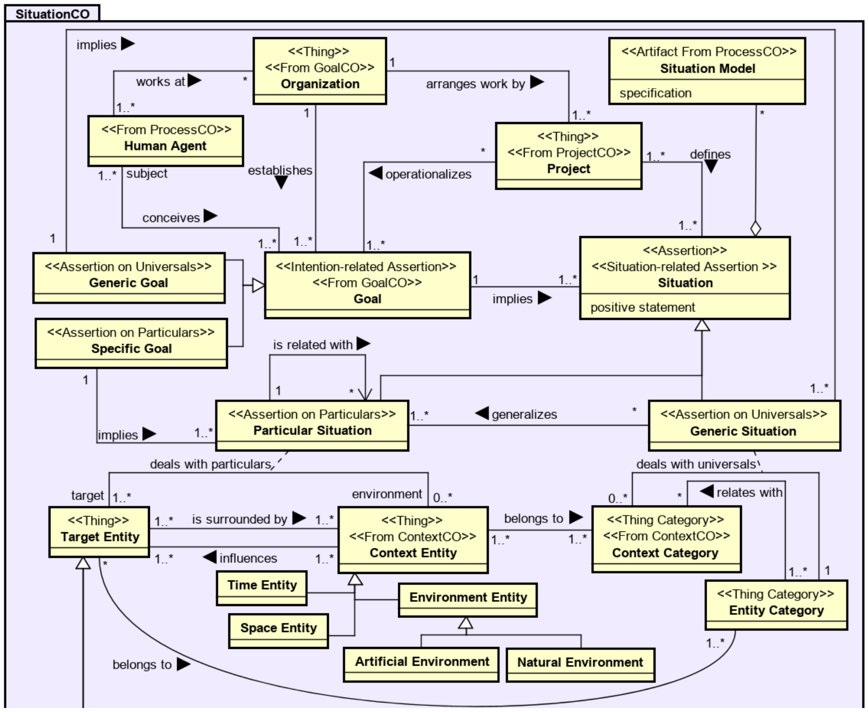

Fig. 5. Fragment of the SituationCO diagram with some terms, properties and relationships enriched from ThingFO.

Depending on the Project and its Specific Goal's purpose, Target Entities can be for instance Developable Entity (e.g. a document, a source code, etc.), Evaluable Entity (e.g. a work product, a system, etc.), or Testable Entity, which has the semantics of Developable or Evaluable in a given Particular Situation as represented in Fig. 6.

Note that the relationship <u>deals with particulars</u> between Particular Situation and Target/Context Entities is inherited from ThingFO, likewise the relationship <u>deals with universals</u>. Also, a Particular Situation can <u>be related with</u> none or many Particular Situations. This reflexive relationship is in the Assertion term as well (Fig. 2).

4.3 ThingFO, ProcessCO and SituationCO semantically enrich to TestTDO

Fig. 6 depicts a small fragment of the TestTDO v1.1 ontology with some terms, properties and relationships semantically enriched or reused from higher-level ontologies. It is placed at the Top-domain Ontological Level in the context of the FCD-OntoArch architecture.

TestTDO is a top-domain reference ontology on software testing built in late 2019 (TestTDO v1.0 [23]), and updated in March 2020 (i.e., TestTDO v1.1, which is available at http://bit.ly/TestTDOv1-1). Most of its concepts primarily extend from ProcessCO, SituationCO and ThingFO, and it also completely reuses a couple of concepts from FRsTDO and NFRsTDO.

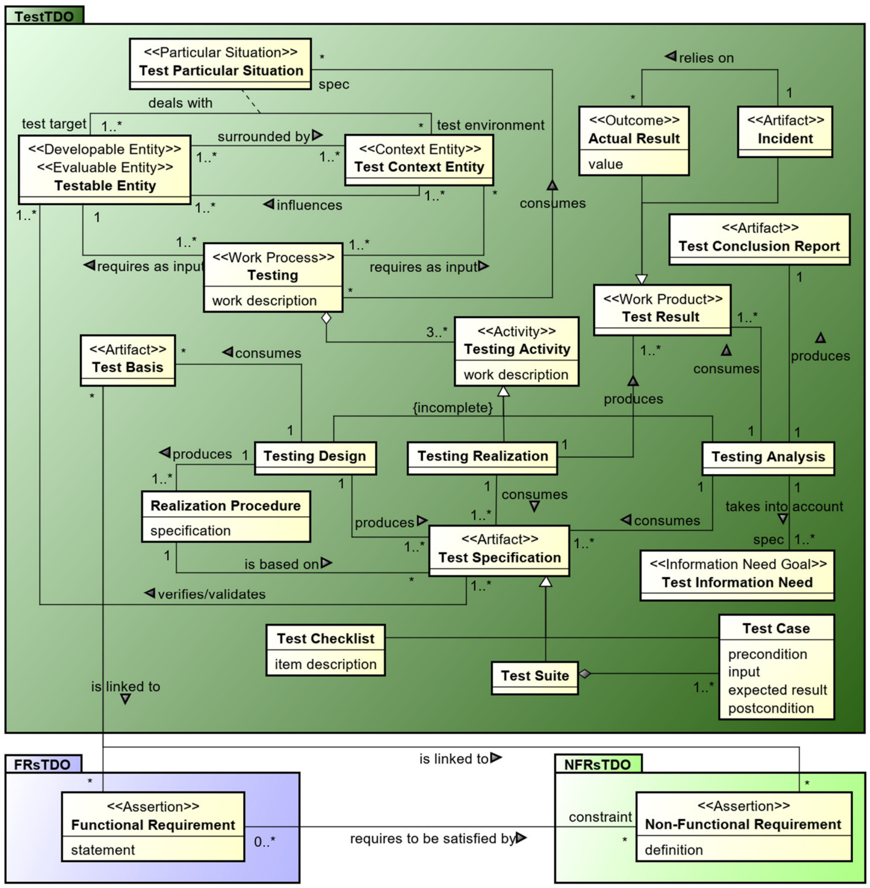

Fig. 6. Some terms, relationships and properties of TestTDO v1.1 (http://bit.ly/TestTDOv1-1) related to Work Product/ Work process/Activity. This fragment from TestTDO also shows its relationship to the Non-functional Requirement and Functional Requirement terms. Many of these top-domain terms are enriched from core ontologies depicted in Fig. 1, as well as from ThingFO.

With semantics of Thing and extended from ProcessCO and SituationCO, the reader can see, in the snippet of the TestTDO v1.1 conceptualization in Fig. 6, terms such as Testable Entity, Testing, Testing Activity, Test Result, Incident, among others.

Looking at the Testable Entity term, and as commented previously, it has the semantics of Developable or Evaluable Entity (as Target Entity, which is a Thing) depending on the given Particular Situation. Any Testable Entity is an Evaluable Entity iff the test requirement that refers to this Thing is linked to a Non-Functional Requirement. Instead, any Testable Entity is a Developable Entity iff the test requirement that refers to this Thing is linked to a Functional Requirement. Because Fig. 6 is a shortened snippet of TestTDO, the term Test Requirement is not there, but the reader can see that trough

Test Basis the terms Functional Requirement and Non-Functional Requirement are reused from FRsTDO and NFRsTDO components at the same domain level, respectively. This link is also represented in Fig. 1, at the component level.

Lastly, the term Particular Situation –as commented previously in sub-section 4.2-, enriches the term Test Particular Situation. We would like to highlight that TestTDO reuses and extends some conceptual blocks or patterns represented in SituationCO and ProcessCO. For example, the Particular Situation pattern, which includes the three abovementioned terms (i.e., Particular Situation, Target Entity and Context Entity), properties and relationships (i.e., <u>deals with particulars</u>, <u>is surrounded by</u> and <u>influences</u>) in Fig. 5, is mirrored in the Test Particular Situation pattern. Similarly, the Work Entity/Work Product pattern in ProcessCO is also reflected in TestTDO reusing entirely the produces/consumes relationships as well.

4.4 Abridged Discussion

The aim of building a foundational ontology is to have a minimum set of particular and universal relevant semantic concepts of the world perceived and elaborated by a human subject, that is, key terms, properties, relationships and possible constraints that can describe the world in different situations so that they can be reused and expanded, and ultimately can be useful and easy to adopt or adapt across all domains of science. ThingFO has terms like Thing, Thing Category, and Assertion in addition to their properties and relationships that spread out, to a greater extent, into all components at lower levels, enriching them semantically.

A living person as a subject is an object with many Properties, but at least the essential one of being alive –that must be true-, and many Powers, including the capability to observe and think about Things and Situations of the world, included him/herself as an object into it. Thus, a person has the capability to create Artifacts as a result of thinking and representing mental models.

ThingFO, as well as ProcessCO, SituationCO, TestTDO, among others, are resulting Artifacts that we built after a long process of obtaining personal and group knowledge and expertise. They are not perfect, but perfectible, as any Thing that produces the human being under the sun. Thus, for example, a conceptualization of an ontology as an Artifact represents a specification that primarily combines substance-, relation-, structure-, and intention-related Assertions, in addition to a constraint-related Assertion for axioms, when necessary.

There are currently warm and valuable discussions on what a conceptual model is, for example, recently by Guarino *et al.* [9], in order to clarify whether some type of modeling constructor –as Artifact- is a conceptual model or not. Under the ThingFO umbrella, we hold that any Artifact is the result of one or more Assertions about the represented Situation at hand, regardless of whether it is a conceptual model or not. Furthermore, without delving into this issue, conceptual models are closer to ontological Assertions, than other Assertions that only focus on partial aspects of Things or Situations, e.g. the states of certain Property in a given period of time, the preconditions that must be evaluated as true for an event to occur, among many others.

As indicated in Section 3, the usefulness of foundational ontologies depends on the greatest possible formal simplicity and transparency, as well as on the completeness and, at the same time, the conciseness of the elements included. Moreover, under these principles, we have tried to delegate some responsibilities to core ontologies so as not to overload the foundational one.

Additionally, there are other quality practices described by D'Aquin *et al.* [7] for ontology design, for which they identify dimensions and features for "beautiful ontologies". These were primarily intended for domain ontologies, although some features apply to core and foundational as well. Among these dimensions are formal structure and conceptual coverage, which are characterized by if the ontology is designed in a principled way; it is formally rigorous; it implements also non-taxonomic relations; it has a good domain coverage; it adheres to international standards; it reuses foundational ontologies, among others features as modularity. From these, we have designed a quality model and then evaluated TestTDO [22]. So we are planning to evaluate ThingFO, considering these non-functional requirements while adding others.

5 Related Work

This Section provides a summary of related work on foundational ontologies, also known as upper or top-level ontologies. As commented in the Introduction Section, while thousands of domain, application and instance ontologies have been built so far, only less than a dozen well-known foundational ontologies have been built in the past three decades, with some applicability impact.

Mascardi *et al.* [13] provide a description and comparison of 7 upper ontologies, namely: BFO [1], Cyc [12], DOLCE [14], GFO [11], PROTON [6], Sowa [21], and SUMO [19], which were the most referenced within the research community at the time of their study. To summarize the comparison information, the authors have designed a template with the following fields: Status of this description; Home page; Developers; Description; History; Dimensions; Modularity; Applications; Alignment with WordNet; and Licensing. In addition, they also provide a summary of existing comparisons drawn among subsets of the top 7 cited ontologies previously made by other authors. Therefore, we invite the interested reader to visit this study to better understand the related work.

Besides, Guizzardi [10] developed UFO (*Unified Foundational Ontology*) in the context of his doctoral thesis. This ontology was not preselected in the Mascardi *et al.*'s comparison surely for chronological reasons. UFO incorporates previous developments mainly from GFO and DOLCE adding new features.

Another contemporary initiative is COSMO (*COmmon Semantic MOdel*), which is a foundational ontology that can serve to enable broad general semantic interoperability. The development of COSMO started as a merger of basic elements from Cyc, SUMO, and DOLCE adding new elements. Note that all the documentation of this open project can be accessed at http://micra.com/COSMO/. The current OWL version (June 2020) of COSMO has over 21,000 types (OWL classes), over 1,300 relations, and over 10,000 restrictions.

As indicated in previous sections, principles and quality criteria that benefit the understandability, usefulness and potential adoption of foundational ontologies –which guided the ThingFO construction process- are, for instance, formal simplicity and transparency promoting also the use of graphical representations for the conceptualization; coverage completeness but, at the same time, conciseness and self-intuitiveness of the elements included; balanced representation of both taxonomic and non-taxonomic relationships; and, under the principle of modularity and loose coupling, a clear delegation of responsibilities to core ontologies.

In brief, qualitatively analyzing the quoted foundational ontologies, none of them simultaneously satisfy all the above criteria. As for the numbers, the smallest are Sowa (with 30 classes, 5 relationships, 30 axioms), and BFO (36 classes linked via the "is_a" taxonomic relation, which make it a taxonomy rather than an ontology). While the Cyc figures are approximately 300,000 concepts, 3,000,000 assertions (facts and rules), and 15,000 relationships, including in these numbers micro-theories. COSMO numbers as mentioned above are also huge.

The foundational ontology that its conceptualization is best represented graphically is UFO, whereas most of the remainder use other formal logic-based representations that are not easy to convey and even to understand for many stakeholders. On the other hand, frequently, a clear delegation of responsibilities to core ontologies is not observed. For example, among the BFO 36 classes, are terms such as Process, Quality, Temporal region (http://ontology.buffalo.edu/bfo/BFO2.png) that we have delegated to lower levels.

Considering the terms, there is often a lack of consensus on semantic matching. For example, the DOLCE distinction between “endurant” and “perdurant” does not fully correspond to that established in GFO. Moreover, COSMO's great effort began as a way to tackle the problem of semantic interoperability by merging basic elements of Cyc, SUMO, and DOLCE, and adding new ones.

In building ThingFO, we have adhered to the principles and criteria stated above. Its three key terms are Thing (particular), Thing Category (universal) and Assertion, which are used in some of the ontologies mentioned above. However, the types of Assertions dealing with particulars and universals shown in Fig. 2 are not represented in this way in the quoted ontologies at the foundational level. In summary, ThingFO figures are 18 terms, 11 properties and 9 non-taxonomic relationships.

6 Concluding Remarks and Future Work

This work has documented and analyzed ThingFO, which is an ontology for particular and universal Things and Assertions placed at the foundational level in the context of a developed four-layered ontological architecture called FCD-OntoArch. This multilayer ontological architecture promotes a clear separation of concerns by considering the ontological levels that allow the allocation of conceptual components accordingly. This architecture therefore encourages modularity, extensibility and reuse of ontological elements at all lower levels.

Since ThingFO is at the highest level, ontologies at lower levels benefit from reusing and extending its three key concepts, namely: Thing, Thing Category and Assertion. In other words, the aim is to have a large number of lower-level ontologies accessible under the umbrella of this foundational ontology.

Besides, to analyze the applicability and usefulness of ThingFO, we have illustrated the semantically enriched terms of the ProcessCO and SituationCO ontologies at the core level, where their concepts are, in turn, cross-cutting concerns primarily for domain conceptual bases of any Science. In particular, to show the applicability of

ThingFO alongside these two core ontologies, we have also addressed the mechanism to not only enrich terms, but also to reuse properties and relationships for TestTDO, a top-domain software testing ontology. Furthermore, we have also presented how two conceptual blocks or patterns available in SituationCO and ProcessCO were clearly reflected in TestTDO.

As future work, we are going to compare the ThingFO conceptualization with a set of preselected conceptualized foundational ontologies, considering quality criteria as mentioned in the Related Work Section. To this end, we will use the GOCAMECom (*Goal-Oriented Context-Aware Measurement, Evaluation and Comparison*) strategy [24], from the family of evaluation strategies to gauge ThingFO's strengths and weaknesses compared to the preselected ones and propose improvement actions, if necessary.

Lastly, it is important to remark that we were primarily interested in the conceptualization of ThingFO and its lower-level ontologies due to our main aim is to have common reference terminologies for enriching process and method specifications for a family of evaluation and testing strategies. However, since we have recently implemented the TestTDO ontology in OWL, we plan to do the same with the rest of the higher-level ontologies. This will allow us to carry out broader semantic verifications.

Ultimately, if, as a produced artifact, the ThingFO ontology were adopted step by step by the academia and industry, this will be a promising fact of its utility and validity.

To conclude, as a metaphor that applies primarily to human beings rather than likely to other creatures in this world: *The eyes of the mental models of things and situations are on a higher level than the eyes of perceived things*. Therefore, *the eyes of the mind must be at the highest level to understand and represent the essentials of the world.*

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