CAD modelling in multidisciplinary design domains

M. A. ROSENMAN, J. S. GERO

Key Centre of Design Computing
Department of Architectural and Design Science, University of Sydney
NSW 2006 Australia
{mike, john}@arch.usyd.edu.au

Abstract

In a multidisciplinary design environment, such as the architecture, engineering and construction (AEC) domain, the various designers will have their own views, concepts and representations of design objects, making communication in a CAD environment a complex task. This paper demonstrates that by taking into consideration the concepts of function and purpose such multiple views and representations can be accomodated. The representation of the functional properties of design objects and their purpose is the underlying basis for the formation of different representations and the coordination of these representations. The paper puts forward definitions for function and purpose which allow for the representation of these properties of a design object and for interdisciplinary communication and integration in a CAD environment.

1. INTRODUCTION

Large scale design projects involve many different disciplines each with their own area of concern and expertise. At various stages of the design designers from different disciplines will represent an abstraction (a model) of the current design according to their views. These different models will initially be incomplete and inconsistent but through collaboration they will undergo changes as inconsistencies are removed and details are added and eventually a consistent representation emerges.

While currently paper-based representations are the conventional method used for representation, it is being realised that the complexity of large-scale design projects can only be adequately handled by a systems integration and automation approach and that computer-aided design (CAD) is the vehicle for providing this integrated information processing (Madison, 1991). However, the use of CAD systems for representing design objects brings into focus the aspects of explicit/implicit representations and especially the requirement of different views and representations of the same design object by different design disciplines.

In order to make CAD modelling useful to designers in a multidisciplinary collaborative environment, such as the Architecture, Engineering and Construction (AEC) domain, each designer's view and representation must be accommodated and integrated within a comprehensive representation of the design under concern. This paper argues that a multiple view approach is essential for any meaningful representation in a multidisciplinary environment. Since views and representations depend upon a functional context, i.e. a particular set of functional concerns, the representation and application of functional properties is an essential aspect of any successful collaborative CAD modelling.

2. MULTIDISCIPLINARY DESIGN DOMAINS

2.1 Concerns and concepts

The AEC domain typifies a multidisciplinary design domain. In the AEC design environment, many disciplines are involved, each dealing with a specialized aspect of the building design and each with its own concepts and interpretations of the object (the building). The fragmentation of the design and construction disciplines in the AEC domain is due to the specialization of each discipline according to functional concerns.

Architects are mainly concerned with providing sufficient, efficient and aesthetic spatial environments for a given set of activities. They are thus concerned with concepts such as spatial sufficiency, spatial organization, comfort, aesthetics, weatherproofness, rooms, storeys, facades, floors, walls, etc. Structural engineers, on the other hand, are concerned with providing stability by resisting or transmitting forces and moments. They are concerned with concepts such as gravity/lateral loads, support, bending, shear, deformations, beams, columns, shear walls, etc. Contractors, on the other hand, are concerned with the constructability of a design and hence with the relationships between the physical elements and the operations and sequence of operations required to construct the building. That is, they are concerned with concepts such as availability, composability, time and place, stability, walls, windows, beams, pipes, etc. Some aspects are the concern of more than one discipline, e.g. stability is the concern of both the structural engineer and the contractor.

2.2 Collaboration between the disciplines

Paper-based representations, in the form of line drawings, have been the conventional method used for representation and communication of information between designers. Each discipline represents its model in its own set of drawings (blueprints) where each such set of drawings represents that discipline's model of the building using that discipline's set of representation conventions. Any inconsistencies between the various models are corrected by marking the appropriate drawings and sending them back to the appropriate discipline. This process usually goes through several iterations. The result is a number of sets of drawings, one per discipline, where, although each set represents the building using a different model, the comprehensive representation is consistent. There is no attempt to integrate the various sets of drawings into one drawing.

The advantages of using CAD as a modelling tool for systems automation and integration and for communication between distributed members of a project have been extensively presented (Madison, 1991; Howell, 1996). The method which has generally been accepted, as the means of enforcing consistent representation and interpretation is the construction of a single unified model of the design object under consideration (Bjork, 1987, 1989; Gielingh, 1989; Nederveen et al, 1991). The argument put forward in this paper is that this single model is incapable of representing the different views and models of the different disciplines and that the traditional paper approach, actually represents a necessary approach which has to be dealt with in any electronic communication medium such as CAD. This multiple model approach needs to ensure that consistency is achieved and maintained throughout the various representations.

3. MULTIPLE VIEWS AND MODELS

3.1 Multiple views

We are concerned with the perception, conception and representation of design objects by different design participants . We build a conceptual model of an object based on that view, i.e. a representation, and manipulate that representation when we communicate. In a design context, the view that a person takes depends on the functional concerns of that person. Given a design object, such as a building, there are many views that we may take, leading to different conceptual interpretations. For example, a building may be viewed as a set of activities that take place in it; as a set of spaces; as sculptural form; as an environment modifier or shelter provider; as a set of force resisting elements; as a configuration of physical elements; etc. A building is all of these, and more.

3.2 Multiple models

A model of an object is a representation of that object resulting from a particular view taken. For each different views of a building there will be a corresponding model, Figure 1.

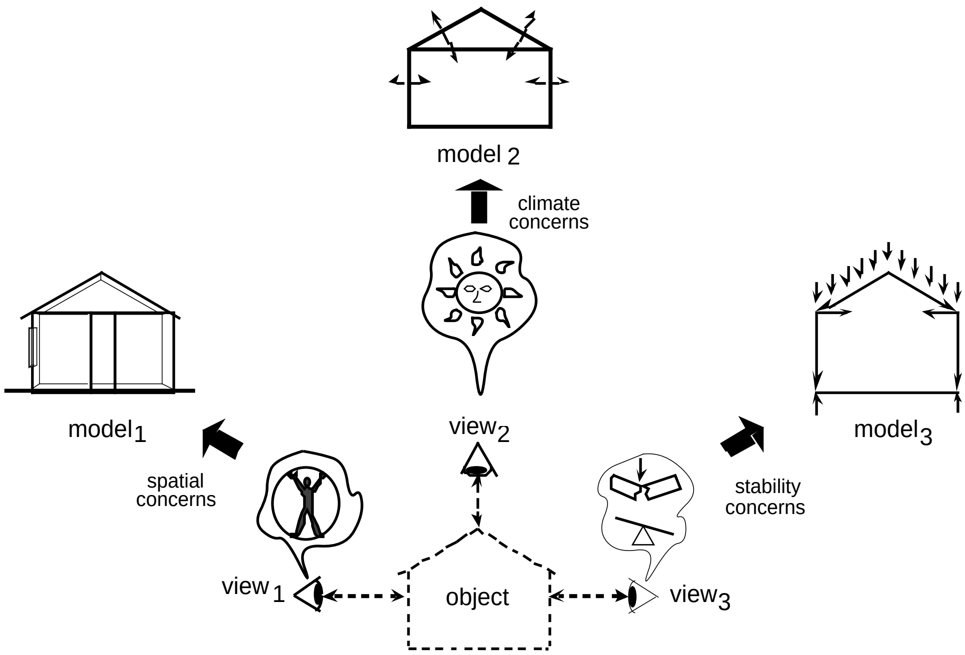

Figure 1. Multiple Views and Models

Depending on the view taken, certain properties and descriptions of the object become relevant. The sound insulating properties of a wall are not relevant to a structural engineer's description of that wall. In fact, many walls may not be relevant at all to a structural engineer if they do not either contribute directly to the stability of a building or indirectly by providing a substantial load. The architects will model certain elements such as floors, walls, doors and windows. For the architects, these elements are associated with the spatial and environmental qualities with which they are concerned. Structural engineers, however, see the walls and floors as elements capable of bearing loads and resisting forces and moments. Both models must coexist since the two designers will have different uses for their models. For example, the structural engineers will need to carry out calculations based on their model while the architects may need to ascribe different properties to their separate wall elements,. The engineers may modify some of the properties assigned to these element by the architect and may add some new elements, such as beams and columns. The addition of such new elements may affect the architect's model (and vice versa). Any such decisions taken by the engineer must be conveyed to the architect by making changes in the architect's model as appropriate. It will be shown that such changes in another discipline's model can be done when the change affects a function which is the concern of that discipline.

3.3 Representing multiple models

There exists considerable work using a single model approach based on the construction of a model from 'primitive' elements from which multiple interpretations are derived (Howard et al, 1992; Amor and Hosking, 1993; Clayton et al., 1994; MacKellar and Peckham, 1994). This approach is analogous to the formation of views in database management systems. However, it is argued that, this approach is insufficient since the 'primitive' elements themselves are subject to the views taken by the different viewers and hence different primitive models are constructed by each such viewer (Rosenman et al. 1993; Rosenman and Gero, 1996). Since the basic description of an object differs from viewer to viewer, each viewer may represent an object with different elements and different composition hierarchies. For example, while architects may model walls on different floors as separate elements, bounding various rooms, the structural engineers may model only a single shear wall. So that, not only is the interpretation of the meaning of a design object different from one viewer to another but, also the description of the structure of the object differs. This approach is similar to that taken by Nederveen and Tolman (Nederveen, 1993; Nederveen and Tolman, 1992) and Pierra (1993). There exists no single unified model nor even a single set of unique elements but rather different descriptions of the same elements and different subsets of these descriptions in different models. Each model must be consistent vis-a-vis the object being described. .

Since the various models constructed by the various disciplines are representations of elemental models as seen through views based on functional contexts the representation of functional properties of design objects is the underlying basis for the formation of different concepts.

4. PURPOSE, FUNCTION, BEHAVIOUR AND STRUCTURE

4.1 definitions

The essential factor in a description of any design object allowing for the formation of multiple interpretations is a description of its functional properties in addition to its structural properties. There have been various attempts at defining the concepts of purpose, function, behaviour and structure, among them the following, (Bobrow, 1984; Sembugamoorthy and Chandrasekaran, 1986; Pahl, and Beitz,, 1988; Umeda et al., 1990; Goel, 1991; Hundal, 1991; Johnson, 1991; Gero et al., 1992; Sturges, 1992). Notwithstanding such a large number of work, there is still confusion especially as regards the relations between the concepts of purpose and function and the concepts of function and behaviour. For example, Umeda et al. (1990) state that 'to support X' is a representation of function, since it is 'to do 'something whereas 'A is supporting B' is a description of behaviour.

The definitions that will be used here are those put forward in (Rosenman and Gero, 1998).

purpose: is the reason why an artefact exists or why it is what it is, what it is intended for;
function: is what is performed by an artefact;
behaviour: is the manner in which an artefact acts under specified conditions;
structure: is what constitutes an artefact (or defines its constitution).

The acceptance that the function of an artefact is what it does, rather than what should do, results in the recognition that artefacts perform many functions, only some of which were intended. Motor cars belch out exhaust fumes, they clog up streets, they make noise. None of these functions were intended but occur.

4.2 Purpose as intended function

Many design problems are removed from direct human needs. While they may be subproblems of some larger design need, nevertheless within their sphere they are treated as design problems. Thus the designs of gears, amplifiers, trusses, etc., are treated by their designers as encapsulated design problems. As such, purposes are assigned to the design of these artefacts which are removed from human socio-cultural needs and hence take on a more technical aspect. Such purposes are, in effect, intended functions. They describe the functions that an artefact should achieve, e.g. transformation of torque, transformation of a signal, transfer of loads, etc. To an architect the purpose of an element may be to provide an unencumbered uniform space under it, to the structural engineer the intended function or surrogate purpose is to transfer some set of loads in a given way. Thus the design of some artefact which is a design problem to some designer but where the artefact will only be used as a component in some larger system is assigned a purpose in terms of its intended or required functions.

4.3 Representing purpose and function in CAD systems

The representation of functional properties becomes the essential factors in a representation schema for modelling in a multidisciplinary collaborative environment. The current practice in CAD systems is to represent merely the structure properties of an object, usually only the graphical representation. It is not always possible to infer functional information from a structural description. For example, one cannot determine that a wall is loadbearing from topological relations alone. Experience in acquiring information from drawings in a case-based reasoning project at the Key Centre of Design Computing has shown that it is not possible to determine information such as whether a beam is part of the lateral force-resisting system, from the structural engineer's drawings, without recourse to the designers (Balachandran et al., 1992). The recognition that graphical properties, while important, are not the only properties that need be described in an object’s representation forms the underlying basis of the STEP effort for electronic data exchange of product information (STEP, 1991).

5. CONCEPTS AND DESCRIPTIONS

Design prototypes describe classes of design elements and include a categorization of purpose, function, behaviour and structure properties (Gero, 1990; Gero and Rosenman, 1990). In a fragmented environment, such as AEC, each discipline has its own set of design prototypes with its own concepts, terminology and visual representations which are not necessarily shared between the disciplines. Specific examples of design prototypes, i.e. instances, are described using the design prototype schema and by instantiating all relevant properties to specific values and form that discipline's model.

However, to provide integration between the concepts of the different disciplines, generic concepts which contain properties common to the disciplines are necessary (Nederveen, 1993; Pierra, 1993).

Any element of any discipline's model will inherit these properties and thus be subject to being part of other disciplines' models. Figure 2 shows an example of generic concepts for walls and columns and the architects' and structural engineers' concepts, which are views of the generic concepts. Not all the behaviour and structure properties are shown.

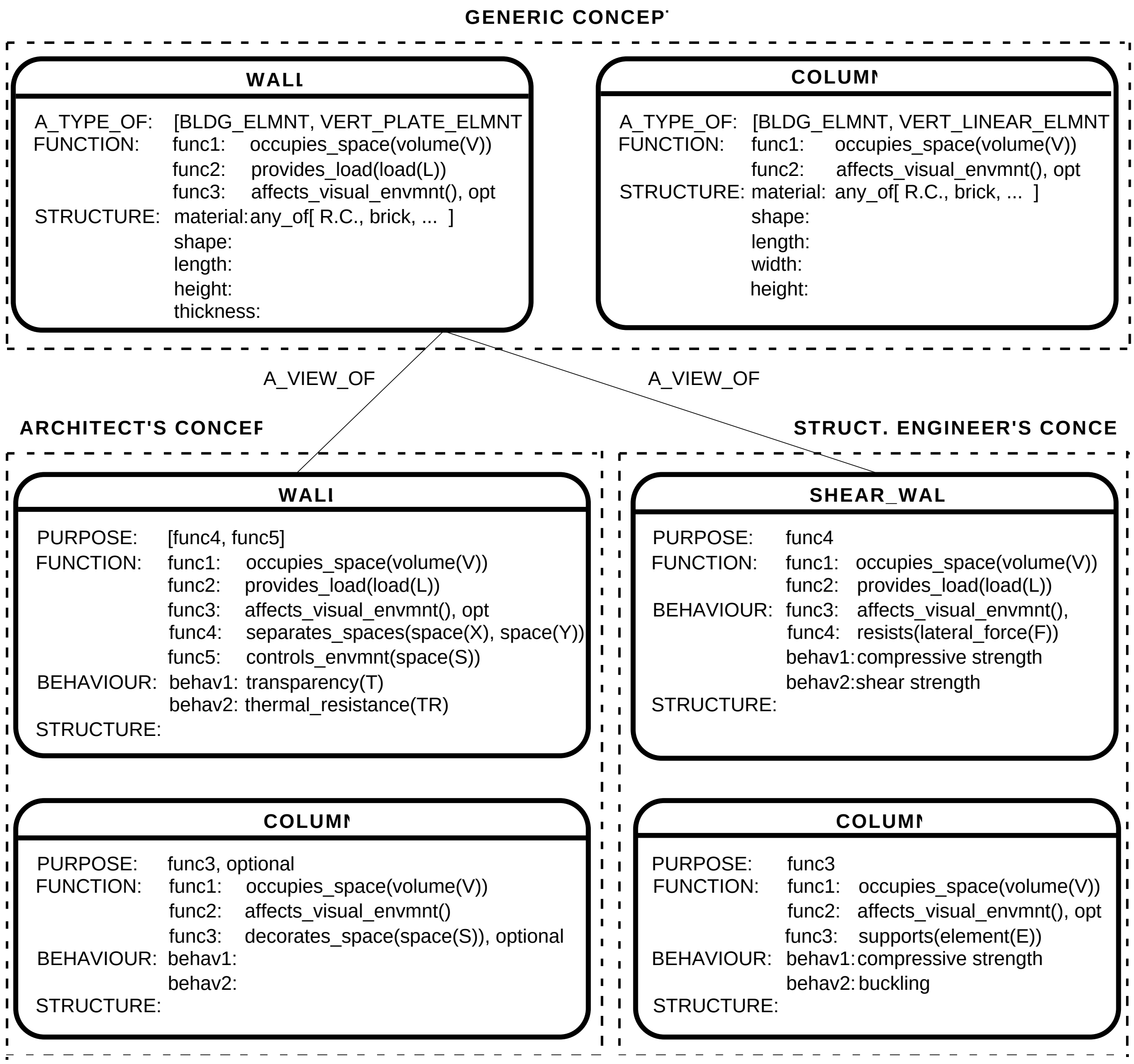

Figure 2. Generic and Discipline Concepts

The generic concepts do not include any purpose, since purpose is strictly a view-based concept but include those functions which occur whenever an element of that type occurs. For example, the generic wall concept includes three functions which occur when a wall exists but are actually side-products to the existence of a wall. That is, these are things which the wall does regardless of intention. The 'provides_load' function is marked as optional since it depends on the actual composition of the wall and the structural engineers's decision. However, any wall element created by the architect for space separation and environment controlling purpose which inherits a possible provide_load function from the generic concept produces a corresponding element in the structural engineers's model. The structural engineers may then assign any of the two optional functions and purpose to this element. Conversely, any wall element created by the structural engineers for a functional purpose will inherit the 'occupies_space' and 'affects_visual_envmnt' functions from the generic model and hence produce a corresponding element in the architect's model.

Once a designer's view has been expressed as a set of concerned functions, all elements, whose functions contribute to those functions defined for that view will become part of that designer's model even if created by another designer. This will be so even if the functions were not intended by that other designer as described above. Finding the relationships between contributing functions is not a simple text match but may have to be carried out through various levels of abstraction (Hwang, 1994).

6. FUNCTIONAL MODELLING IN COLLABORATIVE CAD MODELLING

6.1 Assignment of purpose and function

There are two main ways in which the modelling of functional properties, can help in communication between the different disciplines as they collaborate to achieve the intentions of each designer as well as consistency in the description of the artefact under consideration.

1. assigning purpose to define intentions, i.e. intended functions;
2. assigning functions to elements and relating those functions to the concerns of the various designers.

In the first case, an intended function, a purpose, assigned to an element by a designer will result in an indication that the existence of that element is contingent on that purpose. Thus, the element cannot be modified in a way that will impair the intended function. For example, the assignment of a lateral force-resisting or a loadbearing function to a wall by a structural engineer should now prevent the architect from removing that wall.

In the second case, elements will, by their existence, carry out certain functions which will be associated with their conceptual description, e.g. in a design prototype. So that even if a designer does not assign a particular intended function to an element, this function will still be assigned to the element by default. This function may not be of concern to that particular designer but may be of concern to other designers. For example, the structural engineer may add a column in a space to carry out some intended support function. However, one of the unintended yet existing functions of columns is that they occupy space. This function of space occupation is of concern to the architect and as a result, that description of the column which relates to the space occupation function will now form part of the architect's model. That is, the column will appear in the architect's model.

Thus, it is through the concepts of function and purpose, assigned to design objects, that information is transmitted, allowing for the coordination of the overall decision-making effort.

6.2 Relationship between models

Elements in the different models which are related must be related explicitly through explicit relationships. For example a floor element in the architect's model and a slab element in the structural engineer's model, which refer to essentially the same physical element, must be related by a relationship such as a *same_as* relationship. This 'same_as' relationship specifies that the structural properties of the 'two' elements are the same. Another relationship is the *part_of* relationship. This is not the same as the common understanding of 'part_of' which in actuality is more accurately labelled as *component_of*. Thus, a bicycle wheel is a 'component_of' a bicycle whereas a designated part of a concrete slab is 'part_of' that slab. The 'part_of' relationship allows inheritance of properties whereas the 'component_of' relationship does not. The 'part_of' relationship allows elements of one designer's models to be 'part_of' an element of another designer's model thus allowing for consistency of properties such as dimensions and material. Other constraining relationships need also be stated, as for example, that the height of a wall element in the architect's model is related to the depth of a beam element in the structural engineer's model.

7. A BUILDING EXAMPLE

Below is set out a simplified example of a collaborative CAD session between different disciplines. Firstly, the architect models some concept for part of a horizontal slab-type office building. The wall, floor and roof are represented as lines since their material and thickness are as yet undecided. Some of the dimensions also are not fixed. Figure 3 shows the architects' first conceptual graphical representation.

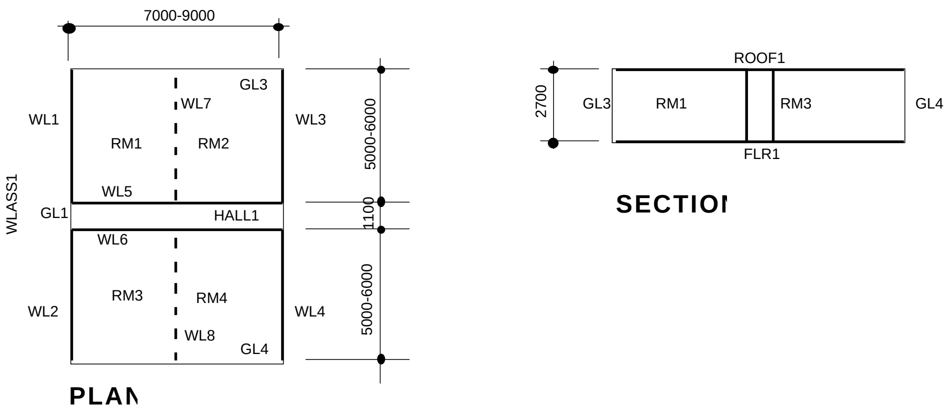

Figure 3. Graphical Representation of Architect's First Model.

Figure 4 shows a simplified description of some of the architect's first model. Only some elements and attributes are shown. Behaviour attributes are not shown.

<u>WL1</u>

AN_INSTANCE_OF:
WALL
PURPOSE:
[func4, func5]
FUNCTION:
func1: occupies_space(volume(W))
func2: provides_load(load(L))
func3: affects_visual_envmnt([facade, RM1])
func4: separates_spaces(exterior, RM1)
func5: controls_envmnt(RM1)
STRUCTURE:
component_of: [WLASS1, RM1]
material:
shape: rectangular_prism
llength: 5000-6000
height: 2700
tthickness:

<u>GL1</u>

AN_INSTANCE_OF:
GLAZED_ELEMENT
PURPOSE:
[func1, func2]
FUNCTION:
func1: allows_light(HALL1)
func2: controls_envmnt(HALL1)
STRUCTURE:
component_of: [WLASS1, HALL1]
material: GLASS
shape: rectangular_prism
length: 1100
height: 2700
hickness:

Figure 4. Non-Graphical Representation of Architect's First Model

The structural engineer examines the architect's first model and notes that walls WL7 and WL8 have intended functions of providing flexibility to the respective room spaces. As such the structural engineer proposes the following scheme, Figures 5 and 6.

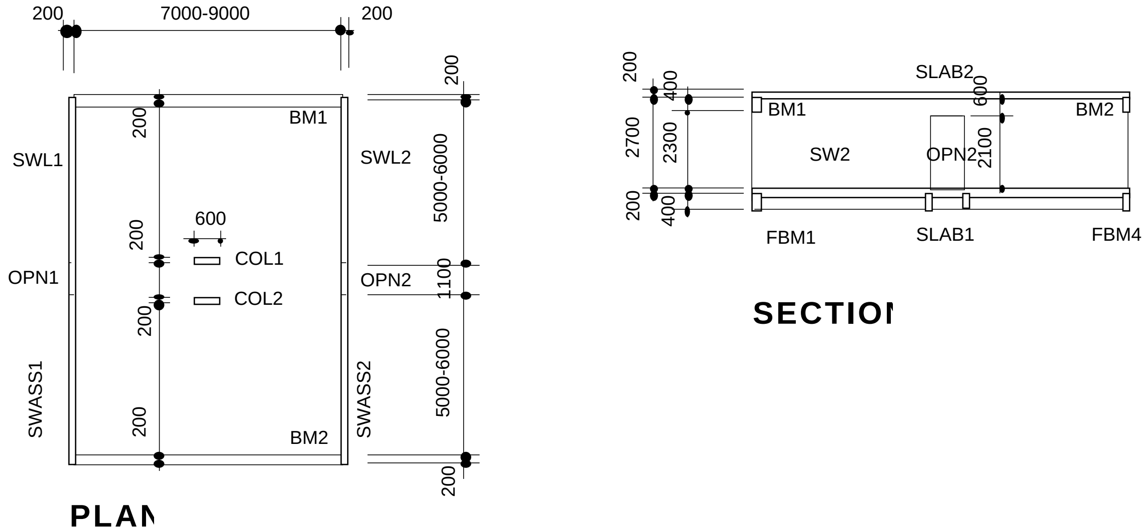

Figure 5. Graphical Representation of Structural Engineer's Model

<u>SWL1</u>

AN_INSTANCE_OF:
[SHEAR_WALL, LOADBEARING_WALL]
PURPOSE:
[func1, func2]
FUNCTION:
func1: occupies_space(volume(V))
func2: provides_load(load(L))
func3: affects_visual_envmnt()
func4: resist(lateral_force(F))
func5: supports(SLAB2)
STRUCTURE:
component_of: [BLDG1]
parts: [WL1, WL2]
material: R.C.
shape: rectangular_prism
length: 11500-13500
height: 2700
thickness: 200

<u>OPN1</u>

AN_INSTANCE_OF:
WALL_OPENING
PURPOSE:
[func1, func2]
FUNCTION:
func1: creates_hole(SW1)
func2: provides_space(GL1)
func3: reduces_strength(SW1)

STRUCTURE:
width: 1100
height: 2100
thickness: same_as(SWL1)

<u>BM1</u>

AN_INSTANCE_OF:
BEAM
PURPOSE:
[func3, func4]
FUNCTION:
func1: occupies_space(volume(V))
func2: affects_visual_envmnt([RM1, RM2])
func3: supports(SLAB2)
func4: transfers_force(F, SWL1, SWL2)
STRUCTURE:
component_of: [BLDG1]
material: R.C.
shape: rectangular_prism
length: 8000-9000
depth: 400
thickness: 200

<u>COL1</u>

AN_INSTANCE_OF:
COLUMN
PURPOSE:
[func3]
FUNCTION:
func1: occupies_space(volume(V))
func2: affects_visual_envmnt([RM1, RM2, HALL1)
func3: support(SLAB2)

STRUCTURE:
component_of: [BLDG1]
material: R.C.
shape: rectangular_prism
length: 600
height: 2700
width: 200

Figure 6. Non-Graphical Representation of Structural Engineer's Model

The structural engineer decides that the transverse walls should act as shear walls as well as supporting the roof slab. The two walls, WL1 and WL2 of the architects are effectively considered as one wall and the height of the opening for GL1 is reduced from full storey height to 2100 mm, thus creating one wall assembly element. The wall opening has no constructive structural purpose (actually it has a degrading effect on the function of the shear wall assembly), but is to provide space for GL1, an architectural purpose, assumed by the structural engineer. This will ensure that the element OPN1 will form part of the architect's model. Further, the relation that the wall SW1 has parts WL1 and WL2 will cause those elements to inherit the material and thickness properties of SW1. Beams BM1 and BM2 are added and two of their functions (inherited from the generic concept) is that they occupy space and affect the visual environment, ensuring that they appear in the architect's model and indicate required changes in the height of the glazed elements. The structural engineer attempts to take into account the architect's intention of a flexible location for walls WL7 and WL8 by orienting the columns with their long dimensions along the hall walls. This provides a constrained flexibility for the location of walls WL7 and WL8. Again the inherited functions for the columns will cause them to be part of the architect's model.

The architects now discover that new elements and inconsistencies exist. They accept the need for the shear walls and beams and the reduction of the height of GL1, GL2, GL3 and GL4, and modify their model accordingly, Figure 7.

```
WL1

AN_INSTANCE_OF:
      WALL
PURPOSE:
      [func4, func5]
FUNCTION:
      func1: occupies_space(volume(6.21))
      func2: provides_load(load(15.5))
      func3: affects_visual_envmnt([facade, RM1])
      func4: separates_spaces(exterior, RM1)
      func5: controls_envmnt(RM1
STRUCTURE:
      component_of: [WLASS1, RM1]
      part_of: [SWL1]
      material: R.C.
      shape: rectangular_prism
      length: 5200-6200
      height: 2700
      thickness: 200
```

```
COL1

AN_INSTANCE_OF:
      COLUMN
PURPOSE:
      [func4, func5]
FUNCTION:
      func1: occupies_space(volume(0.32))
      func2: affects_visual_envmnt([RM1,RM2,HALL1])
STRUCTURE:
      same_as: COL1.SE
      component_of: STOREY1
      material: R.C.
      shape: rectangular_prism
      length: 600
width: 200
      height: 2700
```

Figure 7. Revised Architect's Model

The wall instance, WL1 has values of properties, e.g. material, thickness, inherited from SWL1 resulting from the relationship 'WL1 part_of SWL1'. From the functions of the columns regarding space occupation and visual effects, column instances are created in the architect's model, since these are functions with which the architect is concerned, as defined in the architect's view.The architects may not accept the columns since these interfere with the rooms. However, the architects cannot remove the columns since their purpose is structural. They must notify the structural engineer that this solution is unacceptable. A method of electronic annotation is provided for in the VisionManager system (Fruchter et al., 1996). The structural engineer may either decide on a new system, such as providing for beams above walls WL5 and WL7 or may argue that the columns are necessary. If the beam solution is chosen, the HVAC engineers may subsequently notify the architects that they need penetration for their ducts. The negotiations continue through several stages of development and modelling until all participants are satisfied and consistency is reached.

8. SUMMARY

The paper has shown how the concepts of function and purpose are essential in collaborative CAD modelling between different disciplines to allow the representation of the different viewpoints and yet to provide the necessary coordination and consistency in multidisciplinary design situations. The essential factors are the explicit representation of functional properties of design objects where function is defined as any effect resulting from the behaviour of an object and purpose as intended function. The above simplified example showed these concepts can be used in such a multiview approach.

Work to date has already demonstrated the potential for CAD systems to allow the modelling of different views through the linking of graphic and non-graphic databases using a graphic database a relational database and an interface command language (Hwang, 1994; Rosenman 1993).

Further research and development is required to investigate the degree of automation or the nature of the notification required or possible. Should an architect be allowed to alter the structural engineer's model and vice versa? Can such permission be authorised? Alternatively, should any notifications regarding dissatisfaction or suggested changes be limited to a bulletin board-type notification as in VisionManager (Fruchter et al., 1996).

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