An Ontological Foundation for Conceptual Modeling Datatypes based on Semantic Reference Spaces

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***Abstract*—Traditionally, instances of attributes in conceptual modeling languages are associated to values like "1,86", "small" or "John". But what do such values mean? What is the real-world semantics behind these attributes and their values? An approach to improve the semantics of conceptual modeling languages is to ground them on ontological theories. Following this strategy, over the last decade, the foundational ontology UFO has been applied to create the OntoUML modeling language, an ontologically well founded version of UML. In the current work we present extensions to UFO in order to improve the ontological foundations concerning value spaces by employing the notion Semantic Reference Spaces. A concrete application of this theory is presented, applying the proposed UFO extensions to ground an ontologically founded version of (Onto)UML Datatype classes. A prototype editor of the proposed extension to OntoUML is also presented in order to illustrate the applicability of the ideas discussed here.**

Keywords—Ontological Foundations; Conceptual Modeling; Datatypes; Reference Spaces; Conceptual Spaces

I. Introduction

Conceptual modeling is the activity that aims at capturing the essence of a particular domain of reality for the purpose of understanding and communication. In order to support conceptual modeling, languages like UML and ER are used, originating artifacts known as conceptual models. A major problem related with these languages, particularly with UML is that they are software oriented, i.e., closer to implementation in software and not expressive enough to fully capture the required knowledge about the domain.

An approach that attempts to improve the semantics of conceptual modeling languages consists in using ontological[1] principles as rules and guidelines to model real world domains [1, 2]. Another approach in the same direction but more tied to ontological theories consists in grounding modeling primitives directly in ontological concepts. With the later goal in mind, in a long term research program, the Unified Foundation Ontology (UFO) has been employed for the evaluation and re-design of UML, originating the OntoUML modeling language [3]. OntoUML is an extension of UML and incorporates some of the UFO axioms as syntactic constraints in its metamodel. An important advantage of such an approach consists in enabling modeling tools to develop functionalities for model checking and validation against syntactic errors [4], simulation of model instances [5, 6] and the application of ontological design patterns as modeling primitives [7], resulting in models with higher *domain appropriateness*, i.e., faithfulness w.r.t. the intended conceptualization of domain being modeled. The systematic use of these modeling tools can support the engineering of conceptual models in a way that the only possible instances of the produced models are the ones that represent ontologically admissible state of affairs [5]. Over the years, OntoUML has been successfully employed in a number of industrial projects in several different domains, ranging from Petroleum and Gas [8] to News Information Management [9]. In fact, recently, it has been considered as a possible candidate for contributing to the OMG SIMF (Semantic Information Model Federation) standardization *request for proposal* [10] after a significant number of successful applications in real-world engineering settings [11].

Although UFO provides foundations for classes, relations, weak entities, attributes and value spaces in OntoUML, the ontological distinctions concerning the semantics of value or Datatype based attributes can be improved. Currently, the ontological counterpart of value based attributes (termed quality, detailed in the next sections) is not explicitely present in the syntax of OntoUML and, differently from other UFO concepts, the axiomatic concerning value spaces is not present either. Basically, OntoUML has its core constructs grounded in UFO but it relies in the same infrastructure of software oriented modeling for representing qualities and their value spaces, namely attribute functions and Datatypes. We advocate that the concept of quality should be explicitly present in OntoUML and the semantics behind its value spaces made clear. These distinctions have a positive impact on the modeling language since they can be used to enrich the semantics of other language constructs. Once the semantics behind qualities, its values and value spaces in OntoUML is made explicit, it is possible to compare qualities, constrain formal relations based on the poperties of the value space (e.g., *John being-older-than Peter*), establish mappings of values among different value spaces and calculate similarity among entities based on their qualities.

Another point addressed in our research consists in properly referencing the values of qualities. In order to be communicated, values of qualities need to be referred by lexical elements like "1,86" and "small". But these lexical

[1] In this context, Ontology should be interpreted as a philosophical theory that aims to explain a system of categories and their ties underlying a system of representations.

elements alone have little or no meaning; they need to have their meaning grounded somewhere else. The Semantic Reference Spaces theory proposed by Probst [12] offers a framework for dealing with what is known as the symbol grounding problem [13], i.e., assigning meaning to symbols. As discussed in [12], the lack of proper grounding for these quality values is a major source of semantic interoperability problems. We consider the application of the semantic reference spaces theory as a mean to refer to quality values and at the same time to give an ontological interpretation to standard UML Datatypes, which are currently used in OntoUML to represent value spaces.

In this paper we continue the work started in UFO towards the ontological foundation of qualities and extend these new ontological commitments and axioms to OntoUML. Our ultimate goal is to improve the distinctions in OntoUML concerning value spaces in such a way that: a) OntoUML is free from a purely software oriented infrastructure concerning value spaces for qualities; b) allowing the modeler to better model and constrain the value spaces for the qualities being modeled. This paper is structured as follows: in section II, we review some of the core concepts of UFO and the Semantic Reference Spaces theory, contextualizing the work for the discussions in the sections that follow. In section III, we present extensions to some key categories of UFO and introduce new categories that are needed for enriching the semantics of value spaces. In section IV, we present the case study concerning the application of the proposed extensions to create an ontologically well founded version of Datatypes in OntoUML. Also in session IV the prototype of an integrated editor for OntoUML is presented to illustrate the applicability of the ideas discussed here to support conceptual modeling. In session V, we compare our work to similar approaches and, in session VI, we conclude this work, considering future research directions.

II. BACKGROUND

The Unified Foundation Ontology (UFO) offers an ontological framework based in philosophical, psychological and cognitive theories that can be used to design and evaluate conceptual modeling languages, according to an ontological world view. UFO provides a category system that reflects nuances of reality such as principle of identity, properties, part-whole relations, different modes of dependence and modality that are hardly made explicit in the semantics of conceptual modeling languages like UML, ER and OWL [3]. The core of UFO can be exemplified by the so-called *Aristotelian Square* (Fig. 1), also known as the four category ontology, where there are *Object Universals, Objects, Moment Universals and Moments*.

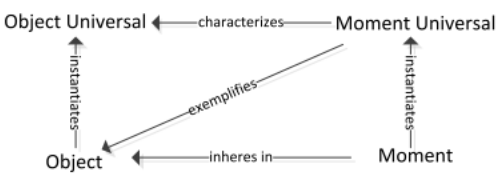

Fig. 1. The four category ontology

A fundamental distinction in this ontology is between the categories of Individual and Universal. Individuals are entities that exist in reality possessing a unique identity. Universals, conversely, are pattern of features which can be realized in a number of different individuals. The word Moment is derived from the german Momente in the writings of E. Husserl and it denotes, in general terms, what is sometimes named trope, abstract particular, individual accident, property instance.Thus, in the scope of this work, the term bears no relation to the notion of time instant in colloquial language. Typical examples of moments are: a color, a connection, an electric charge, a social commitment. An important feature that characterizes all moments is that they can only exist in other particulars (in the way in which, for example, electrical charge can exist only in some conductor). To put it more technically, we say that moments are existentially dependent on other individuals (named their bearers). Examples of objects include ordinary entities of everyday experience such as an individual person, a dog, a house, a hammer, a car, Alan Turing and The Rolling Stones but also the so-called Fiat Objects such as the North-Sea and its proper-parts and a non-smoking area of a restaurant. In contrast with moments, objects are existentially dependent entities.

Moments are further categorized in Qualities and Modes. Qualities are objectification of object properties which can be directly evaluated (projected) into a certain value space (depending on the type of quality, i.e., on the quality universal). Examples of qualities include mass, height, electric charge and color. An important aspect of qualities is that they can (as much as objects) endur maintaining their identity even through qualitative changes. For example, when state that the color of an apple is changing, we do not mean that red is changing. From a cognitive perspective, we countenance the existence of an entity which is existentially dependent on that apple and which can qualitatively change from greenish to reddish and then to brownish, while maintaining its identity. In contrast to qualities, Modes are moments which cannot be directly evaluated in terms of single value space. Examples of modes include beliefs, intentions, goals and dispositions (e.g., the disposition of a magnet to attract electric material).

Quality universals are always associated with value spaces or quality structures that can be understood as the set of all possible regions[2] that delimits the space of values that can be associated to a particular quality universal. Moreover, quality structures can provide ordering for these values, allowing the comparison of qualities associated with the same or equivalent quality structures. For example the height quality universal can be associated with a quality structure isomorphic to the positive halfline of real numbers, thus, defining the set of all possible values for particular heights. Making qualities comparable is a requirement for the establishment of formal relations that are based in the entities' qualities like *older-*

[2] In the literature is common to use the term magnitude to refer to the quality intensity or amount in some object. We use the term region instead of magnitude at this point in order to allow a more general definition, since we consider that there are qualities that cannot be associated with magnitudes but can be associated with regions in an abstract quality structure.

than(John, Peter), *heavier-than(John, Mary)* and determining equivalence between qualities like *same-as(color1, color2)*.

The definition of quality structures in UFO was motivated by the theory of Conceptual Spaces introduced by Gärdenfors [14], which offers a framework to represent knowledge about perceivable or conceivable qualities such as color, height, temperature and currency value. The cornerstone of Conceptual Space theory is the notion of quality dimension. According to Gärdenfors, conceptual spaces are sets of quality dimensions that can be integral or separable from each other. Quality dimensions are integral w.r.t. others when a particular quality cannot be associated to a region in one quality dimension without associating with a region in the other. Quality domains then can be defined as a "set of integral dimensions separable from all the other" [14], therefore constituting geometrical structures. Mass and temperature are quality universals that can be structured by separable quality dimensions, while color (HSB) and volume can be structured by three-dimensional quality domains. UFO introduces the category quality structure as a general category to the categories quality dimension and quality domain.

The percept of a quality is referred in the literature as quale [3, 12, 16, 17]. Originally, the term quale refers to the percept or mental state that is evoked in cognitive agents while observing some particular quality. Thus, qualia are by nature intrinsic to (the minds of) cognitive agents and therefore cannot be shared. In order to be communicated qualia needs to be approximated and then referred by symbols like "1m", "40ºC" or "Crimson Red". As perception is only possible on the magnitudes of substantial qualities like color and height, we use the term quale also to denote the "conceived value" of abstract qualities like currency value and name.

Probst [12] proposes the theory of Semantic Reference Spaces, which separates the value space of quality universals (quality spaces) and the qualia of particular qualities from what is actually referred by lexical representations. According to Probst, after the definition of a quality space, and thus the set possible qualia for particular qualities, it is necessary to partition the quality space for the purposes of approximation and communication of qualia. The partitioning of quality spaces is done using a chosen magnitude as unit of measure. A magnitude is understood as an atomic or absolute quality region, part of the quality structure to be partitioned. After the partitioning, the resulting quality structure is composed by many nonatomic quality regions that group the magnitudes.

Approximation is needed because the exact magnitudes of qualities as they occur in nature are impossible to be captured, even by using the most precise measurement instruments [12]. The same principle applies for perceived or conceived qualia in the minds of cognitive agents. That means one could not know the exact height of a person, but only an approximation or the nonatomic quality region where the quale is located, which can be more or less accurate depending on the partitioning of the quality structure. The same quality structure can be partitioned in many ways, originating many scales. For instance, the quality dimension of height can be partitioned into feet, inches, meters and centimeters and so on. Once partitioned, quality structures are referred by isomorphic structures named Reference Spaces. Reference Spaces are composed by reference regions that are grounded by the (nonatomic) quality regions of the quality space being referred. Lexical elements are used to denote these reference regions, enabling communication of approximated qualia. Notice that different lexical elements can be employed to denote the same quality region, that is, one could use "2", "two", "二"[3] or "II" to refer to the same quality region. An example of reference space for the height quality spaces is shown in Fig 2. In Fig. 2 we use as unit of measure the "a" to illustrate that the partitioning is totally conventional, that is, one could create his own personal reference space, based on his particular unit of measurement.

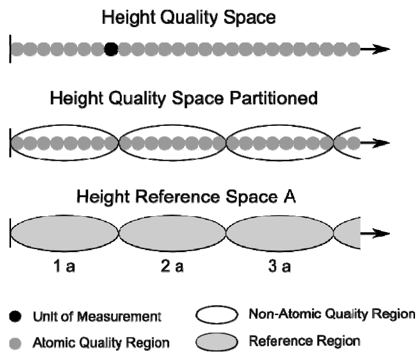

Fig. 2. Example of Reference Space

The classification of Reference Spaces is inspired by Stevens' theory of scales of measurement [20] that separates measurement scales into ordinal, interval, ratio and nominal. According to Stevens, an ordinal scale "arises from the operation of rank-ordering" and allow the definition of relations such as greater and less. An example of such scale would be the scale {tiny < small < medium < big} for the size of apples. Probst points out that these values of ordinal scales are grounded by quality regions that do not need to be of the same "length"; therefore the role of a unit of measurement is not useful in this case. Conversely, in interval scales, all quality regions have the same length, defined according to magnitude as a unit of measure. Examples of interval based scales are the Centigrade and Fahrenheit scales of temperature. In this type of scale is possible to determinate the relations of equality among scales' intervals and rank-ordering operations. Ratio scales are scales that employ a mechanism of a constant for transforming its values, for instance, inches to feet. Nominal scales are used for labeling values uniquely and are not considered as a reference spaces in the semantic reference spaces theory.

As presented in [3], formal relations are binary relations based on entities' qualities that take place as soon as both entities exist and are extinguished if one of the entities is extinguished. For instance the formal relation *older-than(Jonah, Peter)* which is based on the entities' age may hold as soon as the the entities exist and Peter has indeed a higher age than Jonah. Therefore, the operations supported by

[3] Japanese kanji for the number two.

the measurement scale constrain the possible formal relations that can be established between entities, as shown in table I:

TABLE I. OPERATIONS AND FORMAL RELATIONS

Scale	Operations	Sample Formal Relations
Ordinal	rank-order	harder-than(Quartz, Diamond)
Interval	equality of intervals	hotter-than(Canada, Brazil)
Ratio	equality of ratios	heavier-than(Aluminium, Iron)
Nominal	equality	namesake-of(Josh P., Josh C.)

Guizzardi [3] argues that quality dimensions do not need to be dense sets or even ordered, since they can be just a set of conceivable or perceivable values for individual qualities such as color {red, yellow, orange, blue, green, white, black}. Conversely, in the semantic reference spaces theory it is argued that the most prominent feature of a quality space is to impose an order to the set of quality regions. In other words, it would not make sense to have an unordered quality space. In his work, Probst provides foundations for observations and measurements of physical qualities. According to this theory the ordering of quality spaces is made possible by the presence of magnitudes. Although there is an axiom that states that magnitudes are only present in physical quality spaces, this notion of ordering appears to be extended to abstract quality spaces which have no magnitudes (like the quality space of currency value) and therefore can have infinite inner quality regions.

III. EXTENDING ONTOUML TOWARDS QUALITIES AND SEMANTIC REFERENCE SPACES

In this section we present part of our contribuitions concerning the foundation of values spaces (quality structures) in UFO. Some categories of UFO such as Quality Universal and Quality Structure are revisited and extended, while the inclusion of other categories like Quality Region, Reference Structure and Reference Region are considered. We discuss and formalize the distinctions made when convenient, in order to improve readability.

A. Quality Universals

The first distinction concerning quality universals is based on their nature. We refer to the quality universals which can be objectively measured (i.e. its instances located in a region of a quality structure by cognitive agents and measurement devices) as Measurable Quality Universals. It is possible to establish distances or metrics among these quality regions. Examples of measurement quality universals include length, height, temperature, electrical charge and time. This is the notion of quality universal as initially considered by Guizzardi and Probst. Other property universals such as name, national security number and zip code that are based on social conventions can be located at regions in abstract quality structures. The regions of such abstract structures can be referred and denoted by lexical elements composed by alphanumeric characters following specific composition rules. In this case, the region associated with the quality is considered a noun, characterizing a Nominal Quality Universal. We consider nouns to be qualities, since they can be objectively referred and evaluated, change their "value" while still being a noun and have its semantic value referred by many reference structures. At this time, due to scope limitations we will not go further in the investigation of nominal quality universals. Hence, apart from the original definition within UFO, we divide the Quality Universal category into Measurable Quality Universal and Nominal Quality Universal.

Measurable quality universals are further categorized with respect the capability of being directly perceivable by cognitive agents and measured by measurement devices. Some qualities, generally from physical objects like color, length and weight are directly perceivable by sensorial apparatus, while others like currency value are not. Since nouns are not directly perceived (but only through descriptions and verbalizations), we consider all nominal quality universals to be nonperceivable, thus introducing the categories Perceivable Quality Universal and NonPerceivable Quality Universal as subcategories of Measurable Quality Universal only. The resulting taxonomy of quality universals can be seen in Fig. 3:

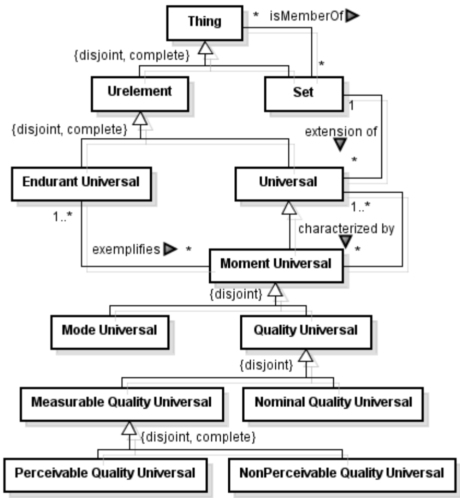

Fig. 3. The extended taxonomy of quality universals

Due to space limitations, we omit here the formalization for these categories in UFO. Since the taxonomy of particular qualities is isomorphic to the taxonomy of quality universals and there are no new distictions concerning particular qualities, we propositally avoid discussing particular qualities at this point. Although the exhaustively definition of taxonomy of quality universals is out of the scope of this work, we believe that for a foundational ontology like UFO proposed to ground conceptual modeling languages, it is important to take into account some basic types of quality that are recurrent in many domains of reality like the ones exemplified here.

B. Quality Structures

Quality universals are always associated to at least one quality structure, which comprehends all possible qualia of particular qualities. This notion is captured in (1) (in which the symbol :: is used to represent the relation of instantiation):

$$\forall u \left(u :: QUniv \rightarrow \exists s \left(s :: QStruct \wedge structures(u, s) \right) \right) \quad (1)$$

We redefine the original categorization within UFO for quality structures considering the nature of the quality universal that it structures, therefore dividing the category Quality Structure into Measurement Quality Structure and Nominal Quality Structure. A measurable quality universal can only be structured by measurement quality structures and nominal quality universals by nominal quality structures. Measurement quality structures are further classified based on the number of its dimensions: the categories Measurement Quality Dimension represent the most elementary, one-dimensional quality structure. In contrast, Measurement Quality Domain represents n-dimensional quality structures. As we do not investigate the nature of nominal quality universals in this work, we do not further classify nominal quality structures.

With respect to the boundaries of measurement quality dimensions, we follow the distinctions proposed by Probst [12] that quality dimensions can have one, two or no boundaries. According to Probst, the boundaries of a quality dimension can be specified by determining its first and last regions. A one-boundary quality dimension has either a first or last region. Examples of one-boundary dimensions are mass and volume, which has a first boundary usually denoted by the number zero. A two-boundary or circular quality dimension has both first and last regions specified; examples of such dimensions are direction and hue (from the HSB color spindle). Finally, the nonboundary quality dimensions have no such limitations, for example, abstract time [12]. We also follow the distinction proposed by Probst with respect to classification of measurement quality domains with respect to the theory used to conceptualize the quality domain. We distinguish the quality domains based on cognitive theories from the quality domains based on scientific theories, therefore creating the categories Cognitive Measurement Domain and Scientific Measurement Domains as subcategory of Measurement Quality Domain. Scientific measurement domains are composed following some kind of algebra, and the practical difference between these two categories is that regions from scientific domains can be quantitatively evaluated and ordered, while cognitive quality domains cannot. We do not further classify scientific quality domains with respect to the arithmetic involved in the composition of the domains as [12]. We consider that measurement quality domains are composed only by quality dimensions and therefore it is not possible to have a recursive tree of quality structures, justifying the need of specialized quality structures by arithmetic operation, such as addition, multiplication and so on [12]. Taking for example the scientific quality structure for the body mass indicator (BMI), which is composed using the dimensions weight and height (BMI = weight / (height x height)), in our approach there would be only one domain with two dimensions and an arithmetic formula that relates them. The specification of the infrastructure needed in order to the use of arithmetic formulas is delegated to the modeling language which employs this framework.

We make explicit the *structuration* relationship between quality universal and quality structures since, in the current work, we consider possible that a quality universal can be structured by many different quality structures. This distinction is necessary in order to allow the conciliation of different conceptualizations regarding the structure of quality universals. For example, one could conceptualize the color quality structure under the HSB theory. However, one could alternatively consider the RGB theory or a monochromatic scale. In any case, all these theories offer different ways to approximate the same qualia. We argue that quality structures that have more dimensions are able to capture more nuances of the qualia. This notion conforms to Gärdenfors' principle that one could expand its knowledge about already known concepts by adding new quality dimensions. An illustration of this situation would be using the color scale RGB to approximate qualia of particular color qualities and then switching to RGBA color scale wich offers a new dimension that captures the alpha making the color more or less translucent. A restriction imposed by allowing quality universals to be structured by more than one quality structure is the assumption that all quality structures associated to a quality universal are compatible, i.e., it is possible to establish equivalence relations among the regions of these structures, even when those relations are not made explicit a priori. Another restriction imposed is that these structures should be of the same ontological nature, for example a measurable quality universal can be structured by a number of different measurable quality structures but not nominal quality structures.

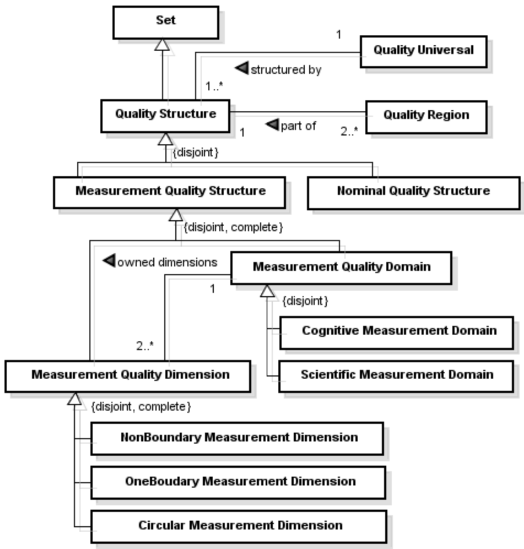

Fig. 4. The extended taxonomy of quality structures

In UFO [3] and Probst [12], quality universals associated to onedimensional quality structures are considerated simple quality universals whereas quality universals associated to n-dimensional quality structures are considered composed quality universals, having indirect simple qualities. As seen in this section a quality universal can be structured by many quality structures (with a different number of dimensions). Thus, we do not enforce the simple vs. composed classification, although the notion behind these distictions remains valid. In other words, particular qualities associated to n-dimensional structures (e.g., HSB color scale) bear some indirect (simple) qualities for each owned quality dimension (e.g., qualities for hue, saturation and brightness). Fig. 4 depicts the extended taxonomy of quality structures.

C. *Quality Regions*

As previously seen, the qualia of particular qualities cannot be directly shared; they need to be approximated and referred by lexical symbols. The quality structures conceived as the value space for quality universals are composed by a number of inner regions, which the qualia of particular qualities are located at by the process of approximation. We introduce the category Quality Region in UFO to denote the regions that approximate qualia for the purpose of reference and communication. In this way, qualia are explicitly separated from what is being referred and communicated about the particular qualities (i.e., the quality regions which approximate the qualia). At the same time, the meaning of lexical elements like "1,86", "small" or "John" is grounded by the quality regions they denote.

$$\forall s(s :: QStruct \rightarrow \exists r(r :: QReg \wedge part\_of(s,r))) \quad (2)$$

$$\forall r(r :: QReg \leftrightarrow \exists s(s :: QStruct \wedge part\_of(s,r))) \quad (3)$$

$$\forall q \left(q :: Quale \leftrightarrow \exists r(r :: QReg \wedge approxim(q,r)\right) \quad (4)$$

We further classify quality regions with respect to the nature of its parent quality structure. The category Measurement Quality Region is introduced to denote the regions that are located inside a measurement quality structure and Nominal Quality Region to denote regions located inside a nominal quality structure. Measurement quality regions are in turn classified into Basic Measurement Quality Regions and Composed Measurement Quality Regions according to the number of dimensions of its parent structure. Basic measurement quality regions are part of measurement quality dimensions, while composed measurement quality regions are part of measurement quality domains.

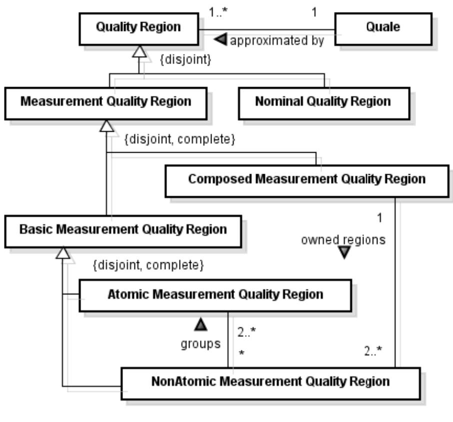

Fig. 5. The proposed taxonomy of quality regions

Basic measurement quality regions are in turn classified into Atomic Measurement Quality Regions and NonAtomic Measurement Quality Regions. Atomic regions can be seen as the absolute magnitudes of qualities that are no further composed by smaller quality regions. Such regions are only present in the measurement structures of perceivable quality universals like length and temperature and are theoretically impossible to be directly captured and shared. Nonatomic measurement regions are composed by smaller regions in the same measurement dimension, which can be in turn either atomic or nonatomic.

Composed measurement quality regions have as parts nonatomic regions, member of the different measurement dimensions that belong to a measurement domain. The structure of quality regions is depicted in Fig. 5.

Apart from the original concept of equivalence in set theory, we consider two quality regions (even on different quality structures) to be equivalent iff the same qualia are approximated by both regions. Following this distinction, one could say that the color red in RGB {Red = 255, Green = 0, Blue = 0} is equivalent to the color red in HSB {Hue = 0, Saturarion = 100, Brightness = 100} because these quality regions approximate[4] the same quale. We formalize this distinction as follows:

$$\forall r1, r2\ (r1: QReg \wedge r2 :: QReg) \rightarrow ((r1 = r2) \leftrightarrow (\forall q\ q :: Quale\ (approxim(q,r1) \leftrightarrow approxim(q,r2))) \quad (5)$$

Gardenförs points out that it is possible to have unordered quality structures like sets of named values e.g. {red, blue, orange, yellow, green, white, black} for the purpose of dividing objects into disjoint classes. Although the specification of a closed set of named values is useful in conceptual modeling languages, according to the notions discussed here it would have no ontological meaning without grounding the values onto quality regions. One could consider formally specifying the meta-properties of these values spaces like symmetry, transitivity and reflexivity in order to make possible to establish ordering or even the relations among its values (e.g. complementary-colors(orange, green) or brighter-than(white, black)) [18]. Although this would be a more flexible approach, it might not be useful or even practical, since the mapping among reference systems pose a major challenge [19] and would require some form of grounding of the named value. For instance, one could want to map the value space {light, medium, heavy} of possible weights of apples to a measurement structure based on the kilogram system, in order to enable the automatic classification of apples measured by a scale in kilograms. Yet, for the mapping to occur, one would have to ground the named values on magnitudes of the weight quality structure, perhaps defining samples or prototypes for each named value [14]. Therefore we follow the approach of Probst concerning the ordering of quality structures, namely, instead of formally specifying the meta-properties of quality structures, we assume that this ordering emerges naturally from the magnitudes and quality regions that compose the quality structure. We justify these choices based on the following reasons: a) foundational ontologies such as UFO aim to provide a category system that relies on real world to provide its semantics. Making use of magnitudes (real world entities) to order the quality structure

[4] Note however, that this is an initial notion of equivalence considering the principles discussed in this work. This notion should further elaborated in future work.

is an approach more intuitive and tied to the real world. b) Concerning the use of such distinctions in OntoUML, we believe that the formal specification of meta-properties of quality structures would not have practical use yet.

D. Reference Structures and Reference Regions

In order to allow quality regions to be associated to lexical elements like “1,86”, “small” or “John” we introduce the categories reference region and reference structure, in analogy to Probst’s categories with the same name [12]. Reference structures can be defined as sets of reference regions which are grounded by quality regions. Other possible interpretation for reference structures is seeing them as scales for qualities. Reference regions are the link between quality regions and lexical elements, allowing the communication about qualia approximated by the quality regions. The categories Reference Structure (RStruct), Reference Region (RReg), Lexical Symbol (LSym) are formalized in the following:

$$\forall s \left(s :: RStruct \rightarrow \exists r \big(r :: RReg \wedge part\_of(s,r) \big) \right) \tag{6}$$

$$\forall r (r :: RReg \leftrightarrow \exists s (s :: RStruct \wedge part\_of(s,r))) \tag{7}$$

$$\forall r \begin{pmatrix} r :: RReg \rightarrow \exists q \big(q :: QReg \wedge grounds(r,q) \big) \\ \wedge \exists l \big(LSym(l) \wedge denotes(r,l) \big) \end{pmatrix} \tag{8}$$

We distinguish the reference structures and reference regions according to the quality structure which they are associated to. This gives rise to the categories Measurement Reference Structure, Measurement Reference Region, Nominal Reference Structure and Nominal Reference Region. This distinction is motivated by the nature of the reference spaces: measurement reference spaces are often denoted by a set of symbols, e.g. {1, 2, 3, 4, 5, 6, 7, 8, 9, 0} or {I, V, X, L, C, D, M} and specific composition rules to form the lexical elements that denote quality regions. A single measurement quality structure can be partitionated in many ways, therefore originating different scales, e.g. time in days, hours and minutes. Nominal reference spaces are similar in the sense of having a set of symbols like the English alphabet, but differ in the composition rules of lexical elements and in the operations. In other words, measurement reference structures act like scales grounded by quality structures while nominal reference regions only pose as naming structures. We do not further investigate lexical elements in this work, although it is assumed that every reference structure follows some rule for denoting its reference regions by lexical elements.

Since reference structures are isomorphic to quality structures (that is, has the same number of dimensions and its reference regions have the same length of the of the associated quality structure), we further classify measurement reference structures with base on the number of dimensions of the quality structure they are associated with. This gives rise to the categories Measurement Reference Dimension a Measurement Reference Domain. The same principle is applied to reference regions, although we consider only nonatomic quality regions for the purpose of reference, therefore originating the categories. Measurement reference structures are also classified based on the relations that can take place in the reference structure, considering Stevens’ work. The categories Ordinal Measurement Reference Dimension, Interval Measurement Reference Dimension and Rational Measurement Reference Dimension are introduced in UFO as subcategories of Measurement Reference Dimension. The nominal scale as introduced by Stevens is represented by the nominal reference structure.

As argued in [19] the mapping among reference spaces pose a major challenge in reference systems theories. These mappings are important for the establishment of the equivalence relation among reference structures and therefore leverage the use of different scales. In the current work we argue that a quality universal can be associated to a number of different quality structures, since there can be many ways to conceptualize quality structures for qualities. Therefore, we understand the mapping problem in two levels. First, on a quality structure level that refers to the mapping of different conceptualizations of quality structures for the same quality universal. Later, we consider the mapping problem in a reference level that refers to the mapping of different reference structures based on the same quality structure. The definition of mappings among quality structures and reference structures is not in the scope of the present article, but it shall be investigated in the future as part of our research program.

IV. THE CASE STUDY AND PROTOTYPE

We employ the theoretical distictions of the previous section as the base to a case study concerning the extension of OntoUML. We divide this section in three parts: first the use the distinctions proposed to UFO to understand and extend the UML Datatype classes. Then, we extend the existing OntoUML classes in order to enable the use of ontologically grounded version of UML Datatypes. Finally, we present the prototype of an OntoUML editor which implements the axioms and restrictions in the syntax of the language, allowing model validation against syntactic errors.

A. Extending OntoUML Datatypes

To model the ontological concept of quality structure in OntoUML, the Datatype construct can be leveraged as proposed by Guizzardi [3]. However, analizing the definition of Datatypes in UML, we have that “A data type is a type whose instances are identified only by their value.” [21], i.e. Datatypes are a suitable choice for representing the value spaces for quality universals because its values can be objectively evaluated. However, we encounter here the symbol grounding problem discussed in the previus sections, that is, the semantic value of a symbol cannot be specified by itself.

Employing the presented distinctions, one could see UML Datatypes, specifically the Primitive Types as a reference structures since they provide a set of lexical elements used to denote their values, built-in composition rules for generating such lexical elements and “may have an algebra and operations defined outside of UML, for example, mathematically” [21]. Therefore, the data type values can be interpreted as reference regions which need to have their semantics grounded by quality regions. As we have discussed in order to be shared, qualia need to be approximated, referred and denoted by lexical elements. Once there are quality regions to ground reference regions and approximate qualia, the values of data types become meaningful.

Here we consider Datatypes to be more adequatedly interpreted as reference structures. Since reference structures are isomorphic to quality structures, our extension to OntoUML is developed focusing on reference structures only. We assume therefore that for each reference structure construct in the model, there is an underlying quality structure construct, but in order to make our extension more pragmatic to be implemented and used we chose to omit the quality structure constructs. Hence, we start our extension by subclassing the (Onto)UML Datatype classifier with the Reference Structure concept. The resulting class structure is almost the same proposed taxonomy of reference structures in UFO depicted in Fig.6, although there are some key differences. Besides the conventional shortening of classifiers' names (removing the "reference" part of it), the first major difference is that we leverage the existing infrastructure, such as the UML's Integer primitive type instead of specifying reference structures manually. As result, we have produced the following integer based measurement dimensions: Integer Ordinal Dimension, Integer Interval Dimension and Integer Rational Dimension. One could theorically define a custom reference structure and his own set of symbols and rules to create lexical elements to denote reference regions, for instance the roman numbers, but under the conceptual modeling perspective, this would have no practical use (unless for very specific scenarios). The principle of employing the existing primitive types of UML is followed regarding nominal reference structures, thus, producing the String Nominal Structure.

We also introduce a new primitive type to UML, namely Decimal in order to represent decimal numbers which is not present at the original UML infrastructure specification. The decimal numbers' composition rules allows one to easily denote smaller reference regions that approximate the qualia. Therefore the decimal-based measurement dimensions Decimal Ordinal Dimension, Decimal Interval Dimension and Decimal Rational Dimension are also included in the proposed extension. For instance one could use either integer or decimal interval dimensions to refer to a temperature quale. In the first reference structure a quale could be approximated by the region "37°C" while in the other, it could be approximated by the region "37,546ºC". The modeler is free to choose which reference structure suits better his needs.

Another characteristic concerning the extension proposed for OntoUML is the possibility of defining the boundaries of the measurement dimensions. The attributes lowerBound and upperBound of Measurement Dimmension allows the specification of the first and last regions of the dimensions. Thus, the concepts of nonboundary dimension, one-boundary dimension and circular dimension can be modeled without the need of specific classifiers.

To model measurement domains, we introduce an attribute to differentiate scientific from cognitive domains, instead of creating specific classifiers for each ontological category. The compositionRule attribute holds a mathematical expression defined in a user language that, when evaluated under certain context and given the proper regions, it yields a resulting value which can be ordered. An example would be measurement domain for volume of pyramids that has as owned dimensions base and height and the following composition rule "volume = (1/3) * base * height". In this work we do not further explore the definition of composition rules, due to scope limitations. Thus, we differentiate scientific measurement domains such as volume from cognitive measurement domains such as color (HSB) simply by the presence or absence of a composition rule.

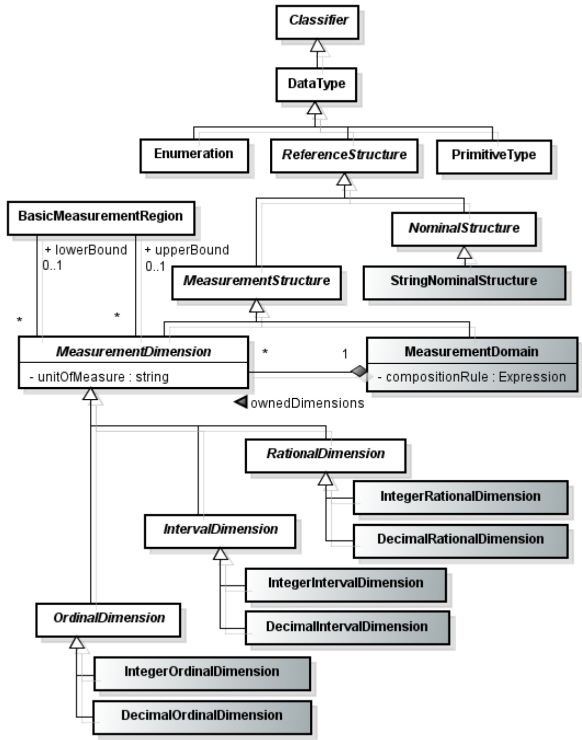

Fig. 6. The OntoUML extension concerning reference structures

At this point, we do not further explore the definition of composition rules although this is an interesting topic that should addressed in future works. Another interesting point observed in our research although not yet addressed is the composition of reference structures as counterparts of data types like Gregorian and Julian calendars. Given the notion of time as a linear one-dimensional unbounded quality structure that can be partitioned in many ways originating the dimensions of year, month and day, one could create composed reference structures based on these dimensions. Unlike other reference domains, the dimensions in such domains are not orthogonal but rather complementary: instead of representing "1,56 years" in a linear interval reference dimension one could represent "1 year, 6 months, 21 days" in such measurement domain. Although not being part of UML, such reference structures are useful for representing qualia across real-world domains and therefore should be taken into account."

To represent the concept of reference region in OntoUML and allow it to be used in conceptual models, for instance when specifying the boundaries of measurement structures, we define the Reference Region as a subclassifier of Value Specification. The resulting structure is similar to the UFO extension although we omit the atomic and nonatomic classification of reference regions in OntoUML. As discussed previously, the atomic measurement quality regions are theorically impossible to be directly refered, therefore the only referable quality regions are the nonatomic ones. This way the classifier Basic Measurement Region is grounded by nonatomic quality regions. The actual instantiated reference regions are the ones in grey depicted in Fig. 7.

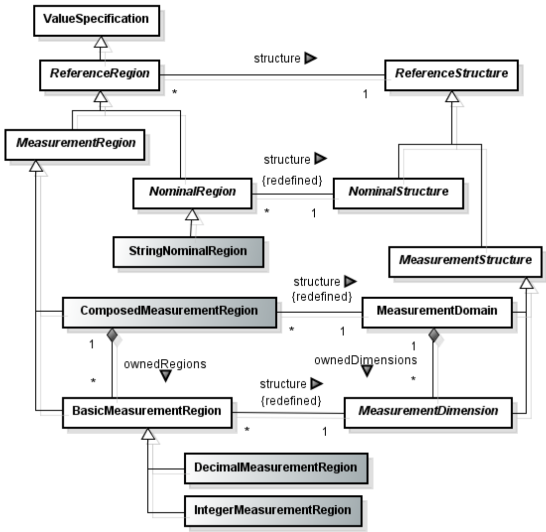

Fig. 7. The OntoUML extension concerning reference structures

As seen previously, Guizzardi considers that quality structures do not need to be dense sets of qualia. Gärdenfors even consider quality dimensions simply for the purpose of dividing objects into disjoint classes but Probst defends the dense set approach which ends up being closer to the real world (as can be verified by the presence of atomic regions). We consider the specification of a set predefined values like enumerations in UML convenient under the viewpoint of conceptual modeling languages, either for the specification of values of qualities such as color {red, green, blue, white, black} or disjoint classes like as gender {male, female}. We understand that enumerations can be seen as reference structures as well and besides the predefined lexical values denoting its reference region, they also should have its semantics grounded in ontological concepts. Therefore we try to conciliate these distinct views about quality structures, in particular considering enumerations. We allow the user to specify a set of predefined values for particular qualities, as long as the values are grounded by some quality region of an underlying quality structure. Thus, we define an extension to the enumeration datatype named measurement enumeration which has as literals measurement literals, as depicted in Fig.8.

Measurement enumeration and measurement literals are in turn grounded by existing measurement structure and measurement region. This way, we allow the modeler to choose an underlying quality structure, for instance the HSB color domain and then a measurable enumeration which defines reference regions like {red, green, blue, white, black} that are grounded by quality regions in the underlying structure. For instance the measurement literal red is grounded by the region {Hue = 0, Saturarion = 100, Brightness = 100}.

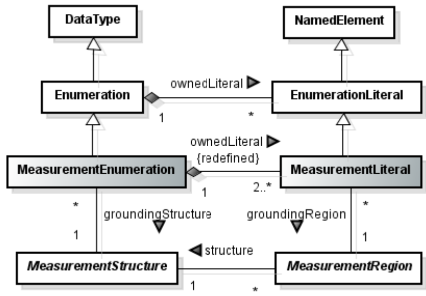

Fig. 8. A version of UML enumerations considering the extensions proposed

Another example would be definition of a measurement enumeration for the heights of people {short, medium, tall} grounded by an ordinal underlying quality structure which actually provides the semantics and ordering to such values. It is important to notice, however, that changing the grounding reference/quality structure causes the possible operations for enumeration elements to also change.

Concerning the separation of objects into disjoint classes, we understand that UFO and OntoUML already provide constructs to achieve such requirement by the means of generalization sets. A generalization set is a conceptual modeling element that congregates generalizations of a common super type. For example one could conceptualize Person as a universal specialized by Man and Woman, and these two specializations belonging to a generalization set.The generalization set is then marked as disjoint so there is no particular object that is a man or woman at the same time. From the ontological point of view, this use of generalization sets would be more appropriate then specifying a closed set of possible genders like {Male, Female}. The same principle applies to classical boolean values, while one could model the mechanical engine entity having an attribute named "running" of the type boolean to represent the states where the engine is "on" or "off". In this case, we understand that a more appropriate modeling considering the use of OntoUML would be the specialization of the entity mechanical engine in two phases (EngineRunning and EngineOff), member of a disjoint generalization set.

B. Extending OntoUML Core

The first extension to OntoUML concerns the explicit representation of quality universals as classes, instead of the notation that employs attributes (visually represented as slots inside the characterized classes). Although this decision might seem unpractical under the modeler's point of view, this is the standard notation of OntoUML to represent Modes, which are moment universals as well. Thus, we avoid using the attribute-slot notation of UML for defining quality universals, in order to make explicit the characterization relation that must exist between moment universals (characterizing) and universals (characterized). As seen in the previous section, quality universals are specialized into measurable, nominal, perceivable and nonperceivable quality universals, although the only concrete elements used in modeling are the leaf ones, namely perceivable, nonperceivable and nominal quality universals. Therefore we include these elements in the OntoUML class hierarchy as subclasses of Moment Universal[5]. Conforming to the original definition of OntoUML, the resulting classes are graphically represented using the stereotype notation for UML profiles. The second extension presented to OntoUML concerns the definition of the *structuration* relation that must exist between quality universal and the corresponding quality structure. The explicit definition of structuration is needed in order to support the structuration of the same quality universal by many different quality structures.

C. The Prototype Editor

To illustrate the applicability of distinctions presented in this section regarding OntoUML, we have developed an adaptation to a OntoUML modeling editor, namely, the OntoUML Lighweight Editor (OLED)[6]. The OLED project aims to offer a simple yet integrated toolset to support the engineering of expressive conceptual models with OntoUML. The development of the modifications to the editor was divided into two parts by a model-driven approach. Firstly, we extended the existing OntoUML reference model, proposed by Carraretto [22]. The reference metamodel consists basically in the UML 2.0 metamodel classes together with the OntoUML concepts and axioms, encoded in an Ecore[7] M3 model. The existing syntactic constraints of OntoUML and the new constraints concerning quality unversals and reference structures are specified in OCL as part of the Ecore model in order to allow model validation of syctatic errors.

The resulting model was transformed in java code and made available for being utilized in the editor. Secondly, the OLED editor was adapted to leverage the language constructs introduced in this work. The language constructs that are effectively instantiated in OntoUML conceptual models and their descriptions/ restrictions are detailed in table II. Fig. 9 illustrates an example of the proposed extensions to OntoUML for the creation of a trivial conceptual model, where the substantial universal Person is characterized by the quality universals Height and BodyTemperature with their respective reference structures. For the height quality universal, we exemplified the structuration by multiple reference structures, instantiating the measurable reference structures HeightFeet and HeightMeter. Although not explicit we stress that there is an equivalence relation that holds between HeightFeet and HeightMeter quality structures because they structure the same quality universal.

An important feature implemented in the editor is the reference structures library, which enables the modeler to create and reuse reference structures across different conceptual models. The reference structures library is integrated to the OLED editor and is depicted in Fig.10.

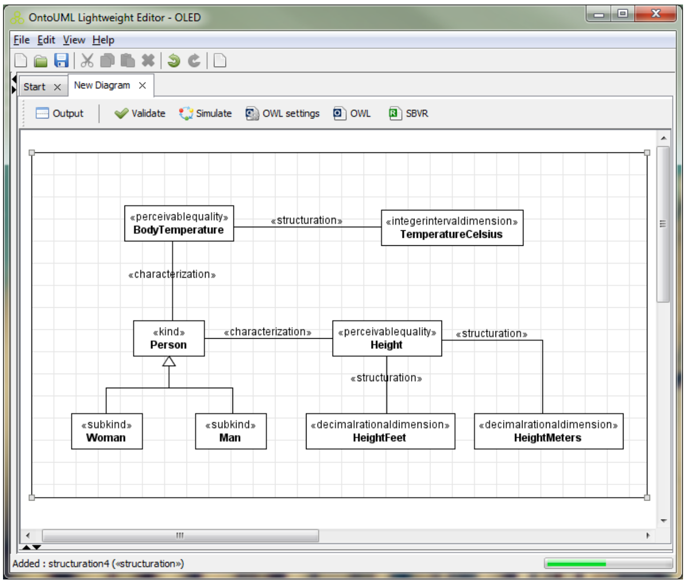

Fig. 9. An image of the OLED

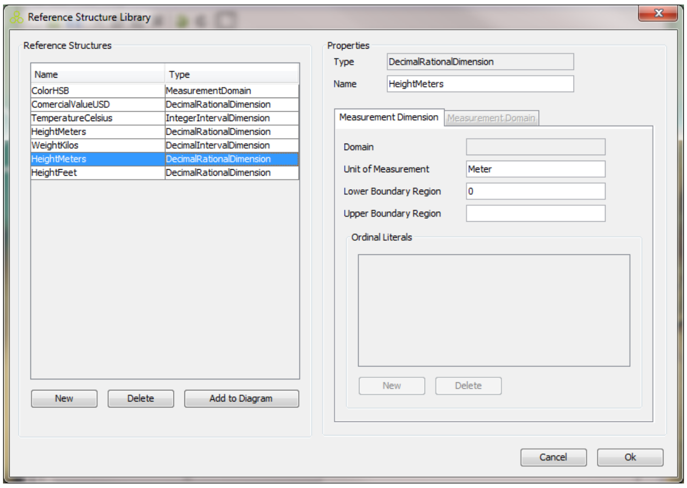

Fig. 10. An image of the OLED's reference structure library

V. RELATED WORK

Concerning the effort towards ontological grounding of modeling languages and in particular of UML, this work is similar to Evermann and Wand [1] and Li and Parsons [2], although in both works there are no particular approach for dealing with the value spaces of the concepts properties or even the properties values. The works analized rely on the software-oriented infrastrucutre of UML for value spaces (Datatypes). Thus, in this central aspect, these works cannot be properly compared to ours.

[5] Note that in OntoUML the "Universal" suffix of the UFO categories are omitted, although they still denote universals and should not be taken as particulars.

[6] http://code.google.com/p/ontouml-lightweight-editor/

[7] http://www.eclipse.org/modeling/emf/?project=emf

TABLE II. THE PROPOSED ONTOUML CONSTRUCTS FOR REPRESENTING QUALITY UNIVERSALS AND ITS QUALITY SPACES.

Classifier	Description
«IntegerOrdinalDimension»	Measurement dimensions based on the notion of ordinal scale, used for representing rank-ordered quality structures. ***Constraints:*** (1) Should always be associated to an instance of measurable quality universal by a structuration relation.
«DecimalOrdinalDimension»	
«IntegerIntervalDimension»	Measurement dimensions based on intervals (of the length of the unit of measurement), used for representing interval based quality strcuctures, such Celsius and Fahrenheit scales. ***Constraints:*** (1) Should always be associated to an instance of measurable quality universal by a structuration relation.
«DecimalIntervalDimension»	
«IntegerRationalDimension»	Measurement dimensions based on intervals (of the length of the unit of measurement) which can be converted to others, by multiplication/division of a constant, like the meter/decimeter/centimeter scales. ***Constraints:*** (1) Should always be associated to an instance of measurable quality universal by a structuration relation.
«DecimalRationalDimension»	
«MeasurementDomain»	Multi-dimensional measurement structures, composed by measurement dimensions. ***Constraints:*** (1) Must have two or more owned dimensions (2) All owned dimensions must be instances fo measurement dimensions.
«StringNominalStructure»	Nominal structures wich allows the reference of nouns. ***Constraints:*** (1) Should always be associated to an instance of nominal quality universal by a structuration relation
«MeasurementEnumeration»	Measurement structures with a predefined set of reference regions that needs to be grounded by an existing reference structure. ***Constraints:*** (1) Should always be associated to an instance of measurable quality universal by a structuration relation (2) Must have two or more measurement literals (3) The structure and its measurement literals should be grounded by an existing groundingStructure and groundingRegion respectively.
«Structuration»	A binary relation that associates quality structures which are abstracted as reference structures and quality universals. ***Constraints:*** (1) Should always be associated to a quality universal (structured end) and a reference structure (structuring end) (2) The structured end should be always read only (3) The only possible cardinalities in both end is 1..1.
«PerceivableQuality»	A quality universal which its qualia originates from observation and measurement. ***Constraints:*** (1) Should always be associated to a measurable reference structure by structuration relation (2) Should always be associated to an universal by a characterization relation.
«NonPerceivableQuality»	A quality universal which its qualia originates from conception processes. ***Constraints:*** (1) Should always be associated to a measurable reference structure by structuration relation (2) Should always be associated to an universal by a characterization relation.
«NominalQuality»	A quality universal which its qualia originates from social conventions. ***Constraints:*** (1) Should always be associated to a measurable reference structure by structuration relation (2) Should always be associated to an universal by a characterization relation.

Regarding the extensions proposed to UFO based on semantic reference spaces, this work is influenced by Probst's work concerning DOLCE, but it was out of our scope to propose a full featured taxonomy for quality universals, quality structures and reference structures. We kept the distinctions as simple as possible, avoiding making unecessary categorizations. For example, we do not categorize quality universals with respect to the number of dimensions of its quality structures, since we consider that the quality structure is only a way (of many) to conceptualize quality structures of quality universals. The assumption that there can be different conceptualizations of quality structure for the same quality universal is also a different approach. For instance, a cognitive agent could structure the color quality universal in a scale HSB-like (three-dimensional), while a measurement device could use a monochromatic-like one-dimensional scale with the regions {lightest, light, medium, dark, darkest} to measure the same particular quality. Another key difference between the approaches consists in the consideration of nominal quality universals and its related structures. Even not going further at this point in the investigation of nominal quality universals, given its importance and recurrence in real world domains, we find it necessary to include such category in the presented extensions.

VI. CONCLUSION

In this paper we have addressed the issue of providing ontological foundations for *value based attributes* and its related *value spaces* in modeling languages. We focused our investigation towards the extension of the ontologically well founded version of UML based on UFO named OntoUML. We argued that the ontological distinctions concerning quality universals and quality structures should be incorporated in the syntax of OntoUML, in order to allow adequate representations for attributes and values spaces in OntoUML models. To guide our investigation, we used as reference the Semantic Reference Spaces theory proposed by Probst, which presents a way for dealing with the symbol grounding problem that arises when values of datatypes are used for representing the semantic values of qualities.

The main objectives of our research consist in freeing OntoUML from a purely software oriented infrastructure concerning value spaces for qualities. At the same time, allowing the modeler to better model and constrain the quality structures being modeled. Another important objective in our research program consists in explicitly separating the lexical values of attributes from the ontological entities which give meaning to them, thus, providing an ontological grounding for

UML Datatypes. To achieve these objectives some categories of UFO were extended while others were introduced. We presented a basic taxonomy for quality universals and quality structures, which cover most of the scenarios in conceptual modeling. In the extensions presented, the concepts of nominal quality universal and nominal quality structure are introduced. Even not further investigating nominal qualities at this moment, we find they pose interesting research questions given the many possibilities that nominal reference structures offer for representing the values of social-convension qualities.

An important point that was not addressed in the current work is the investigation of the conditions for the establishment of equivalence among quality regions. We believe that the equivalence relation envolving approximation can tolerate some degrees of imprecision and might be useful for problems envolving inexact matching. At the moment we only briefly introduce the topic but we consider that more research is needed on this direction. Another important notion advocated in this work that needs further development is the possibility of estabilishing of mappings among different quality and reference structures. We argued that such mappings can ocour naturally as fruit of different conceptalizations of quality structures for the same quality universal. Another possibility is the mapping of different reference structures for the same quality structure. An example is time that, despite being one-dimensional, can be partitioned in different granularities. We see some opportunities for future works concerning the investigation of transformations between OntoUML and other representation languages such as RDF, OWL and CSML [23]. Since one of the noticeable applications of expressive conceptual models or domain ontologies is related to interoperability in the semantic Web, the knowledge of the structures used to approximate qualia can be useful for supporting the integration of measurement data originated from heterogeneous sources and based on different scales.

We also presented an adaptation to the OLED editor for OntoUML that illustrate the applicability of the distinctions presented here in a modeling environment. Despite of having an academic nature, the OLED project aims to create a toolkit for supporting the engineering of high quality conceptual models, by putting together tools for model checking and validation against syntactic errors, simulation of model instances and the application of ontological design patterns. An important feature implemented on the editor is the reference structure library for encouraging the reuse of reference structures across conceptual models.

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REFERENCES

[1] J. Evermann, Y. Wand, Toward Formalizing Domain Modeling Semantics in Language Syntax, IEEE Transactions on Software Engineering, 31(1), pp. 21 – 37, 2005.

[2] X. Li and J. Parsons, Ontological semantics for the use of UML in conceptual modeling. In: Challenges in Conceptual Modelling. Tutorials, posters, panels and industrial contributions at the 26th International Conference on Conceptual Modeling, Auckland, New Zealand, November 5-9, 2007,179-184.

[3] G. Guizzardi, Ontological foundations for structural conceptual models. PhD thesis, 2005, Enschede.

[4] A.B. Benevides, G. Guizzardi, A Model-Based Tool for Conceptual Modeling and Domain Ontology Engineering in OntoUML, 11th International Conference on Enterprise Information Systems (ICEIS), Milan, 2009. Lecture Notes in Business Information Processing, Springer-Verlag.

[5] A.B. Benevides, G. Guizzardi, B.F.B. Braga, J.P.A. Almeida, Validating modal aspects of OntoUML conceptual models using automatically generated visual world structures, Journal of Universal Computer Science, Special Issue on Evolving Theories of Conceptual Modeling, Editors: Klaus-Dieter Schewe and Markus Kirchberg, 2010.

[6] B.F.B. Braga, J.P.A. Almeida, G. Guizzardi, A.B. Benevides. Transforming OntoUML into Alloy: Towards Conceptual Model Validation using a Lightweight Formal Method, Innovations in System and Software Engineering (ISSE), Springer-Verlag, 2010.

[7] G. Guizzardi, A.P. Graças, R.S.S. Guizzardi, Design Patterns and Inductive Modeling Rules to Support the Construction of Ontologically Well-Founded Conceptual Models in OntoUML, 3rd International Workshop on Ontology-Driven Information Systems (ODISE 2011), together with the 23rd International Conference on Advanced Information System Engineering (CAiSE'11), London, UK.

[8] G. Guizzardi, M. Lopes, F. Baião, R. Falbo. On the importance of truly ontological representation languages, International Journal of Information Systems Modeling and Design (IJISMD), 2010. ISSN: 1947-8186.

[9] F. Carolo, L. Burlamaqui, Improving Web Content Management with Semantic Technologies, Semantic Technology Conference (SemTech), San Francisco, 2011.

[10] Object Management Group, Semantic Information Model Federation (SIMF): Candidates and Gaps, online: http://www.omgwiki.org/architecture-ecosystem/.

[11] U.S. Department of Defense, Data Modeling Guide (DMG) for an Enterprise Logical Data Model (ELDM), available online: http://www.omgwiki.org/architecture-ecosystem/lib/exe/fetch.php?media=dmg_for_enterprise_ldm_v2_3.pdf.

[12] F. Probst. Observations, measurements and semantic reference spaces. Journal of Applied Ontology, 3(1-2), 2008.

[13] S. Harnard. The Symbol Grounding Problem. Physica D: Nonlinear Phenomena, 42:335-346. 1990.

[14] P. Gärdenfors. The Geometry of Thought. A Bradford Book, 2000.

[15] N. Goodman, The Structure of Appearance. Cambridge, Mass.: Harvard University Press. 1951

[16] C. Masolo, S. Borgo, A. Gangemi, et al.. WonderWeb Deliverable D18, Ontology Library (final). Technical report, ISTC-CNR. 2003.

[17] B. Heller, H. Herre, P. Burek et al. General Ontological Language, Technical Report no. 7/2004, Institute for Medical Informatics, Statistics and Epidemiology (IMISE), University of Leipzig, Germany, 2004.

[18] N. J. Fischer, A Conceptual Space Logic.. In Proceedings of the 9th European-Japanese Conference on Information Modelling and Knowledge Bases, pp. 39-53. 1999, Hachimantai, Iwate, Japan.

[19] J. Ortmann, G. Felice, D. Wang and D. Daniel. An Egocentric Semantic Reference System for Affordances. The Semantic Web Journal, IOS Press, 2012

[20] S. S. Stevens. On the Theory of Scales of Measurement. Science, New Series, Vol. 103 No. 2684, pp 677-680, 1946.

[21] OMG. Omg unified modeling language (omg uml), infrastructure, v2.0. Technicalreport, Object Management Group. 2007

[22] R. Carraretto. A Modeling Infrastructure for OntoUML. Technical Report, Computer Science Department, Federal University of Espírito Santo, 2010.

[23] B. Adams, M. Raubal. Conceptual Space Markup Language (CSML): Towards the Cognitive Semantic Web. ICSC '09 Proceedings of the 2009 IEEE International Conference on Semantic Computing