Foundational Choices in Enterprise Architecture: The Case of Capability in Defense Frameworks

Gabriel M. Miranda[1], João Paulo A. Almeida[1], Giancarlo Guizzardi[1,2] and Carlos L. B. Azevedo[3]
[1]*Ontology & Conceptual Modeling Research Group (NEMO), Federal University of Espírito Santo, Vitória, Brazil*
[2]*Conceptual and Cognitive Modeling Research Group (CORE), Free University of Bozen-Bolzano, Italy*
[3]*Data Science and Complex Networks Research Group, Federal Institute of Espírito Santo (IFES), Serra, Brazil*
gabriel.m.miranda@ufes.br, jpalmeida@ieee.org, giancarlo.guizzardi@unibz.it, carlos.azevedo@ifes.edu.br

***Abstract*—Enterprise Architecture (EA) description frameworks embody a "worldview" which is used by architects to conceptualize the enterprise and its elements. This "worldview" manifests itself in the choice of language constructs and in modeling rules and guidelines, and, whether explicitly or not, reflects some foundational ontological choices. This paper reflects on the practical consequences of some of these choices. We focus on the capability-related elements in EA defense frameworks (DoDAF, MODAF and NAF). In particular, we analyse the support for modeling capabilities in these frameworks from the prism of a fundamental distinction in formal ontology: two-category vs. four-category ontology. By analyzing the current choices in these frameworks and identifying some adverse consequences, we are able to suggest well-founded recommendations for improvements.**

***Index Terms*—Capabilities, Foundational Ontology, Enterprise Architecture Modeling, DoDAF, MODAF, NAF, IDEAS**

1. Introduction

Enterprise Architecture (EA) frameworks play an important role in the EA discipline [18]. They facilitate EA management by providing concepts for expressing knowledge about an enterprise's elements and their relations. As such, they embody a "worldview" which is used by EA architects in conceptualizing the enterprise and its elements. This "worldview" manifests itself in the choice of language constructs, notations, and in modeling rules and guidelines.

In several cases, this "worldview" is overlooked in the design of an EA framework and accompanying modeling languages. This often results in representational gaps and ontological deficiencies, which have been scrutinized for over two decades now under the banner of "ontological analysis" [27], [36] (or "representational analysis" [37]). Several studies have shown issues in the representational capabilities of EA frameworks and conceptual modeling languages (e.g., [1], [3], [28], [37]), employing *reference ontologies* in this task. A reference ontology serves in this case as an "analysis theory" [9] or "representation theory" [37] and is contrasted with the language's underlying "worldview". Many of these studies triggered (re)design efforts, whose effectiveness has been demonstrated by empirical studies (e.g., [26], [35]).

In some other cases, however, this "worldview" is *defined explicitly and employed systematically* in the design of the EA description framework. For example, in the RM-ODP framework, foundations were explicitly defined in the standard's Part 2 [16], and used as a basis for the enterprise language (among others) in Part 3 [17]. More recently, the defense EA frameworks DoDAF [7], MODAF [31] and NAF [24] have adopted an explicit formal foundation captured in the International Defence Enterprise Architecture Specification (IDEAS) ontology [15].

As they shape a framework's representational strategy, the quality of the adopted foundations become a key factor in that framework's representational qualities. In this paper, we reveal the consequences of some key ontological choices in the foundations underlying the EA defense frameworks DoDAF, MODAF and NAF. We focus on the conceptualization and representation of *organizational capabilities*.

We show that the way in which capabilities are conceptualized by the adopted reference ontology (IDEAS) has some adverse implications for capability representation. More specifically, we show some limitations of a *two-category ontology* (such as IDEAS) in conceptualizing capabilities and their properties. In a nutshell, a two-category ontology is centered around two basic ontological categories: the *universal* (concepts, types) and the *particular* (things, individuals). In contrast, a *four-category ontology* [20]—in line with the Aristotelian view—further distinguishes between *substantial* independent entities (roughly, objects) and the *non-substantial* existentially dependent entities (features, objectified properties), to generate four basic ontological categories. Using a four-category ontology, we revise the frameworks' metamodels, improving the semantic clarity and usefulness of their capability representation support.

This paper is further structured as follows: Section 2 describes the ontological foundations considered in this paper; Section 3 describes the current support for capabilities in the EA frameworks for the defense domain, revealing their underlying foundations and discussing the consequences of these foundations for capability representation; Section 4 presents a revised metamodel for capabilities in the defense frameworks; Section 5 discusses another important foundational matter (*endurantism* vs. *perdurantism*) and Sections 6 and 7 present related work and conclusions.

2. Ontological Foundations

2.1. Basic Ontological Categories

There has been significant debate throughout the history of philosophy concerning the fundamental categories needed in constructing a description of reality [21]. Different philosophical stances propose to carve reality in different ways, leading to different basic ontological categories (i.e., different *kinds of beings* [20]) and their relations.

The idea of an ontology founded on four basic categories comes originally from the second chapter of Aristotle's Categories [20]. Such a system recognizes two fundamental categorical distinctions which cut across each other to generate four fundamental ontological categories, these distinctions being between: (i) the *universal* and the *particular*; and the distinction between (ii) the *substantial* and the *non-substantial*.

The first dimension (i) concerns whether entities have a predicative nature: *universals* are "repeatable" patterns of features recurrent in a number of *particulars*, while *particulars* (also termed *individuals*) are the "non-repeatable" entities that instantiate one or more *universals*. For example, "John" is a particular that instantiates the universals "Man", "Person", "Animal" and "Living Being".

A two-category ontology employs only this first dimension, thereby admitting two categories of entities. As discussed in [29] this choice reflects in the ontological foundation the "predicate-argument structure of atomic formulas in first-order logic." In this view, "reality, we are to suppose, is made up of concrete individuals (a, ...) plus abstract 'properties' or 'attributes' (F, ...)." Smith discusses the consequences of this philosophical view in depth in [29]. An important consequence to us here is that no distinction is made between two kinds of predication: in the category of substance ("John is a human being", "Henry is an ox") and in the category of (to use an Aristotelian term) *accidents* ("John is hungry", "John is capable of speaking fluent Greek", "Henry is heavy"). This distinction is also present in Aristotle's original differentiation between what is *said of a subject* (*de subjecto dici*), denoting *instantiation* and what is *exemplified* in a subject (*in subjecto est*), denoting a particular relation of *exemplification*, or non-substantial predication [11].

Often, the term "property" is used at the universal level in a two-category ontology to encompass all of these kinds of predication (including relational predication with relations construed as universals, e.g., "married to", "greater than"). In contrast, we obtain a *four-category ontology* [20], when this second dimension (ii) is introduced honoring the aforementioned distinctions. As a consequence, we have a system that differentiate particulars in *substantial and non-substantial particulars* and universals into *substantial and non-substantial universals*.

Substantial particulars are property-bearing particulars which are not themselves borne by anything else [20], usually corresponding to the common sense term "object". In contrast, *non-substantial particulars* are those that depend on their bearers and can only exist in them (e.g., "John's weight" and "his headache"). *Non-substantial particulars* have been given many names and variants in the literature, including "modes", "individual accidents", "moments", "qualities", "tropes", "individualized properties", "particularized properties", "aspects", or "property particulars". They may have a relational or non-relational nature. For example, "John and Mary's marriage" is a relational non-substantial particular, while "John's weight" is a non-relational (i.e., intrinsic) non-substantial particular.

Substantial universals (e.g., "Person" and "Statue") are those instantiated by substantial particulars (e.g., "Mick Jagger" and "the Statue of Liberty"), while *non-substantial universals* (e.g., "Weight", "Marriage") are those instantiated by non-substantial particulars (e.g., "the weight of the Statue of Liberty" is an instance of "Weight", "John and Mary's marriage" is an instance of "Marriage").

Figure 1 illustrates the four basic categories identified here, forming the so-called *Aristotelian Square*. The figure employs the terminology of the Unified Foundational Ontology (UFO) [11], where non-substantial particulars are termed "moments". Vertical placement corresponds to the first dimension (i), with universals placed at the top and particulars at the bottom. Horizontal placement corresponds to the second dimension (ii), with substantial universals and particulars at the left-hand and non-substantial universals at the right-hand side.

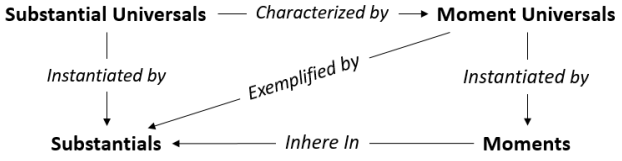

Figure 1. The Aristotelian Square (adapted from [11]).

The figure also reveals various relations established between the basic categories. Substantial universals and moment universals are *instantiated by* substantials and moments respectively. The relation of *characterization* between substantial universals and moment universals indicates that certain types of moments (e.g. "Weight", "Height") can characterize certain types of substantials, in the sense that their instances may bear *moments* of that type (e.g., the type "Person" can be characterized by "Weight" and "Height"). Moreover, the relation of inherence between *moments* and *substantials* indicates that instances of *moments* (e.g., "John's weight", "Mary's height") inhere in and, hence, are existentially dependent on other *substantials* (e.g., "John", "Mary") (even if indirectly via other moments).

In such a four-category ontology, not only substantials but also moments may change qualitatively in time while keeping their identity [10]. This allows us to account for statements such as "John's weight has changed significantly since last year", and "Mary's programming knowledge is always improving".

2.2. Capabilities as Non-Substantial Particulars

We assume that *moments* encompass both what are termed *qualities* (also called "categorical" properties), e.g., the color of an eye, the atomic number of an atom, as well as what are termed *dispositions* ("powers" or "capacities") in the philosophical literature [23], e.g., the fragility of a glass, the disposition of a magnet to attract metallic material, a person's language skills [12].

We account for organizational capabilities as *dispositions*. *Dispositions* [12] are moments that may be manifested through the occurrence of events [13]. Take for example the disposition of a magnet m to attract ferrous material. The object m has this disposition even if it is never manifested, for example, because it is never close to any ferrous material. Nonetheless, m can certainly be said to possess that property, which it shares with other magnets. In its turn, a particular ferrous material also has the disposition of being attracted by magnets. Given a situation in which m is in the presence of a particular ferrous object (at a certain distance, of a certain mass, in a surface with a certain friction, etc.), the dispositions of these two entities (ferrous object, magnet) can be manifested through the occurrence of an event, namely, the movement of that object towards the magnet. In the case of capabilities of persons and organizations, the events which are the manifestations of capabilities are (complex) actions [1].

By conceiving of dispositions as moments in a four-category ontology, we recognize here both *disposition particulars* and *disposition universals*, serving as a foundation for the representation of capabilities and their types.

3. Capabilities in Defense Frameworks

In this section, we briefly present the defense frameworks we analyze in this paper, namely, DoDAF, MODAF and NAF. We focus on the fragments of the frameworks' metamodels that introduce organizational capabilities and core related constructs. We then discuss the ontology that grounds them (IDEAS).

3.1. DoDAF

The Department of Defense Architecture Framework is an Enterprise Architecture framework developed by the US Department of Defense. DoDAF 2.0 includes a Capability Viewpoint (CV), defining a capability informally as an *"ability to achieve a Desired Effect under specified standards and conditions through combinations of ways and means (activities and resources) to perform a set of activities"* [7].

A fragment of the CV metamodel with its core concepts is depicted in Figure 2, adapted from [7], following the representation conventions adopted in the original text: classes in blue represent concepts at "type level", i.e., whose instances are types, classes in orange represent concepts at "individual level", i.e., whose instance are individuals,

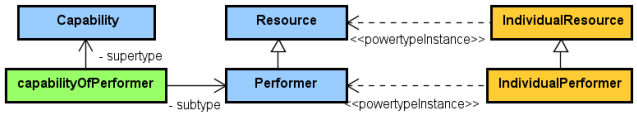

Figure 2. Fragment of the Capability Viewpoint metamodel in DoDAF.

and classes in green represent reified relations (the same conventions are used throughout this paper).

According to DoDAF, particular organizations, persons and objects are instances of *Individual Performer* (specialization of *Individual Resource*). Types capturing the general features of organizations, persons and objects that may participate in organizational activities are instances of *Performer*. *Individual Performer* is related to *Performer* in a powertype pattern [5] (instances of *Performer* are thus specializations of *Individual Performer*).

An instance of *Capability* may be related to an instance of *Performer* through the *capabilityOfPerformer* relation (reified and represented as a class). This relation represents the specialization between two types, i.e., an instance of *Performer* may specialize an instance of *Capability*. Thus, in DoDAF, instances of *Capability* are themselves types.

3.2. MODAF and NAF

The Ministry of Defence Architecture Framework (MODAF) is an enterprise architecture framework developed by the British Ministry of Defence [31]. Since it shares a common metamodel with the North Atlantic Treaty Organization Architecture Framework (NAF) [24], we present these two frameworks together. They also include the representation of capabilities, which are defined as *"a classification of some ability – and can be specified regardless of whether the enterprise is currently able to achieve it"* [31]. A fragment of this common metamodel focusing on the elements of the so-called Capability Viewpoint (CV) is depicted in Figure 3.

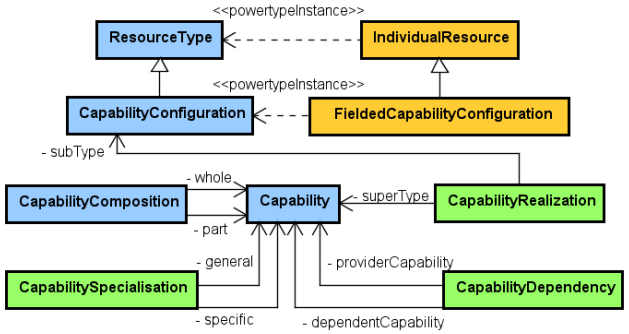

Figure 3. Fragment of the CV metamodel in MODAF and NAF.

The overall solution for capabilities is quite similar to that of DoDAF. A *Capability* is a type which may be

specialized by a specific *Capability Configuration*. A *Capability Configuration* is a *Resource Type* and is defined as *"a composite structure representing the physical and human resources that when brought together provide one or more Capabilities"* [32]. The notion of *Resource Type* in MODAF corresponds directly to *Resource* in DoDAF, despite the different naming.

Both the *Capability Configuration* concept and the *Performer* concept of DoDAF are types of entities that provide capabilities. The MODAF construct is more expressive, as it can capture an arbitrary structure of elements that interact to provide a capability (decomposition not shown in the model fragment of Figure 3). Further, differently from DoDAF, both MODAF and NAF are explicit about some other relations between capabilities, including *Capability Specialisation*, *Capability Dependency* and *Capability Composition*.

3.3. The IDEAS Ontology

The metamodels of the three defense frameworks are anchored in the same underlying foundations through the International Defence Enterprise Architecture Specification (IDEAS) ontology [15]. Here, we briefly present a relevant fragment of the IDEAS ontology, with focus on the IDEAS notion of *Property*, which is later specialized by the various frameworks to account for capabilities.

In IDEAS, instances of *Property* are types (universals) *"whose members all exhibit a common trait or feature"* [32]. *Property* specializes the notion of *Individual Type*, which is the powertype of *Individual*. Thus, instances of instances of *Property* are individuals (particulars). The type "Heavy Person" would be an example of an instance of *Property*, and specific persons (e.g., "John" and "Mary" could be examples of instances of "Heavy Person").

A *Property* in IDEAS is either: (i) a *Categorical Property*: *"a Property that is always exhibited by its instances (Individuals)"* or (ii) a *Dispositional Property* which is *"a Property whose members are Individuals that are capable to manifest a Categorical Property under certain conditions"*. Figure 4 illustrates the fragment of IDEAS that is relevant for our purposes here.

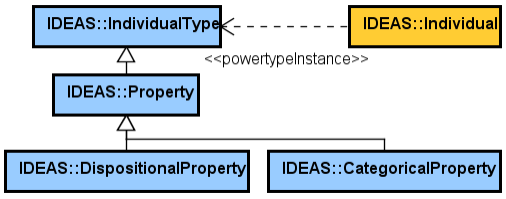

Figure 4. Key concepts in the IDEAS ontology.

IDEAS, given its historical relation to the Business Objects Reference Ontology (BORO) [15], is a perdurantist ontology, and as such, changes in individuals are explained via variation of successive temporal parts. This means that to model a qualitative change in an object, we have to consider that a new temporal part of this object appears, and then that this temporal part instantiates a different type (i.e., a different *Property*). For example, consider that we want to explain the fact that John lost 10Kg after a heavy diet. According to IDEAS, the following individual types could be admitted in this scenario: "Object Weighing 80kg", "Object Weighing 70kg" as two different types (i.e., instances of *Property*) and "Person". "John" in this scenario would be conceived as the sum of the temporal part "John weighing 80kg" (which instantiates both "Person" and "Object Weighing 80kg") and the temporal part that occurs later "John weighing 70kg" (and instantiates "Person" and "Object Weighing 70kg").

Because of this choice of foundations, IDEAS can be considered a two-category ontology (admitting only perdurant particulars and their types). All the characterizing (and accidental) features have to be accommodated in types, since particularized properties (*moments*) are not considered.

Figure 5 presents a model connecting the three defense frameworks and the IDEAS ontology, with focus only on the fundamental concepts and relations for our analysis and revision. We retain here the naming convention of MODAF for *Resource Type* (this convention seems more adequate as it clarifies that instances of *Resource Type* are types of resources), and include MODAF's *Capability Configuration* instead of DoDAF's *Performer*, as it is a more general notion. Despite the minor naming differences, this fragment is representative of the defense frameworks' support for capabilities and is assumed further in our analysis.

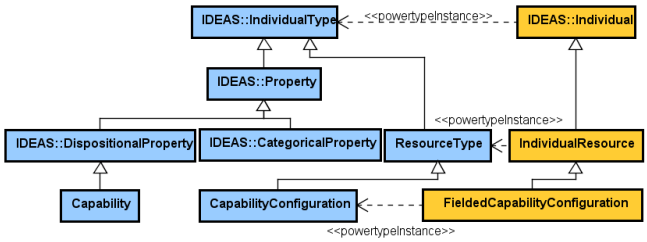

Figure 5. Fragment of the defense frameworks aligned with IDEAS.

Note in Figure 5 that all concepts of the frameworks specialize a more general concept of IDEAS, and *Capability* is a specialization of *Dispositional Property*. This means that the framework's designers have chosen to consider instances of *Capability* as types: their instances in turn are *individuals* capable of manifesting certain categorical properties in certain conditions.

3.4. Modeling Consequences

Here, we exemplify capability representation in the defense frameworks adopting the Unified Profile for DoDAF and MODAF (UPDM) specification [25]. This specification presents an abstract and concrete syntax, providing a modeling standard that supports both DoDAF and MODAF. We take an example of a "Search and Rescue" (SAR) scenario included in the specification itself (Figure 6, adapted from

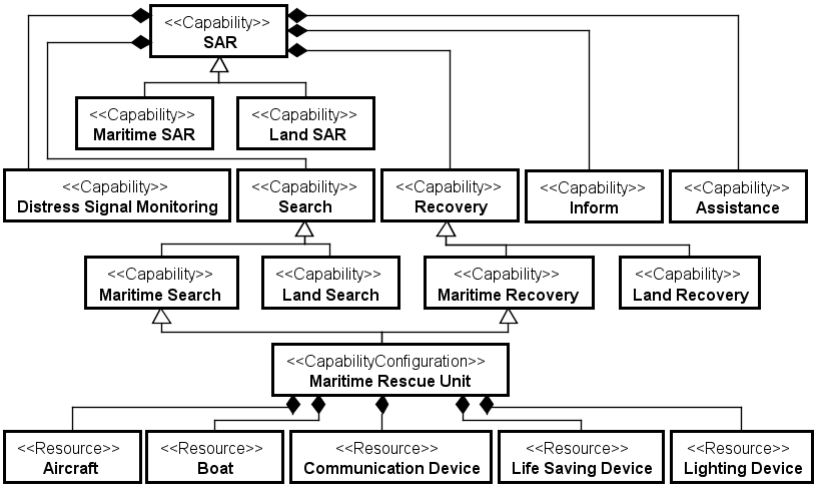

Figure 6. Search And Rescue (SAR) Example in line with the IDEAS ontology.

[25]). *Capabilities* and *Capability Configurations* are represented as classes marked with stereotypes ≪*Capability*≫ and ≪*Capability Configuration*≫ respectively.

The model represents instances of ≪*Capability*≫ named: "Search", "Maritime Search", "Recovery", "Maritime Recovery", etc. It also includes an instance of ≪*Capability Configuration*≫ named "Maritime Rescue Unit", which specializes "Maritime Search" and "Maritime Recovery". Specific instances of "Maritime Rescue Unit" (say maritime rescue unit X) are, consequently also instances of "Search", "Maritime Search", "Recovery" and "Maritime Recovery".

The model makes it plain that the classes stereotyped ≪*Capability*≫ are in fact representing *types of capable individuals*, following the framework's ontological foundations as shown in Figure 5.

Intuitively, more adequate names for the classes stereotyped ≪*Capability*≫ could be "Capable of Search", "Capable of Maritime Search", "Capable of Recovery" and "Capable of Maritime Recovery". Hence, every "Maritime Rescue Unit" is "Capable of Maritime Search" and "Capable of Maritime Recovery". While this seems to be at first glance, a mere problem of naming convention, in fact, it reveals that in these frameworks, there is no support to represent what we refer to as an *individual capability* or a *capability particular* but rather just types of capable things. In any case, even if these models were revisited with more adequate naming conventions, there would be expressiveness problems, as the capabilities themselves are never represented.

4. Four-Category Ontology to the Rescue

4.1. A Revised Metamodel

In this section, we propose improvements to the language based on the observations in the previous sections, leading to a revised metamodel of the defense frameworks. We have attempted to preserve the original concepts and relations whenever possible, while addressing the identified shortcomings. Among the improvements are: (i) the inclusion of the *substantial–non-substantial* distinction, adding new concepts and relations to improve expressiveness and (ii) changes in nomenclature (to better reflect foundational choices).

Figure 7 presents a fragment of the revised metamodel concerning *Individual Types* (a taxonomy of universals); classes in blue represent original concepts, and classes in gray represent additions. We have partitioned *Individual Types* into a hierarchy of substantial universals (starting with *Resource Type*) and a hierarchy of non-substantial universals (starting with *Particularized Property Type*). *Particularized Property Type* can be used to focus on a property of an entity (e.g., "Flying Capability", "Current Speed", "Weight"), as opposed to its *Resource Type* (e.g., "Airplane", "Person", "University"). *Quality Types* (such as "Current Speed", "Weight") characterize *Categorical Properties* and *Disposition Types* (e.g., "Vulnerability to Attack") characterize *Dispositional Properties*.

The original hierarchy of *Property-Based Individual Type* was maintained, except for the renaming of the original

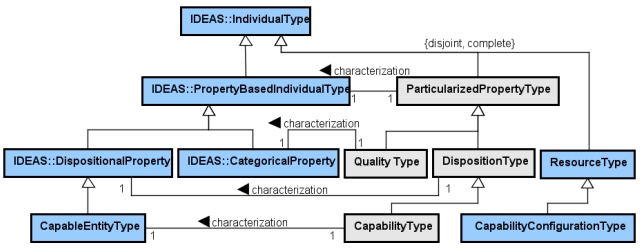

Figure 7. Fragment of the revised metamodel concerning *Individual Types*.

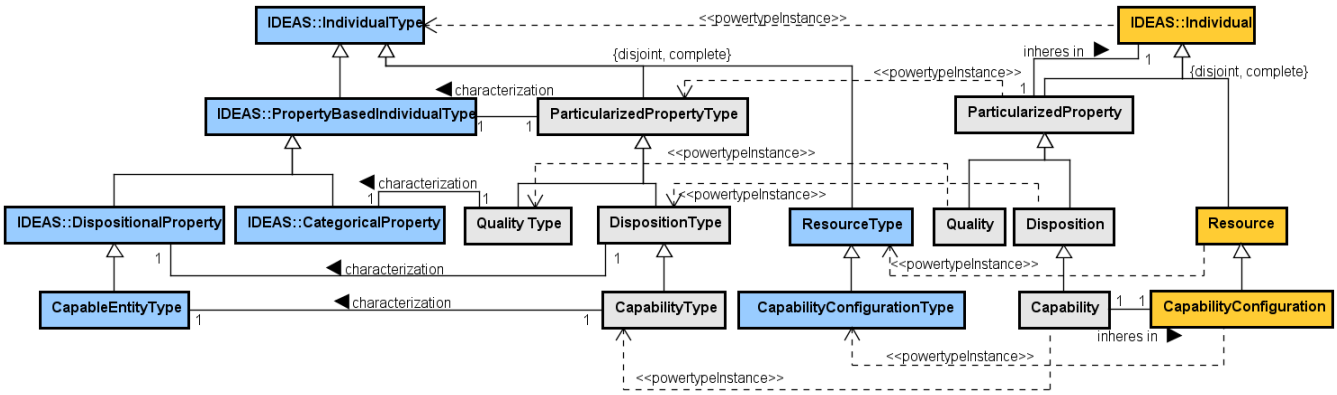

Figure 8. Revised metamodel including the taxonomy of universals and the taxonomy of individuals.

concepts. Most importantly, we propose *Property* should be renamed *Property-Based Individual Type* to clarify its standing as a universal. We propose *Capability* should be renamed *Capable Entity Type* not only to clarify its standing as a universal, but also to clarify it applies to capable entities and not to capability particulars.

Instances of *Property-Based Individual Type*, *Dispositional Property* and *Capable Entity Type* are *characterized by* instances of *Particularized Property Type*, and consequently, an instance of an instance of *Particularized Property Type* inheres in an instance of an instance of *Property-Based Individual Type*. For example, an instance of *Property-Based Individual Type* named "Capable of Flying" is characterized by an instance of *Particularized Property Type* named "Flying Capability", i.e., entities capable of flying (e.g., functioning airplanes) are characterized by their capability of flying. Therefore, for each entity capable of flying, there is a capability to fly that inheres in it.

In the revised metamodel, there are two orthogonal generalization sets specializing *Individual Types*: on the left-hand side, the original hierarchy, and on the right-hand side the introduced *non-substantial—substantial* distinction. Because they are orthogonal, a *Property-Based Individual Type* may be classified also as either *Particularized Property Type* or as *Resource Type*. This means that we are now able to make a distinction that was not possible in the previous metamodel (which we consider was *semantically overloaded*, in the technical sense of [36].)

This orthogonality means that not only *Resource Types* (e.g., "Airplane") may be characterized by a *Disposition Type* (e.g., "Passenger Carrying Capability") or a *Quality Type* (e.g., "Current Speed"), but also a *Disposition Type* (such as "Passenger Carrying Capability") may be characterized by a *Quality Type* (e.g., "Passenger Capacity"). This opens us the possibility for representing capability measurement and capability improvement over time.

The taxonomy of *Individuals* has also been adjusted accordingly. An *Individual* can be classified into either *Particularized Property* or *Resource*. A *Particularized Property* is specialized into *Quality* or *Disposition*, and the *Disposition* can be further specialized into *Capability*. A *Resource* is specialized into *Capability Configuration*. It worth to point that the Capability concept represented in the metamodel of the defense frameworks is not same of the revised metamodel, the original concept of Capability was renamed to *Capable Entity Type* and the concept of *Capability* was included to account for capability particulars.

The elements of the *Individual Type* taxonomy are related to the elements of the Individual taxonomy by the powertype modelling standard (instances of *Individual Types* are, in this way, specializations of *Individuals*). Figure 8 presents a complete view of the revised metamodel, including all concepts and relations discussed in this section.

4.2. Revisiting the Search And Rescue Scenario

In order to exemplify the usage of the revised metamodel, we revisit the SAR scenario (presented earlier in Figure 6). The following conventions are applied (see Figure 9): (i) instances of the concepts *Capable Entity Type*, *Capability Configuration Type*, *Quality Type* and *Resource Type* are represented as classes marked with the stereotypes ≪*Capable Entity*≫, ≪*Capability Configuration*≫, ≪*Quality*≫ and ≪*Resource*≫ respectively; (ii) the ≪*characterization*≫ stereotype indicates that a class is characterized by another; (iii) instance specifications (as in the UML object diagram) are used to represent particulars, and are connected to their types graphically with dashed arrows; (iv) inherence links are represented as dashed arrows from a dependent entity to its bearer.

The example reveals that ≪*characterization*≫ can be used to represent both the capabilities inhering in entities (e.g., the "Passenger Carrying Capability" of an "Airplane", the "Search Capability" of a "Capable of Searching") and the qualities inhering in capabilities (e.g., the "Passenger Capacity" of the "Passenger Carrying Capability" of an "Airplane"). In addition, "capable things" also are represented, however there is a separation between the capable object (instance of a *Resource Type*) and its capabilities. For example, the "Search and Rescue Unit" is a specialization of both the "Capable of Searching" and the "Capable of

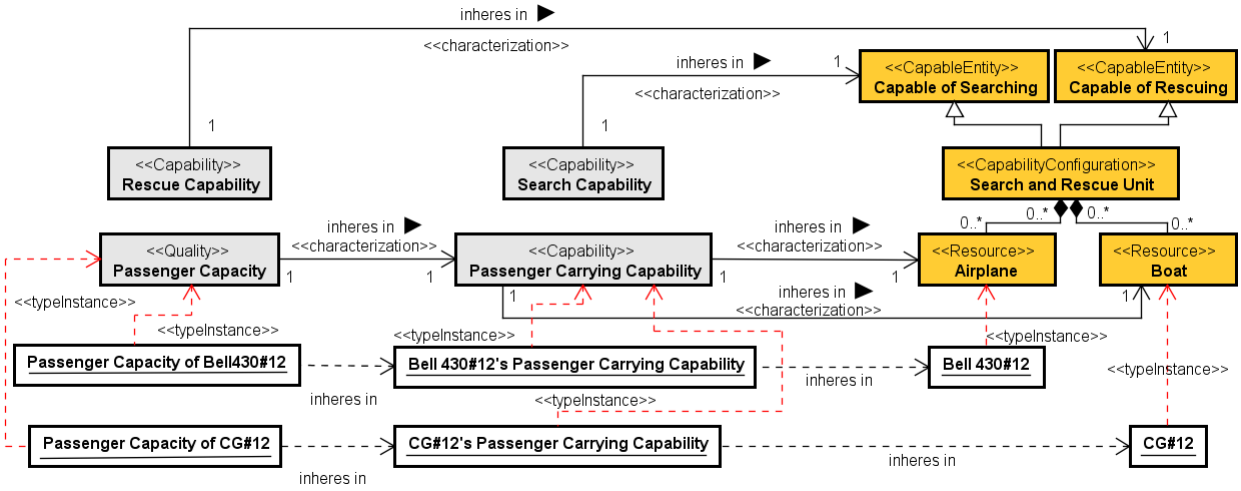

Figure 9. Revised Search-And-Rescue example in line with a Four-Category ontology.

Rescuing", which in turn are characterized by the "Search Capability" and the "Rescue Capability" respectively.

5. More Foundational Matters

So far, we have discussed the practical consequences of the revision of an important foundational choice. By considering the distinction between substantials and non-substantials, we were able to do justice to the intuition behind ordinary "capability talk" and represent capabilities, their qualities and capability types, which were not represented in the original frameworks.

Despite that, there is another foundational choice with practical consequences, and is concerned with the relation between entities and time. There are two classical views in this respect, namely "endurantism" and "perdurantism" [11].

In the *endurantist* (or 3D) view, "things as persons, rocks, and tables are three-dimensional continuants that literally persist through time in spite of the many qualitative changes that they may undergo" [33]. Endurants (or continuants) are entities that exist in time while keeping their identity, in the sense that if we say that in circumstance $c1$ an endurant e has a property $p1$ and in circumstance $c2$ the property $p2$ (possibly incompatible with $p1$), it is the very same endurant e that we refer to in each of these situations. For instance, we can say that "John" weighs 80kg at $c1$ but 68kg at $c2$. Nonetheless, we are in these two cases referring to the same endurant, namely, "John" [11]. In the 3D view, there is a distinction between endurants and the so-called perdurants (or occurrents), such as, events and actions ("things that happen to or are performed by" endurants [6]).

Opposite to the 3D view, the *perdurantist* (or 4D) view defends that all objects (including "ordinary objects such as persons, rocks, or tables") are perdurants. In the 4D view, they have spatial as well as temporal parts, or stages, and to say of such objects that they persist through time is to say that they have different parts that exist at different times. So on this view, the person in front of us now is not John in his entirety. It is only a temporal part of John, just as we are not exposed to his whole life but only to his current stage. Thus, entities that otherwise would be seen as 3D continuants are taken in a perdurantist stance as four dimensional "space-time worms" whose temporal parts are slices (snapshots) of the worm. In other words, if a perdurant p has a property x at the point in time t_1 and other property y (possibly contradictory to x) at t_2, there are tp_1 and tp_2, which are temporal parts of p, where: (i) tp_1 occurs at t_1 with property x and (ii) tp_2 occurs at t_2 with property y. Note that the complex perdurant p composed of its various temporal parts cannot be said to exhibit property x at t_1 and property y at t_2, because in this view perdurants do not change.

As we briefly pointed out earlier, IDEAS is a perdurantist ontology. This means that any change must be captured by the instantiation of a different universal. Consider, e.g., the variation in the maximum speed of an airplane. Each temporal part of the airplane instantiates different determinate universals (e.g., "Capable of Flying at Max Speed 800Km/h", "Capable of Flying at Max Speed 900Km/h", etc.) that specialize the same determinable universal ("Capable of Flying"). This would require numerous (and sometimes infinite) determinate universals, for each admissible value associated with a determinable universal (i.e., a type of capable thing). This is problematic in a representational strategy in which each universal corresponds to a type in the conceptual model.

Even after the proposed revision, this problem remains. Consider, e.g., an upgrade in "CG#12's passenger capacity". If we maintain the perdurantist stance, change in the capability would have to be modeled by admitting temporal parts of the capability associated with corresponding temporal parts of the quality that instantiates different universals. The proliferation of universals only shifted place and remains for each variation in quality ("Passenger Capacity 1", "Passenger Capacity 2", ...) IDEAS works around this problem with

the concept of "Measure" which is used to represent "the magnitude of some attribute of an individual" [8].

Despite the philosophical arguments in the philosophical literature concerning the merits of each view, we believe comparison should be subject to empirical investigation, as it concerns the cognitive aspects of a representation framework based on either view. As demonstrated in [34], the choice of an ontological paradigm can lead to significant differences in term of model comprehension and problem solving by subjects. In particular, as the author shows in that empirical study [34], the following *derivations* are warranted: (i) the paradigm underlying a 4D ontology is more difficult to comprehend than the paradigm of a 3D ontology; (ii) the notion of time is easier to comprehend with 3D ontology-driven models than with 4D ontology-driven models; (iii) the formation of relationships is easier to comprehend with 3D ontology-driven models than with 4D ontology-driven models; (iv) a deep level understanding is more rapidly attained with 3D ontologies than with 4D ontologies.

In conclusion, a broader revision of the ontological foundations may be required, admitting endurants in the foundation. If understood as an endurant, a quality changes by being associated with different values in a suitable quality space, which typically corresponds to a (complex) datatype in a representation strategy (see [11]). Since this amounts to a significant overhaul of the current foundations of existing defense frameworks, we refrain from working it out in this paper.

6. Related Work

The main goal of this article is to: (i) make explicit the ontological choices underlying the modeling of capabilities in current defense frameworks; (ii) elaborate on how these foundational choices can have important consequences from both a conceptual and practical points of view (e.g., in terms of model comprehensibility, model support for problem-solving, semantic clarity, expressiveness). In that respect, the body of work that is the closest to ours comprises exactly the DoDAF, MODAF and NAF frameworks and their grounding in terms of the IDEAS ontology. These frameworks and the subtleties of this grounding are discussed in depth in Section 3. As demonstrated here, those frameworks adopt a two-category ontology. Here, instead, we defend the use of a four-categorical approach, and demonstrate the benefits that can be attained by these frameworks if a *conservative* extension of its ontological foundations in that direction were to be adopted.

Capabilities are also addressed in a number of Enterprise Architecture (EA) approaches other than the reviewed defense frameworks. For example, in [4], TOGAF has been extended to support the modeling of the capabilities that a Business Component (BC) can perform. A BC is a business unit that encompasses a set of activities, supported by assets including people, processes and technology. The approach uses capabilities as "an idealized conceptual structure that describes what a BC can do to create value for customers". Stirna et al. [30] propose a meta-model that relates enterprise capabilities to the context of the domain, business processes and enterprise objectives. Modeling the context of the capabilities of the enterprise enables the design of adjustable services that can adapt to changes in parameters of the capability context. Iacob et al. [14] propose the Business Strategy and Valuation Concepts (BSVC) extension to the ArchiMate metamodel with the notion of capabilities, resources, competencies and value to enable the alignment of business strategy, EA and portfolio management.

Despite the support for the representation of capabilities in these EA approaches, the lack of a precise conceptualization for the capability notion may lead to some problems. In particular, the definitions for capabilities and capability-related constructs provided in these approaches could remain unclear and conflicting usage may arise as a consequence. Among the three works presented above, only the last was subject of an ontological analysis, performed in [3]. The concepts of the BSVC extension of ArchiMate have been analyzed and some issues were identified in the original proposal conceptualization of resource, capability and competence concepts. The capability conceptualization adopted by the authors in the analysis was focused on explaining its properties, such as that: capabilities are only manifested in particular situations; they can also fail to be manifested; when manifested, they are manifested through the occurrence of events. UFO was used as semantic foundation in their ontological analysis and, some problems identified by their analysis were revealed exactly because of its four-category stance. For example, there is, in BSVC, neither support for the representation of quality types (e.g., "Weight") characterizing resources (a kind of Substantial, such as, "Airplane"), nor for the representation of capability types[1] (e.g., "Search Capability") characterizing structure elements (a Substantial, such as, "Search and Rescue Unit"). It is worth to point that the relations between capabilities and resources were also a focus of that work.

Lastly, the foundational ontology BFO also incorporates the distinctions of four-category ontologies, and it is plausible to suggest that an analysis based on BFO could also have revealed the issues in these defense frameworks. BFO includes a notion of "realizable entity" [2], which is similar to the notion of disposition in UFO. For example, by doing that, BFO also supports the explicit modeling of changes in the capability itself (and not only variations of temporal parts of the capable thing). Unlike in UFO, however, in BFO any change in a capability is modeled as an instantiation of a different determinate universal for the same determinable. This leads to the modeling challenges that we have previously discussed, i.e., the proliferation of a multitude of (possibly infinite) universals.

1. We should clarify that ArchiMate lacks in general a clear distinction between universals and individuals, and, hence, one could use the capability construct to represent either a capability type or a capability (individual). This is in any case a problem of construct overload [36], which results in ambiguous models.

7. Final Considerations

The importance of capabilities for portfolio management and business strategy has been recognized both in literature and practice. Capability-based theories have been commonly employed to identify existing and required capabilities, to support capability improvement, to enable the planning of acquisition of new capabilities, etc. In defense portfolio management, the notion of capability is included in a number of Enterprise Architecture (EA) approaches, including DoDAF, MODAF and NAF, albeit not without conceptual problems. In this paper, we have presented an ontological analysis of capability-related concepts in three enterprise architecture (EA) frameworks for the defense domain (DODAF, MODAF and NAF).

We have been concerned here with the merits of ontological theories as a basis for conceptual modeling and knowledge representation in enterprise architecture frameworks and tools. The choices involved in these alternative theories have ontological and cognitive consequences. For example, as discussed in [11], there is solid evidence for *particularized properties* in the literature. On one hand, in the analysis of the content of perception [19], moments (dependent individuals) (e.g., individual colors, tastes, symptoms) are the immediate objects of everyday perception. However, the impact of these choices are not only conceptual in nature, but have practical consequences for the use of metamodels and languages that embody the conceptual choices.

Our main aim has been to clarify the concepts and relations presented in the defense EA frameworks and the IDEAS ontology, and to reveal shortcomings in the usage of the metamodel of the three defense EA frameworks. The identified issues can be summarized as follows: (i) capability particulars are never represented (only types of capable things), which inhibits the explicit representation of properties of capabilities (e.g., maximum flight speed, freight carrying capacity), capability measurement and capability improvement over time; (ii) the terminology and naming conventions used in example diagrams differ from the underlying formal account of capabilities as types of capable things, suggesting problems in real-world usage that arise from a lack of clarity; (iii) the *Property* concept does not distinguish between substantials and non-substantials, ultimately disregarding the latter; (iv) qualitative changes in entities can only be modelled by means of its temporal parts, with an instantiation of numerous (and, sometimes, infinities) universals, resulting in a less parsimonious representation in contrast with the endurantist view (or appealing instead to the notion of "measurement").

We have observed that the original formal notion of a capability as a *type of individual that is capable* is at odds with the informal definition for capability provided in the DoDAF specification, which defines capability as the "ability to achieve a Desired Effect [...]" [7]. In order to match the foundational choice in the IDEAS ontology, the text would have to refer instead to *types of resources able to achieve a desired effect*.

This paper significantly revises our previous work [22] by re-examining the defense framework's metamodels in light of a four-category ontology and by extending that previous work with a revision of the frameworks' metamodels. The revised version of the metamodel based on a four-category foundation, is aimed at improving the framework's clarity and expressiveness. The resulting metamodel was applied to the Search And Rescue scenarios, showing the applicability of the new constructs and relations, especially to represent capabilities inhering in entities, properties inhering in capabilities of entities and "capable things" with a separation of the entities and their capabilities.

Finally, in line with our discussion in Section 5, in a future work, we intended to propose a fuller revision of the ontological foundations of capability modeling in defense frameworks. We intend to advance an approach that combines the advantages of a *four-categorical view*, with the ones of an *endurantist view*.

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