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DEFINITION OF SPATIAL ELEMENTS OF THE BUILDING SYSTEM: <<REASONER A>> IN THE CASTORP SYSTEM

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Abstract

This paper tackles the problem of the functional and morphological definition of elementary spaces (in relation to the overall definition of the building object) through the study and the modelization of the designer's knowledge and of the cognitive processes which use it. An interactive automatic system which solves the problem of the placing of objects within a predefined environment is then described. This is the first element in a more general system which is meant as an intelligent aid to building design.

1. Introduction

An architect carries out his design work in several stages. He starts with the artistic and creative idea and develops it towards the project's definition, i.e. the definition of the overall building system and of the global elements of which it is composed.

Automatizing the idea-project passage is a difficult and interesting challenge that requires deep study and also modelling of the various of types the designer's knowledge and of the deep cognitive processes he applies to his knowledge in order to envisage a project that complies with the given constraints.

Broadly speaking, the two hallmarks of human reasoning are the abilities to qualitatively conceive physical objects and the space around them and to think by 'work hypotheses' made plausible by past experience, and kept valid until they are invalidated by new fact. These abilities also play a prominent role in architectural design.

Therefore, it was only natural for us to tackle our problems with Artificial Intelligence techniques [1]. Artificial Intelligence was developed to study and simulate ordinary ways of thinking, therefore it lends itself to providing both a set of methods for the theoretical formalization of our problems [2] and a set of well-established tools for attempting experimental simulations of architectural design.

At present, we cannot automatically generate a complete project, but, we can try to implement an 'intelligent aid' that can interactively help the architect to verify the plausibility of his hypotheses and also to suggest revisions and corrections of his work, from local details to broader issues, to the point of a completely new design [3].

This paper focuses on the placing of objects within a pre-defined space. This problem rises at many different stages of the design work: e.g. during the assessment of design quality or at the more abstract level of functional and spatial design of the building's constituent parts (rooms, corridors, etc.) with particular reference to their dimensional and morphological definition.

The main aim of our research is to define a system that can place functional objects (furnishings and fittings) following a strategy that takes into consideration the geometrical aspects that are connected to the relations existing between the spaces they occupy (actual space and functional pertinence), together with the spatial relations existing between an object and the others and those existing between any object and the surrounding environment [3], In this way, one can assign quality markers to the temporary and final patterns that were generated; this method may show the most promising path for the placing of further functional objects or point at the optimal final solution.

Our first and most important problem has been to define a conceptual model of the 'space' that would form the basis for successive representation of spatial relations between objects. Traditional set theory provides an excellent starting point for the representation, for instance, of the space occupied by a sofa in a sitting-room or of the pertinent space of a window. However, due to the strict (binary) on/off mechanism used to attribute elements to sets, set theory is no longer suited to express looser constraints, such as those expressed by such phrases as: "near the table", "in the middle of the room", "at the right of the window", "beneath the sink etc. Therefore, we had to resort to Fuzzy Set Theory [4] in which the mathematical of definition allowed us to account for this feature.

During the process of placing, one may have to add new constraints and/or modify some structural parameters (e.g. adding or erasing doors or windows, changing wall shapes and positions, perturbing room perimeters, etc.). This may invalidate previous hypotheses and cause the complete review of the process. Typically, this occurs when previously placed objects form a lay-out in which the further placing of objects causes pertinent spaces or actual space occurred, to overlap. The situation is particularly relevant, when a whole library of inventories must be modified in accordance to the requirements of a new project. It is then necessary to define the strategies to follow, in order to discard old hypotheses and formulate new ones.

Geometrical representation of objects deserves special attention. We chose not to use the complex representations typically employed in CAD; instead we limited ourselves to considering only the pertinent and actual spaces occupied by our objects (see figure 1).

2. The representation of space and of the relationship between objects:

Formalizing a model that represents the spatial relations between objects must be based on a representation of space [5]. As we said in our introduction, traditional set theory is not the perfect instrument for this task since the mechanism that defines whether members belong to sets is too strict and does not suit well the definition of vaguer notions. Some recent developments, collectively known as Fuzzy Set Theory [4], provide the ideal mathematical instrument to tackle this kind of problem. Formally speaking, let U be a set (called 'universe of discourse'), a fuzzy set μA (related to U) is characterized by a function A for which:

$$\mu A \;/\; U \;{-}{-}{-}{>}\; [0,1]$$

Function μA (called 'membership function') assigns a number $\mu A(u)$ that lies in the interval [0,1] to each member u of U; this determines the degree of membership of u with respect to A. The definition of nonfuzzy sets is a sub-class of fuzzy set theory and is valid only when the membership function is either 0 or 1.

As an example, let us consider the room shown in figure 2a. Supposing that the sofa could be placed along the wall A, the membership function that expresses the relation 'near to the window' has a shape similar to the one shown in figure 2b.

Fuzzy sets allow us to model many constraints (that can be expressed by means of spatial relations) and default data, to which human designers frequently resort. These concern the typical positions of the objects to be placed with respect (1) to the room that accepts them, (2) to the other objects. As, an example of the former, a table in a bedroom is typically positioned along a wall, while it is generally in the middle of a living-room; as for the latter, imagine the pattern of two armchairs and a sofa. More particularly, the need to account for many constraints at once is immediately met by fuzzy set operations. In fact, as in traditional set theory, operations of union, intersection, and inclusion can be defined. If an object A has an R relation with objects $B_1, \ldots, B_n$, the fuzzy set I of the points in which the possibility of placing A is to be calculated results from:

$$I = \cap_i R(A, B_i)$$

A list of elementary spatial relations (henceforth called 'spatial primitives') have been found and defined in fuzzy terms. These can be expressed, for instance, by the following phrases: 'far from', 'to the, right of', 'in the middle of', 'opposite to'. The complete list is given in table 2; the composition of these elements affords a description of the widest range of relations between objects. Still referring to the example given above (figure 2a), if one wanted to place the cupboard C far from the door and in front of the sofa, one should only compose the two membership relations expressing their corresponding elementary constraints; the eventual outcome is shown in figure 2e.

Since each spatial primitive is characterized by its function, it is necessary to correctly define such functions ('correctly' here means 'as close as possible' to the intuitive notions concerning the meaning of spatial relations we use in everyday life). This is a typical problem of 'commonsense modelling' which, in literature, is generally dealt with by statistical analyses covering the widest possible range of subjects and situations. The study and classification of a thorough taxonomy of objects in different design contexts opened the way to some algorithms which capture the commonsense that lie behind many design choices. Since our analysis was carried out according to our own judgement, some of our definitions of membership functions may seem strongly subjective. Actually, judgement discrepancies affect few individual values of our functions, not their overall qualitative shape, since it is indisputable that all men have the same notion of such elementary concepts as 'nearness', 'middle', etc.

Generally speaking, it can be said that the definition of the membership functions of spatial relatives must be based on the geometrical characteristics of the objects in question; in particular, on the dimensions of the space they occupy. Therefore, spatial primitives do not generally respect the commutative law nor, if a primitive R reciprocal of the primitive. P existed (as is the case in the notions of 'right' and 'left'), we would have:

$$^{\mu}A\ P\ B^{(u)} = {}^{\mu}B\ R\ A^{(u)}$$

where A and B may be objects of any sort. Let us consider, for example, the situation shown in figure 3; if it can be said that the said that the bedside-table is at the right of the bed, it cannot be said that the bed is at the left of the bedside-table.

This observation carries with it a very important with respect to the general problem of object placing. Since neither the reciprocal nor the commutative laws hold, the sequence in which objects are placed is relevant. It is necessary to study and define suitable 'placing strategies' to which the next chapter will be devoted.

Our membership functions deserve one final remark. They could be expressed analytically by of a suitable mathematical continuous representation on the required domain. From a computational point of view, however, defining these functions, by means of tables is much more efficient. They are calculated in a finite number of points which implies that the space is, as it were, granular. Let us consider the example of a rectangular room and let us call L its longer side. $2^{-n}*L$ (where n is the arbitrary index that controls the definition threshold) yields the measure of the side of any individual square in which the room area is made discrete. Where, for instance, L=6 and n=5 we obtain a definition in decimeters that is useful for a quick and preliminary placing of objects; while n=9 gives a definition in centimeters for finer placing.

Among spatial primitives, special relevance must be given to 'on_contact' that expresses the way an object stands on its support area. This primitive is always calculated, regardless of the object to be placed, and is used to account for the preferred positions of an object in a given room. Figure 4a shows one possible function for a 'central' object (e.g. a table), while figure 4b deals with a 'lateral' object.

The actual placing of an object implies a large enough space to host it; this is to say that one must prevent 'conflicts' of actual physical space occupied and of function pertinences. From this observation one can deduce further constraints for the object to be placed which are dealt with by defining a fuzzy set labelled 'available space'. Needless to say that when the space is actually occupied by objects its membership function is 0; when, on the other hand, the space can host functional pertinences to a certain extent, the membership function corresponding intermediate values. As an example, the space in front of the closet of figure 5 must be kept free to open its doors, while the space around the bed can be occupied by the desk's functional pertinence.

The following points summarize the placing process:

i) The function connected to the 'on_contact' primitive for the object to be placed is calculated. It includes default information about the typical position of the object, in the room;
ii) all the functions connected to the primitives expressing typical relations with previously placed objects are calculated;
iii) the function connected to available space is calculated;

iv) the functions calculated are intersected

The membership function's values thus obtained are obviously a 'preference indicator' for the barycenter of the object to be placed. However, in order to use this piece of information, it is necessary to introduce the notion of α-cut of a fuzzy Set. Given a fuzzy set A, described by $^{\mu}A^{(\mu)}$, α-cut of A (indicated by Aα) is defined as the traditional set made up of all those values of u for which $^{\mu}A^{(\mu)} > \alpha$.
α-cut is a thresholding tool that can be used to questions in terms of yes/no. In the case of placing, the optimal position of an object is expressed by the pair (Y, y) for which:

$$k = \max \mu^{ris}(x,y) \qquad \text{where } k > \alpha \qquad (1)$$

3. The reasoner's strategy

All 'commonsense modelling' is based on algorithms that are capable of reproducing human decision taking which seems to follow imponderable notions such as obviousness, commonsense and plausibility. In fact, the act is the product of a complex, series of mental operations, of which we are more or less aware, that are based on concepts we can at first regard as non-questionable.
Likewise, our discussion moves from the tenet that there is a series of default assumptions from which our strategy for placing, can be developed.
In this way, the activity of formulating reasonable work hypotheses can be simulated, that, as is, commonly thought, comes from past experience. The reasoner's knowledge base contains information about the usual position of any functional object (fittings, elements of electric and heating systems, sanitary fixtures) in any given room. It also refers to their use and to spatial patterns (e.g. position of the bookcase in a living-room = adjacent to a wall if the room is small; adjacent to a wall or across the room if the room is large or of irregular shape.
As has already been said, this, information is fuzzy, which means that it can be revised until satisfying patterns are attained.
The geometrical features of the objects and of the rooms that would host them can be considered as defaults (they have a low degree of 'fuzziness' which can be null when objects are considered as having unquestionable features).
These assumptions allow us to build a very large and flexible knowledge using few basic concepts.
As an example, the concept of 'table' is strictly bound only to the function of sustaining other objects. Its other features such as shape, number of legs, etc. are extremely variable and depend on the room in which it is placed, on the relations with the other objects of the same room, on the frequence of use, etc.
Essentially, our reasoned, has to decide whether the, kitchen table is to be round or rectangular according to how many people live in the dwelling, the shape and features of the available space, and so forth.
The placing of objects is carried out on a hierarchy based on the following parameters:

i) rigidity of preferred positions on the object in the room;
ii) representativeness of the object;

iii) flexibility of shape and dimension;
iv) utility of the space left free after the object has been placed.

In this way, we can simulate human decision-making processes, which adopt this technique whenever the number of variables that define a problem becomes too high to be economically managed.
Obviously, default data can be revised going backwards along the same path as the one followed during placing.
Altering room features (e.g. doors and windows positioning, dimensional changes) should only be the last resort after all solutions have proved unsatisfactory. At all events, it is signalled as a perturbation of the domain of the expert that works on the building.
The rules that are activated in case of failure point at its causes and suggest possible corrections. A guided backtracking is therefore possible, surely a more efficient and flexible alternative to the mere recursive positioning of objects.
The conditions to be satisfied may concern the type of failure, the type of objects involved and the failure of other similar rules. On the other hand, the actions taken include changing objects' orientations and positions or the constraints imposed on them.
Using an anthropomorphic metaphor, the system behaves like a draftsman who uses an eraser everytime his work does not comply with the specifications. There are essentially two causes for the failure of placing processes: there is not enough free space to host a new object and the object cannot satisfy all the spatial relations with the existing objects at the same time. In either case, two steps can be distinguished in the repositioning strategy: attempting local changes (e.g. stretching available space by little movements of the surrounding objects or rotating objects to make them satisfy the required relations) followed by the search for new positions for those elements which are thought to be responsible for the incongruence in the scene.
Let us look at the example shown in figure 6a. Previous placing created a situation in which the space at the right of the bed was occupied by the closet. Placing the first bedside-table forces the closet to be defined since it is considered as an obstacle, while placing the second bedside-table (hindered by the door) forces the position of the bed to be redefined. One possible result is _shown in figure 6b.
When an object cannot comply with all the. constraints determined by the other objects at once, these have to be re-positioned, starting from those with lesser constraints. Further heuristics can be used to select which objects to move, for instance, it may be preferable to move smaller objects first.
The procedure that commands re-placing may be summarized as follows:

i) verifying the causes of failure;
ii) activating the rules connected with local strategies and checking the result;
iii) in case of failure of local strategies, search for obstacles and for the objects to displace, together with the preferred displacement direction;
iv) determining new positions for the objects found in the previous stage and re-activation of local strategies in the new lay-out;
v) assessment of the overall result.

The following chapter is devoted to this last point.

After displacing an object, it must be verified that the objects which were dependent from it a congruent position; displacing, a table, for instance, implies redefining the position of all the chairs around it. The reconfiguration algorithm is thus recursively applied on objects, this triggers a new phase of analysis. It is possible to work with 'functional units' made up of several elements and first to solve the placing of the units followed by that of its component elements.

4. Automatic quality assessment of the found solutions

As already stated, our reasoner succeeds when the placing attains a valid lay-out. After this, it may look for further solutions for a better-quality lay-out or merely provide several solutions to choose from. For this purpose, traditional set theory can be used with good results.
This chapter aims at describing the logical approach for the recognition of the parameters connected to the quality of a room. We will discuss some examples illustrating simple typological requirements.

4.1 Path distribution

A dwelling's fitness, for use is strongly determined by the pattern and quality of its paths. It is easy to determine the set P of a dwelling's paths by subtracting the set I, the sum of furnishings and fittings, to the set S, the net dwelling's area (P = S/I). The area occupied by furnishings would include functional pertinences if comfortable paths were studied; it would not include them if possible paths were studied (see figure 7).
That P be a continuous set is the necessary condition for the dwelling to have all the connections of use.
It can be said that a dwelling is usable when it is verified that there are paths that connect all doors and windows and when all the pieces of furniture are touched by paths at least in one point A (Fp/As) where Fp stands for functional pertinences and As for actual space occupied.
After determining the set of paths and verifying that it is continuous, it is possible to use simple algorithmic procedures to make a of tests on the quality of the connections. For this purpose, it is necessary to find a series of values that may be considered as indexes of quality such as:

i) minimal path width;
ii) path regularity;
iii) geometrical incidence of paths on the dwelling's net area, etc.

4.2 Interference between furnishings

As previously said, my functional object can be defined in terms of the space it actually occupies and in terms of its functional pertinence.
Actual space overlapping can be assumed as impossible (in fact we are working with two dimensions, the case of a chair upon a table cannot be considered).
Functional pertinences, on the other hand, may be:

i) distinct, adjacent;
ii) intersecting.

In i), the degree of usability is kept within the limits of the full functionality of the lay-out in question (adjacency is the border where a minimal space for use is still kept).
In ii), on the contrary (intersection of functional pertinence sets), two further cases can be distinguished:

i) actual space occupied distinct from functional pertinence of the adjacent object;
ii) actual space occupied intersected with the functional pertinence of the adjacent object.

Let A and B be actual spaces occupied by two furniture items and let A' and B' be functional pertinences, the first of the two cases may be formalized as follows:

$$\left| \begin{array}{l} A' \cap B' = \emptyset \\ A' \cap B = \emptyset \\ B' \cap A = \emptyset \end{array} \right.$$

In this case it is possible to use the two objects although not at the same time.
On the contrary, our second situation is:

$$\left| \begin{array}{l} A' \cap B = \emptyset \\ B' \cap A = \emptyset \end{array} \right.$$

In this case functional objects cannot be fully used; their usage is at best very uncomfortable.

4.3 Shielding the living area from the entrance

Other typological factor determine the quality of a dwelling; they are linked to the relationships between its units usually represented by their uses.
Shielding the living area from the dwelling's entrance is one relevant example of such a relationship.
Practically, the presence of an entrance room or at least of a partition between the front door and the living room is the necessary condition for checking the possibility to shield the living room from the entrance. From a quantitative point of view, a set V can be determined that is the projection of the living area's volume that is visible from the front door on the plan (see figure 8).
The one's complement of the division between surface V and that of the living room can be taken as an index of the degree of satisfaction of our requirement.
These simple examples hint at the possibility of analyzing most of the technological requirements that can be approached with a similar logic.

5. Conclusions

The paper tackles the problem of the placing of objects in space. An automatic system fro its solution has been described. The non-monotone strategy adopted causes the system to carry out continuous quality test on the found configurations. Some examples have been presented which, although very simple, show that some aspects of the design process can be dealt with by means of automatic reasoning techniques.

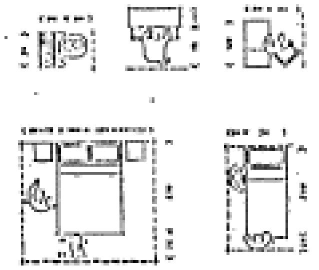


Fig.1

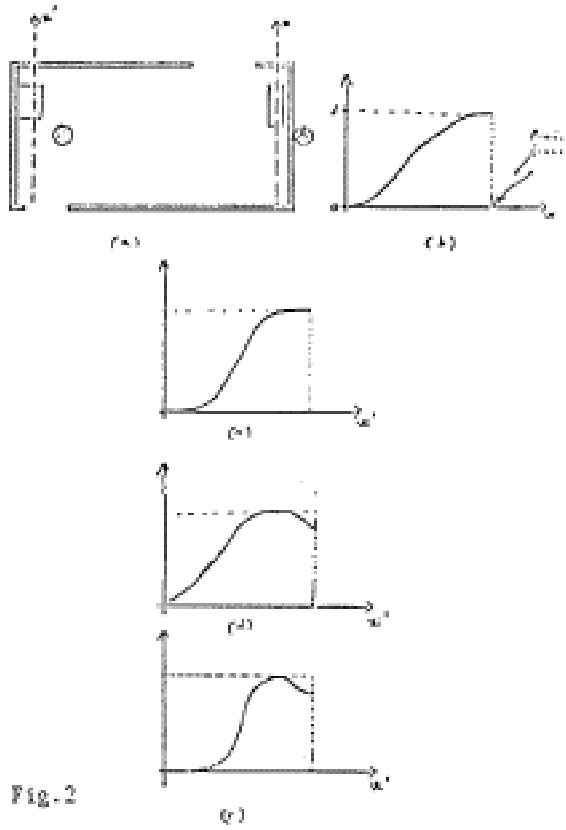


Fig.2

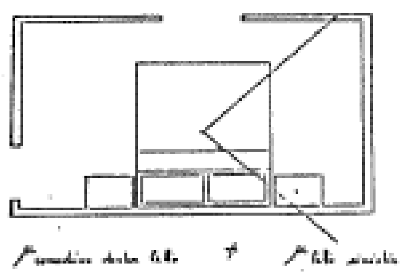


Fig.3

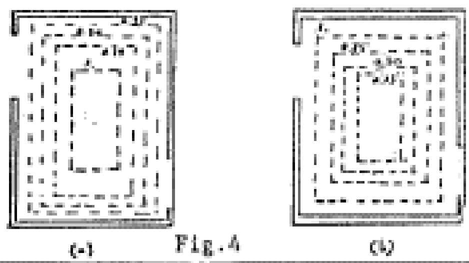


Fig.4

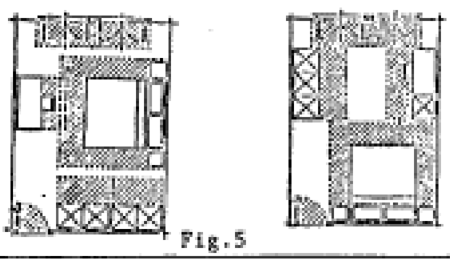


Fig.5

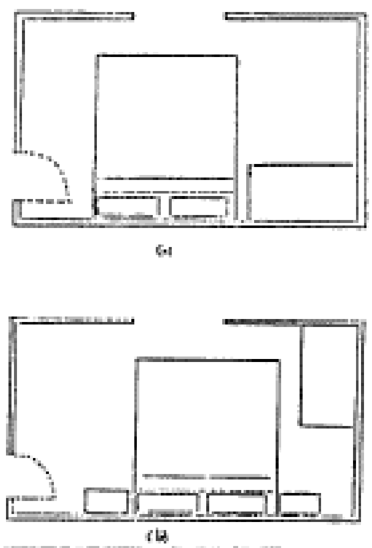
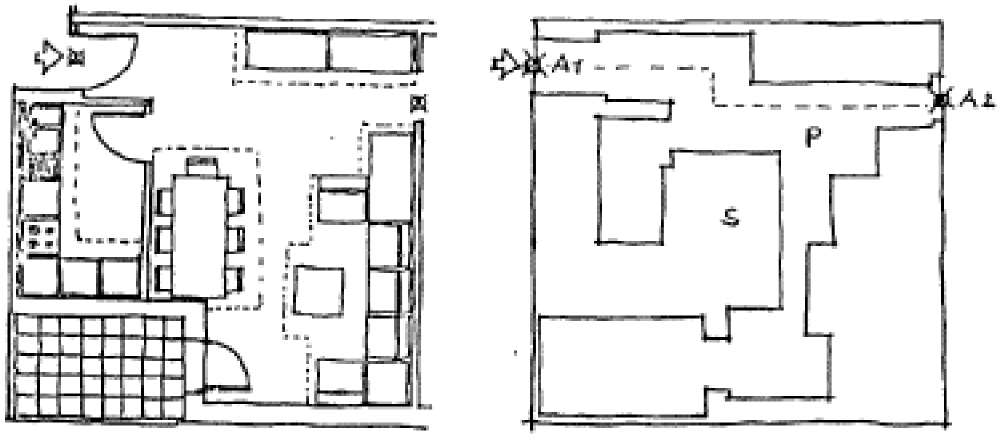


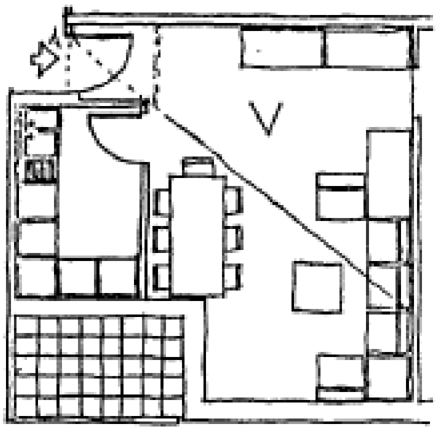
Fig.6



Extracting the set of paths

P = S/1

Fig.7



. Finding the areas that can be seen from the throshold.

Fig.8

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