CIB W78 Workshop on Computer Integrated Instruction
22nd - 24th of August 1994, Espoo, Finland

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CONCEPTUAL MODELING THROUGH A CONCEPTUAL STRUCTURE

Abstract

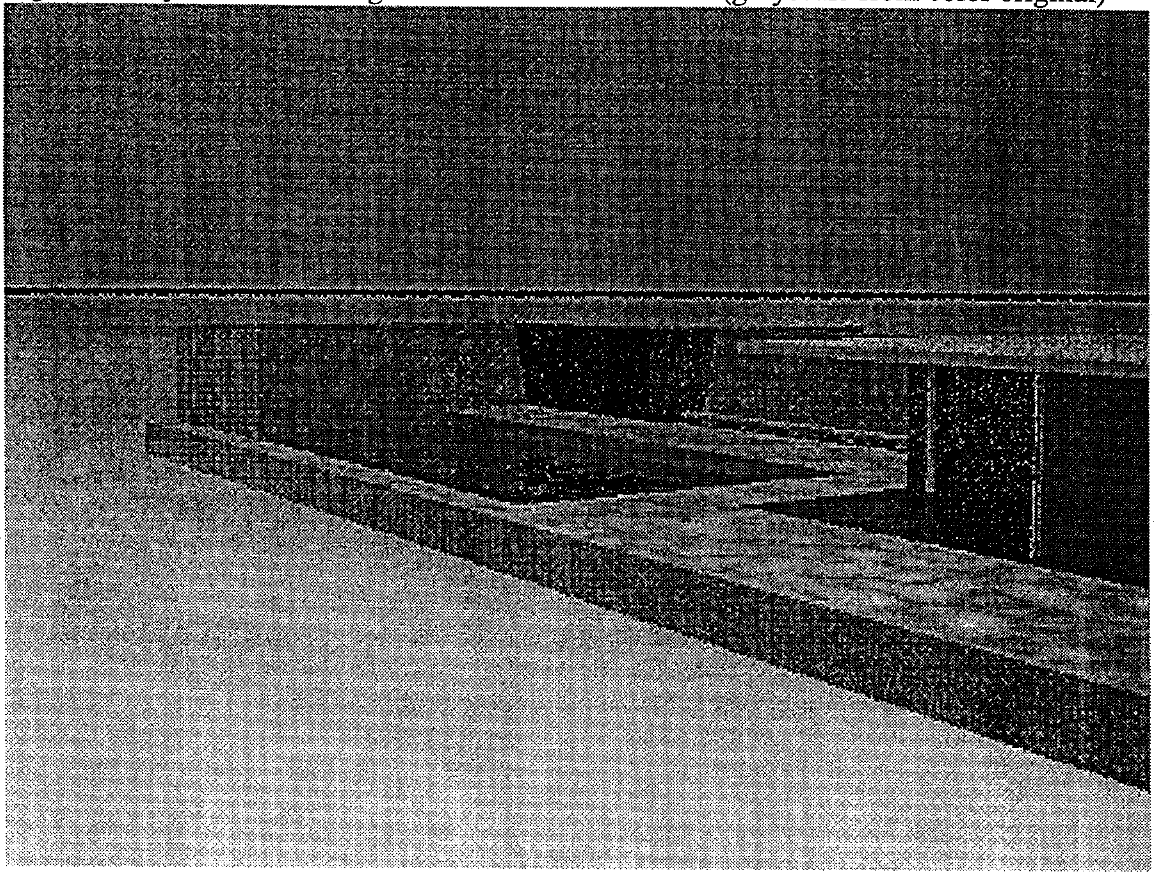
This paper reports on a computer aided design system which I have developed to handle problems of ambiguity in the description of architectural objects during the schematic design phase. The knowledge base underlying this system is referred to as a "conceptual structure". Within the "conceptual structure", an ambiguous "child" object may inherit attributes from many alternative kinds of "parent" objects. The "conceptual structure" can also accommodate a design process through which a "child" object such as a "wall" can become less ambiguous over time. The end of this design process is the "disambiguated" specification of the final designed object. This system was first developed as part of my Ph.D. Dissertation at Harvard University (Mark 1993).

Introduction

At the CIB W78 Conference in Lund, 1988, I presented a paper titled "A Design Automation Paradox" (Mark 1990). The paper described a difficulty with then conventional computer aided design systems. The paradox of those systems is that the more highly automated the software, the more limited the design modeling domain. For example, a typical "walls program" provides a user with the ability to easily automate the joining, intersection, copying, mirroring, translation and rotation of detailed walls. However, the kinds of walls which may be automated are often limited to a very restricted set of wall types. Conversely, basic 3D geometrical modeling systems can represent a greater variety of wall types, but it takes greater effort on the part of the user to construct them using more primitive kinds of construction sequences.

The "conceptual structure" of the alternative computer aided design system described here adapts the artificial intelligence techniques of "frames", and "multiple inheritance". It also adapts the conventional computer aided design techniques of "instantiation", and "parametric variation" (described below). The system has been applied to a set of case studies, including Mies Van der Rohe's German Pavilion. It is intended to work around some of the restrictions imposed by the design automation paradox. It does so by allowing for much ambiguity in the description of architectural objects. That is, it provides for a greater variety in the descriptions of schematic wall types, and then provides a way for these wall types to become more detailed.

Figure 1: Raytraced rendering of Mies' German Pavilion (grayscale from color original)



A premise of the "conceptual structure" proposed within this alternative system is that designers work by associating abstract concepts with graphic representations. For example, at an early stage of the design process, an architect may associate the concept "wall" with the simple drawing of a rectangle. At this early stage of the design process, the conceptual model of a wall may be relatively ambiguous. That is, the "wall" may be of undetermined materials, construction, elevation and structure. It may be a kind of marble wall, or a kind of brick wall, or a kind of wood frame wall, etc.. It may be transparent, translucent or opaque. It may be load bearing or non-load bearing. These alternative possibilities may exist in the mind of the architect. The alternatives may also be annotated on an architectural drawing. However, the typical computer aided design system of today would not contain any database reference to the wide set of possible kinds of objects that the rectangle could be. Within the "conceptual structure", however, all of these alternative associations for the "wall" are retained. The "conceptual structure" is then refined and the "wall' is dis-ambiguated as part of the design process.

The theory

The theory proposes that for any design object the architectural design process is an activity in which there are many conflicting classifications at work. These classifications may converge in the description of the design object but are never fully reconciled. They may co-exist all the way through the design process and also co-exist with respect to the end product. An architectural object may have some but not all the characteristics of any of the classifications to which it is assigned. It may simultaneously have characteristics of several classifications. The transformation of a designed object in relationship to its multiple classifications is in this theory a critical objective of the design process. New objects are assigned to classifications. Occasionally, new classifications are created.

As a research tool, a computer aided design and rendering program was developed in which objects can be accounted for in terms of multiple classifications. The knowledge base which underlies this program is called a *conceptual structure*.[1] The *conceptual structure* represents objects and the properties that they inherit from multiple classifications. The *conceptual structure* also is used to illustrate how objects could be modified towards the realization of design objectives. In other words, the *conceptual structure* can be used for managing the transformation of objects in the design process.

As an application of the hypothesis, *conceptual structures* have been prototyped for the design of existing and historically important works of architecture. A case study comparison of Palladio's Villa Malcontenta with Corbusier's Villa Stein was developed after the essay "The Mathematics of the Ideal Villa" by Colin Rowe. A more extensive case study was made of Mies Van der Rohe's German Pavilion in Barcelona, parts of which are reported on in this paper.

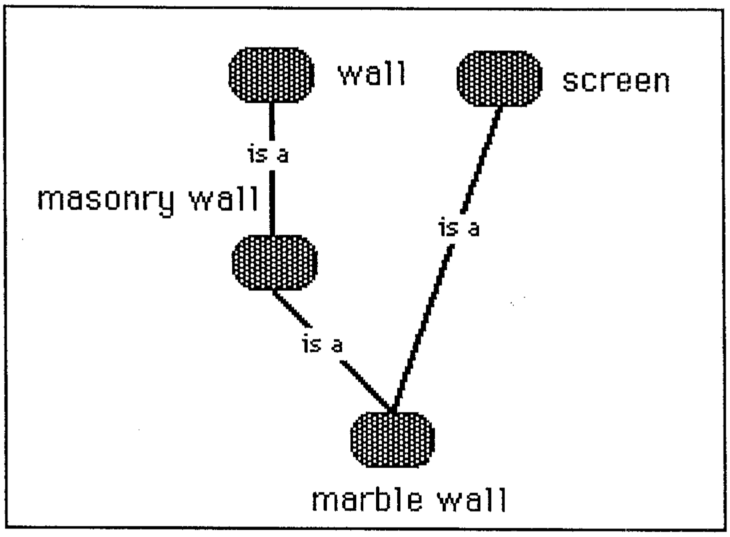
Implicit classification system

Text labels, such as "wall", "door", etc., are typically assigned to objects in an architectural drawing. These labels may constitute an implicit classification scheme. Each label refers to a class of architectural objects. For example, the label "marble wall" on a floor plan drawing may assign the wall to the class of "marble wall" objects. An alternative label on a floor plan may refer to a "concrete wall". The label "concrete wall" assigns the wall to the class of "concrete wall" objects.

Once assigned to a class, an architectural object may be presumed by the architect to inherit properties of that class. An object assigned to the class "marble wall" may inherit some structural attributes of the class "marble wall". Some of the construction attributes of marble walls are likely to be constant. According to traditional construction methods, there is typically a compressive load bearing capacity of the wall. However, the wall object may be assigned to more than one class. A marble wall may be assigned to the class "screen" and inherit the non-load bearing structural attributes of the class "screen". More specifically, in the case of Mies van der Rohe's German Pavilion, the marble "screens" do not have a compressive load bearing function. An object may also inherit attributes from less immediate ancestral classes, such as the ancestral class "wall" of the parent class "masonry wall" (see figure 2).

1 The term *conceptual structure* was suggested by Prof. William Mitchell, MIT, 10.25.92, while reviewing an early draft of my dissertation.

Figure 2: Marble wall with more than one parent



The labeling of architectural objects may apply not just to a finished drawing, but also to a schematic sketch. For example, an architect may sketch a floor plan early in the design process and label an object with the text "marble wall". The object is thereby implicitly assigned to a general class of objects referred to as "marble wall", and yet the choice of all of its specific material properties may be deferred until other aspects of the design are worked out. Later in the design process, more decisions may be made with regard to the materiality of the wall. An object labeled "marble wall" may then be assigned to a more specific class by the use of label "travertine marble wall".

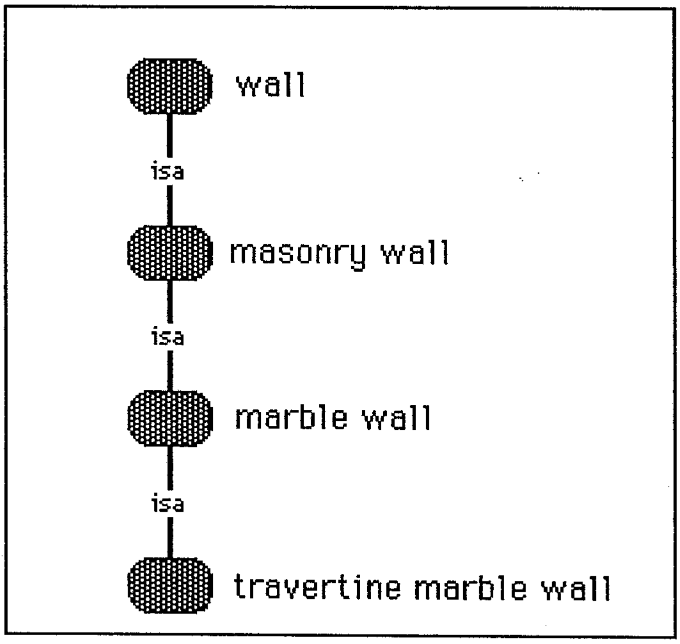
Still, a text label, such as "travertine marble wall" can refer to many different kinds of objects. The text label and the corresponding architectural object are not necessarily synonymous. For example, a particular "travertine marble wall" may yet have further distinguishing features, such as its geometry, its location, and other properties that would make it a specialized instance of the class "travertine marble wall".

The kinds of labels that are used for a design object may reflect individual differences among architects, different periods in the career of an architect, or different periods in architectural history. The theory presumes that the labeling will vary. In other words, it presumes that for the same architectural object, there will be variation in the text labels for it and in the nature of classifications to which the labels may refer. Still, the theory concerns how any set of classifications in effect may be related to the design process. The hypothesis is summarized in the following statement: The inherited properties derived from multiple classifications help to determine the behavior of objects through their varying transformations as a design moves from schematics to a detailed final stage.

Classes and sub-classes

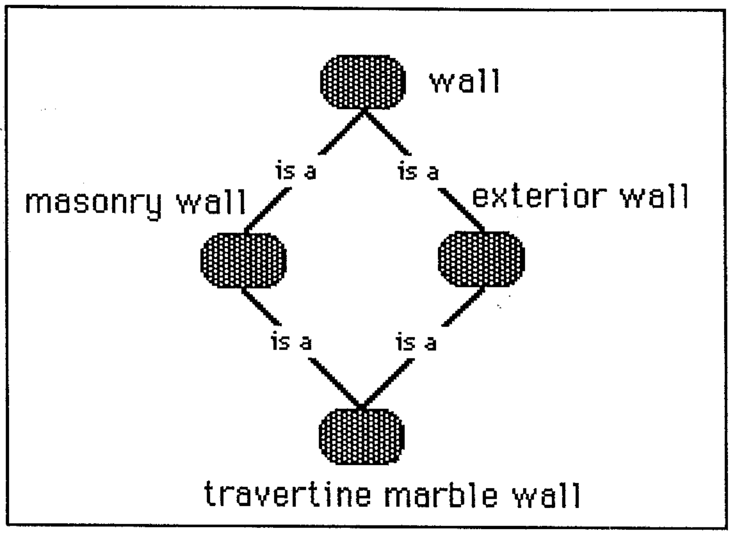
A diagrammatic representation of several classes that may be applied to an object at one time is given in figure 2. Similar diagrams are automatically generated by the software written in support of this study. For example, a "marble wall" may be labeled generally as a "masonry wall". As a design process unfolds, a "masonry wall" may become labeled more specifically as a "marble wall" and then evolve later into a "travertine marble wall" (see figure 3). The label "wall" refers to a general class of objects, the label "masonry wall" refers to a sub-class of objects, the label "marble wall" refers to yet a further sub-class of objects, and so on. In figure 3, the class "marble wall" includes the sub-class "travertine marble wall".

Figure 3: Class and sub-classes



Note that an *instance* of the sub-class is a particular "travertine marble wall" that is placed through a process called *instantiation* at a specific location within a given floor plan. The *instance* inherits attributes and the attribute values of the sub-class "travertine marble wall", such as for the attributes of "specularity", "roughness", "red-color", "green-color", and "blue-color". Other attributes of the instance are uniquely assigned to it rather than inherited. These attributes include its location, orientation, dimensions, scale, and other individual features. The scale of the instance can be varied along its x, y, and z axis. The scaling of the instance is referred to as *parametric variation.* The description of parent classes and sub-classes could evolve as may be related to the unique ideas of a design process. For example, figure 4 is different than figure 3 in that there is a different network of parent classes with respect to the sub-class "travertine marble wall".

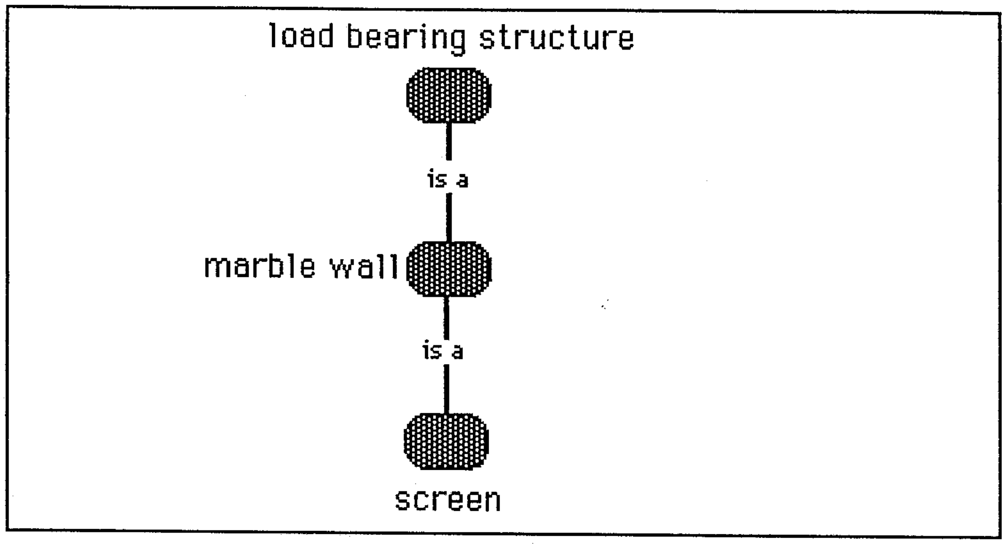
Figure 4: Class and sub-classes



The several parent classes that may be associated with a child object do not need to be consistent or relevant to each other. In the early part of the design process, there may be greater inconsistency between the parent classes of any child object than in the later part of the design process. An architect may at first designate two parent classes that have seemingly inconsistent attributes, such as the parent class "screen" that was typically non-load bearing and the parent class "masonry wall" that was typically load-bearing (during the time that Mies' German Pavilion was first conceived). The inconsistency between "load bearing and "non-load bearing" may remain later in the design process. For example, the masonry walls at Mies' German Pavilion may function as screens and yet are non-load bearing.

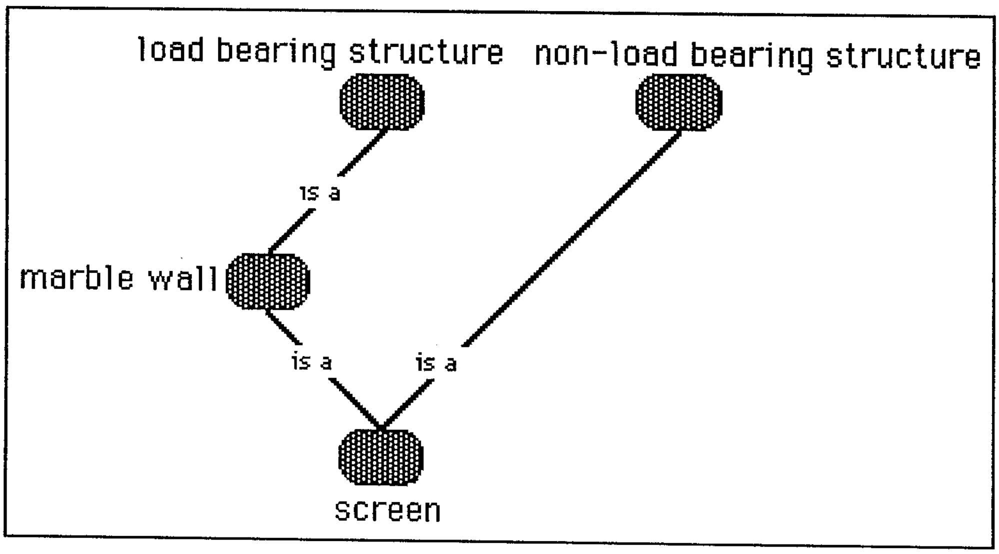
Mies' changed our views about masonry walls in the German Pavilion. That is, the presumed link of the class "masonry wall" with the parent-class "load bearing wall" has been changed. The sub-class "masonry wall" is not only a child of the parent class "load bearing wall.", but is at other times a child of the parent class "non-load bearing wall". The change in classification might be described as that of moving from figure 5 to figure 6 below.

Figure 5: Classification of marble wall as a load bearing wall



An ambiguity of figure 6 exists in the potential for the screen to be viewed as either a load-bearing or a non-load bearing structure. The ambiguity may reflect the actual nature of a "marble screen" until it is put to use. The mechanism which allows this ambiguity to be utilized within a *conceptual structure* is based on the inferential distance algorithm (Mark 1993, Rich and Knight 1991).[2] The algorithm flags potential conflicts in inherited attribute values for an object, and provides the user with the means of selecting from among them.

Figure 6: Classification of screen as a non-load bearing structure



2 A detailed description of this is given in *Conceptual Structure: A Multiple Inheritance Classification and Design System*, Op. Cit.. The algorithm is developed in Rich, Elaine, and Knight, Kevin, Artificial Intelligence.(New York: McGraw-Hill, Inc., 2nd Edition, 1991).

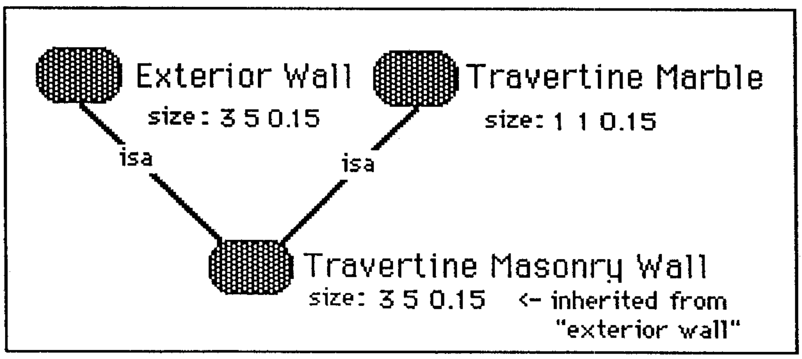
Classification is a dynamic activity that may serve as a conceptual basis for design. This activity can occur throughout the design process. It may occur either with regard to objects that are modified or with regard to new objects that are created. If an object is modified from a schematic state into a more finished design then (1) the set of its classifications may change, (2) the relevance of its classifications may change, and/or (3) one or more of the classes with which it is associated may be redefined. For example, the classification "load bearing wall" may become more relevant for a masonry wall that is re-designed to support beams. Conversely, the classification "load bearing wall" may become less relevant or inapplicable to a masonry wall that is re-designed to not support beams or any other loads. Alternatively, the classification "masonry wall" may no longer be a standard sub-class of the parent class "load bearing wall", if architects like Mies' establish a pattern of designing non-load bearing masonry walls.

Labeling is a key to the classification process. A label may refer to an old, a newly defined or a hybrid classification. In other words, if a new object is added to a drawing, such as a marble wall, then it may be labeled (1) according to an existing class, such as "travertine marble", or it may be (2) labeled according to a newly created class, such as the class "screens", or (3) it may be labeled according to a hybrid class that combines familiar classes, such as the class "travertine marble screen". These labels can have implications with respect to the attributes of the wall, and may have a role in determining the various renderings of it.

Multiple inheritance

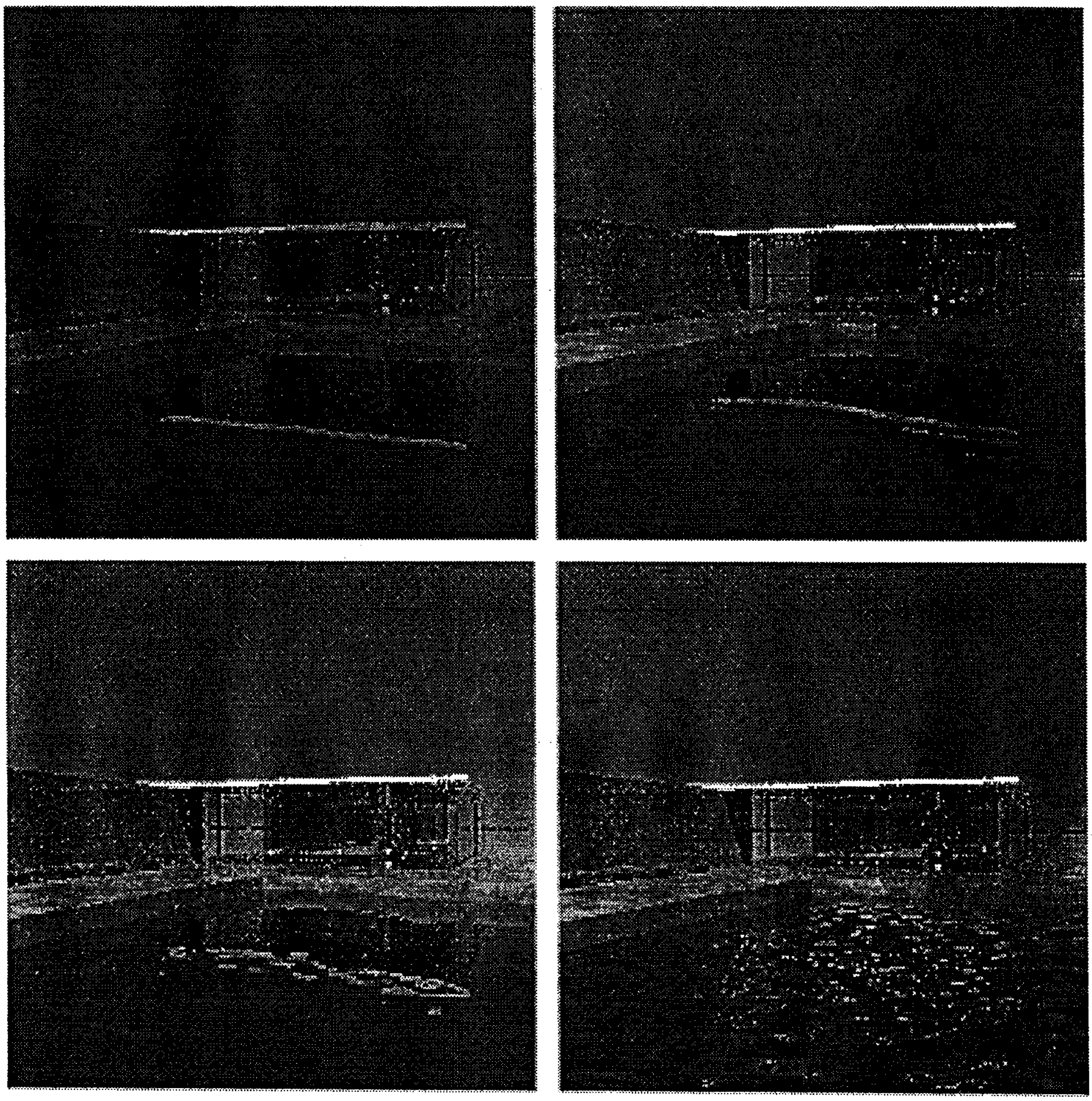
The inheritance of attributes of a wall from any one of its several classifications may be selective. For example, a "travertine masonry wall" may inherit the attributes of "color", "specularity", and "roughness" from the class "travertine marble", but not the attribute of "size". It may inherit the attribute "size" from the class "exterior wall". In some cases, the attributes of an object may be inherited from one of several competing classes. In the preceding example, the "size" of the object "wall" in Mies van der Rowe's German Pavilion could be inherited from the "size" attribute of the class "travertine marble" (1 x 1 x 0.15 meters) or from the "size" attribute of the class "exterior wall" (3 x 5 x 0.15 meters). As stated earlier, the inheritance of potentially different values for an attribute gives the description of an object some ambiguity. This ambiguity may be especially appropriate to an early stage in the design process when there is uncertainty as to which attribute values may be more desirable.

Figure 7: Travertine masonry wall



A study of Mies' German Pavilion developed how a classification label may impact the visual appearance of materials. In figure 8, ray-tracing renderings (Ward 1992) are automated with respect to the materials used in the Pavilion and their attribute values (Mark 1993).[3] Figure 8 depicts a range of possible coefficient values for the perturbation of water (0.0 to 0.25). Note that when the coefficient is 0.0, the relatively still water reinforces the visual appearance of symmetry within the pavilion. This low coefficient value therefore seems to have the most desirable effect.

Figure 8: Raytraced rendering of Mies' German Pavilion with a range of coefficient values for the perturbation of water, grayscale reproduction from color original (0.0 to 0.25)



3 A raytracing program was incorporated into the CAD system developed for this research. An interface was written to Radiance 2.1, Synthetic Imaging System, developed by Greg Ward of Lawrence Berkeley Laboratory, 5.20.92.

Application of a conceptual structure

The case study of Mies' German Pavilion provides an opportunity to consider a range of values for specularity, roughness, red-color, green-color and blue-color of marble and steel materials. The range of potential values for these attributes is an example of the kind of ambiguity that is resolved in the design process. A brief introduction is given here as to how the conceptual structure is used to manage this range of attribute values. Since this publication is gray scale and not in color, a case study of *specularity* is presented here with respect to the steel columns in the pavilion. The attribute of *specularity* refers to the level of shininess in a material.

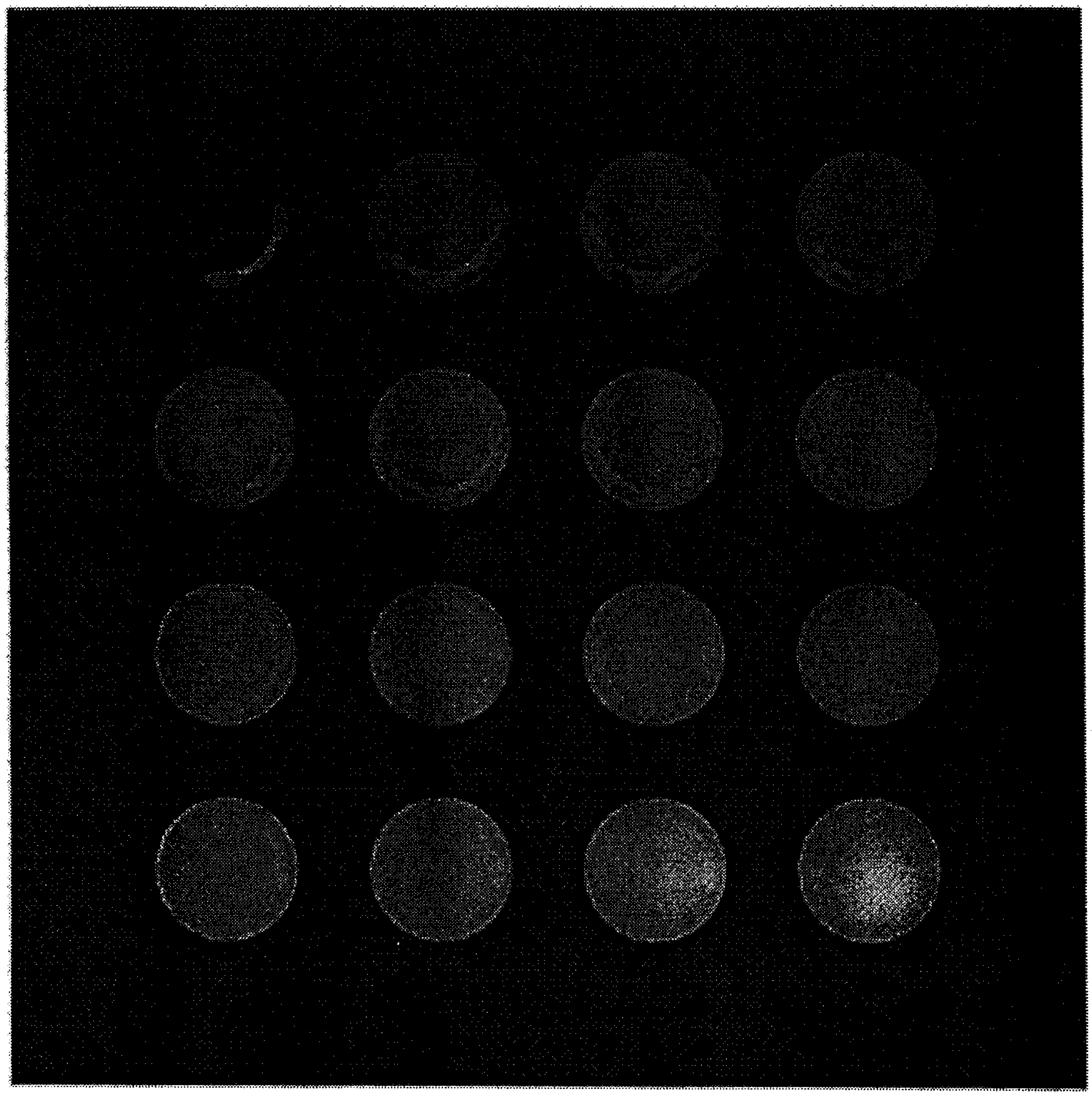
The range in specularity can be expressed as a range of coefficient values from 0.0 to 1.0. The numerical values of the coefficients are meaningful only with respect to a particular raytracing technique; however, a rough interpretation is possible. The different values may be related to different kinds of steel materials and their different finishes. A value of 0.0 would correspond to a material with very non-specular finish, such as that of a flat-tone brushed metal. A value of 1.0 would correspond to a highly specular finish, such as that of a highly polished chrome. One of the alternative values for specularity must be selected to determine the final design of the column.

A conceptual structure was used to encode the specularity of the steel used to build the columns of the German Pavilion. Within the conceptual structure, a class of objects is represented by an object, such as the object "steel". The specularity of the object "steel" may be determined in one of two ways: (1) the specularity attribute can be inherited from one of several parents; or (2) the specularity attribute can be assigned directly to the object and take any one of a set of possible coefficient values. In either case, the designer must resolve what specularity coefficient the final version of the object will have. A conceptual structure that is tied to a visualization tool makes the set of choices easier to test.

In the case of the German pavilion, a sub-class object "column" represents the class of all the columns in the German pavilion. Instances of this column were placed within a 3D CAD model of the pavilion. The sub-class "column" inherited its specularity coefficient from the parent class "steel". In turn, the instances of the "column" inherited their specularity coefficient from the sub-class "column". This situation involves inheritance, but multiple parents are not involved. Rather, a range of specularity values is assigned directly to the class "steel". Therefore, this scenario is most similar to the case 2 above (the specularity attribute can be assigned directly to the class steel and can take any one of a set of possible coefficient values).

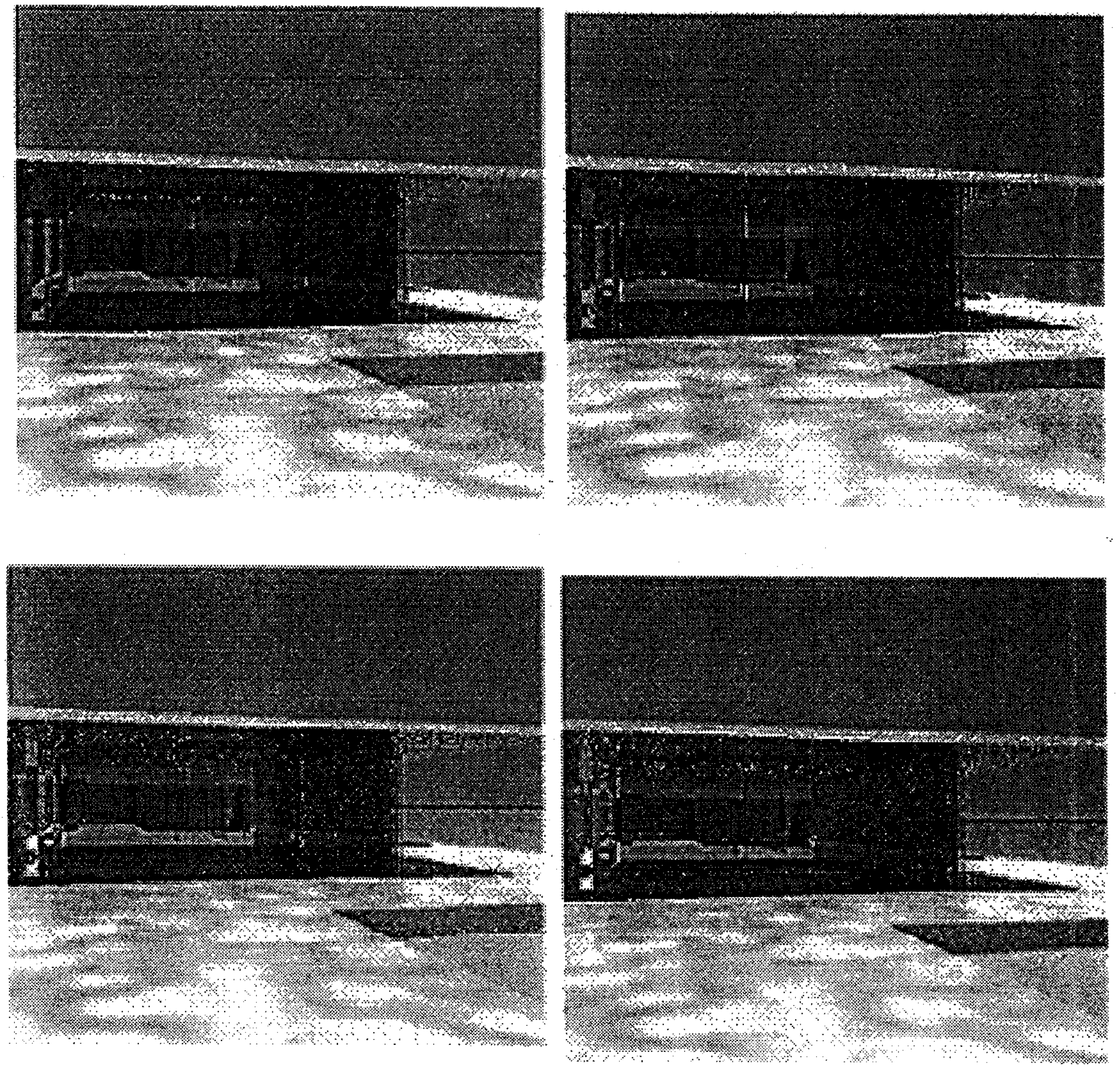
The conceptual structure provides a mechanism for testing a set of attribute values for the specularity of the object labeled "steel". A driver was encoded into the software in order to automate the raytrace renderings. A raytraced rendering is automatically produced that corresponds to the alternative coefficient values for the specularity attribute of the steel. The specularity coefficient ranges from 0.0 to 1.0 in the figure below at increments of approximately 0.09 from left-to-right and top-to-bottom.

Figure 9: Raytrace rendering of specularity of steel material



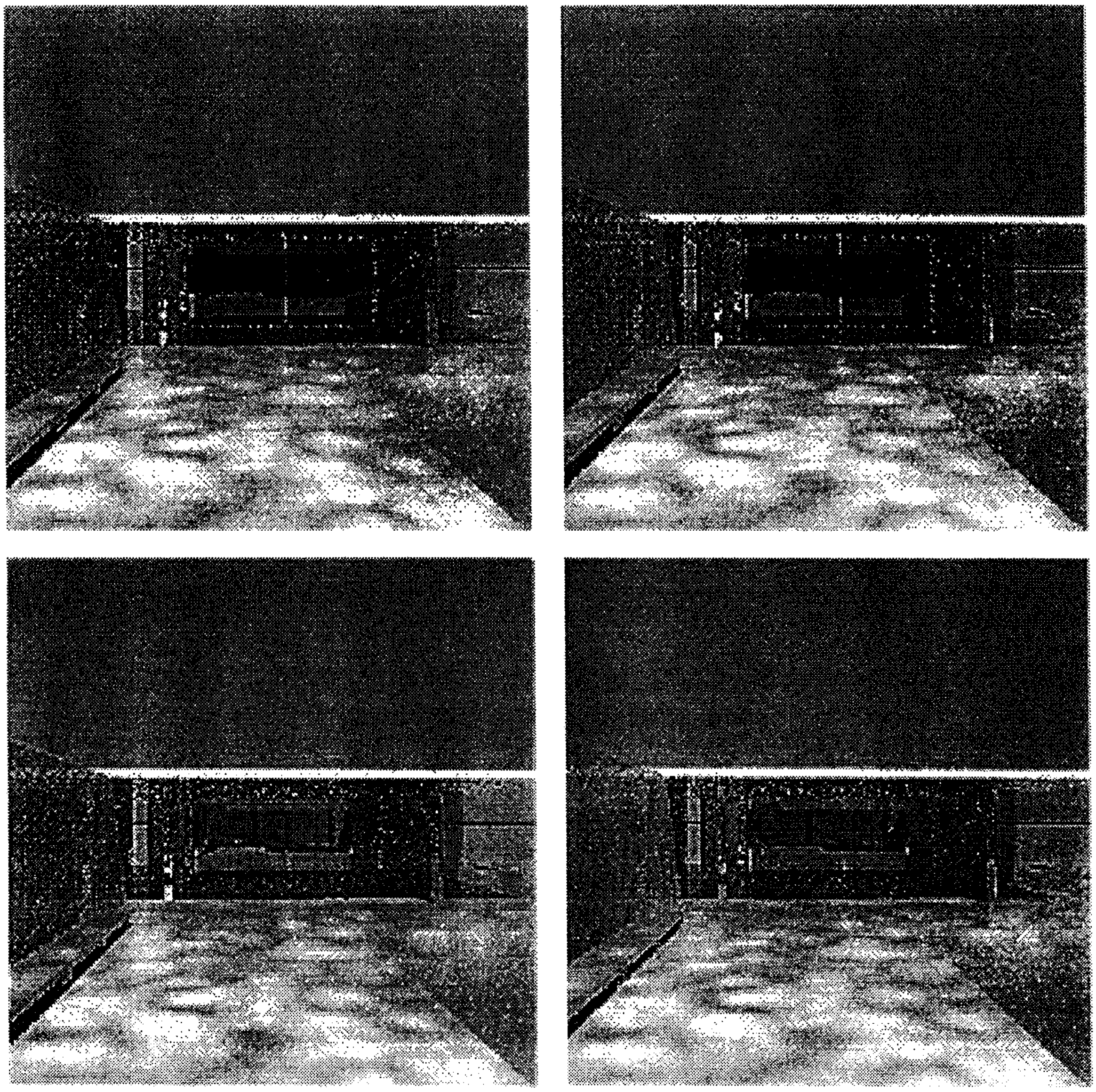
In the next raytraced rendering, the coefficient values for the object labeled "steel" are inherited by the columns within a 3D model of German Pavilion. As in the previous illustration, each of the raytraced renderings are automatically generated from the conceptual structure via a batch file command sequence. The renderings correspond to a range in specularity coefficient values inherited by the steel columns. The specularity coefficient ranges from 0.0 to 0.09 in the figure 10 at increments of 0.25 from left-to-right and top-to-bottom. Note that the interior of the pavilion is more visible from the exterior when the specularity of the columns is higher. The heightened visibility of these regularly spaced columns has the effect of reinforcing the symmetry of Mies' design.

Figure 10: Raytrace renderings for a range of specularity coefficient values



A similar test of coefficient values was examined with respect to the transparency of glazing. The coefficients range in figure 11 at increments of 0.25 from left-to-right and top-to-bottom. Note once again that the interior of the pavilion is more visible from the exterior when the transparency of the glazing is higher. Too great a transparency for the glazing (lower right) has a less subtle effect on the reinforcing the symmetry of Mies' design. The mid-level coefficient (upper right) is more consistent with the aesthetics in effect at the pavilion.

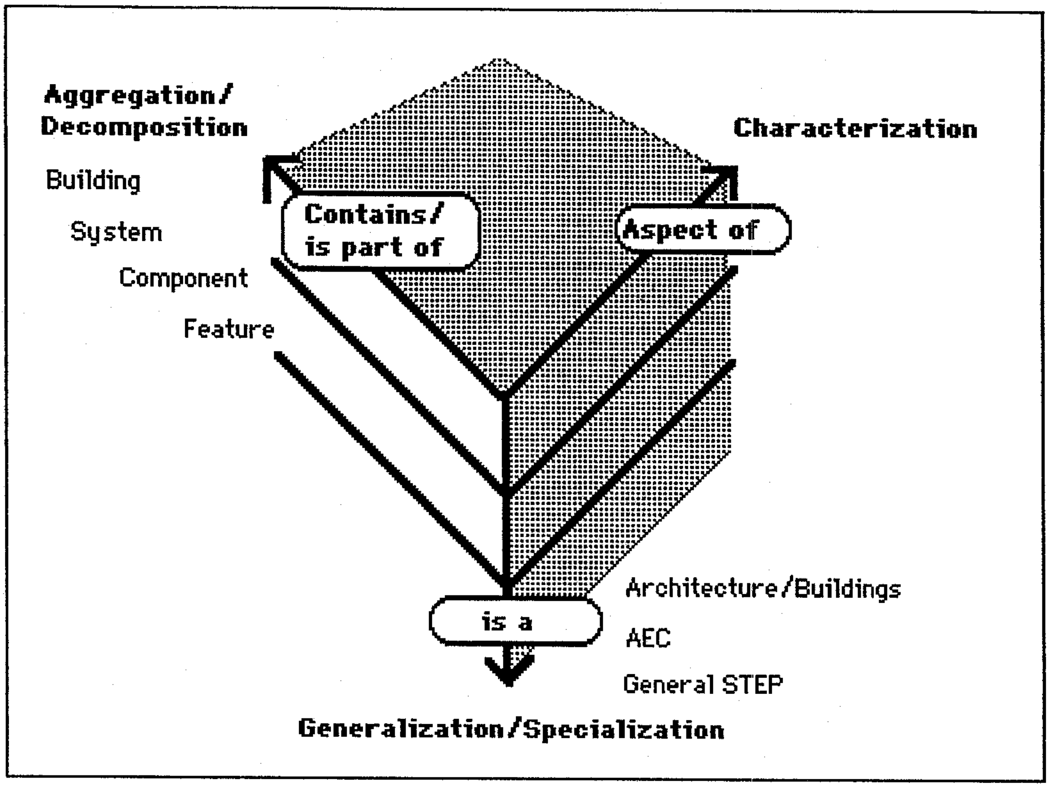
Figure 11: Raytrace renderings for a range of transparency coefficient values.



Organized sets of labels

Labels can be organized hierarchically. Labels that refer to general classes of objects, such as the label "wall", are located high within the hierarchy, and labels that refer to more specific sub-classes of objects, such as "travertine marble wall", are located low within the hierarchy. Advocates of architectural standardization have proposed that a hierarchical system of classes and sub-classes could be used for managing documents in the building construction industry. An example of such a system is the AEC reference model developed under the auspices of the International Standards Organization. Its authors have made the argument that to help reduce the present chaos that exists in architectural practice, it is necessary to implement a uniform classification scheme by which objects can be communicated between different partners in the building design process.

Figure 12: ISO General AEC Reference Model (redrawn after paper by Gielingh 1990)



The simplistic approach towards standardization, however, is to make the presumption that all labels with the same name have the same meaning. Yet, a particular label may have a variety of meanings depending on the context in which it is used. For example, a label such as "room" could have a different meaning when used with regard to an open space plan as compared to when it used with regard to a non-open space plan. Therefore, a more considered approach is to develop a hierarchic classification system where it is not assumed that a specific name for a label has a universal meaning. Rather, the meaning associated with a particular label may be determined on the basis of certain attributes which are also specified (see figure 13).

This approach may not require that a label of a given name have a consistent meaning whenever it is used. Yet, it makes the less obvious presumption that the label have a consistent meaning at a lower level. In particular, it make the presumption that the label's attributes would have consistent meaning. For example, figure 4 illustrates the label "TRAVERTINE" and some of its attributes (excerpted and modified from a database developed for this dissertation). The attributes of "OBJECT-CHILDREN", "OBJECT-NAME", "ORIGIN", "GEOMETRY", etc., would need to have a universally consistent meaning. However, the meaning of an attribute may be difficult to standardize. The interpretation of what the specularity coefficient 0.01 means and how it is applied could be subject to some variation. Therefore, the problem of consistent meaning is deferred to the attributes but not really solved.

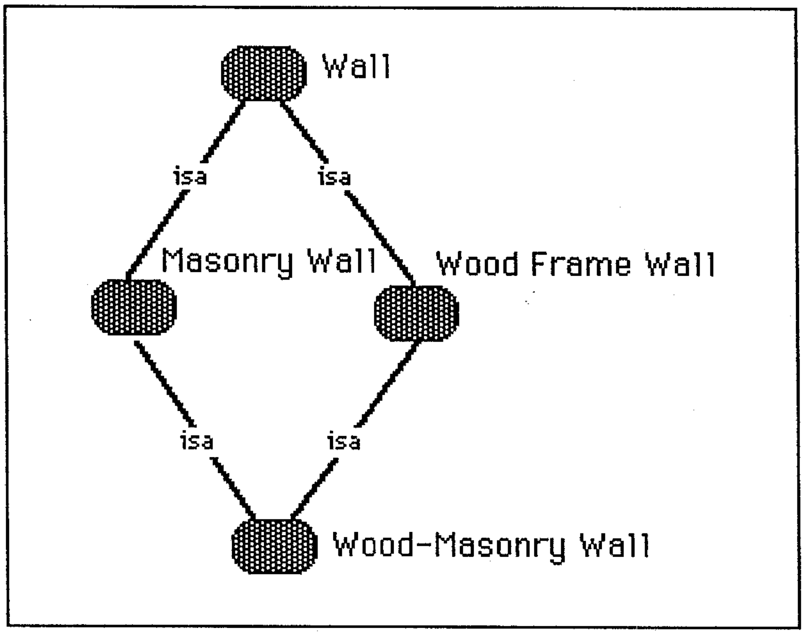
Figure 13: Attributes of object "travertine" excerpted from a database

```
** architecture object **
TRAVERTINE
(OBJECT-CHILDREN (TRAV-WALLS TRAV-ROOFS TRAV-FLOOR))
(OBJECT-NAME TRAVERTINE)
(ORIGIN (0 0))
(GEOMETRY ((FRAME-RECT 0 0 50 50)))
(PEN-THICK 262148)
(PEN-PAT *light-gray-pattern*)
(STATE 1)
(ORIENTATION 0)
(SIBLINGS NIL)
(CONSTRAINTS ((NIL NIL) (NIL NIL) (NIL NIL) NIL NIL NIL))
(RED 0.75)
(BLUE 0.4)
(GREEN 0.4)
(SPECULARITY 0.15)
(ROUGHNESS 0.5)
* end object *
```

A standardized hierarchical classification scheme, such as the proposed AEC reference model, may be practical and necessary for managing documents in the construction industry where any conventional system may be better than no system at all. However, it may be too rigid a system for the schematic design process. The problem of schematic design is not just the uncertain meaning of a label for an object, or the uncertain meaning of the attributes associated with the label, but also the ambiguity of the object itself.

An object labeled as a "wall" may have a number of different meanings. In one sense, the designer may want to think of it as a kind of "masonry wall", and in another sense as a kind of "wood frame wall". While the designer is mulling over the alternative possibilities for the "wall", it may be correct to classify it in some contradictory ways. The designer may want it to inherit some attributes of "masonry walls", such as massiveness and compressive strength, and to inherit other attributes that exist within "wood frame walls", such as "openness" and "span". The designer could be seeking to develop a hybrid "wood-masonry wall" that is a sub-class of several types of walls (see figure 14). This kind of hybrid wall is not readily accommodated within a database reference system that does not provide for ambiguity.

Figure 14: Wood-masonry wall



Classification as a dynamic activity with convergence

The theory proposes that the architectural design process is an activity in which a number of inconsistent classifications may be applied to a design object. These classifications may co-exist all the way through the design process and also co-exist within the end product. Ambiguity exists since an architectural object may have some but not all characteristics of a classification to which it is assigned. Ambiguity also exists since an object may simultaneously have characteristics of several classifications. Some ambiguity is resolved as the design progresses from schematics to a more detailed final stage. A "wall" becomes a "marble wall". When available marble materials and their overall composition are taken into account, the "marble wall" may then become a "travertine marble wall".

The assignment of an object to its classifications may be developed over time, and the classifications themselves may be in a state of flux. At one time, the object may be a "travertine marble wall", and at another time the object may be a "green tinian marble wall". At one time, the class "wall" may mean a load bearing element, and, at another time, the class "wall" may mean a non-load bearing screen or protective membrane.

Architectural historians provide some of the classifications that architects are likely to use. Wittkower describes classifications used by important architects and used during particular periods in architectural history. He has described how the classification of an architectural object may change over time according to structural properties and according to its associations with particular architectural components (Wittkower 1952). For example, in the case of architect Alberti, columns are thought of as non-wall ornaments during one period in his architectural career, and are thought of as wall elements during another period. For Alberti, the class of objects "wall" seems to have gone through a period of transition from meaning one set of objects to meaning another set of objects. The column on the front of Alberti's Facade for S. Francesco, Rimini are ornamental and not identified closely with the structure of the wall behind them. Yet the column pilasters on the side of the cathedral are more closely integrated within the wall, and may be thought of more directly as a sub-class of "wall elements".

The general set of architectural classifications may be uncertain with respect to the objects used within a particular design project or with respect to the objects used by a single architect over the span of a career. This uncertainty is at odds with attempts to predefine classes of objects in advance of a design project. The uncertainty is problematic in conventional approaches to computer aided architectural design. In a conventional computer aided architectural design system, objects are pre-defined according to architectural classes, such as sets of windows, doors and walls. Compositions are restricted to the pre-programmed possible ways of handling compositions of the predefined architectural types. An automated "walls" package contains specific algorithms that are predefined to manage the joining, deleting, inserting, projecting, trimming and scaling of walls that fit some presumed topological descriptions. Yet, an architect may want to explore new possible topologies in every instance of design. Accordingly, in every design effort, an architect may need to afford the possibility to redefine classifications of walls and to redefine their possible topologies.[4]

Conclusion

The problem of the *design automation paradox* is addressed in part by the use of a *conceptual structure*. Walls can be drawn schematically and classified at a high classification level (i.e., classified in terms of the class "wall" rather than in terms of the sub-class "travertine marble wall"). It is easier to automate the drawing of schematic walls than it is to automate the drawing of detailed walls. As the specification of wall materials becomes more certain, walls become sub-classified as a more detailed kind of object. The drawing of more detailed walls then may or may not be difficult to automate, depending on the complexity of their geometry. At this stage in the design process, the architect has the option to use the less automated drawing processes if needed. In the interim, the drawing of more schematic walls is easier to automate, and there is no loss of generality.

This paper assumes that the architectural design process can be characterized with respect to individual objects which are multiply classified. A more complete study of Mies' design for the German Pavilion developed separately illustrated how the classification for an object can transform over five stages in the evolution of the design, and how classification may play a significant role in determining the properties of the object that emerge throughout the design process (Mark 1993). According to this theory about classification, the following is held to be typically true about the design process:

1. The classifications are in flux.
2. The objects inherit characteristics and behavior from their classifications.
3. The objects may switch classifications.
4. The objects are in flux (are redefined, partitioned, assembled differently).
5. Emergent objects are fitted within classifications.
6. Emergent objects may give rise to new classifications; however, this is rare.
7. New classifications may emerge; however, this is rare.
8. Some of the classifications of an object may be mutually exclusive.
9. The number of classifications overall is kept economical.
10. The number of classifications associated with any one object is kept economical.
11. Transformation rules can be described as object oriented.
12. Transformation rules can be described as class oriented, including the class of all objects (the universal class).

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4 The problem of predefined classifications in a conventional computer aided design systems is taken up in the paper *A Design Automation Paradox* (Mark 1990).

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