Formal Ontology in Information Systems
S. Borgo et al. (Eds.)

doi:10.3233/978-1-61499-910-2-149

A Foundational View on Nominal and Actual Qualities in Engineering

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Abstract. Engineers distinguish between nominal and actual qualities, a dichotomy that is fundamental to guarantee that physical objects satisfy design requirements. Computational ontologies are broadly exploited across engineering domains, even though they do not attempt at making explicit the intended semantic of the two notions. The purpose of the paper is to present a foundational analysis of nominal and actual qualities to support their robust specification for knowledge representation. Instead of presenting an ontology, we discuss various modeling alternatives on which users can rely to develop their ontologies.

Keywords. Actual quality, Nominal quality, Conceptual spaces, Information object

1. Introduction

In data modeling and knowledge representation for engineering, experts need to specify the qualities that products are meant to satisfy once fabricated [14,15]. This is done by defining the values of the qualities together with their range of permissible variability, when necessary. In the engineering literature this situation is expressed with the distinction between *actual* and *nominal* qualities; the former are the characteristics that products bear, whereas the latter are the characteristics that they are only *meant* to bear [14].

Despite the distinction between actual and nominal qualities is well recognised, most of the ontologies for the engineering domain fail to recognise and characterise it. As a result current ontologies cannot adequately support the representation of experts' knowledge. From a foundational perspective the distinction between actual and nominal qualities raises interesting questions concerning their ontological nature, as we will see.

The purpose of the paper is to present an analysis of the actual/nominal qualities dichotomy targeted to applications in engineering. The paper is structured as follows. In Sect. 2 we introduce the notions of actual and nominal qualities, which are then analyzed throughout Sect. 3. The purpose is to explore modeling alternatives upon which we rely for engineering modeling purposes. In Sect. 4 we report on the state of the art relevant to our study. Sect. 5 concludes the paper and addresses the need for future work.

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2. Nominal and actual qualities

The dichotomy between actual and nominal qualities grounds on the distinction between the qualities that a *physical* product bears *at some time* with *precise* values, and the values, possibly with some range of variability, that they are meant to satisfy, respectively. In the case of qualities referring to sizes like heights and widths, the McGraw-Hill Dictionary of Engineering defines *nominal size* as follows [14, p.372]:

> "Size used for purposes of general identification; the actual size of a part will be approximately the same as the nominal size but needs not be exactly the same".

Along the same lines, Wikipedia provides the following definition for the same term:[2]

> "In manufacturing, a nominal size or trade size is a size "in name only" used for identification. The nominal size may not match any dimension of the product [...]."

As both definitions say, actual qualities do not necessarily match (*comply*) with the corresponding nominal ones; in some cases they may only approximate them, while in other cases they may completely fail to meet the specified value range. Nominal qualities are indeed often represented along with *tolerances* used to specify "permissible deviation[s] from a specified value expressed in actual values" [14, p.571].

Consider the following example, where $\pm 0.2\,mm$ in (1.1) stands for the tolerance on the nominal diameter:

1. Nominal dimensions:
    - 1.1 Nominal diameter: 17 ± 0.2 mm;
    - 1.2 Nominal thickness: 2.0 mm;
2. Actual dimensions:
    - 2.1 Actual diameter: 16.8 mm;
    - 2.2 Actual thickness: 2.3 mm.

According to (1.1) the nominal diameter assumes a value spanning from 16.8 to 17.2 *mm*, whereas the thickness is fixed to 2.0 *mm* (1.2). Assuming that the actual dimensions in (2) are meant to comply with the nominal ones, it is clear that the actual diameter in (2.1) complies with the value in (1.1). This is not the case for the actual thickness in (2.2) whose value is greater than the value in (1.2).

3. Ontological analysis

We now explore different ontological perspectives to support the conceptualization and representation of actual (Sect. 3.1) and nominal (Sect. 3.2) qualities. Before that we recall some basic notions on qualities that we will use throughout the paper.

In applied ontology, foundational theories consider qualities as dependent entities that *inhere* in objects, among other entities [9].[3] Ontologies like DOLCE [10] and UFO [6] assume that qualities *specifically* depend on their bearers and cannot migrate across

[2] See the entry 'Nominal size', last accessed on June 2018.

[3] For the sake of simplicity we consider objects' (*continuants*') qualities only.

multiple objects.[4] Additionally, they allow to represent qualities of different kinds together with their values. In the core revisitation of DOLCE (DC) [1] this is done by distinguishing between *qualities*, *quality kinds*, and *quality spaces*. The first ones are the characteristics inhering in individual objects, e.g., the quality q_1 inhering in and *only in* the object o_1. Interestingly, DC allows for an individual quality to change over time while maintaining its identity (see example below). The second ones group qualities on the basis of similarity criteria grounded on, e.g., measurement or cognitive systems. For example, q_1 may be considered as a quality of kind diameter. The third ones are spaces used to model and organize qualities' values in (taxonomical, mereological, etc.) structures. The relationship of *location* (L) allows to link an individual quality to the (space) region where it locates *at a certain time*. For instance, (f1) $L(16.8mm, q_1, t_1)$ represents the quality q_1 that, at time t_1, is located in the region $16.8mm$, whereas the diameter-kind to which q_1 belongs can be easily specified. Since the *location* relationship includes a temporal argument, it can be used to describe changes of q_1 over time; e.g., (f2) $L(17mm, q_1, t_2)$ expresses the growth in diameter of q_1 at t_2. For each individual quality DC assumes the uniqueness of its location within a space at a certain time; e.g., (f1) cannot hold together with (f3) $L(17mm, q_1, t_1)$ with $16.8mm$ and $17mm$ being in the same space.[5]

3.1. Actual qualities

From the first definition reported in Sect. 2, the way in which actual qualities are understood resembles the overall approach in [6,10]. At first glance, as said, actual qualities are used to talk about the characteristics of physical objects. At a closer look, however, it seems that the expression 'actual quality' refers to a value rather than a quality. On the other hand, it is clear that reference to different quality kinds is necessary, since one has to distinguish, e.g., diameter- from weight-values. It is also interesting the use of the term 'actual', which seems to fix the temporal dimension in which a value is considered.

From an ontological perspective, alternative approaches are available to make sense of actual qualities. Following DC [10], one can keep the distinction between quality, quality kind, and quality value, as we saw above. In an alternative setting, one can get rid of qualities and quality kinds altogether, and adopt a *location* relation directly defined on objects (see the theory ES in [9]). For instance, (f1) can be rewritten as (f4) $L(16.8mm, o_1, t_1)$, where o_1 – standing for the object in which q_1 is meant to inhere in the case of (f1) – replaces q_1 and is directly located in the $16.8mm$ region at t_1.[6]

It should be clear that the two approaches can well support engineering modeling needs, the core difference being that in the second one there are no qualities in the domain of quantification. From a practical perspective, e.g., when using Semantic Web technologies, getting rid of individual qualities may simplify data representation or the execution of queries. However, one cannot directly speak of qualities, while engineers commonly refer to them as first-order citizens of their application domains [7]. E.g., if actual qualities correspond to qualities rather than values, then we need to quantify over them and the first approach has to preferred over the second one.

[4] The subtle differences between DOLCE and UFO are not relevant for the discussion. Also, note that a similar approach for qualities is adopted in BFO [18].

[5] Recall that, given a quality kind, DC allows to link it to several spaces, which have different structures motivated by epistemic or empirical considerations.

[6] In order to distinguish between different spaces, this approach clusters regions in *generalized spaces* (see [9] for a technical insight).

3.2. Nominal qualities

We present here three alternative perspectives on nominal qualities based on different ontological points of view.

Nominal qualities as qualities. The first perspective on nominal qualities that we explore is driven by the terminology, which suggests to consider them as qualities in the sense of [6,10]. Following this approach, objects end up in bearing two different types of qualities, the actual and the nominal ones. From an ontological perspective, we need to understand, e.g., whether (instances of) both types of qualities *inhere* in the same way in objects, or whether *inherence* has to be rather tuned to the two different cases. On the other hand, as engineers, we can ask if it is possible to have *empirical* access to nominal qualities, since by measuring objects, we reasonably measure only their actual qualities.

Apart from these issues, consider that a nominal quality can 'characterize' multiple physical objects. An engineer may indeed establish that the nominal height of the screws she is designing has a value of 3cm. This means that the value is meant to be carried by (the actual qualities of) many different physical screws which will be *possibly* created. If this consideration is correct, then a nominal quality cannot be a quality in the sense of [6,10], since we saw that one and the same quality cannot inhere in different objects. Additionally, consider that for a nominal quality there may never be a corresponding actual quality, because the product that is meant to bear it may not be produced. A nominal quality can thus exist without inhering in any object. These considerations suggest that we better leave aside the idea of treating nominal qualities as DC's or UFO's qualities.

Looking back at the second definition in Sect. 2, note that a nominal size is understood as a size "in name only". Also, when we give a closer look at the practice of product designing, what happens is that designers establish how products, once fabricated, have to look like. There is thus a cut-off distinction between a physical product and the *design* that it is meant to satisfy, where the latter is the core result of a designing activity [3,17]. For instance, when the designer of our previous example establishes that the heights of its screws have to be $3cm$, this constraint is included in the design that the physical screws are required to satisfy if fabricated. We will see in the following that this conceptualization can be understood in (at least) two alternative manners.

Nominal qualities as properties. Despite there exist various theories on the nature of properties [13], the general agreement is to understand them – in opposition to *particulars* – as things that can instantiate. They are also assumed to bear an *intensional* rather than *extensional* nature, which means that different properties can have the same instances (extension) without being identical. Obviously, a consequence is that properties are not identified with the entities that (possibly) instantiate them.

Following this (minimal) view, designs can be seen as complex properties formed by simpler properties, among which nominal qualities. For example, a design for gears may comprise the nominal qualities of *having diameter* $17 \pm 0.2mm$ and *having color grey*, among others. The approach is interesting because, first, designs and nominal qualities – by being properties – can be instantiated by multiple physical entities; second, since they bear an intensional nature, one is not committed to their extensions, which may not exist. The intentional view matches also with the practice of designing, where experts do not develop new designs by listing their instances but rather by establishing their properties.

From a representational perspective, this way of understanding nominal qualities (and designs) can be based on what proposed in [17], where the authors sketch a first-order theory for knowledge representation in design. The idea is to model properties that are relevant for design by distinguishing between *basic* and *complex* properties. Since [17] quantifies over properties in a first-order setting, they are reified into the quantification domain and are treated as *concepts* in the sense of DC [1]; they therefore exist in time. Basic properties stand for the conceptual knowledge shared by experts and, by relying on DC's theory of qualities (see beginning of Sect. 3), they are equivalent to regions in quality spaces. As such, they may be non-atomic; e.g., one may have the property of *being red* as a non-atomic region comprising *being crimson* and *being scarlet*. Complex properties are properties 'characterised' by at least two basic properties and are meant to be created to satisfy design requirements. In this sense they correspond to designs. The theory also allows to relate a (basic or complex) property to the entities that satisfy it, if the latter exist. This relation is a sort of *instantiation*, which can be tuned to grasp engineering assumptions about compliance. For instance, assume for the sake of the example that basic properties are instantiated by individual DC's qualities. An axiom for compliance can establishing that, when a quality x instantiates a basic property y, then x's value has to be included within y (an example follows).

Following this approach nominal qualities are treated as basic properties that characterize designs. For limits of space we cannot show the formalism here. What is relevant to be said is that the overall approach is compatible with the modeling perspectives about actual qualities discussed in Sect. 3.1. For instance, let us write NQ for nominal quality; then (f5) $NQ(16.8\_17.2mm)$ stands for a basic property, i.e., a non-atomic region in a space for diameters. Assume that the actual quality q_2 is meant to comply with (f5). As said, this can be understood in the sense that the value of q_2 has to be within the range established by (f5). Then, by (f6) $L(17.3mm, q_2, t_1)$, it is clear that q_2 does not satisfy (f5), since its value is outside the established range.

Nominal qualities as descriptions. We now consider nominal qualities (and designs) as descriptions.[7] From a design stance, this amounts to understand them in tight connection with the technical specifications (aka documents), e.g., geometric models made with Computer Aided Design (CAD) systems, that are produced during designing activities. It should be clear that since multiple and equivalent specifications can be produced, attention has to be paid in distinguishing a specification from its *content*. For example, we can create a CAD model and then print it on a paper sheet; call cad_1 the first entity, $print_1$ the second one. cad_1 and $print_1$ cannot be identified, since the former is a digital object, whereas the latter is an object made of paper, among other materials. Despite this difference, we reasonably want to say that cad_1 and $print_1$ share something in common, i.e., they have the same content, a fact which allows us to claim that they are different but equivalent specifications with respect to *what* they specify. To rephrase these considerations in terms of nominal qualities and designs, they can be both understood as specific types of 'contents' (aka descriptions) related to the practice of designing.

From an ontological perspective, a specification like a CAD (digital) model is a physical object, a computer file indeed. On the other hand, what is the ontological nature of the 'content' of the model is challenging to be characterized. First, it cannot be identified with a single specification, since it can be present in different specifications at

[7] The meaning of 'description' has to be intuitively understood, while it is our purpose to make it more clear.

the same time. Hence, it is not a physical entity. Second, it cannot be identified with a set of signs (e.g., strings), since it can be 'encoded' via multiple signs, e.g., a graphical geometric model and the corresponding mathematical equations (assuming the former can be exactly represented in mathematical terms).

According to the YAMATO ontology [12], a document's content is a *proposition*, an entity that is *semi-abstract* in that it requires time but not space in order to exist. For instance, following YAMATO, when we consider a novel, say Dante's *Comedy*, we need to distinguish it from (at least) the paper-made books which we can buy and where the *Comedy* is 'realized'. YAMATO does not define what a proposition is; [12] sometimes speaks of 'meaning', while other times it refers to the SUMO ontology,[8] where a proposition is "a statement that affirms or denies something and is either true or false". The idea is inherited from philosophy, where the ontological nature of propositions is highly debated [11]. Even leaving this debate aside, if we assume with SUMO that propositions are required to bear truth-values, it is hard, if intelligible at all, to understand what it means for the 'content' of a design specification (or a book) to be true or false. As argued in [20], design models can be evaluated with respect to various criteria, e.g., precision or completeness, but not with respect to truth-values since there might not be anything in the world against which its truth-value can be stated.

A different, yet preliminary, approach to characterize documents *vs* their contents is presented in [16]. By relying on DOLCE, the authors distinguish physical from non-physical objects, where both are present in time but only the former are also in space. Then, *information objects* – as the contents of documents – are introduced as non-physical objects that in order to exist have to be related to some physical objects, upon which they *generically depend*.[9] The authors do not compare their work with YAMATO, although information objects are not things that can be either true or false.

Following this approach, designs may amount to information objects that comprise other information objects among which nominal qualities. Hence, *having diameter 17 ± 0.2mm* is now an information object that can be specified in multiple documents. Clearly, a relationship for compliance is needed to link an information object to the physical entity that possibly satisfies it, e.g., an actual quality.

As the reader may have already noticed, this approach shares some commonalities with the previous one based on properties, the radical difference being that now nominal qualities (and designs) are objects rather than properties. Despite the object *vs* property dichotomy is rather strong in formal ontology, what is surprising is that information objects and properties behave similarly. We saw that both approaches distinguish (i) a non-physical yet temporal entity (property or information object) from (ii) the physical objects that possibly satisfy it, and (iii) include a relation for instantiation/compliance. Unfortunately, it is hard to make a precise comparison between the two approaches, which would allow us to evaluate their pros and cons, given the lack of a robust conceptualization and formal treatment of information objects (or propositions). At first glance the latter correspond to properties in the sense of [17]; the two views may be therefore unified into a single theory to handle design knowledge taking [17] as starting point.

[8] See http://www.adampease.org/OP/, last accessed in June 2018.

[9] Recall that generic dependence holds between an entity x and some entities of a certain type ϕ. The reader should not understand information objects in [16] along with the Information Artifact Ontology, see Sect. 4.

4. Comparison with the state of art

The representation of nominal qualities is explicitly addressed in [15,19]. Solano and colleagues [19] propose an ontology for process planning based on DOLCE. The class `NominalValue` is introduced by specialising DOLCE's quality spaces, an approach that resembles what said above about nominal qualities as properties. However, [19] does not discuss the ontological difference between nominal and non-nominal qualities, e.g., what it means for a product to bear a nominal quality. Qin et al. [15] address the need for a formal language supporting geometric dimensioning and tolerancing based on the Geometrical Product Specifications (GPS) language. With respect to our study, their work consists in the formal representation of some of the constraints in the GPS, whereas the ontological foundations of nominal qualities are not discussed.

From a foundational perspective, Guarino [4] proposes an analysis of nominal qualities by distinguishing them from the qualities that physical objects bear. In his view nominal qualities inhere in what he calls *conventional* artefacts, which are the objects created during designing activities and represented in technical specifications. The nature of these artefacts remains however ambiguous. [4] explores the possibility of considering them as (immaterial) *parasitic objects* hosted in physical artefacts, while they are *mental prototypes* existing in experts' minds in [5], this second reading being very close to the approach about properties presented above. What is interesting is that in Guarino's approach, when a conventional artefact has a nominal quality and is hosted in a physical artefact, the latter 'inherits' the nominal quality. It should be clear that something similar concerning the ascription of nominal qualities to physical artefacts can be done in the approaches discussed in Sect. 3.2 by comparing artefacts to their corresponding designs.

Finally, the BFO-based IAO is focused on the notion of *information content entity* (ICE), which is defined as "an entity which is generically dependent on some material entity and which stands in a relation of aboutness to some [existing] entity" [2]. It should be clear that nominal qualities cannot correspond to ICEs since there may not be anything to which they refer. Also, ICEs do not correspond neither to YAMATO propositions nor to information objects in [16], since BFO does not cover non-physical objects [18].

5. Conclusion

We presented in the paper an ontological analysis of engineering actual and nominal qualities. Differently from the state of the art, our purpose was to explore the foundational assumptions behind the two notions. The result is an initial 'library' of alternative perspectives, which can be taken as starting point for a robust treatment of qualities in computational ontologies for engineering. As we saw throughout Sect. 3, while we discard some modeling views, e.g., the identification of nominal qualities as qualities in DOLCE's or UFO's sense, alternative approaches are feasible in other cases. Hence, we suggested that the choice of which perspective to adopt needs to be based on both experts' conceptualizations and the robustness of the modeling approach.

Future work is necessary to strengthen the maturity of what presented in the paper from both a conceptual and formal perspective. For instance, if we consider actual qualities from an engineering standpoint, they are strictly dependent on measurement procedures. Looking back at formulas in Sect. 3, this means that the values expressed by the relationship of *location* stands for a *measure*. What this suggests is that an ontology for representing and reasoning over qualities in engineering has to be grounded on an ontological theory of measurement procedures (see, e.g., [8]). From a formal perspective, the analysis needs to be formalized to better explore its consequences, as well as the relations between the modeling alternatives. In particular, even though we showed how the theory in [17] can be used to represent engineering qualities as properties, the approach needs to be further extended to meet engineering modeling requirements.

Acknowledgments: We wish to thank Claudio Masolo and the anonymous reviewers for their valuable comments on previous versions of the paper.

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