Fuzzy Modeling of Floor Plan Layout

Alexander Koutamanis
Delft University of Technology, The Netherlands

Abstract
Fuzzy modeling provides methods and techniques for qualifying and quantifying imprecise and uncertain information. The main advantages of fuzzy design representation are fluency, abstraction and continuity, at a level similar to that of analogue techniques, as well as the possibility of local autonomy, i.e. segmentation of a representation into self-regulating and cooperating components. The paper investigates the applicability of fuzziness to digital architectural sketching of floor plan layouts. Based on an analysis of the paradigmatic dimension in analogue floor plan sketches three alternative forms are proposed: (1) Canonical objects with tolerances, (2) objects described by minimal and maximal values, and (3) point sets which decompose the form of an object into a number of discrete, autonomous particles that describe the object by their position and spatial or structural relationships.

Keywords
Representation, Sketching, Floor Plan, Fuzziness
1 Modeling complex and irregular forms
The computer provides arguably the first instruments capable of representing architectural form adequately. The accuracy, precision and flexibility of computer-based representations facilitate the legible and controllable specification of the most complex and irregular forms. While such forms have been also produced in the past, the limitations of analogue media and of conventional drawing have impeded visualization and communication (Evans 1995). In comparison, computer technologies not only aspire to the highest standards in the representation, visualization and communication but also promise total design, from the extensive use of precedent information in early design to the application of rapid prototyping and robotics for the transition from design specification to building construction.

To achieve this, especially with complex and irregular forms, the designer must adopt a strategy that matches the form of the design to the capabilities of the computer. We distinguish between two strategies: (1) parsing into elementary components, and (2) correlation with complex geometric structures. The first entails analysis and discretization of architectural forms into basic elements, usually instances of the built-in geometric primitives. The main advantage of this strategy is that the representation maximizes on the flexibility of the computer, provided that the designer manages to control the highly interactive processing of extensive, largely unstructured information.

The second strategy attempts to reduce architectural complexity by reference to geometry: the designer correlates a design’s form with geometric constraints that derive usually from construction but can also be morphological. The correlation determines the applicability of complex geometric structures and hence of formulaic representations to the description of a design. The product of this application is generally variable in quality, depending upon the designer’s grounding in rather advanced geometric subjects and his ability to integrate constraints from different aspects in the definition of the design’s geometry. In practice, this approach is generally successful in cases where a design can be described by one or a few basic structures with few if any transformations.

Both strategies and their combination offer possibilities for the improvement of effectiveness and efficiency in the modeling of architectural form. However, they are hampered by two main limitations: (a) crispness and (b) over-reliance on implementation mechanisms. Crispness refers to the high precision and detail in the definition of geometric elements in CAD and modeling systems, which inhibits many designers and may reduce the perceivable solution space, especially in early design. But even when precise and detailed representations are called for, designers appear to confuse the primitives of the representation (i.e. architectural entities such as spaces and building elements) with the implementation mechanisms used for their description (i.e. geometric primitives such as lines and surfaces). A common effect of this is that architectural entities seldom remain integral objects but are described by unstructured collections of low-level geometric elements. These become unmanageable as the complexity of a design increases, thereby reducing flexibility. What is more, as the designer often becomes preoccupied with the accuracy and precision of implementation mechanisms, design reasoning degenerates to discussing similes (Marr 1982).

2 Fuzziness in floor plan sketching
An alternative to the crispness and determinism of current modeling techniques are fuzzy methods for qualifying and quantifying imprecise and uncertain information. The possibilities offered by fuzzy modeling suggest that it can be applied to the representation of architectural designs in the early stages. The intention behind this is the development of digital architectural sketching. Currently we encounter two main forms of digital architectural sketching. The first is diagramming, e.g. for indexing and retrieving a design (Gross 1995). The second is voxel-based painting (de Vries, Jesserun, and Engeli 2000; Donath and Regenbrecht 1999; Segers et al. 2000). Both forms represent insightful and useful extensions of CAAD technologies but are hampered by crispness in the implementation mechanisms (either in the analogue original or its digital equivalent). Consequently, the starting point of our investi-
gation into digital architectural sketching is an analysis of floor plan sketching.

2.1 Architectural entities in floor plan sketching

A drawing comprises several dimensions common to various representations, from writing to speech. The analysis of sketching normally focuses on three of these dimensions, the syntagmatic, the paradigmatic and the mechanical. The syntagmatic dimension concerns the sequential structure of the representation. In a drawing this is the sequence of graphic production. In comparison to other representations, this dimension is relatively weak in drawing. In written text the sequence of words in a sentence reflects the syntactic and grammatical constraints of a language. A drawing can be produced by different sequences that are not necessarily linked to the structure of the design or the designer’s thinking. The paradigmatic dimension concerns the range of standard primitives in the representation. Drawing primitives are generally graphic objects such as lines, circles and dots. These can be analysed at the level of the domain entities they represent (e.g. spaces) or at the level of implementation mechanisms (e.g. closed contours indicating the boundaries of spaces). Finally, the mechanical dimension relates to the anatomy of the drawer in interaction with drawing surfaces and implements. Mechanical constraints determine several aspects of the representation such as stroke matching and the direction of rotation in circles (Van Sommers 1984). Our analysis focuses on the paradigmatic dimension towards the identification of discrete, meaningful primitives and their relationships (Koutamanis 1999).

Probably the most frequent primitive in a floor plan sketch is organizational lines, which indicate a framework of drawing. Relationship lines are also guiding structures. The abstraction of sketching means that building elements are seldom depicted as discrete objects. More often, they form relationship lines that indicate arrangement (e.g. alignment in a line representing a colonnade). In addition to semantic guidance, organizational and relationship lines provide constraints to mechanical aspects, e.g. guidance for drawing lines in a direction not favored by the drawer’s handedness (Van Sommers 1984). Spaces are frequently explic-
2.2 Implementation of entities in floor plan sketching

A floor plan sketch comprising organizational and relationship lines, salient building elements and spaces is usually implemented with a limited number of graphic primitives. The most generic category of such implementation primitives is solid, continuous lines. These can be applied to practically everything, from space contours to organizational lines. The arrangement of lines into an architectural entity or a configuration of such entities follows a number of general principles:

- Continuation: formation of closed shapes
- Collinearity: correlation of structurally similar or connected elements
- Parallelism: grouping of two or more lines into e.g. a grid
- Connection and cotermination: association of lines belonging to the same shape
- Completion: elimination of discontinuities and emergence of e.g. illusory contours (Kanizsa 1979; Leeuwenberg 1971)

Multiple lines are used to indicate organizational lines or the boundaries of spatial elements in an indefinite manner. This agrees with the abstraction, informality and metric flexibility of both sketching and early design. Broken and dotted lines represent a diversification of the basic solid line. They are normally used to indicate relationship lines and graphic annotations. Blobs are small, usually filled contours, which indicate an isolated building element or highlight a salient point.

3 Fuzzy modeling of floor plan layout

Fuzzification of floor plan sketching starts with the transformation of the crisp values of entities and corresponding implementation mechanisms. The resulting fuzzy numbers are represented in their simplest form by triangles. In these triangles the apex is set above the crisp value $C$ and the base indicates the tolerances (range of fuzziness) for this value. The base has a left-hand limit $L$ and a right-hand limit $R$. The number is therefore described as $(L, C, R)$, e.g. $(3, 5, 8)$. The values in the range have various degrees of membership, ranging from 1 at the apex to near 0 at the left and right-hand limits.

Fuzzification results into a unification of implementation mechanisms. The addition of tolerances to a solid line eliminates the need for multiple lines. Blobs become contours of small size and tolerances. The extension of grouping principles makes broken and dotted lines a collinear arrangement of short solid lines. Consequently, we consider only two basic fuzzy shapes: lines and contours (open or closed). Fuzzy shapes are implemented in three alternative forms: as canonical objects with tolerances, as forms described by minimal and maximal values, and as point sets.

3.1 Canonical objects with tolerances

In analogue sketching the designer describes the form of a primitive in a *canonical form*. The media

![Figure 4. Grouping principles](image1)

![Figure 5. Triangular representation of the fuzzy number (3, 5, 8)](image2)

![Figure 6. Canonical spaces with tolerances](image3)
used for the description indicate the geometric and spatial tolerances for the primitive. In fuzzy modeling the canonical form is explicitly described, together with tolerances that express the allowable variation in position or structure. In lines tolerances are described by a left-hand offset distance $L$, the canonical shape $C$ and a right-hand offset distance $R$:

$$(L, C, R)$$

In contours the fuzzy shape $F$ is described by an inner limit $I$, the canonical shape $C$ and an outer limit $O$:

$$F = (I, C, O).$$

The coordinates of a fuzzy shape are described by fuzzy numbers. A canonical shape $C$ with the coordinates $(x_0, y_0, x_1, y_1, \ldots, x_n, y_n)$ becomes the fuzzy shape $F$:

$$F = (I, C, O) = ((I, x_0, R) (I, y_0, R) (I, x_1, R) (I, y_1, R) \ldots (I, x_n, R) (I, y_n, R))$$

This suggests that tolerances can be attached either to the shape or to its salient features such as its vertices.

3.2 Objects described by minimal and maximal values

If we dispense with the canonical form, the tolerances define an entity by its minimal and maximal values, i.e. its potential extent as a range of acceptable positions and sizes. The definition of a fuzzy shape $F$ becomes $F = (I, O)$. Such a definition implies a greater degree of flexibility or uncertainty.

3.3 Point sets

The complete fuzzification of a form returns a point set of particles which define a fuzzy boundary for each entity. Each particle of the boundary is defined as a fuzzy shape with or without a canonical shape, depending upon the hardness and related properties of the overall shape. The behavior of particles is semi-autonomous, on the basis of affinity with other particles of the same boundary (density and hardness of the boundary) and its spatial relationships to particles of adjacent boundaries (proximity and composition of neighborhood). Such relationships form the basis for the transformation of the particle model into a continuous geometric model (Horváth et al. 1999).
4 Autonomously processes in a fuzzy model

Fuzzy sketching reinforces and facilitates the autonomy of entities and the consequent automated resolution of local problems without intervention by the designer. The first stage of local intelligence and autonomy concerns the self-regulatory adaptation of a form. In its simplest form, adaptation becomes uniform scaling of the canonical form within the defined tolerances.

If we relax the orthogonality constraints and attach tolerances to the vertices rather than to the whole shape, flexibility increases and allows for controlled deformation. Further relaxation concerns the integrity of the shape, i.e., the number of vertices. The ability to adapt by changing the number of vertices and sides means that an entity can react to e.g., overlapping conditions and create its own perturbations.

Autonomous, self-regulatory transformation is triggered by spatial relationships between fuzzy shapes, primarily overlapping. As in analogue sketching, the vagueness of a boundary is instrumental for the resolution of such conflicts. In canonical shapes with tolerances we distinguish between three main cases of overlap: intrusion of outer zone, intrusion of inner zone, and interruption of the shape. Each case triggers a different action. Intrusion of the outer zone is treated lightly, even if there are more than one such intrusions in a shape. Intrusion of the inner zone is a problem of higher priority because it concerns the canonical form, which corresponds to a primary constraint (e.g., morphological or floor area).

The conflict resolution system that determines the response to such problems relies on criteria derived from the structure of the fuzzy shape, such as the range of fuzziness and external constraints, such as the character of a space (use spaces are harder than e.g., horizontal circulation spaces). Such criteria determine the plasticity of a fuzzy shape. When shapes with different plasticity overlap, the softer shapes are more easily deformed. Soft shapes can be translated and deformed, provided that the basic constraints (usually area and topology) are not violated. When a soft shape reaches its minimum, the request for adaptation is passed on to the harder shape in the relationship. If this shape cannot be modified so as to...
solve the problem, the decision in deferred to the user.

In shapes described by their minimal and maximal values conflicts are treated similarly. Lack of a canonical shape and the consequent unification of the inner and outer zones normally indicate a softer shape. Point sets behave initially in a different manner. The actions stemming from the autonomy of the shape are delegated to the particles that describe its boundary. Each particle attempts to link itself to similar neighboring particles. Isolated particles die out. The remaining ones form groups using chain coding (Freeman 1961). Conflicts between these groups are resolved similarly to canonical shapes with tolerances.

References


