SPATIAL DATABASES AND THE ANALYSIS OF DYNAMIC PROCESSES IN BUILDINGS

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Abstract. This article investigates the potential applications of geographic information systems (GIS) in the analysis and simulation of dynamic processes in buildings and explores it within the context of life safety analysis of buildings. In doing so, the primary focus of the article is to look at how architectural components and spaces can be represented in a spatial database system and what types of methods must be used in the analysis of such a database. Until now GIS applications have primarily been seen as tools suitable for the analysis of urban design and planning problems, therefore an additional objective here is to bring GIS to the attention of architectural researchers as a potential tool for the representation and analysis of spatial data in architecture.

1. Introduction

The concept of "database" has been used in a wide variety of contexts in architectural research, ranging from graphic database of CAD systems to knowledge base of architectural design knowledge systems to relational database management systems for project management as well as for facility management purposes. Since the late '80's, the power of databases emerged more forcefully with the ability to build knowledge structures that allow systematic retrieval, manipulation and updating of data through relational and spatial database management systems (i.e. geographic information systems, GIS).

On the other hand, the analysis and simulation of built environments, whether they involve a single building or an urban environment, cannot be undertaken without the representation of the spatial relationship of objects to each other. Methods such as geometric reasoning with polygon/polyhedra data structures, object models (component models) of buildings, and node and link representation of spaces have been used in the past for spatial analysis and reasoning purposes (Turner, 1990; Shaviv et. al, 1991; Ozel, 1992; IAI, 1998). Within this context, GIS systems have also been very powerful in evaluating and analyzing spatial data with applications in areas ranging from urban growth management to emergency response management to temporal-spatial reasoning (Egenhofer, M. et. al., 1998; Laurini, R. et. al., 1992; www.fireforecast.com). Unfortunately, architectural researchers have paid little attention to GIS systems as analysis tools, since these systems have mostly been presented as software applications suitable for urban scale research problems. Whereas, many spatial analysis problems encountered in evaluating the performance of individual buildings can also be resolved using GIS tools. Among these are problems that require the navigation of people, goods and matter through spaces in buildings, those that rely on differences in the attributes of individual spaces such as their materiality, finishes, contents, and those problems that require the representation of spatial relationships in buildings such as adjacency, overlap, etc. Within this context, facility managers have long been aware of the potential of GIS applications for structuring and manipulating architectural data. Thus, among the earliest examples of GIS applications for buildings are those that are undertaken by facility management departments.

Until now, most computer simulation models of fire safety processes such as fire/smoke spread or emergency egress behavior of people have been based on models of the built environment that are simplified either in the form of network models where rooms are represented as nodes and the relationships between them as links or grid based models which do not lend themselves easily to spatial analysis tasks (Stahl, F. 1979; Chalmet et. al, 1982; Gwynne et. al, 1998). On the other hand, life safety analysis systems and simulations that rely on complex CAD databases have also been developed (Ozel, 1988; Ozel, 1992). These can be difficult to update and expand due the complexity of the graphic algorithms needed for such an expansion. In this study, the potential of spatial databases in representing building spaces and life safety features of buildings for life safety analysis purposes is explored.

Most human behavior in buildings requires spatial action such as moving through and in-between spaces. Furthermore, processes such as travel distance, smoke area and horizontal exit calculations require mostly the use of 2 dimensional data structures of polygon, line and point. While component based representation of buildings can rely on geometric models of architectural elements, they do not readily provide spatial database and analysis tools as GIS systems do. Therefore, when point, line, polygon data are sufficient for the analysis and simulation of the process that is under study, GIS tools can be quite powerful. Furthermore, most GIS software such as ArcView (ESRI, 1997) come with macro languages that allow programming of simulations and additional analysis algorithms using its spatial object database.

These methods can also support the modeling of temporal properties of the simulated processes and the change through time of selected features.

2. Representing Architectural Environments in GIS Applications

As GIS systems represent spatial, thematic, and temporal qualities of a given physical environment, they are designed to respond to the queries that deal with the questions of where, what and when. While the spatial data in the form of base maps constitute the basic structure of the database, thematic information (attributes) and temporal information assist the user to extract subsets of spatial objects from the database to understand its structure better. The proper inputting of base maps are crucial in the correct functioning of the system. Parallel to the concept of "base map" and within the context of individual buildings, here the concept of a *base drawing* is introduced. A base drawing must essentially include a representation of all of the individual spaces in a building as well as the architectural elements such as doors, windows, and stairs. Furthermore, life and fire safety features such as sprinklers and alarms or spatial aggregates such as fire zones and smoke areas must also be included.

GIS software typically rely on 2-dimensional vector graphics, although it is also possible to include bitmapped images. In spatial representation of architectural elements and spaces, clearly vector graphic tools of *point, line, polygon* data structures will be needed for the spatial analysis processes such as the measurement of distance and area, the indication of containment and the representation of spatial relationships such as adjacency, overlap, etc., therefore GIS tools are suitable for such representations.

In setting up a GIS system for the analysis of dynamic processes in buildings, two major issues must be addressed. First, the question of how to develop a representation of the building components and spaces that would facilitate the analysis to be undertaken, secondly (although directly related with the first issue), what mechanisms to use during the analysis process. These two issues can only be resolved after one thoroughly understands the dynamic process to be simulated or analyzed.

The primary question to be answered in the representation of building spaces would be at what level of granularity to represent the building. Buildings obviously have two distinct types of objects: components and spaces. Although they are inevitably related to each other, usually *components defining the spaces*, it may also be necessary to define spaces as unique objects with their own record entry and graphic entity type. The options in representing structures in GIS would be:

1. All architectural components and spaces can be represented as nodes, i.e. as points, to create a network representation of the building,

2. One can also represent components such as doors/windows as nodes, but represent rooms as polygons.
3. The third alternative would be to represent both object types, i.e. components and spaces as polygons.

Since each entity must also be tagged with attributes in order to perform attribute-based analysis, the level of granularity by which the building components and spaces is represented will completely depend on the type of analysis to be performed. Issues such as having to represent contained objects (people, furniture, fire, smoke etc.) as well as the building itself also become a concern when the problem is viewed within the context of emergency egress simulation and analysis. More often than not, this leads to the selection of option 2 as the primary mode of representation.

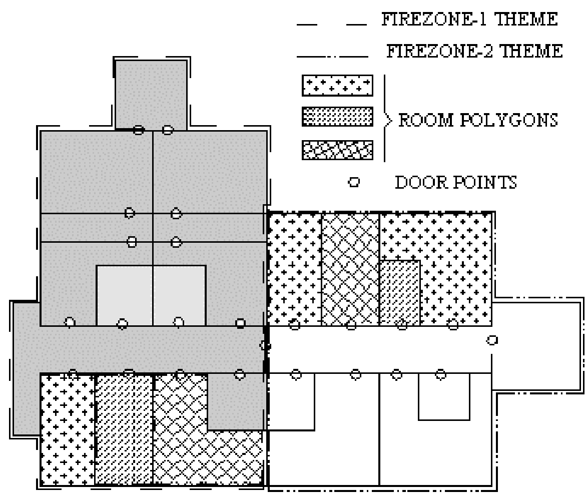

Figure 1. Base drawing with room polygons

In GIS applications, objects can be grouped according to their attributes using the concept of *theme*. One way representing life safety properties of architectural elements would be through the definition of themes. Spatial entities such as rooms, exit access corridors, enclosed staircases must be represented as polygons, while other elements such as travel routes, smoke barriers, fire walls as lines; and sprinkler heads, internal doors and exit doors as points. Spatially, the smallest unit that must be represented as a polygon is obviously a "room". Therefore, while the geometry and spatial properties (coordinates) of each room are based on the concept of a "polygon", all of the other spatial elements, such as fire zones, smoke areas, enclosed stairs can be defined through set operations on room polygons. By defining a fire zone as a theme or a smoke area as a theme, subsets of rooms that belong to a single fire zone or a smoke area can be identified. On the other hand, enclosed stairs and exit access corridors can be defined through the activity attributes of room polygons or activity themes.

Therefore, the spatial data for a *base drawing* in a GIS application that models architectural environments and their life safety attributes must be primarily in the form of room polygons. These allow analyses such as area, adjacency, proximity, and containment calculations. Representing components such as walls, doors, and windows as polygons are unnecessary, and can in fact hinder some of the analyses that need to be performed. For example, finding the distance to the exit doors would require that both the target door and the initial location in a room be represented as points not as polygons (Life Safety Code (NFPA 101) clearly defines how travel distances must be calculated), so that the distance between two points can be calculated.

Software that aim to perform life safety analysis of buildings can take one of two routes:

1. Simulate the processes such as fire/smoke spread and human movement/ behavior,
2. Identify the methods that exist in the Life Safety Code (NFPA 101) or other building codes and check to see if a given architectural project is compliant with the code by modeling these processes.

In either case, the geometry of the building as well as its life safety characteristics must be defined within the base drawing. In today's professional environment, most representation work is done in CAD systems which are vector based to begin with. One of the ways of creating a GIS compatible base drawing would be through the control of the interface with which the CAD drawing is generated so that the proper base drawing is automatically generated by the CAD system. Since CAD systems do not typically reference real world entities and their attributes, steps must be taken during input to ensure that the database reflects the spatial properties and relationships of the real world objects. In fact, inputting the room information in the form of polygons into the base drawing will be the main task in the design of such a CAD interface. The rest of the input task (such as the definition of the enclosed stairs or protected egress routes as themes, or inputting the location of the alarms as points) can be easily handled through the interface of the GIS development environment once the base drawing where each room is represented as a polygon is created.

3. Temporal Aspects of GIS Applications

While the real world environment can be represented at a slice of time in a spatial database system, what is more interesting and useful for the representation of dynamic processes is the issue of *change through time*. The data that are used in creating the base drawing and the initial attributes of the spatial objects simply represent what the real world environment is like at a slice of time, and this is usually called the *database time*. Therefore, in architectural applications, the base drawing includes the building or project data as they exist at the time of the development of the GIS database. For general purpose GIS applications, there are two other types of time dimension. One has to do with the *real world time* (e.g. what the building was like in 1938), and the other one deals with the *display time*, i.e. the time the analysis is performed and the database is displayed per a particular query. In this case, for example, although the physical nature of the building may not have changed at the time it was displayed, the organizational structure and its correspondence to the physical structure may have changed. In a facility management application in GIS, the location of people or whole departments may have changed. In these examples, one still deals with slices of time, and not a representation of change through the continuum of time.

As in 3-D modeling, change through time is best represented through animations in GIS systems. Kraak et.al (1996, p. 192) identify these to be of three types: frame by frame generation, key frame generation and algorithmic generation. While, these are primarily seen as dynamic data visualization methods, the third one which is defined as "a computer program defining what will happen during animation" (Kraak et.al, 1996, p.192), has great potential for the simulation of dynamic processes. This is because it can be used to project and generate data to represent the future states of a given spatial database, without the need to preload the data into the system (which is not possible anyhow, since the data re the future states of the system are not available). In fact, the method of patch dynamics in GIS systems is used for exactly this purpose, simulating for example ecological change in a given environment by using a mathematical model that projects future states of the system.

Dynamic simulation of egress behavior in buildings will clearly require such a modeling and algorithmic generation method, as opposed to code compliance checking applications which primarily look at the state of a building at a slice of time during database time.

Some of the general Life Safety Code objects and their representations in a GIS system can be listed as follows:

a. Building - GIS project in the form of a set of tables that correspond to lower level spatial objects such as rooms polygons, fire wall lines, door points, alarm points, etc. A building can also be defined in a hierarchy of upper level objects such as lots, neighborhoods, etc.

b. Floor - a set of room polygons with common themes such as "occupiable spaces", "street floor", "exit level", etc.

c. Corridor - all room polygons with an activity theme of "corridor".

d. Atrium - all room polygons with an activity theme of "atrium".
e. Enclosed stairs - all room polygons with an activity theme of "enclosed stair".
f. Protected egress routes - all exits as points, exit access as polygons and exit discharge as points with a common theme of "protected egress route'.
g. Fire zones - a set of room polygons and exit doors as points with a common theme of "fire zone".
h. Smoke barriers - all wall lines with a common theme of "smoke wall"
i. Fire door - all door points with an attribute of "fire door"
j. Hazardous area - all room polygons with a common theme of "hazardous area".
k. Occupancy type - an attribute of the project, i.e. the building

One of the difficulties in deciding how to model the room polygons is when there are subspaces such as aisles, stage, intervening rooms, nurses desks, reception areas that do not necessarily have physical boundaries in the form of walls, but are more of an indicator of an activity. Therefore the definition of a *room* must be carefully considered and determined before the base drawing is generated. The common definition of a room may not always be the best concept in defining room polygons.

4. Analysis Methods in GIS Applications

Methods of analysis in GIS applications that apply to a single time slice are typically done through the theme-on-theme selection process. What this means is that objects that belong to a theme are selected on the basis of their spatial overlap with the objects in another theme. For example, doors (points) in a fire zone (set of room polygons with a theme a "fire zones") can be selected by the theme-on-theme selection method. This can mostly be utilized for plan checking (i.e. code checking) purposes with the database time corresponding to the time the project was submitted to the City for approval. Since, at the present time many clients request a copy of the plans in electronic format with the intention to use them to generate base drawings for GIS based facility management systems, the development and coordination of code compliance checking base drawings with facility management base drawings can reduce redundancy of effort and data considerably. Furthermore, both types of applications require room data in the form of polygons and can share the base drawing very easily.

Some of the analysis tools that exist in GIS and their potential application to code compliance checking can be summarized as follows:
- finding points near a given line (simulates proximity to walls or to travel paths in buildings)
- finding points that are near selected points (if contained objects such as people, furniture, functions are represented as points, then other similar objects can be selected based on proximity)

- finding adjacent features (by representing rooms as polygons, adjacency to travel paths that are defined as lines or to other rooms that are defined as polygons can be determined)
- finding points within polygons (by defining rooms as polygons and contained objects such as people as points, the simulation can determine if a person is in a selected room)
- finding polygons within polygons (fire or smoke spread can be represented as polygons, which in turn include rooms as polygons. This enables the programmer to identify how far smoke and fire might have spread beyond the initial fire zone.)
- finding lines that intersect other lines (used in identifying if travel paths of different occupant groups, such as fire fighters and evacuees cross each other)
- finding polygons that intersect other polygons (smoke spread when represented as polygons can be analyzed to see how far it has spread into rooms or fire zones)
- joining attributes based on containment (used in finding how many people there are in a given area, or the location of sprinklers in a given section of the building)
- joining attributes based on proximity (used in finding all those people who are at a given distance from a selected feature such as an exit door)
- creating weighted distance models (finding the shortest path between two points such as between a person and an exit door is not always the intention of the simulation builder, since that may not necessarily represent the actual process that is being simulated. GIS systems can create weighted paths that find the best route under weighted conditions rather than the shortest route)
- using themes to add weights to parameters that affect the simulated process (by designing multiple themes based on the same set of spatial data, it is possible to find the preference levels for different paths based on cognitive factors, familiarity levels, daily routines, etc.)

5. Summary

As the examples of analysis methods listed above indicate, many of the spatial analysis tools needed for the analysis and modeling of dynamic processes in buildings exist in GIS applications. Therefore, architectural researchers need to take a fresh look at GIS as an analytical tool for the modeling of dynamic processes at the building scale rather than at the customary urban scale, and this article intended to discuss methods of achieving this. The methods of representing buildings in spatial databases and their potential uses in the analysis as well as in the simulation of processes in built environments were addressed.

The trend to develop spatial databases for facility management purposes renders the use of such databases also for code compliance checking feasible. Since they both require a base drawing that includes room polygons, with very little additional investment of time and money, the same base drawing can also be used for a multitude of analytical purposes including code checking, energy analysis, rental/maintenance cost analysis, etc. Furthermore, the ability to include temporal properties allows the researcher to model dynamic processes such as fire and smoke spread, crowd movement (for assembly occupancies) and the navigation of occupants through the building, such as for way finding or for fire fighting purposes. Therefore, the potential use of GIS base drawings for code checking and other performance analyses of buildings indicates the need for more research in this area of inquiry.

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http://www.archibus.com/, FM automation and visual infrastructure management software.

http://ci.bluefield.wv.us/gis/gis-fireservice.html, GIS in the Fire Service - ArcView GIS based system to improve response and pre-planning capabilities. Single buildings or entire neighborhoods may be modeled.

http://www.fireforecast.com/, Fire Forecast is a GIS based tool for risk assessment and fire prediction, estimates the risk from forest fires to urban areas, predicts the risk form forest fire for each building located nearby the forest.

http://itre.ncsu.edu/gis/projects/ws/ws-2.html, During an emergency, information is available in graphic form on the PC in the fire vehicle. In addition to urban maps, information such as floor plans, water or gas lines, and sprinkler systems can be selected.

http://www5.ced.berkeley.edu:8005/aegis/, AEGIS, located at UC Berkeley, College of Environmental Design, seeks to apply GIS solutions to environmental problems and issues that avail themselves to the GIS framework.