Purpose and function in design: from the socio-cultural to the techno-physical

M. A. Rosenman and J. S. Gero, Key Centre of Design Computing, Department of Architectural and Design Science, University of Sydney, Sydney, NSW 2006, Australia

Design is a purposeful human activity in which cognitive processes are used to transform human needs and intent into an embodied object. Humans operate in a socio-cultural environment, whereas artefacts form part of an artificial or techno-physical environment, the two being integrated into a socio-technical environment. Design is about the transition of concepts from the socio-cultural environment to the description of technical objects. Different interpretations of the concepts of purpose, function, behaviour and structure currently exist in the design research domain. This paper aims to clarify these concepts through the realization that certain concepts are associated with the socio-cultural environment and other concepts are associated with the techno-physical environment and that a transference is required from one to the other to achieve the necessary flow of information during the design process. The paper shows that a clarification of these concepts, especially that of function, leads to a clearer understanding of the design process and sub-processes such as problem formulation, synthesis, analysis and evaluation.

Keywords: design theory, design rationale, purpose-function-behaviour-structure, collaborative design

Design proceeds from a conceptual description of a need to a concrete description of an artefact as a solution to a problem created as a representation of this need. The process of moving from needs to a problem statement to a syntactic description is not a simple linear or tree-like decomposition, but involves many iterations and reformulations in what has been described as an exploration-search or problem-making/problem-solving process by Smithers[1,2]. Nevertheless, there is a clear shift from a semantic to a syntactic description, from

1 **Smithers, T** Design as exploration: puzzle-making and puzzle solving. In *Exploration-Based Models of Design and Search-Based Models of Design*, Workshop Notes AID '92. CMU, Pittsburgh (June 1992)

2 **Smithers, T** On knowledge level theories of design process. In *Artificial Intelligence in Design '96*, eds J. S. Gero and F. Sudweeks. Kluwer Academic, Dordrecht (1996) pp 561–579

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semantically stated intentions to a design problem statement, in terms of functional and behavioural requirements, to a syntactic description which, when realized, achieves the intentions. To encompass the full scope of design information, we need to be able to represent this full range of information from the semantic to the syntactic, especially if we are to use formal processes, such as CAD and knowledge-based systems, to assist us in the design process.

Design is characterized as a purposeful human cognitive activity. Hence statements such as "it happened by design, not by chance". There is a clear understanding that design is intentional, an artefact is generated intentionally. This paper categorizes intent as a human concept and then discusses how such a semantic concept is assigned to the formulation of the design problem and its solution in terms of function, behaviour and structure. The main thrust of this paper is the differentiation made between the human socio-cultural environment and the artefact techno-physical system in terms of setting a general problem statement and a formulation which leads to the design of an artefact.

The categorization of the different concepts involved in the design process, namely purpose, function, behaviour and structure (each of which is defined later in this paper), has the advantage of clearly identifying the role that each category plays in the design process. It allows for decomposition of the design process into clear, identifiable and manageable roles that identify the flow of and the type of information in the design process.

The importance of representing all the concepts in the design process is illustrated by their need in computer-aided design (CAD) systems if they are to be of use as intelligent assistants.

There has been a shift in CAD systems from purely documentation systems to modellers and to knowledge-based assistants, e.g. for design verification, design prompting. However, in order to carry out such knowledge-based tasks, there has to be a shift from a purely syntactical or structural description to incorporating a semantic or functional description as well. Current CAD systems represent only the structural properties of a design object, mainly the geometric properties. The reasoning required to carry out tasks such as design verification requires semantic modelling as well as syntactic modelling. Knowledge-based systems, such as representations of design codes or design rules, utilize semantic concepts, such as 'loadbearing walls' where such semantic concepts cannot be determined from an inspection of current CAD representations. For example, it is not possible to determine whether a wall supports the element above it from a geometric description or visual inspection.

Different design disciplines, during the course of the design process, need to collaborate but have different views of a design product according to their functional concerns. These views translate into different models of a product, which need to be accommodated in any comprehensive description of a design product. It is only by accommodating the functional concerns of the different agents and representing the functional properties of products that useful representations for designs and design processes, which require collaborative participation, can be effected.

There are many cases where the functional aspects of a design are required to be known but cannot be derived from current documentation. Re-design and justification are two such examples. For legal reasons, design intentions need be documented associated with design decisions where justification may be required, e.g. in case of failures and disputes about performance requirements.

In the remainder of this paper, the concepts of purpose, function, behaviour and structure will be defined and their roles in the design process described. Issues such as decomposition and specialization will be addressed.

While in this paper, design objects, or artefacts, will be referred to as *physical* objects, this is in no way meant to exclude *non-physical* objects, such as computer programs, graphic designs or other symbolic objects, but merely as a convenient differentiation between an environment which exists as a human concept and provides for the semantics of a design problem and that environment in which the descriptions are syntactic descriptions of objects. Readers may replace the term *physical* by other suitable descriptions.

1 Design

Artefacts (artificial objects), come into being through intent[3]. Design implies a conscious purposeful activity to arrive at a state which did not previously exist in order to (presumably) improve some (perceived) unsatisfactory existing state of affairs. Design is a human activity related to human needs regarding the necessity to change the present state of the environment. Examples of non-human design are still the subject of controversy. A perception of dissatisfaction with the present state causes a conceptualization of a desired state which is not yet a realization of how to achieve this state. For example, getting wet by rain causes the conceptualization that a desired state would be one where one would not be getting wet (Figure 1).

This conceptualization of a desired state causes the activation of an intentional or purposeful process. It is the intention of achieving this

3 **Simon, H A** *The Sciences of the Artificial.* MIT Press, Cambridge (1969)

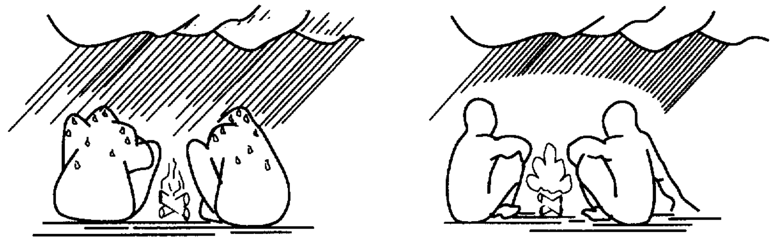

Figure 1 Conceptualization of desired state. (a) State of dissatisfaction, (b) conceptualized state of satisfaction.

conceptualized desired state that brings about the effort to produce a course of actions that will result in the desired state of satisfaction achieved[4,5]. Artefacts are thus the realization or embodiment of the course of action required to satisfy needs. They are brought into existence as a result of the intentions of humans.

Humans exist in the natural physical environment and operate in a socio-cultural environment of their own conception The socio-cultural environment prescribes values and goals which together with the physical environment establish needs (real or perceived). Needs may be non-physical, as for example the need for aesthetics. The property of style in a design object satisfies a need for relating an object in a specific socio-cultural context. Even though the activities in a church may be very similar to those in a theatre we expect the church to 'look like a church' and not a theatre (and vice-versa).

In order to satisfy our needs we create new artefacts. These artefacts create a techno-physical or artificial environment[3] which interacts with the natural and socio-cultural environments so that each environment influences and is influenced by the other (Figure 2). Figure 2, however, shows that the interactions between the socio-cultural environment and the other environments are mediated by humans, since the socio-cultural environment only exists as human concepts and interpretations.

We create artefacts to perform certain functions, be they utilitarian or aesthetic, so that these functions produce the required new state of affairs. To do this we propose required behaviours which the artefact must exhibit in order to effect such functions and then propose descriptions of artefacts whose behaviours will meet those required behaviours. While this is a simplified description of a more complex process and does not go into details about precise steps, nevertheless it shows that our reasoning hinges on a representation of intentional, functional, behavioural and structural properties. We must first be clear about these concepts.

4 **Archer, L B** The structure of the design process. In *Design Methods In Architecture*, eds G. Broadbent and A. Ward. Architectural Association Paper No. 4. Lund Humphries, London (1969) pp 76–102
5 **Mathur, K** 'The problem of terminology: a proposed terminology for design theories and methods' *Design Methods and Theories* Vol 12 No 2 (1978) pp 131–138

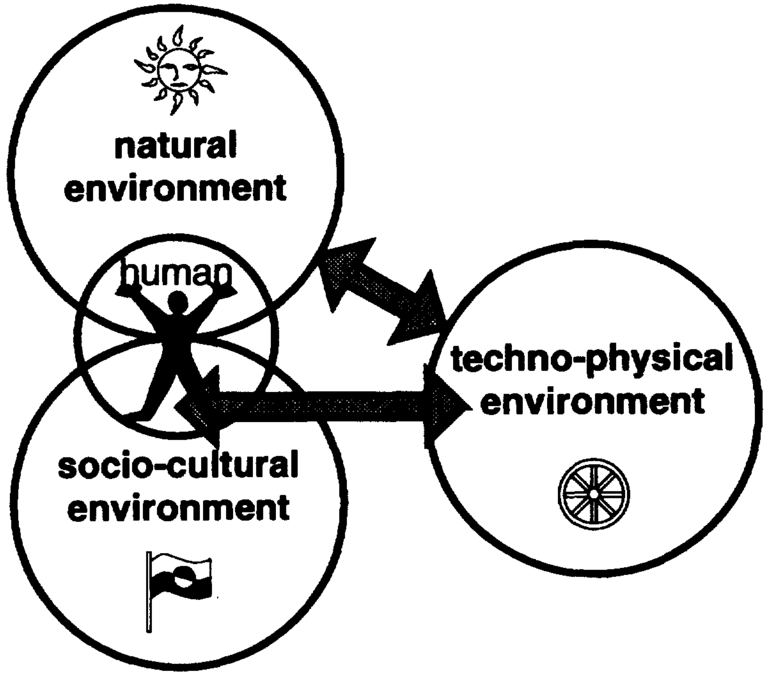

Figure 2 Environments and interactions.

6 **Bobrow, D G** 'Qualitative reasoning about physical systems: an introduction' *Artificial Intelligence* Vol 24 (1984) pp 1-5
7 **Rodenacker, W** *Methodisches Konstruieren*, 3rd edn. Springer, Berlin (1984)
8 **Sembugamoorthy, V and Chandrasekaran, B** Functional representation of devices and compilation of diagnostic problem-solving systems. In *Experience, Reasoning and Memory*, eds J. Kolodner and C. Riesbeck. Lawrence Erlbaum, Hillsdale, NJ (1986) pp 47–73
9 **Gero, J S** Prototypes: a new schema for knowledge-based design. Working Paper, Department of Architectural Science, University of Sydney (1987)
10 **Pahl, G and Beitz, W** *Engineering Design: A Systematic Approach*. Springer, Berlin (1988)
11 **Ulrich, K T and Seering, W P** Function sharing in mechanical design. *AAAI-88* (1988) 342–346
12 **Goel, A K and Chandrasekaran, B** Use of device models in adaptation of design cases. In *Proceedings of the DARPA Case-Based Reasoning Workshop*, Pensacola, Florida (1989) pp 100–109

2 *Purpose, function, behaviour and structure*

The terms purpose, function, behaviour and structure have been discussed by many researchers in many design disciplines[6–18]. However, notwithstanding such a large number of works, there is still a large amount of confusion especially as regards the terms purpose and function and function and behaviour.

The difficulties in categorizing the concepts seem to lie with categorizing such concepts as 'providing enjoyment', 'providing music', 'providing sound,' 'transforming magnetic information into sound', 'supporting' and 'transferring loads'. Many of the viewpoints expressed come from the physical engineering disciplines, such as mechanical and electrical engineering. In the main, the design problems, which these disciplines express as their concern, are further removed from the human expression of needs than those problems which are the concerns of design disciplines such as architecture or industrial design. These physical disciplines see the purpose of their artefacts as carrying out certain physical functions, e.g. the purpose of gears is transforming torque. They take a physical systems view of the concept of function as being the purpose of the system. In some cases confusion exists between function and behaviour. For example, Umeda *et al.*[13] 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. While all authors accept that behaviour and function are closely related, efforts at reconciling the concepts of purpose, function, behaviour within this framework are still largely confused.

The *Oxford English Dictionary* gives the following definitions:

> **intent** *n.* intention; purpose; design;...
> **purpose** *n.* 1. the object which one has in view; 2. the action or fact of intending or meaning to do something; intention;... *v.* design; intend.
> **function** *n.* 1 the action of performing; 2. activity; action in general; 3. the special kind of activity proper to anything; the mode of action by which it fulfils its purpose. *v.* to fulfil a function; to perform one's part; to act.
> **behaviour** *n.* 1. the manner in which a thing acts under specified conditions or circumstances, or in relation to other things.
> **structure** *n.*... 3. the mutual relation of the constituent parts or elements of a whole in determining its peculiar nature or character;... 6. an organized body or combination of mutually connected and dependent parts or elements.

The terms 'intent' and 'purpose' are interchangeable and relate to human mind acts. Moreover, they are defined as being synonymous with 'design'. The confusion between function and purpose in some of the literature stems from the use of the term function as (a) 'the function of this object is to make me happy' and (b) 'this machine functions perfectly'. In the first case the term function is used as role or intent, i.e. purpose, and in the second case in an operational sense as performing some action. The second case relates more closely to the dictionary definition regarding 'the action of performing'. Moreover, we need to differentiate between notions such as 'providing a comfortable thermal environment', 'providing heat' and 'resisting electrical flow'. The differentiation between purpose and function is achieved through the consideration of the human factor as against the performance of artefacts. A notion, such as, 'telling the time' only becomes relevant when we include the human factor in the system, as 'telling the time' is a human-related activity, as are the notions of 'writing', 'dining', etc. The term 'telling the time' answers the *why* the clock *does what* it *does* or *what* it is *for*. This is its purpose, indeed the reason for its existence, since we stated earlier that designed objects only come into existence to satisfy human purposes. Behaviour is clearly defined as how something acts in response to its environment, while structure is the organization or arrangement of the constituents of an object. The differentiation between function and behaviour is achieved by considering results versus how the results are achieved.

13 **Umeda, Y, Takeda, H, Tomiyama, T and Yoshikawa, H** Function, behaviour and structure. In *Applications of Artificial Intelligence in Engineering V, Vol. 1: Design*, ed. J. S. Gero. Computational Mechanics Publications, Southampton (1990) pp 177–193

14 **Goel, A K** Representation of design functions in experience-based design. In *Intelligent Computer Aided Design*, eds D. C. Brown, M. Waldron and H. Yoshikawa. North-Holland, Amsterdam (1991) pp 283–308

15 **Hundal, M S** Conceptual design of technical systems. In *Proceedings of the 1991 NSF Design and Manufacturing Systems Conference*, Society of Manufacturing Engineers, Michigan (1991) pp 1041–1049

16 **Johnson, A L** 'Designing by functions' *Design Studies* Vol 12 No 1 (1991) pp 51–57

17 **Gero, J S, Tham, K W and Lee, H S** Behaviour: a link between function and structure in design. In *Intelligent Computer Aided Design*, eds D. C. Brown, M. Waldron and H. Yoshikawa. North-Holland, Amsterdam (1992) pp 193–225

18 **Sturges, R H** A computational model for conceptual design based on function logic. In *Artificial Intelligence in Design '92*, ed. J. S. Gero. Kluwer Academic, Dordrecht (1992) pp 757–772

Thus, structure is *what is*, behaviour *how does*, function *what does* and purpose *why does* or *what for*. Figure 3 shows the relationships between the concepts and the environments. The dashed box in Figure 3 shows that behaviour and function are closely related, as one would expect from any cause/effect relationship. So that in summary:

STRUCTURE exhibits BEHAVIOUR effects FUNCTION enables PURPOSE

PURPOSE enabled by FUNCTION achieved by BEHAVIOUR exhibited by STRUCTURE

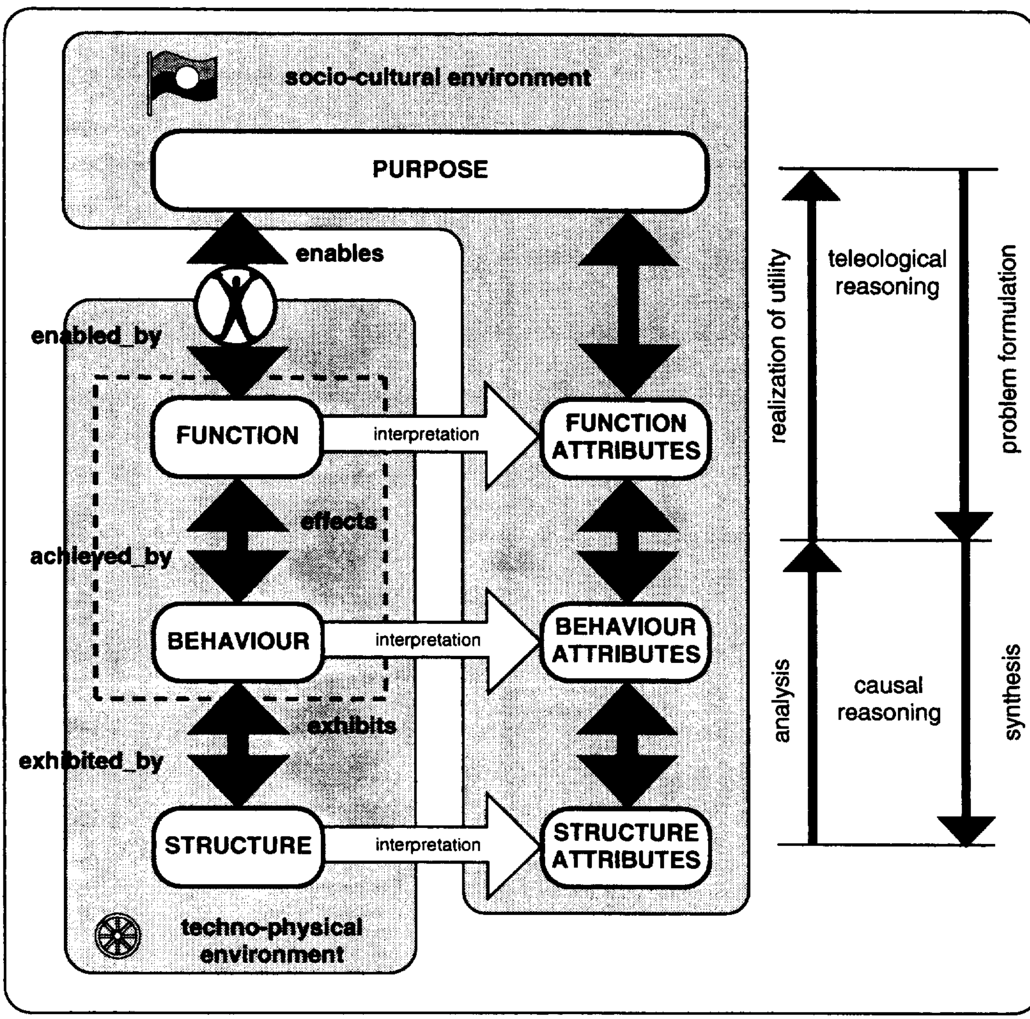

Figure 3 Concepts, environments and processes.

Structure is the state of the artefact in a given physical environment, and, in that environment, exhibits certain behaviours. These behaviours effect various functions. These functions are interpreted according to human values within a particular socio-cultural environment as enabling certain purposes to be fulfilled. Additionally, human values are used to interpret the physical manifestation of behaviour and function in a qualitative way by ascribing descriptive behavioural and functional attributes to the artefact and ascribing attributes to structure, such as shape, dimensional properties (length, width, etc). In a simplified description, a dining table consisting of a timber top of certain shape and dimensions on four timber legs, exhibits the behaviours of horizontality and rigidity for a plane located at a given height, thus effecting the functions of providing stable support for utensils and allowing the disposition of some number of chairs around it, thus enabling the purpose of dining. A steel beam of, e.g. I-shape, of certain dimensions under a slab, transfers the load from the slab to supports by bending, thus supporting the slab and enabling an unencumbered space below.

2.1 *Structure*

Structure represents the composition or form of an object. What an object is, in an absolute sense, is not of concern here but rather its representation, since all references to an object by us will be a representation. An object may be simple or complex. A simple object is termed an *element* and by definition is homogeneous, otherwise it can be decomposed into separate elements each being homogeneous. Note that homogeneity can refer to composite materials like reinforced concrete, which are treated as conceptually homogeneous. An element is thus a composition of material units. A complex object is termed an *assembly* and is composed of objects termed *components*. Recursively, components may be assemblies or elements. A formal description is as follows:

O:	A I E	*An object is an assembly or an element*
A:	(C, R(C))	*An assembly is a set of components and a set of relationships among the components*
C:	$\{\cup(C_i\}$	
R(C):	$\{\cup(R_k(C_i, C_j))\}$	
C_i:	O	*ith component is an object*
E:	$(M_m, R(M_m))$	*An element of material,* M_m *is a set of material units of type* M_m *and a set of relationships among the material units*

M_m: $\{\cup(M_{mp}\}$

$R(M_m)$: $\{\cup(R_l(M_{mp}, M_{mq}))\}$

M_{mi}: ith unit of material M_m

In the case of a homogeneous single element, the structure is its material arrangement. We usually do not treat this at such a low level, but rather represent an arrangement of material units as the shape of the element. In the case of objects composed of components (assemblies), structure includes the identification of the components, their arrangement and their connectivity. The resulting composition may be described by its shape and dimensions, if this makes sense. In some cases, an assembly may be referred to as being of a certain material, usually the most significant one, even though it is composed of several materials, e.g. aluminium widows.

A structural description thus includes only the physical, topological and geometrical properties necessary and sufficient to syntactically describe the object so that it can be constructed (physically or symbolically). In other words, only those properties of material (e.g. type, finish, quantity) and the disposition of the various materials is required for a structural description. These structural properties are those which a designer directly manipulates in order to generate a physical solution to an abstract problem. Thus, while designers take many things into consideration in the course of designing, ultimately what they do is select structural variables and assign to them values representing material properties, shape descriptions, dimensions, location and connectivity. In architectural design there is some discussion about whether space is a material, which is manipulated like any other material, or is an emergent state defined by the disposition of its bounding entities. While architects deal with spaces as primary elements, constructors are concerned with the physical elements of the building. Thus architects think about the shape, dimension of spaces and their connections to other spaces to achieve certain emotive expressions. The bounding elements of the spaces contribute to the character of the spaces and their properties are selected accordingly.

2.2 *Behaviour and function*

The interaction between an object's existence and the natural environment causes the object to act in a certain manner, i.e. its behaviour. A behaviour is thus a description of the object's actions or processes in given circumstances. Function is the result of the behaviour, i.e. as its product or effect, so that function is closely related to behaviour, the latter being the mechanism by which results are achieved. A function may be a physical function, such as 'providing sufficient space', or a non-physical function such as 'providing an ambience'.

In much of the work noted previously, function has been described as transforming material, energy or signal or as an abstraction of behaviour and as a transformation of input to output. This fits in well with a mechanistic view of function, but not with a social view of function. Thus there is confusion when function is used at one time to describe 'telling the time' and 'transforming an analog signal into a digital signal'. Many authors use a restricted set of verbs and nouns to represent such transformations. Umeda *et al.*[13] point out the difficulties with this approach, asking where is such a transformation between input and output in the function of the wearing of a watch. However, as pointed out previously, they themselves present a confused description of function and behaviour.

The representation of function as the result of behaviour concurs well with the work by Chandrasekaran and his various co-authors where a representation is given for a buzzer device as[8]:

> FUNCTION:
> buzz: TOMAKE buzzing
> BY: behaviour1

The behaviour, behaviour1, is described by a state transition description. This treatment of function allows for the representation of functions of an artefact which occur, but were unintended and may be of positive or negative benefits. As such, the concept of side-effects, i.e. functions which are not intended, but nevertheless occur, has been added as[12]:

> FUNCTIONS:
> TO-MAKE Change angular momentum of Telescope
> BY: BehaviourChangeMomentum
> SIDE-EFFECT: Generation of Heat in Bearing

While behaviour and function are usually discussed in an 'objective' way as physical actions related to the 'laws' of nature, physics, etc., excluding the human observer, these actions and their effects are interpreted (by humans) in a descriptive way as the exhibiting of certain qualities, e.g. the beam deflects, it bends; the amount of deflection is described qualitatively as its rigidity; a glass object transmits light, it exhibits the property of transparency. Performance variables can be ascribed to such qualities allowing for evaluation. Thus a function of a pane of glass of 'transmits light' can be explained by the behaviour quality 'transparency' measured by the performance variable 'light transmittance'. Values of light transmittance achieved by various glass panes can be compared to desired values.

2.3 Purpose

Purpose only exists when related to human values of utility. Humans relate to artefacts through their purpose. An artefact has an intended purpose and may have unintended or realized purpose. For example, the cup may have been designed with the intended purpose of enabling the drinking of hot liquids. From its function of containing an approximately standardized amount of liquid (or other matter) it was realized that it could be used for the purpose of measuring. The realization that a cup has weight (a qualitative interpretation of behaviour and function) can lead to the realization of its utility as a paperweight. As the 'wedge-shapedness' of a pencil is realized, its utility as a doorstop may be realized.

At times needs arise explicitly for which artefacts at hand may be used in a way not intended in their design or ascribed to them. For example, there may arise the need to change a light bulb when no ladder is readily available. No artefact at hand will have a function of 'allowing climbing'. However, with this new focus, re-examination of the behaviour and possible functions of artefacts such as chairs, tables and filing cabinets may ascribe such a function to those artefacts. In a formalized representation scheme, we would probably not have associated those behaviours and functions with those objects. However, given the new intentional and functional context we will interpret these objects with regards to associated behaviours. The behaviours we require are those of strength, stability and appropriate height. Note that we have not designed the table or filing cabinet, but have ascribed a new function and hence purpose for them from existing properties which we had not previously take into account.

If we take an artefact out of a socio-cultural environment, it will continue to behave and function in the same physical way, but its purpose will change. For some societies an amplifier may have no purpose other than that of being a curiosity.

2.4 Humans purposes and artefact functions

The above makes a differentiation between the socio-cultural environment as a human conception and the techno-physical/artificial environment in which the artefact exists. Thus it is argued that artefacts do not have any intrinsic purpose except as assigned to them by humans or in relation to human concerns, but that, by nature of their existence, they exhibit behaviours which produce functions which can be utilized. Obviously this is a somewhat back-to-front argument, since the explicit aim in design is to conceive an artefact which will produce certain functions. Can we make a separation between the representation of artefacts and those of human notions? All artefacts come into being by human design (even if their synthesis is achieved through serendipity) and, therefore, they must have implicit, if not explicit, intent or purpose assigned to them. Since both humans and artefacts co-exist and interrelate in an overall environment, clearly any such differentiation is merely for convenience. Moreover, any representation by humans regarding artefacts will carry human interpretations based on human concerns. However, this convenient differentiation may be useful in discussing the processes involved in design, the different views of an artefact held by different designers and for discovering new interpretations of an artefact.

Even though designed by humans, once an artefact has been designed (and realized), it exists and exhibits properties independent of human ascriptions. It now forms part of a physical world and is subject to the natural environment. It is subject to, but also in turn, influences both the natural and socio-cultural environments. Although brought into being according to particular intents, it performs according to its physical existence in relationship with the environment over a wide range of behaviours and functions, not all of which may be assigned to the artefact by humans. Thus, while human interpretation of artefacts will only ascribe to those artefacts those behaviours and functions related to the particular sphere of interest of the human at that time, conceptually, all artefacts may be thought of as potentially exhibiting a wide range of behaviours and carrying out a wide range of functions (some with zero level of performance). In various circumstances, these behaviours and functions, which were not originally ascribed to the artefact, may be brought into focus and may be found to be useful for a variety of purposes other than those for which the artefact was originally intended. This may occur as a need arises for which only existing artefacts can be used or as a realization of unrealized properties and hence new utility of the artefact.

3 Design—from purpose to structure

3.1 Design processes and reasoning

Figure 3 shows that the processes involved in design become comprehensible through the clarification of the above concepts. These processes are shown in Figure 4.

Teleological reasoning comes into play when human values are brought in. The process of interpreting function for purpose is the process of realization (of possible utility), whereas the process of interpreting required pur-

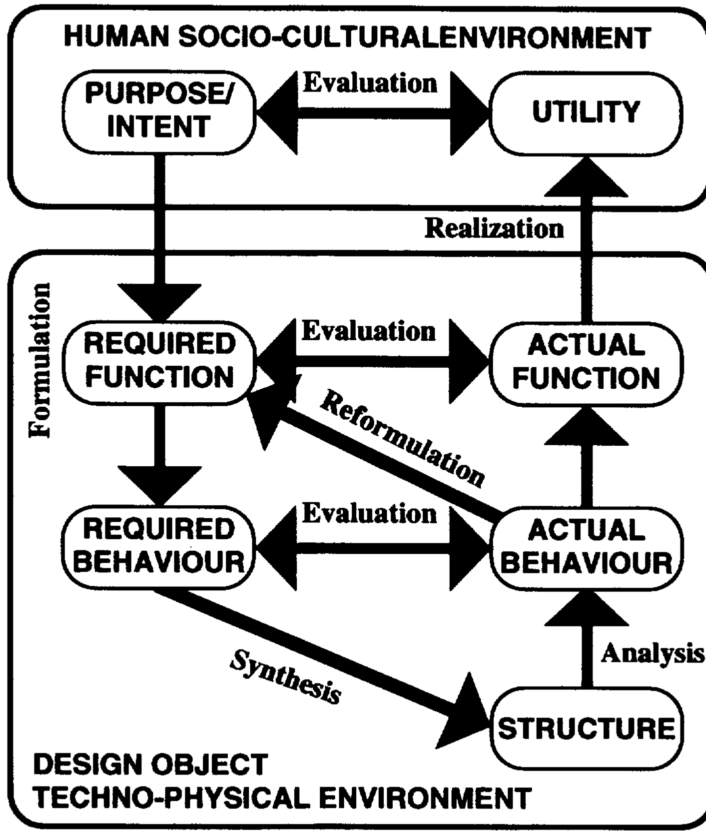

Figure 4 Design processes.

poses as desired functions and then desired behaviours is a process of problem formulation. These last two processes provide the communication between the human value system and the techno-physical design object environment. The process of going from required behaviour to arrive at a given structure (object) is the process of synthesis. No direct connections exist to produce structure directly from required behaviour except in routine design situations. The interpretation of structure to determine the behaviour and function of a proposed structure is the process of analysis. The process of evaluation is the process of comparing values of like concepts. For example the comparison of required behaviour and function performance values to actual performance values may result in acceptance, new synthesis (modification of the structure) or reformulation of requirements (functional or behavioural).

3.2 The ill-structured nature of design—design as exploration/search

Functional properties are properties ascribed to the artefact as formulations from human needs. The differentiation of the human environment from the artefact environment allows us to deal with the design of the artefact starting from the functional level. Thus, the design of an artefact can begin at the level of functional requirements. Design as exploration[2,19] begins at this level and proceeds through various iterations of formulations of functional and behavioural operational objectives and synthesis of structure and reformulation of such functional requirements as found necessary during the course of the design process. Design as exploration is seen as problem-setting and problem-solving where the problem-setting is the generation of a set of functional requirements which adequately represent the needs. Human needs rarely change in a design process, the reformulations being at the functional and behavioural levels.

Design has been described as an ill-structured problem-solving activity[20,21]. In terms of purpose, function, behaviour and structure, this means that while the purpose of a required design is given by the client (real or virtual) at the posing of the design problem, the required functions and behaviours that any design will need to manifest may not be known. These may, in fact, not be clarified until a certain amount of hypothesizing, i.e. the proposing of structure solutions, is carried out. For example, assuming that the intended purpose for an object is to allow writing, it is not until a particular solution is proposed, that includes, say ink, that the functions of providing controlled flow and providing drying manifest themselves. A solution using graphite does not require such functions. The purpose of a toilet cabinet is to allow ablutions. It is not until a fixture utilizing water is proposed that the waterproofing of the wall surfaces becomes a required function. This exploration for functions and behaviours to create the design problem within the artefact environment leaves the purpose as originally given, otherwise the whole context of the design problem changes. Of course, this still allows for the possibility that functions are 'discovered' which allow new utilities to be realized in addition to those intended.

3.3 Classification of design objects

The classification of design objects may be along any of the conceptual categories, structure, behaviour, function or purpose or any combination of them. However, while classification into the same class can be made on any of the concepts, it can always be made on functional aspects[22,23] (see Figure 5). This is of importance for creative design using analogy, since similarities can be found between objects of different structures, but effecting similar functions.

19 **Logan, B and Smithers, T** Creativity and design as exploration. In *Modeling Creativity and Knowledge-based Creative Design*, eds J. S. Gero and M. L. Maher. Lawrence Erlbaum, Hillsdale, NJ (1993) pp 139–175

20 **Churchman, C W** 'Wicked problems' *Management Science* Vol 4 No 14:B (1967) pp 141–142

21 **Rittel, H W J and Webber, M M** Wicked-problems. In *Man-Made Futures*, eds N. Cross, D. Elliott and R. Roy. Hutchinson, London (1974) pp 272–280

22 **Rosenman, M A and Gero, J S** 'The what, the how and the why in design' *Applied Artificial Intelligence* Vol 8 No 2 (1994) pp 199–218

23 **Rosenman, M A and Sudweeks, F** Categorization and prototypes in design. In *Perspectives on Cognitive Science: Theories, Experiments and Foundations*, eds P. Slezak, T. Caelli and R. Clark. Ablex, Norwood, NJ (1995) pp 189–211

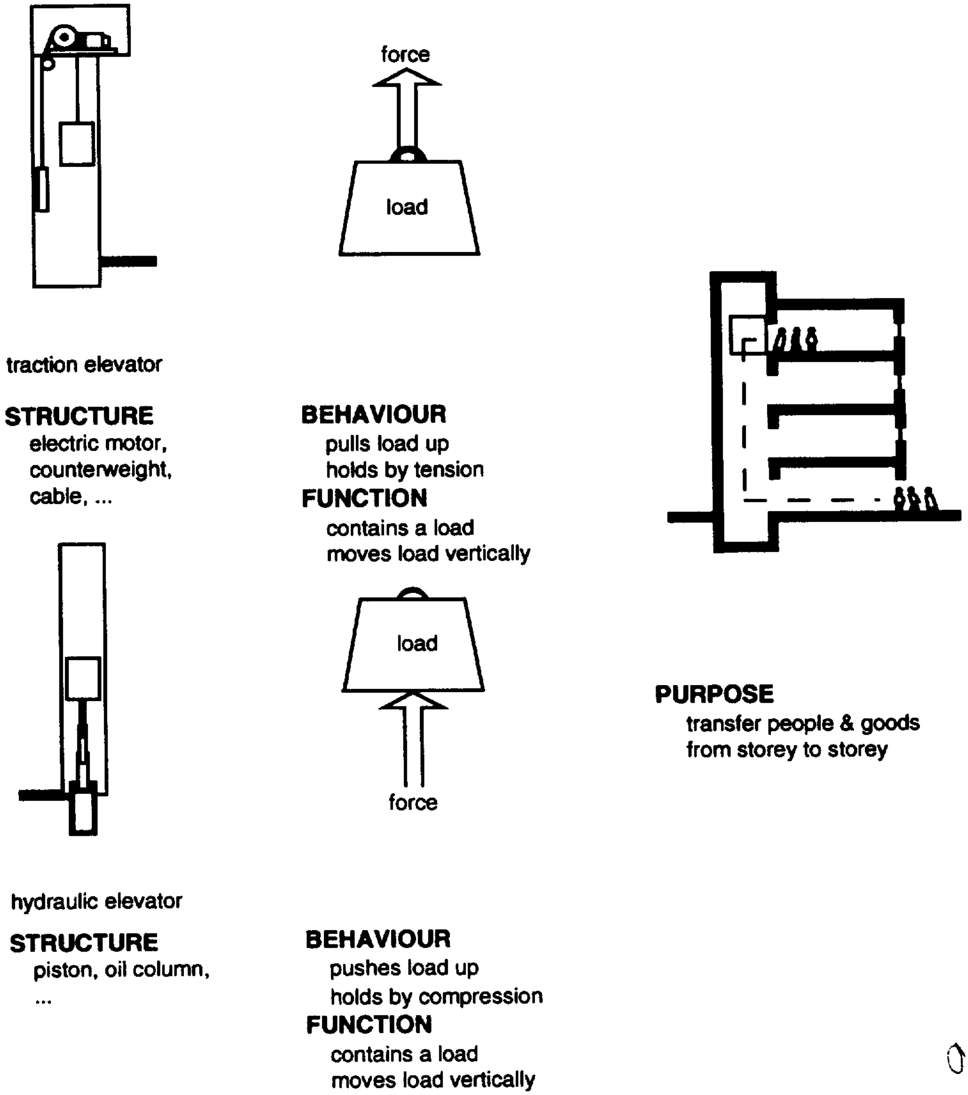

Figure 5 Different structures, different behaviours, same function and same purpose.

3.4 Decomposition and formulation

A concept represented by a single term, may, generally, be decomposed into more detailed concepts. This holds for all the concepts of purpose, function and behaviour. For example, the purpose of allowing dining 'means', for example, allowing eating, allowing drinking, enabling the partaking in social intercourse. Decomposition can be carried out along as many levels as it is felt necessary to explain the concept. When a satisfactory level of decomposition is reached in one category, the concepts thereby represented must be translated into concepts in a more operational category. Purpose concepts, which are part of the human value system, must be formulated into function concepts, in the physical environment system, by teleological problem formulation. Allowing eating can be translated into provide space for eating utensils, support eating utensils, etc. These function concepts are then decomposed as necessary until a satisfactory function decomposition is reached. Support eating utensils may be decomposed into provide rigid surface, provide horizontal surface, etc. Each function concept is then formulated, using causal problem formulation, into behaviour concepts which are decomposed as necessary. Finally, the behaviour concepts are synthesized by structure concepts. Figure 6 shows the decomposition-formulation structure.

Note that Figure 6 is not intended to represent the design process but merely to represent the relationships between the different concepts. As

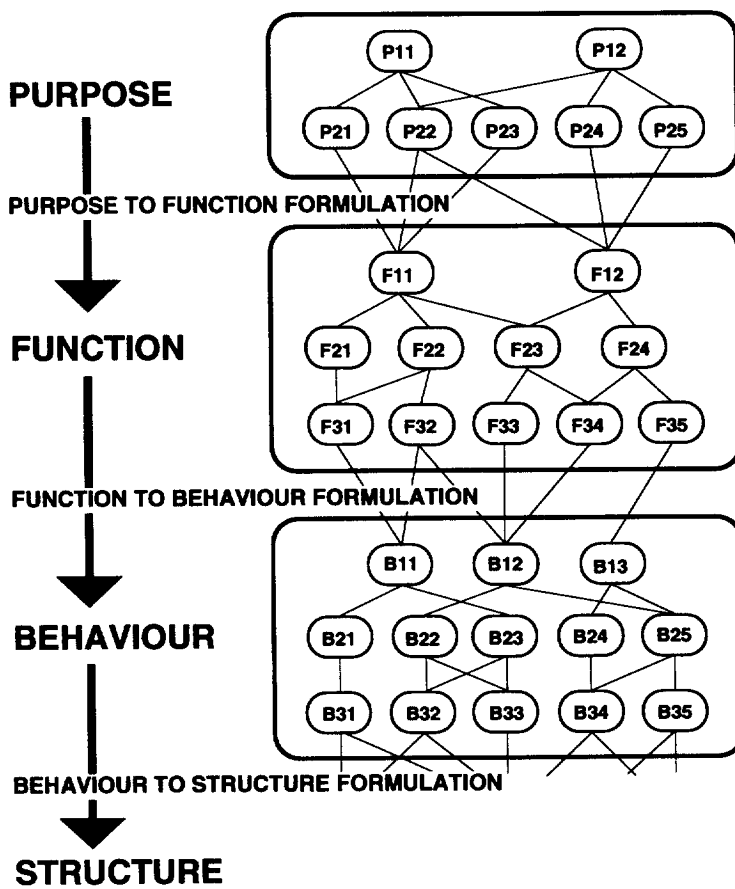

Figure 6 Decomposition and problem formulation.

stated previously, in a process model of design, there is no simple 'linear path' from purpose to structure, but rather a complex number of iterations between any of the concepts in a set of formulation-synthesis-analysis-evaluation cycles. Each concept may be achieved by more than one (sub)concept and each concept may contribute to more than one (super)concept. Figure 7 shows an example of a function decomposition hierarchy in which the function allows activity A, is decomposed into functions, provides a suitable space S for activity A, and controls the access to space S. These two subfunctions are further decomposed into other subfunctions.

3.5 *Specialization*

A class of design objects is defined such that all its members have something which allows them to be classified within that class. As stated above, classification into the same class can always be made on functional grounds, i.e. all objects with the same function can be classified as belonging to that class of objects with that function, e.g. cutting implements. It is not always easy to recognize similarity in the purpose of objects of the same class. For example, the class of tables should all have purposes which are common to all types of tables. Yet, we have dining tables, kitchen tables, bedside tables, operating tables, etc. Dining tables and kitchen tables are both used for eating, but there is a difference in the type of eating. Bedside tables are used to provide for bedside lamps, books and other objects to be readily available to and from the bed. So where are the commonalities and where are the differences? At the purpose level all are different, e.g. to enable dining, casual eating, allow for bedside accessories and enable surgical operations. Dining means more than just eating. It also includes concepts of ambience, conversation, longer periods, more people, more formality, status and others. Eating in a kitchen is more casual with usually smaller groups of people. There is a notion of a kitchen table being

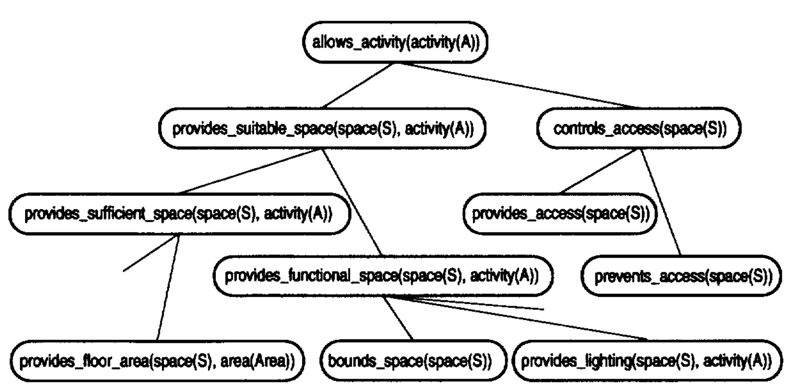

Figure 7 Example of functional decomposition.

more utilitarian than a dining table (although the aesthetics cannot be totally ignored). At a functional level, however, we can see the commonalities. All tables provide for the stable support of a number of objects at a particular height. This is achieved by the provision of a rigid horizontal plane of a suitable material of suitable shape and size at the required height. This in turn is achieved by transferring the loads on this plane and the load of the plane itself through supports or other means to the floor or other element. With this functional commonality, we can see that a dining table could, in fact, be used to support a lamp and in certain cases, a dining table could indeed be used as an operating table and while an operating table might be used for dining, it would not add much to the decor.

The class-subclass relationship among descriptions of objects means that the functions of subclasses must specialize the functions of the class. For example, all walls separate space in general. External walls separate internal space from external space, whereas internal walls separate internal space from internal space. A particular internal wall (an instance) separates a particular internal space or room from another particular internal space or room. Given the table example above, all tables provide for the stable support of a number of objects at a particular height. Specific table types provide for the support of more specific numbers of objects, at specific height ranges and may have additional functions, such as enhancing the particular environment. This class-subclass and class-instance specialization must be taken care of in any representation of function.

4 Function as surrogate purpose

4.1 Wholistic and component design

Some of the confusion that exists regarding function and purpose is due to the design domains of various design disciplines. Many disciplines are concerned with the design of artefacts which by themselves do not serve a purpose of direct use to humans, e.g. an amplifier or a gear. These artefacts are only useful when used as components of a whole or other system, e.g. a hi-fi system, a car. The design of such component artefacts, although treated by the respective designers as a 'stand-alone' design in their own right is really only a part of a more complex design chain and hence the design of such component artefacts begins at the functional requirement level. Figure 8 shows the relationship of components to the whole.

Note that purpose and the socio-cultural environment are not shown for the components. The *why* or *what for*, in the sense of social purpose, is not directly relevant in the design of these components. The designer who is concerned only with the design of artefacts which are to be used as

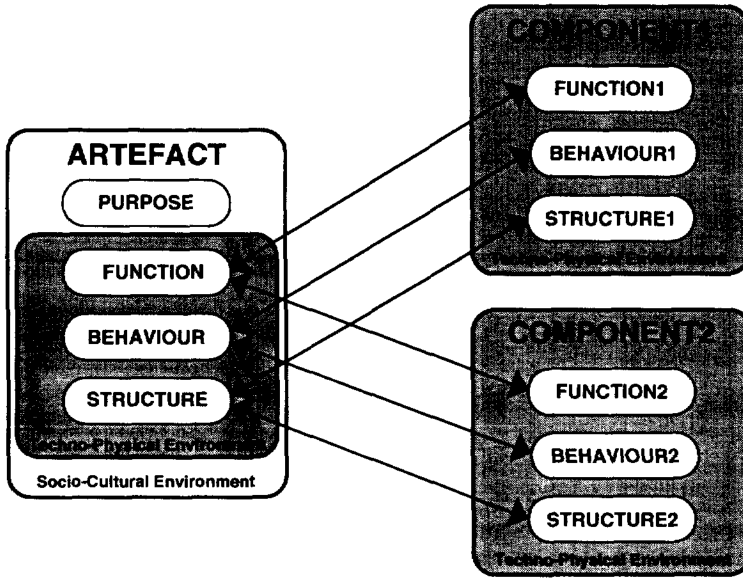

Figure 8 Whole-component decomposition.

components in some whole is, in fact, starting at a level which begins with the *what does*, i.e. at the level where functional requirements have already been formulated. Although a designer of an amplifier may be told in common parlance that the *what for* (i.e. the purpose) of the amplifier is to magnify a signal, this should be more formally stated as *what* the amplifier *is to do*. What the amplifier is for, is to be used in some other system. The function of an amplifier is to magnify a signal, but the purpose for magnifying a signal is so that humans can hear it (or some other device can discern it). The purpose related to the human purpose rests only in the whole object, e.g. the hi-fi system or other audio equipment.

On the other hand, some artefacts, which form components of wholes and which by themselves have little meaning, e.g. doors, do relate to human needs directly. Doors provide security, they act as barriers to humans (and other things). Their social utility is obvious.

4.2 *Intended function—an operational view of purpose*

As was stated above, 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. That is, 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. Thus all design descriptions, whether of whole artefacts or component artefacts, can include a purpose description. In some cases this purpose description will include socio-cultural as well as techno-physical descriptions, while in others it will include only techno-physical descriptions.

4.3 *Intended and non-intended functions*

As was stated previously, all artefacts come into existence through human intention. That is, they are designed for some purpose(s). As such, they effect certain functions, some of which relate to the purpose and some which are not intended. While cars are designed for the purpose of transporting people and effect such intended (and hence useful) functions as carrying loads, moving, providing an enclosed space, etc., they also effect unintended (and disadvantageous) functions such as occupying space, producing effluent gases, producing noise, etc. Both intended and non-intended functions can be utilized for ends other than intended purposes, e.g. cars can be used as ramming devices for smash-and-grab robberies or to commit suicide through carbon monoxide poisoning. The recognition of the function of a cup that it holds a fairly constant amount of substance leads to a realization of its utility as a measuring device and to the subsequent ascription of a purpose of measuring quantities.

4.4 *Emergent function—mixtures and compounds*

A complex object is an assembly in which the function(s), and hence the purpose(s), of the whole emerge from the interactions of the components. A bicycle moves 'forward' when pedalled, its purpose is to transport people at a faster rate than by walking. None of the parts by themselves do this. There are, however, some assemblies or aggregations where the whole has no apparent emergent function(s) other than the sum of the functions of its components. For example, a wall with a function of separates(space(S1), space(S2)), a wall opening with a function of allows access(space(S1), space(S2)) and a door with a function of controls access(space(S1), space(S2)) can be aggregated into a wall assembly which will merely have the functions of its components. The two types of assemblies can be compared to compounds and mixtures in the chemical domain. In compounds a chemical interaction takes place from the constituents and new properties emerge, whereas in a mixture the constituents remain separate and no new properties emerge.

In the case of the 'compound' object, the overall emergent function is achieved by the contributions of the functions of the components in a particular relationship. So that if a particular function is required to be produced, contributing component functions have to be determined as well as the relationships (i.e. input/output relationships) between these component functions. These contributing component functions will be produced by components which themselves may be 'compound' objects.

5 *Multidisciplinary design—integrating different functional concerns*

5.1 *Concerns and concepts*

Most design projects are large and complex and thus involve multidisciplinary design teams. 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 the form and organization of spaces and those elements relevant to those purposes and 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. Mechanical engineers are concerned with providing functions such as transportation and climate control through the provision of mechanical facilities, such as transportation systems and mechanical HVAC systems. They are concerned with concepts such as flow, capacity, time, energy and power, elevators, escalators, motors, coolers, heaters, piping, 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. environmental aspects are the concern of both the architect and the HVAC engineer.

At different stages of the design process, different kinds of information are communicated. At the preliminary or conceptual stage of the design process, the main aim is to communicate concepts and intentions to enable the selection of systems and elements. At the detailed design stage, the main aim is to set consistent values for the structure attributes of the elements.

5.2 Multiple views and models

We are concerned with the perception, conception and representation of design objects[24,25]. Our view of an object depends on our collective experiences and concerns. We build a conceptual model of an object based on that view, i.e. a representation, and manipulate that representation when we communicate. Within certain common groupings, such as design disciplines, there are, generally, common views and common understandings and agreements regarding the interpretation and description of objects, thus leading to common representations. In a design context, the view that a person takes depends on the functional concerns of that person, where functional concerns include, in addition to technical functions, non-technical functions such as aesthetics, symbolism, psychological effects, etc. 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. In fact, a building is all of these, and more.

A model or abstraction of an object is a representation of that object resulting from a particular view taken. Since there are many different views of a building there will be many corresponding models (Figure 9).

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. 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 architects are concerned. Structural engineers,

24 Rosenman, M A and Gero, J S 'Modelling multiple views of design objects in a collaborative environment' *CAD* Vol 28 No 3 (1996) pp 207–216

25 Rosenman, M A, Gero, J S and Hwang, Y-S Multiple concepts of a design object based on multiple functions. In *Management of Information Technology for Construction*, eds K. S. Mathur, M. P. Betts and K. W. Tham. World Scientific, Singapore (1993) pp 239–254

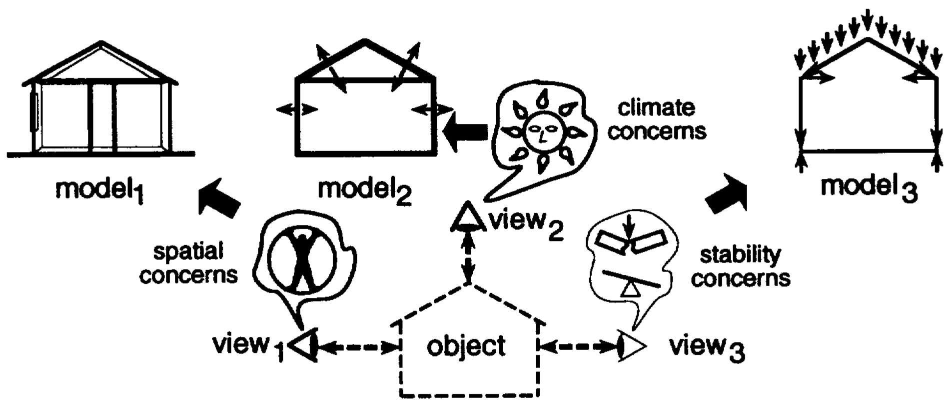

Figure 9 Multiple views and models of a single object.

however, see the walls and floors as structural elements capable of bearing loads and resisting forces and moments. Both models must coexist since 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, e.g. different finishes. 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.

In a multidisciplinary domain, different disciplines will assign different purposes to the same artefact or element arising from their different functional concerns or views. Different functions, and hence behaviours and structure descriptions, will be of concern to the different disciplines.

Since in the object techno-physical environment, intentions or purpose are commonly interpreted as intended functions, the representation of functional properties and functional concerns become 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 and assume that all other information can be determined. It is not necessarily 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 themselves[26]. 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[27].

5.3 Concepts and descriptions

Design prototypes describe classes of design elements[9,28,29]. They are object-centred schema specifically dealing with design objects through their categorization of function, behaviour and structure properties. 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. A particular designer's model consists of the instances created by that designer augmented by any other instances created by other designers but whose functions come under the concern of that designer.

Once a designer's view has been expressed in terms of particular 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. Finding the relationships between contributing functions is not a simple text match but may have to be carried out through various levels of abstraction[30].

5.4 Functional modelling in collaborative CAD modelling

There are two main ways in which functional modelling, that is 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

26 **Balachandran, M, Villamayor, R and Maher, M L** Using past design cases to support structural system design for buildings. Progress Report for Acer Wargon Chapman Associates, Design Computing Unit, University of Sydney (1992)
27 **STEP**, Product Data Representation and Exchange—Part 1: Overview and fundamental principles. Technical Report, STEP document ISO TC184/SC4/PMAG (1992)
28 **Gero, J S** 'Design prototypes: a knowledge representation schema for design' *AI Magazine* Vol 11 No 4 (1990) pp 26–36
29 **Gero, J S and Rosenman, M A** 'A conceptual framework for knowledge-based design research at Sydney University's Design Computing Unit' *Artificial Intelligence in Engineering* Vol 5 No 2 (1990) pp 65–77
30 **Hwang, Y S** Design semantics and CAD databases. Ph.D. thesis, Department of Architectural and Design Science, University of Sydney (1994)

is contingent on that purpose. Thus, the element cannot be modified in a way that will impair the intended function. Obviously this includes the removal of that element unless something is done to replace the intended function. For example, the assignment of a stabilizing function to a wall by a structural engineer should now prevent the architect from removing that wall unless the function of that wall is replaced by, for example, a beam.

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. Note that this is a description of what a column does, not what it is thought it should do. 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.

Since it was stated that each discipline has separate concepts and therefore builds different models of the elements under consideration, 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. The same—as relationship may be made between two elements or between specific properties of the elements. For example, the shape of one element may be stated to be the same—as the shape of another element. 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.

6 Conclusions

This paper has argued that design is a process which transforms semantic representations into syntactic representations by proceeding from a human socio-cultural environment to an artefact techno-physical environment. It has shown that a conceptual separation of the two environments is convenient for being able to clarify the concepts of purpose, function, behaviour and structure such that a better understanding of the processes involved in design is achieved. Taking this view has related this work to the view of design as not just search but exploration and search, i.e. problem-making and problem-solving.

It has stressed the importance of functional reasoning as central in the life-cycle of the design process and the importance of CAD systems to use such representations if they are to be more than mere graphical assistants. It has taken a multidisciplinary view and shown how the clarifications of the concepts can lead to the various functional concerns of different design disciplines being integrated to lead to a useful collaboration between these disciplines in a CAD environment.

Acknowledgments
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