A Formal Specifiction for Conceptualizationsin Computer Aided Visual Design Processes

Ewa Grabska
Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 11 Łojasiewicza, Krakow, Poland

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Abstract: The paper is the next attempt to formalize an ontology-based knowledge framework helpful for CAD process. Our previous research has showed the need for a more expressive specification in order to capture the intended models corresponding to a certain design conceptualization. This paper presents a more general approach to ontological framework which will be illustrated with examples of designing floor-layouts. This formal framework can be useful for many different applications, for instance to biological systems, cultural heritage and economical aspects.

1 INTRODUCTION

This paper is an attempt to analyse conceptual design phase in Computer Aided Design (CAD) system in the framework of computational ontology.

Ontologies in computer science started to become a relevant notion in the 1990's. At that time ontologies were related to work in knowledge acquisition. From computer science point of view the basic definition of an ontology is as follows: "An ontology is an explicit specification of a conceptualization". In other words the ontology analyses relevant entities and organizes them into concepts and relations (Guarino et al., 2009).

Conceptualization is one of the most challenging aspects of designing because it forces designers to considers many disparate factors. There exists the need to keep in mind objects, concepts, and other entities that are assumed to exist in the considered design domain of discourse, and the relationships that hold among them. It is perhaps for this reason drawing is such a popular tool of initial stages of designer's conceptualization. Drawings, being externalization of designer's conceptualization, are seen as thinking aids (Suwa and Tversky, 1997). It seems helpful if there exists a commitment between the drawing and the level of certainty in the designer's mind at the time. A CAD system communicates with the designer via drawings displayed on the monitor screen.

Nowadays, construction projects are commonly represented in the Building Information Modelling (BIM) to store all project 3D elements in a central data-base and generate 2D drawings and 3D renderings (Eastman et al., 2008). However, during the conceptual design phase most of these tools do not use data structures to reflect the design knowledge extracted from design drawings on the monitor screen, although this knowledge provides a starting point for design refinement (Lawson, 2001). The importance of visualization in design was discussed in (Visser, 2006), while visual conventions allowing for man-machine interaction were described in (Booch, et al. 2005). It turns out that referring to ontological terminology the communication between the designer and the computer can be improved (Yurchyshyna and Zarli, 2009).

Besides CAD there exist many different applications based on ontologies. They are related for instance to biological systems, cultural heritage and economical aspects. This paper presents common rational grounds for existence of different applications in the similar ontological framework. The formal framework based on ontological terminology will be illustrated with examples of designing floor-layouts.

2 CONCEPTUALIZATIONS AND OBSERVABLE WORLD STATES

A conceptualization is an abstract and simplified

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view of the world created in a domain of discourse that is a subset of some cognitive domain. In this paper design aided by computer is our cognitive domain, while designing floor-layout makes the domain of discourse. Formally, we start with the definition of conceptualization stated by Genesereth and Nilsson (Genesereth and Nilsson, 1987).

Definition 2.1

*A **conceptualization** is a tuple (D, R), where*

- *D is a set called the **universe of discourse**, and*
- *R is a set of **relations** on D.*

Each element of *R* is an *extensional* relation, reflecting a *specific* world state involving the elements of *D,* such as one depicted in Fig. 1. In design aided by computer we need to explicitly specify conceptualization, while conceptualizations are typically implicit in the mind of designer. In CAD system conceptual process in designer's mind is supported by a cognitive tool, such as computer screen. There exists many specialized editors for drawing floor layouts on the monitor screen, where for instance a floor layout is composed of polygons representing functional areas or rooms (Grabska, 2011).

Example 2.1

Let assume that the designer visualizes an initial drawing shown in Figure 1. We can extract the following knowledge that specifies the universe of discourse and relations:
D = {room, wall, door} .
R = {bedroom, living-room, hall, adjacent- to, accessible- to}.

A generalization/specialization hierarchy, i.e., a taxonomy forms the backbone of an ontology. Then *room*, *bedroom*, *living room*, *hall* might be relevant concepts, where the first is a super-concepts of the latter three. On the other side, we have a content hierarchy a *room* consists of *walls*, a *door* is contained in a *wall.* Relations of *R* can be defined between rooms:

adjacent-to = { (living room, bedroom), …}, accessible-to = {…,(living room, bedroom)}.

The designer on the base of the conceptualization can generate an *observable world state*. However, this does not meet designer's needs because it depends too much on a specific state of the world. In each step of design process the designer can change number of elements of the domain of discourse *D* and/or relations of *R* on *D* because both the requirements and the design become more refined as the project proceeds.

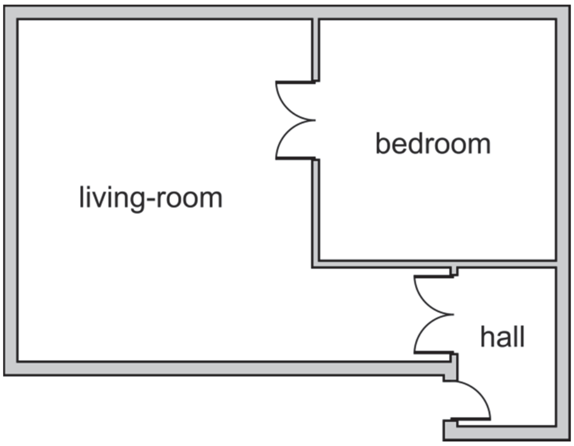

Figure 1: The drawing reflecting a specific world state for the conceptualization *(D,R).*

Example 2.2

Let assume that the designer on the base of the conceptualization in Fig. 1 decides to divide the bedroom into two rooms: bathroom and smaller bedroom. Although only one room is added we obtain the second conceptualization (see: Fig. 2),

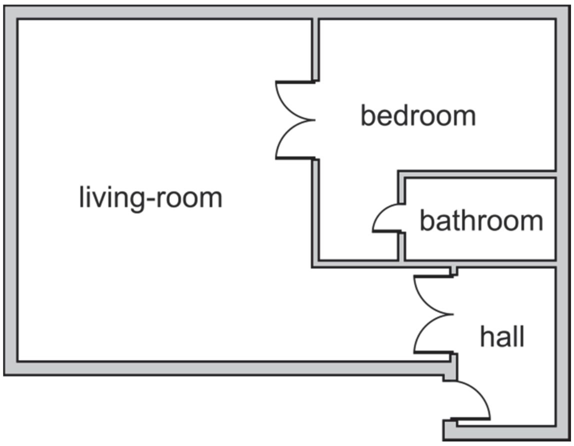

Figure 2: Another world state for the concep-tualization *(D',R').*

where *D' = D* and *R' = R ∪ {bathroom} ∪ adjacent-to' ∪ accessible-to', where adjacent-to' = adjacent –to ∪ {bathroom, (bedroom, bathroom*), (*bathroom, hall), (bathroom, living room)},* and *accessible-to' = accessible-to ∪ {bedroom, bathroom}.*

A conceptualization should not change when the world changes. We need to focus on the meaning of the underlying concepts, which are independent of a single world state: the meaning of *accessible to* is related to two rooms in the floor-layout. Understanding such meaning implies having a rule to decide, observing different patterns, whether or not there exists a relation accessibility between two rooms. Between rooms in an accessibility relation there exists a door opening which can be with or without a door. They are hundreds of different types of door. Moreover, instead a door a curtain can be hung in the door opening. In most cases this is impossible to list all elements of the relation, which are independent of a single world state.

The meaning of "accessibility" can be defined as a function that, for each global context involving all our universe, gives us the list of pairs of accessible rooms. The revers of this function grounds the meaning of a concept in a specific world state. Linking this with conceptualization we define a function from a set of possible world states into extensional relations. To formalize this function, we first have to clarify what *a world* and a *world state* is. In the stage of conceptual process aided by computer when the conceptualisation is formed in the mind of designer he/she try to externalize own concepts using drawings. In other words initial solutions in the form drawings being observable states of affairs constitute states of designer's world. In this paper to represent the world state, the concept of *visual site* will be used (Shimojima, 1996). A *visual site* is a drawing along with a surface on which it is drawn. In general different surfaces can be used for drawing, e.g., a sheet of paper or a monitor screen. Two different drawings on the same surface determine two different visual sites. In visual design aided by computer, monitor screen is a basic visual site on which besides drawing some information from computer system can be generated (Grabska, 2014).

Each designer generates his/her own world. Observable states of the world should be defined with the reference to the notion of a design space *S*, i.e., a piece of reality we want to model. In our case the design space will be all configurations of rooms with its components such as walls, doors, etc., which can be treated as admissible floor-layouts.

Definition 2.2

*A **world** is an ordered set of world states, corresponding to the evolution of the design space in time.*

Definition 2.3

Let S be a design space, D an arbitrary set of distinguished elements of S, and W the set of possible states for S. The tuple (D, W) is called a domain space for S.

*A **conceptual relation** ψ^n of arity $n \geq 1$ defined for a domain space (D, W) is a function $\psi^n : W \rightarrow \mathcal{P}(D^n)$ from the set W into the family of all subsets of the set of n-ary relations on D.*

A conceptual relation is a function from a set of possible world states into extensional relations. This function allows one to extend the notion of conceptualization for all observable world states (Guarino et al., 2009).

Definition 2.4

*A **conceptualization for W** is a triple $\mathcal{C} = (D, W, \mathbf{R})$, where*

- *D is a domain of discourse,*
- *W is a set of world states, and*
- *$\mathbf{R} = \{\psi^n\}_{n \geq 1}$ is a family of all conceptual relations ψ^n on the domain space (D, W)*

3 MODELS IN ONTOLOGY

In practical applications we use a language to describe the elements of a conceptualization. For instance, *accessible to* is a predicate symbol which expresses the fact that *bathroom* is accessible to *bedroom.* The symbol represents a certain conceptual relation. Our language denoted by ***L*** should commit to a conceptualization. Let assume that ***L*** is a first-order logical language with its vocabulary as the set *{bathroom, bedroom, living room, hall, accessible-to, adjacent-to}*. We shall not consider function symbols here.

The basic problem is to interpret each symbol according to the conceptualization we commit to. It turns out that the vocabulary can be interpreted in many different ways even if the cognitive domain and its subset – the domain of discourse were fixed. A conceptualization is specified in two ways: *extensionally* and *intensionally*. An extensional specification of the conceptualization requires listing the extensions of every conceptual relation for all possible worlds. However, it is impossible if the universe of discourse *D* or the set *W* of possible states of world are infinite. A conceptualization is often specified by means of examples related to selected world states. A more effective way to specify a conceptualizations is to fix a language and to constrain its interpretation in an intensional way, by means of axioms called *meaning postulates*. For our example, we can write simple axioms stating that *accessible-to* is symmetric, irreflexive, and transitive, while *adjacent-to* is symmetric, irreflexive and intransitive.

According to (Guarino et al., 2009) the notion of ontology can be tentatively defined in the following way: *An ontology is a set of axioms, i.e., a logical theory designed in order to capture the intended models corresponding to a certain conceptualization and to exclude the unintended ones.*

In other words we have to deal with an approximate specification of a conceptualization: the better intended models will be captured and non-intended models will be excluded.

Now when we have an intuitive grasp of ontological commitment and ontology, let us embed them in a more formal framework. We start with the definition of model.

Definition 3.1

*Let **L** be a first order logical language with vocabulary V and (D,R**)** be a conceptualization. A **model for L** is a triple M = (D,R, I **)**, where I: $V \rightarrow D \cup R$ is an **interpretation function** that maps each symbol of V to either an element of D or a relation belonging to R.*

Let us consider the model shown in Fig. 1. We can assign suitable rooms depicted in the Fig. 1 to symbols *bathroom, bedroom, living room,* and *hall.* The two symbol relations *accessible-to* and *adjacent-to* are defined by listing all suitable pairs of rooms. Two rooms are *adjacent* if they have at least one common wall, while room1 is *accessible* to room2 if there exists a common wall with door. Wall and door are represented by a segment and door icon, respectively.

Definition 3.2

Let *L* be a first-order logical language with vocabulary *V* and *C = (D,W,**R**)* be a conceptualization for *W*. An ***ontological commitment*** for *L* is a tuple *K = (C, **I**)* where
I*: $V \rightarrow D \cup$ **R*** that maps each vocabulary symbol of *V* to either *D* or a conceptual relation belonging to the set ***R***.

The notion of ontological commitment is an extension of the standard notion of model to intensional meaning. Now we can define a notion of intended models corresponding to a certain conceptualization. As it has been considered capturing these models is the biggest challenge in ontology.

Definition 3.3

*Let **C = (D,W,R)** be a conceptualization for **W**, **L** be a first-order logical language with vocabulary **V** and ontological commitment **K = (C, I)**.*

*A model **M = (D, R, I)** is called an **intended model** of **L** according to **K** iff*

1. *For all constant symbols **c** $\in$ **V** we have I(c)= **I (c)**,*
2. *There exists a world **w** $\in$ **W** such that, for each predicate symbol **v** $\in$ **V** there exists an intensional relation $\rho \in$ **R** such that **I(v)** = ρ and I(v) = $\rho(w)$.*

For intended model the mapping of constant symbols to elements of universe of discourse is the same for *I* and ***I*** and there must exists a world such that every predicate symbol is mapped into an intensional relation whose value, for that world, coincides with the extensional interpretation of this symbol. The set ***I_K(L)*** of all models of ***L*** that are compatible with ***K*** is called *the set of intended models of **L** according to **K.***

Finally, the next tentative definitions of ontology is proposed (Guarino et al., 2009):

Definition 3.4

*Let **C** be a conceptualization for **W**, and **L** a logical language with vocabulary **V** and ontological commitment **K**. An ontology **O_K** for **C** with vocabulary **V** and ontological commitment **K** is a logical theory consisting of a set of formulas of **L**, designed so that the set of its models approximate as well as possible the set of intended of **L** according to **K.***

Example 3.1

We build an ontology *O* for floor-layout design, which consists of a set of logical formulae. Floor-layout domain is specified with increasing precision.

- *Taxonomic Information:*
  O_1 = { living room(x) $\rightarrow$ room(x), bedroom(x) $\rightarrow$ room(x), ...}
- *Domains and Ranges of Relations:*
  $O_2 = O_1 \cup$ {accessible-to(x,y) $\rightarrow$ room(x)$\wedge$room(y),...}
- *Symmetry:*
  $O_3 = O_2 \cup$ {accessible-to(x,y) $\leftrightarrow$ accessible-to(y,x), ...}

4 ONTOLOGIES IN CAD SYSTEMS

When considering ontologies in computer science the conceptualization should be expressed in a formal machine readable format. In design aided by knowledge based computer system we need to make knowledge representation extracted from conceptu-

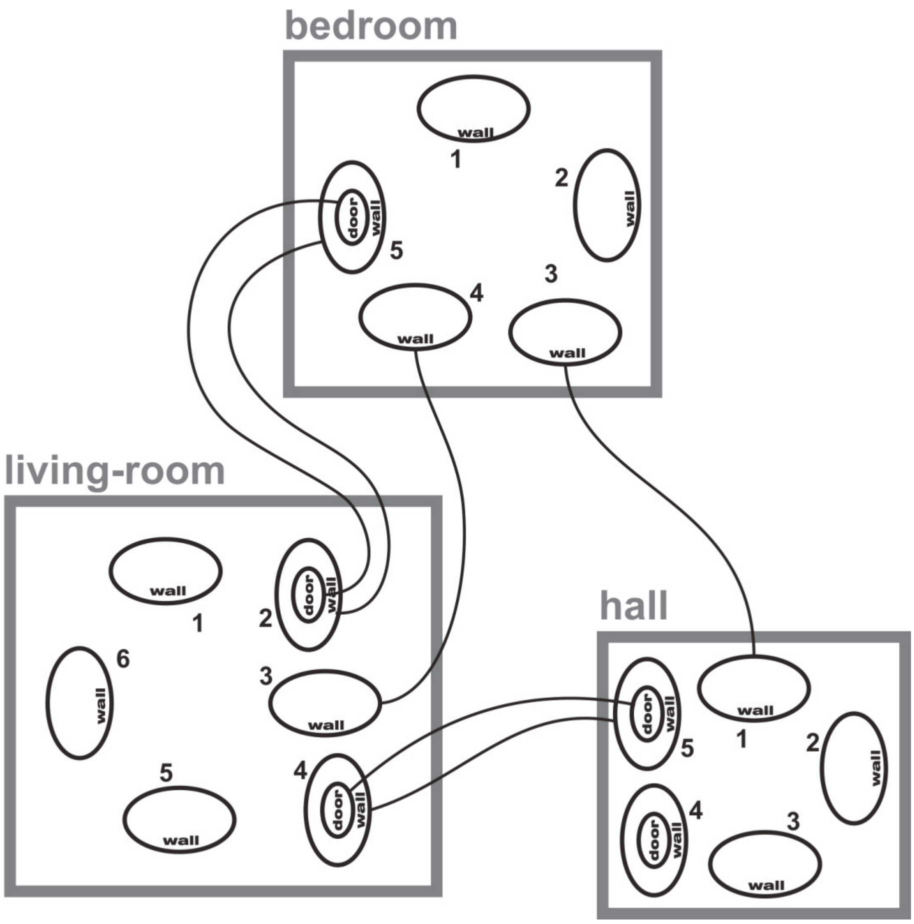

Figure 3: A B-graph representing the world state in Fig. 1.

alization: accessible electronically; structured and understandable by computers, interoperable, and transparent. Graphs can be combined with the most popular logic-based knowledge representation technique, where knowledge is represented explicitly by symbolic terms and reasoning is the manipulation of these terms. Graph data structures are used to reflect the design knowledge extracted from design drawings on the monitor screen. This knowledge provides a starting point for design refinement.

There exist many types of graphs useful for specification and modelling of design knowledge during conceptualization in CAD processes. In this paper we use a specific graphs called B-graphs whose nodes represent objects of the domain of discourse. Their nodes contain bonds which are also nodes representing arguments of relations. Relations are defined between bonds (Grabska 1994). Two kinds of bonds are distinguished*: engaged* and *free* bonds which correspond to arguments of existing and potential relations, respectively. B-graphs are content-hierarchical. Hierarchy also allows for sub-bonds (for example, a room consists of walls and one of them has a door – this door is contained in the room, but also is subordinate to the wall).

The Fig. 3 presents the B-graph corresponding to the drawing considered in Example 2.1. Three nodes represent three rooms. The number of walls of room determines the number of bonds representing them. If the wall has a door then the bond representing the door is contained in the wall bond. An edge between the door bonds represents the accessibility relation, while between the wall bonds – adjacency one. The walls of each room shown in Fig. 1 can be ordered clock-wise starting from the top left –most one. The distinct of bonds is essential in definitions of operations on graphs that reflect modifications of design phases (compare: Fig. 3 with Fig. 4).

The B-graphs shown in Fig. 3 and Fig. 4 can be treated as internal representations for the drawings created on the monitor by the designer and shown in Fig. 1 and Fig. 2. These drawings reflect the results of some phases of designer's conceptualization while B-graphs corresponding to them determine

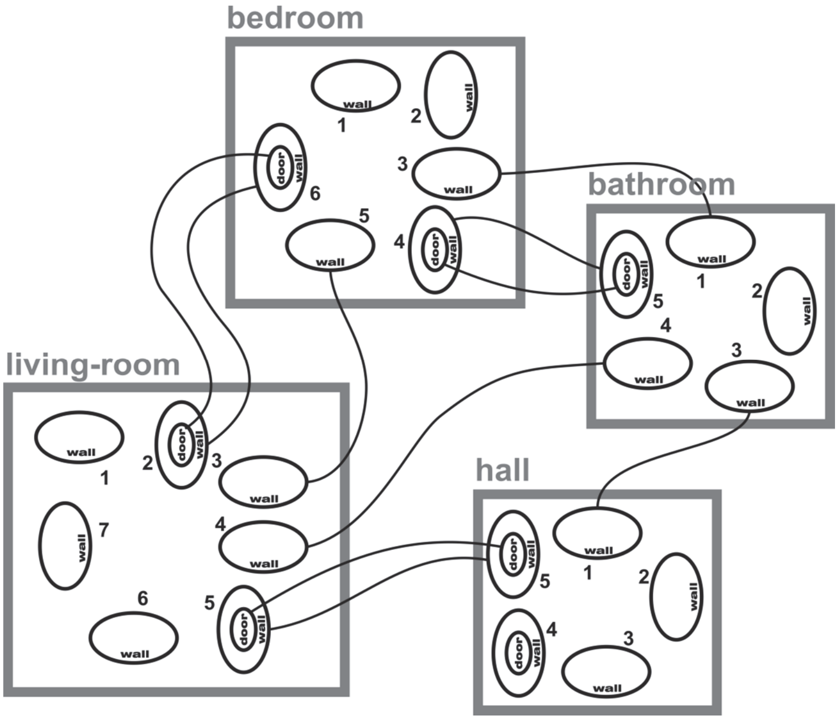

Figure 4: The B-graph for the drawing in Fig. 2.

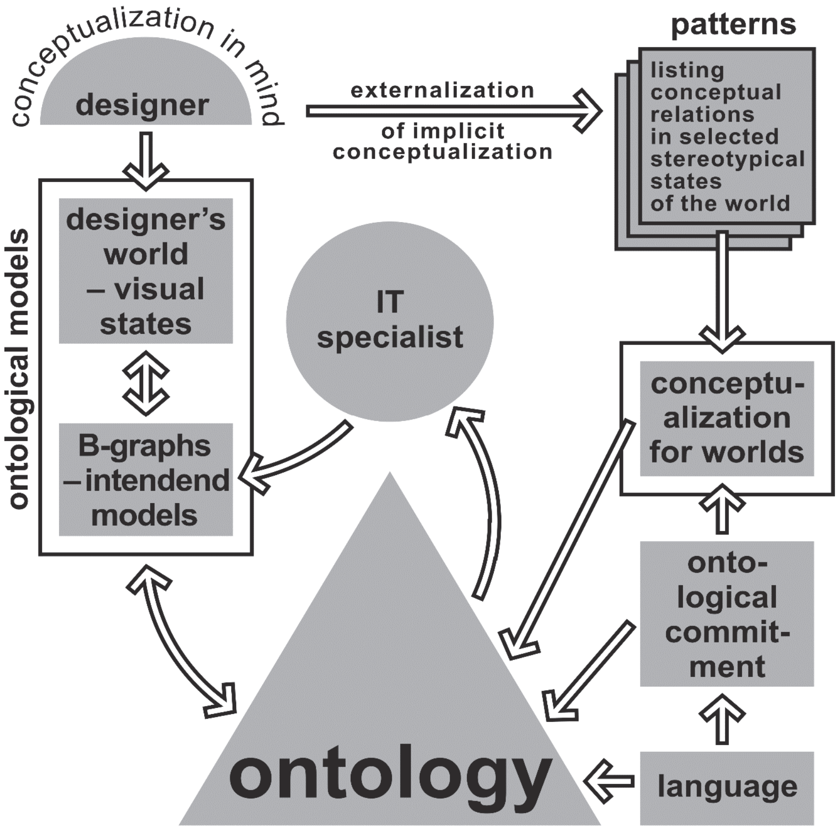

Figure 5: The relationships between designer's conceptualization, the formal conceptualization for worlds, the logical language used to describe ontology, the IT specialist, and ontological intended models.

elements of the graph based data structure. B-graphs are specified by the IT specialist.

The presented approach allows to define formally correspondence between drawings and B-graphs in the framework of ontology. The B-graph in Fig.3 reflects a world state shown in Fig. 1. The visual site with drawing presented in Fig.1 and the B-graph in Fig. 3 belong to the set of intended models of ***L*** according to the same ontological commitment ***K.***

The summary of our consideration is shown in Fig 5.

5 CONCLUSIONS

Within architectural design, key aspects of the anticipated function of buildings are determined by their structural form, i.e., their shape, layout, or connectivity. The formal modelling of structural form for CAD systems remains elusive. The structural form emerges during the conceptual design phase.

This paper has presented the practical concerns surrounding the formal interpretations of the structural form with respect to its applicability in CAD systems in the ontological framework. The basic notions of ontology: conceptualizations, models, ontological commitments, and intended models have been defined in a formal way.

One of the challenges of CAD systems is to automatically transform design drawings on the monitor screen into appropriate graph based date structures. The framework of ontology proposed in this paper allows to define the correspondence between the drawings and their graphs in a formal way. This formal approach to the definition of ontology facilitates the development of reasoning modules of CAD system which are based on graph data structure. Thanks to this, dialogue between the designer and computer can be improved.

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