Chapter 12

Constraint-bounded design search

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12.1 The representation of building objects

The design process requires continual checking of the consistency of design choices against given sets of goals that have been fulfilled. Such a check is generally performed by comparing abstract representations of design goals with these of the sought real building objects (RBO) resulting from complex intellectual activities closely related to the designer's culture and to the environment in which he operates.

In this chapter we define a possible formalization of such representations concerning the goals and the RBO that are usually considered in the architectural design process by our culture in our environment.

The representation of design goals is performed by expressing their objective aspects (requirements) and by defining their allowable values (performance specifications). The resulting system of requirements defines the set of allowable solutions and infers an abstract representation of the sought building objects (BO) that consists of the set of characteristics (attributes and relations) which are considered relevant to represent the particular kind of RBO with respect to the consistency check with design goals. The values related to such characteristics define the performances of the RBO while their set establishes its behaviour.

Generally speaking, there is no single real object corresponding to an abstract representation but the whole class of the RBO that are equivalent with respect to the values assumed by the considered characteristics. The more we increase the number of these, as well as their specifications, the smaller the class becomes until it coincides with a single real object -given that the assessed specifications be fully consistent. On the other hand, the corresponding representation evolves to the total prefiguration of the RBO.

It is not therefore possible to completely define a BO representation in advance since this is inferred by the considered goals and is itself a result of the design process. What can only be established in advance is that any set of characteristics assumed to represent any RBO consists of hierarchic, topological, geometrical and functional relations among the parts of the object at any level of aggregation (from components to space units, to building units, to the whole building) that we define representation structure (RS). Consequently the RS may be thought as the elementary structures that, by superposition and interaction, set up the abstract representation that best fit with design goals.

12.1.1 Hierarchic structure

Building objects, as complex systems, can be represented by means of their parts, which are, in turn, conceivable as sets of parts of a lower level, and so on to the desired specification level. This means to define on the BO set an order based on the transitive, reflecting and antisymmetric relation 'To-be-part-of' ($\supseteq$). To the set B ($\supseteq$) ordered by the $\supseteq$ relation corresponds an algebraic structure called 'semilattice'. The hierarchic structure is the most general of the representation structures and defines the set of the allowable organizations of the BO parts, whose reciprocal dispositions are analysed and defined by the toplogical structure.

12.1.2 Topological structure

The BO expressed in the hierarchic structure, considered as subsets of a space, define on it the base of a topology T. In fact, for any point x □ W there is an element B □ T, such as x □ B. However, given two elements B1 and B2 □ T, B1 □ B2 $\neq$ 0 results, which is an element of T.

The set of existing or requested relations on T defines the topological structure of the investigated BO. Such relations describe the reciprocal disposition of the considered spaces and physical elements, the access and communication conditions among space units and building units.

A topological structure can be represented by means of generalized graphs $G(B_i)$ such that $G(B_i) = (B_i, T_i, R_i)$, where B_i, T_i, and R_i, are the BO, its subset family and specific relation that is considered, respectively.

12.1.3 Geometric structure

While the hierarchic and toplogical structures represent the constitution of BO and the reciprocal disposition of their parts, the geometric structure represents the shape and the positions of the physical elements of BO together with the form of the space system.

To this end there are many geometrical representation systems belonging to the two following main classes: CSG (constructive solid geometry) and B-Rep (Boundary representation). In CSG representation a complex volume results from Boolean operations on elementary volumes; in B-Rep volumes are defined by their bounding surfaces. In both, however, volumes are defined in a space that is not an element of the representation.

Because of the relevance that void spaces have in architectural design as a result of the definitions of solid volumes, an overcoming of the above-mentioned schemes is needed: the definition space of volumes is entirely filled by void spaces and solid shapes; the surface of every shape will thus separate two different kinds of volumes, the void and the solids, independently of the adopted kind of representation.

12.1.4 Functional structure

The characteristics of a functional element (FE), beyond the kind of BO that it seeks to define, its interactions with other BO and its particular shape, result from the tasks it has in defining and classifying the building space, in allowing safety and stability and establishing required environmental comfort levels.

Such characteristics will be represented on the one hand by identifying every FE as an element of a functional class that can be specified at will, according to the requirements of the representation (e.g. from enclosure to external envelope, internal division; from external envelope to vertical walls and floors; from vertical walls to walls and windows and so on). The FE will inherit all the functions of the class it belongs to besides its own ones. On the other hand, the above-mentioned characteristics will be represented by means of calculation schemes that simulate the behaviour of the FE and of the system to which it belongs.

12.2 The frame formalism

The definition that has been given for RBO representation corresponds to that which is usually accepted in the field of artificial intelligence. By means of requirements, performances and performance specifications we can realize a selective mapping among real and abstract objects defined by the representation structure. Among the available formalisms the *frame* has been chosen to realize the representation structures.

A frame is a structured set of characteristics (slots) related to a BO which, when a characteristic requires further specification, can be expanded by a new frame. To a slot we can relate a set of expected values *(defaults)* that define a set of expectations.

A frame can be utilized as a prototype of a class of objects; so when an expected values set is substituted by real values, we can establish an *instance* of the class of which the object inherits the characteristics. The ranges of values connected to a slot are defined by means of suitable *facets*. A slot, by means of a suitable facet, can be connected to a procedure *(demon)* that is executed whenever the slot is touched by the program. Such a *procedural attachment* makes possible the representation of complex relations among BO and a corresponding slots (modelling), and simplification of the processes performed on the representation, suggesting strategies and suitable operations connected with the state of representation.

A frame system can be implemented by means of generalized lists in which every element can be a list in its turn. To this end the most suitable language seems to be LISP. This makes list management and procedural attachment easy, since programs and data are expressed by the same list structure.

12.3 Representation of building objects and design process

The representation structures can be expressed by means of the frame formalism, defining a set of suitable slots, the most basic being the following:

(1) IMP, IMS express the hierarchic structure of a BO. IMP contains the BO frame names that are directly subordinate to the considered object. IMS, on the other hand, contains the higher-level ones.

(2) ADJ, COM contains the BO which are in adjacency and communica-

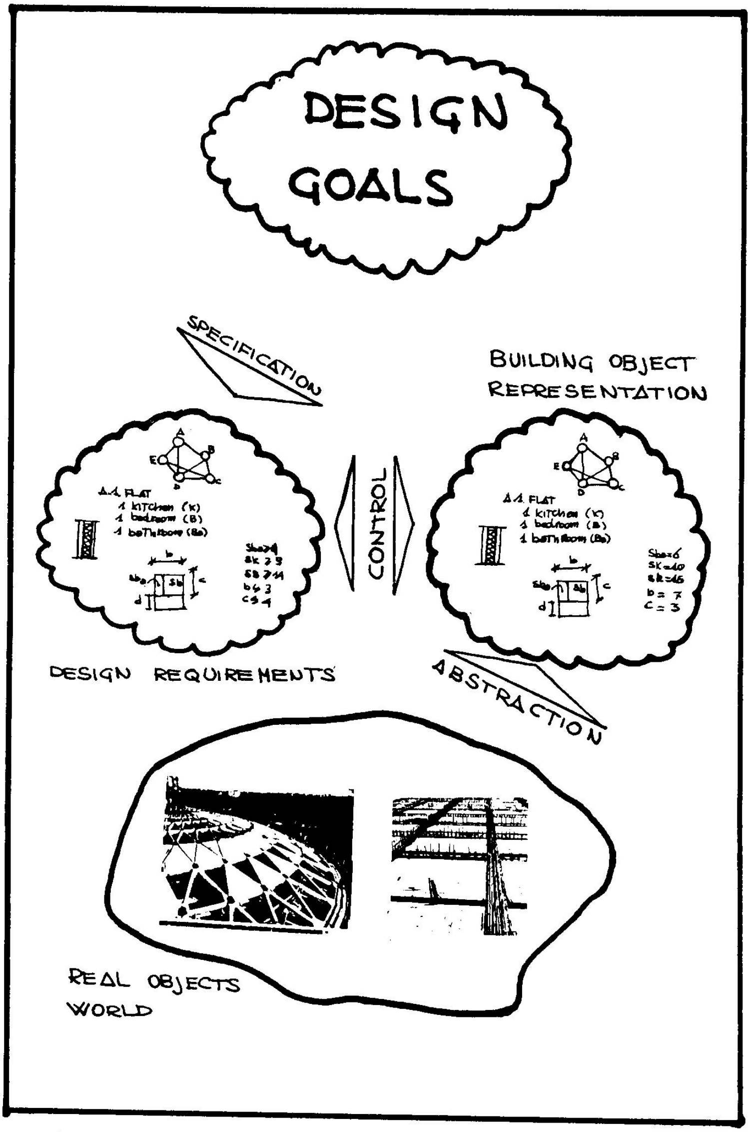

Figure 12.1. Control of design choice is performed by a design goal specification and building-object abstraction by representation structures

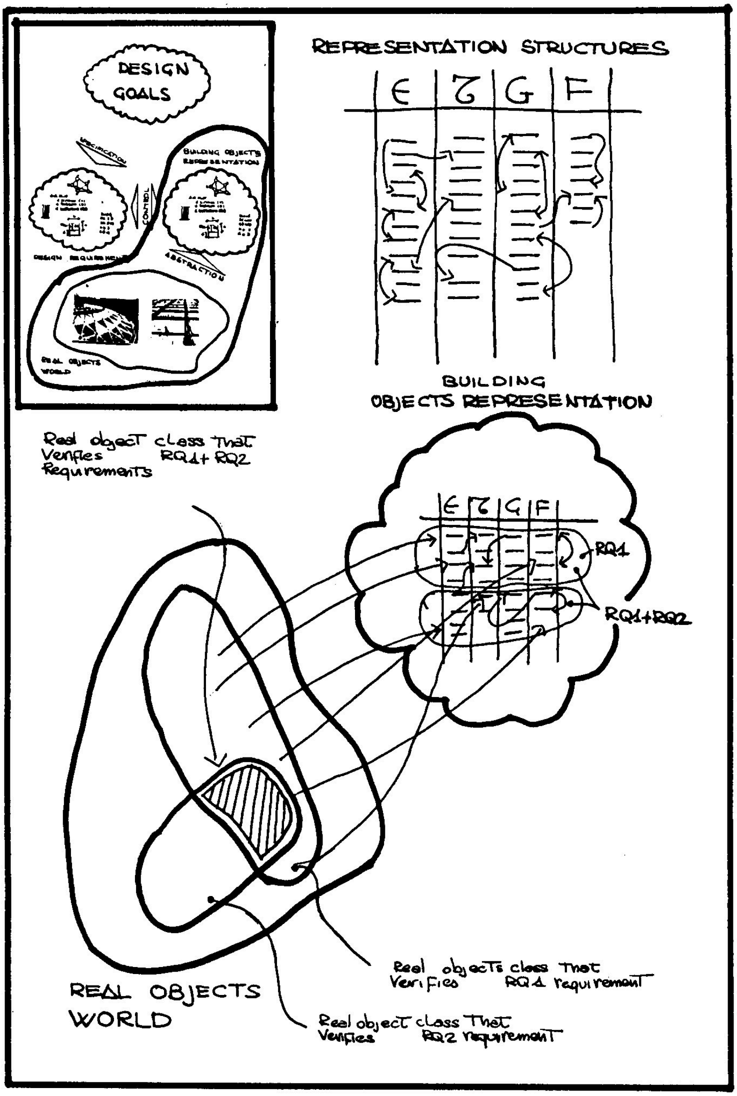

Figure 12.2. Building-object representation by means of representation structures

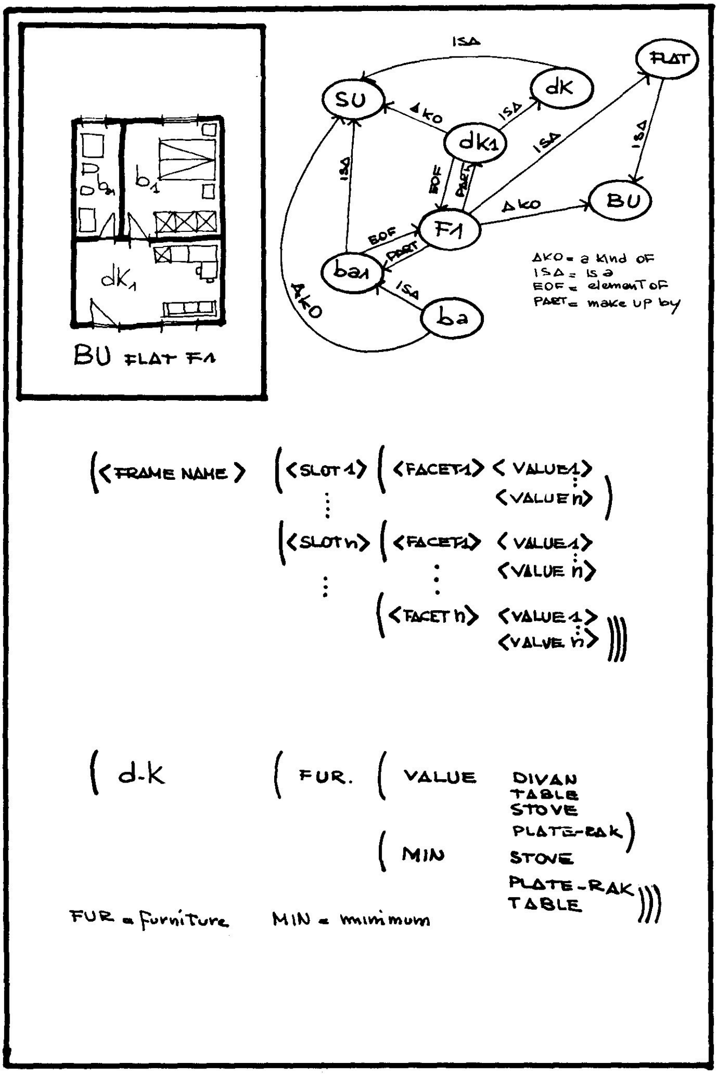

Figure 12.3. A frame representation by means of the Lisp language and the prototype mechanism.

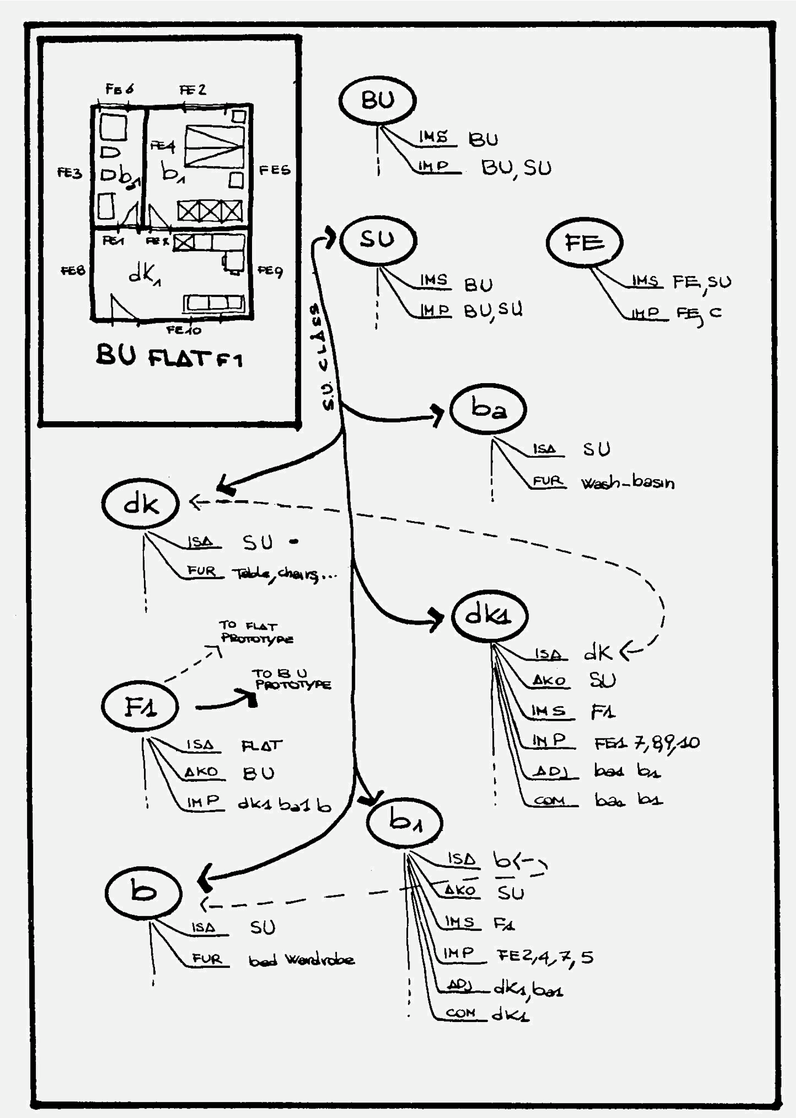

Figure 12.4. Part of the Fl flat representation by means of frame formalism (only the class-subclass and subclass-instance links have been shown)

tion to the considered object; they define therefore its topological structure.

(3) SHAPE contains the geometric elements that define the shapes of a BO, they can be surfaces, edges or vertices when using boundary representation, half-spaces or elementary volumes when using CSG.

(4) ISA, AKO (is a, a kind of), slots belonging to the formalism that define the contained frame as an instance of a class (ISA) that in turn is a subclass of a more general one: they make possible the prototype mechanism. The functional structure can be expressed by ISA and AKO slots and suitable procedures.

12.3.1 Design-requirement representation

By means of the frame formalism design requirements can be expressed and made operative. To this end it has been shown that the prototype mechanism makes it possible to define classes of BO; moreover, a slot represents a characteristic of a BO and the connected facet the kind of its value.

A requirement can consequently be expressed by a suitable slot for a considered prototype or by a new frame. [slot, facet, value] term allows the performance specification connected to a given requirement to be expressed. Some special facets will be used to define the set of allowable values of a performance specification. Among them are the following:

(1) RANGE, SET, respectively, define a continuous or a discrete set of values; RANGE is defined by its extremes, SET by a list of elements;
(2) CLASSES indicates the variation classes;
(3) VALUE defines the value (performance) performed by a specific BO.

12.3.2 Design-choices verification

Prototype mechanism and inheritance procedures allow the consistency of design choices with considered goals to be checked. Such a check is performed whenever the designer defines an object belonging to a known class: in this case the object inherits characteristics and performance specifications from the class prototype, with a consequent constraint propagation to the object itself. The constraint verification is thus possible by comparing the requested with the performed values. The inheritance procedures, moreover, make it possible for a Supervisor Program to request the definition of characteristics which are considered by the class prototype but not defined by the designer. On the other hand, by means of generalization procedures, the prototypes can be enriched by introducing new characteristics learned by examples.

12.3.3 Automatic control

The procedural attachment make possible the automatic control of the coherence of the representation of building objects within the design process. Such a control is necessary to prevent local variations producing contradictory information on the representation. The automatic control of

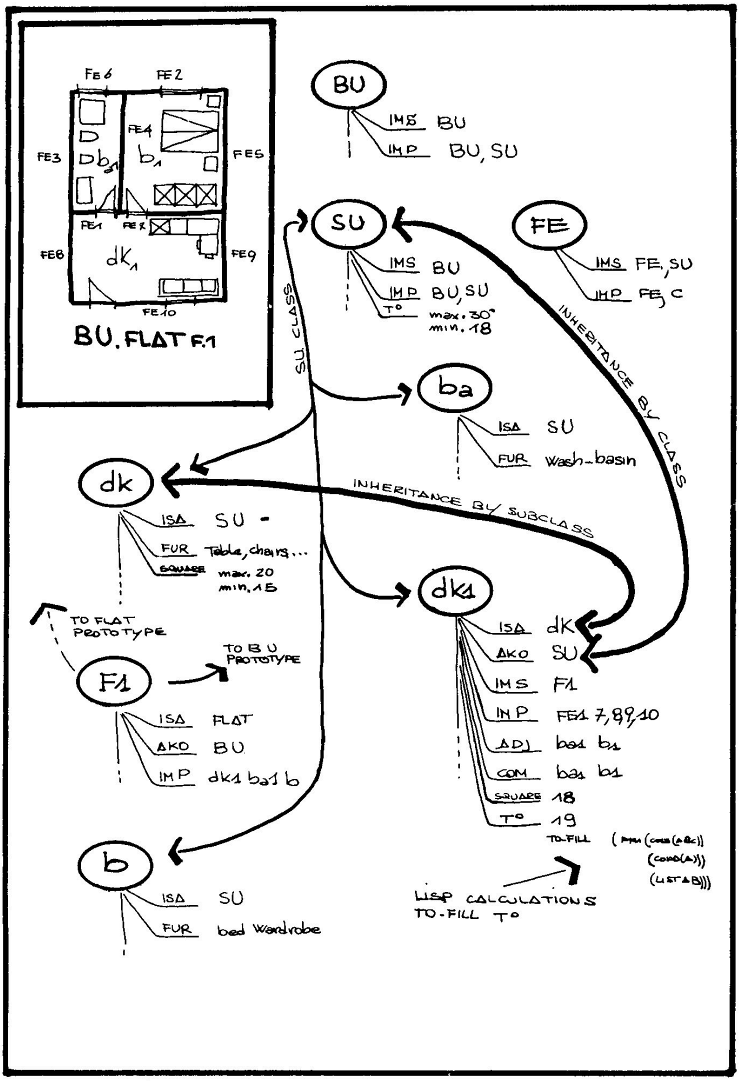

Figure 12.5. Requirements, performance specification and performance representation

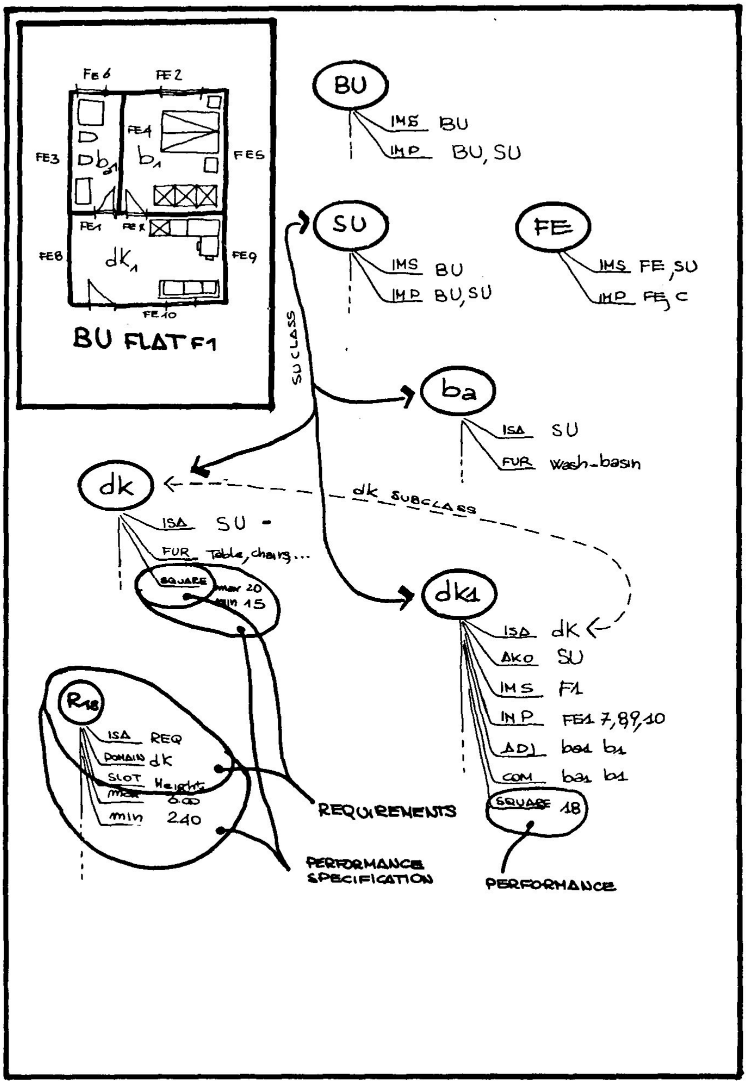

Figure 12.6. Automatic control allowed by inheritance mechanism

the design process is performed by establishing the effects produced by every design choice and by executing control procedures of these values. Such procedures, called *demons,* are peformed by suitable facets *(advices)* when the connected slots are touched by the program.

12.4 Prospects

As outlined above, an expert system is being developed to supervise building design at any stage of its development. This work can be considered as a basis of realizing a design system in which the computer's task will be an active design aid. The proposed system operates mainly in the verification phase and only indirectly in the definition of possible design solutions. We can therefore think of a set of semantic primitives (shanks) based on representation structures by means of which design actions could be expanded. Such a system could be used to describe the differences among performances and constraints and translate them into a plan to modify BO definition. In other words we can think of a system that, by iteration of definition and verification phases, can find optimal solutions to specific problems given by the designer.

References

BAER, A., EASTMAN, C. and HENRION, M. (1979). Geometric Modelling: a Survey. *Computer-Aided Design 11,* No. 5, September

BOBROW, D. G., and COLLINS, A. (1975). *Representation and Understanding,* New York: Academic Press

BOBROW, D. G., *et a!.* (1977). GUS. A Frame Driven Dialog System. *Artificial Intelligence* B(2), 155-173

CARRARA, G., COCOMELLO, P., GORI GIORGI, C. and PAOLUZZI, A. (1978) A Systems Approach in Building Component Design. *Proc. of IFAC Conference,* New York

CARRARA, G. and PAOLUZZI, A. (1980). *Systems Approach to Building Program Planning,* Istituto di Architettura, edilizia e tecnia urbanistica, Facoltà di Ingegneria, Rome

CARRARA, G. (in draft). *L'oggetto edilizio e la sua rappresentazione*

CHECCHUSSI, V., TOGNOLIA, A. and VESENTINI, E. (1977) *Lezioni di topologia generale,* Feltrinelli

GIRARD, C. (1984). Presque half-planes: Toward a general representation scheme. *Computer-Aided Design 16,* No. 1, January

HOFSTADTER, D. R., (1979). *Gödel, Escher, Bach: An Eternal Golden Braid*

LEVESQUE, H. J. (1984). Foundation of a Functional Approach to Knowledge Representation. *Artificial Intelligence* 23, 155-212

LATCOMBE, 5. C. (1977). Artificial Intelligence in Computer Aided Design. In J. J. Allen (ed.) *CAD System,* Amsterdam: North Holland

MANTYLA, M. A Note on the Modeling Space of Euler Operators. *Computer Graphics and Image Processing*

MANTYLA, M. and SULONEN, R. (1982). GWB - A Solid Modeler with Euler Operators. *IEEE Comp. Graphics Appl.* 2(7), 17-31

MCDERMOTT, D. and DAVIS, E. E. (1984). Planning Routes through Uncertain Territory. *Artificial Intelligence* 22 107-156

MONK, J. D. (1969). *Introduction to Set Theory,* New York: McGraw-Hill

NILSSON, N. J. (1971). *Problem-solving Methods in Artificial Intelligence,* New York: McGrawHill

NILSSON, N. J. (1982). *Principles of Artificial Intelligence,* Berlin: Springer-Verlag

PREPARATA, F. and YEH, T. (1963). *Introduction to Discrete Structures for Computer Science and Engineering,* Reading, Mass.: Addison Wesley
LOMBARDO RADICE, L. (1982). *Istituzioni de algebra astratta,* Feltrinelli
REQUICHA, A. A. G. (1980). Representation for Rigid Solid: Theory Methods and System. Computing Surveys 12, 4, December
REQUICHA, A. A. G. and VOELCKER, H. B. Boolean Operations in Solid Modeling Boundary Evaluation and Merging
Algorithms. *Proceedings of the IEEE 75,* No. 1, January 1985
REQUICHA, A. A. G. and VOELCKER, H. B. (1982). Solid Modeling: a Historical Summary and
Contemporary Assessment. *IEEE, Comp. Graph. Appl. 2,* No. 2, March
STEFIK, M. I. (1980). *Planning with Constraint,* Stanford University Press
WINSTON, P. H. *Artificial Intelligence,* Reading, Mass.: Addison-Wesley