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Computational algorithms to evaluate design solutions using Space Syntax

Sang Kyu Jeong, Yong Un Ban *

Department of Urban Engineering, Chungbuk National University, 410 Seongbong-Ro, Heungduk-gu, Cheongju, Chungbuk, 361-763, Republic of Korea

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ABSTRACT

In the past, conventional computer-aided architectural design (CAAD) systems could not manage semantic information on building components and spaces but only graphical and geometric information. However, since the advent of Building Information Modeling (BIM), which has been used for managing semantic building information, determining spatial relationships as well as quantities and properties of building components in CAAD systems has become easier. It is necessary to make current CAAD systems capable of performing spatial analysis functions using BIM because they can easily recognize building components and spaces. Accordingly, this study aims to develop the computational algorithms to evaluate design solutions using Space Syntax during the process of computer-aided architectural designing. To extract topological information from design solutions, this study proposes algorithms to recognize building information produced in the form of Industry Foundation Classes (IFC), deduce the necessary topological information, and store the information in the form of matrices. The Space Syntax theory is employed to evaluate the solutions based on social properties of spaces in a building and examine the potential for adding a spatial analysis function into CAAD applications. The developed algorithms calculate the integration value for each space from spatial connectivity based on J-graphs. To validate the proposed algorithms, a program named J-Studio for Architectural Planning (J-SAP) was developed to evaluate design solutions easily and quickly. The validation results are as follows: (1) the topological information extracted from building information was decoded into a dimensionless representation and legible J-graph, (2) mathematical analyses for choosing a better design solution during computer-aided architectural designing were presented, and (3) the examination of the privacy level of each space in a building through Space Syntax analysis was discussed. Thus, this study demonstrates the possibility of determining the social properties and accessibility of spaces during the process of computer-aided architectural designing to meet client requirements by extracting topological information from building information model and performing Space Syntax analysis for evaluating alternatives using the information.

1. Introduction

Rapid development of digital technology has influenced conventional computer-aided architectural design (CAAD) systems to be equipped with excellent capacity to manage graphical and geometric information. However, the CAAD systems that focused only on drafting and modeling capabilities could not manage semantic building information, including the entities of building components and spaces. To overcome these shortcomings, novel approaches such as building information modeling (BIM), product modeling and object-based data modeling have been employed to improve or replace conventional techniques in CAAD. These techniques allow CAAD applications to manage semantic information generated and maintained throughout the life cycle of a building, in addition to geometric and graphical information. They cover elements such as geometry, spatial relationships, geographic information, and quantities and properties of building components [1]. Traditional CAAD systems could manage only symbols, geometric and text information; they could not include semantic information pertaining to building components and spaces. Therefore, if only this information is available, it is difficult to construct algorithms that evaluate design solutions through spatial analysis. However, since the advent of BIM, finding the quantities and properties of building components and spatial relationships in CAAD systems has become easier. This improves the possibility of constructing algorithms for design evaluation through spatial analysis, as well as building design by drawing and rendering. Current CAAD systems with BIM capability can recognize building components and spaces, but cannot yet perform spatial analysis that measures the topological properties of the building entities using Space Syntax technique. Currently, BIM is used mainly for the purposes of costing, scheduling, performance simulation, code checking, and visualization. Few studies have focused on analyzing spatial relations using BIM because it is currently in the early stages of

* Corresponding author. Tel.: +82 16 281 1316; fax: +82 43 273 3391.
E-mail addresses: neoshaky@hanmail.net (S.K. Jeong), byubyu@cbnu.ac.kr (Y.U. Ban).

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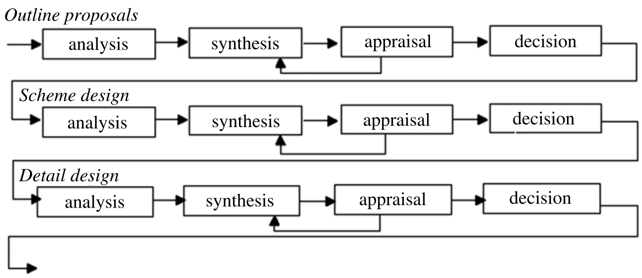

Fig. 1. The Markus/Maver map of the design process.
Source: [8, p. 35].

development. The Space Syntax method introduced by Hillier and Hanson [2,3] has mainly been used for the quantitative analysis of spatial relations. Therefore, the aim of this study is to develop computational algorithms that can evaluate design solutions using Space Syntax during computer-aided architectural designing.

2. Backgrounds and literature review

In this section, we introduce the theories and techniques employed in this study and review related works on evaluating design solutions in architectural design.

2.1. Design process

The building design process has been practiced for hundreds of years but was only first formalized in the 1960s [4]. Markus [5,6] and subsequently Maver [7] suggested that we need to go through the decision sequence of analysis, synthesis, appraisal, and decision at increasingly detailed levels of the design process [5–9]. They elaborated maps of the architectural design process detailed in decision sequence as shown in Fig. 1.

The inter-winding phases in this process are as follows [10],

- Problem analysis is the phase in which the designer attempts to identify all the elements of the problem.
- Solution synthesis is the creative phase of the design process, in which the architect forms ideas and possible solutions that might address the goals, constraints, and opportunities established during the problem analysis.
- The solutions that emerge from the synthesis phase of the design process are often incomplete, may not address all the requirements, and contain internal conflicts. They must be evaluated rationally in the evaluation phase.

2.2. BIM

The concept of BIM has many origins. The term BIM was introduced by Autodesk [11] in 2002. It is an innovative approach to building design, construction and management. BIM stands for both the building information model and building information modeling. The building information model is a set of information generated and maintained throughout the life cycle of a building. The building information modeling is the process of generating and managing a building information model [12]. According to Wikipedia, the free encyclopedia [1], "BIM covers geometry, spatial relationships, light analysis, geographic information, quantities and properties of building components".

Eastman extensively used the concept and term of building product model which is basically the same as the BIM, in his book and paper [1,13,14]. Jeong et al. [15] developed a program that can generate and correct a building floor plan using shape grammars to operate semantic building information represented as building components such as a wall, window, or door. Hwang and Choi [16] suggested an approach for constructing the floor plan's database on the basis of the content of space. The BIM is able to achieve such improvements by modeling representations of the actual parts and pieces being used to build a building.

Traditional CAAD programs internally represent data using geometric entities such as points, lines, rectangles, and planes (Fig. 2(a)). Thus, they cannot capture domain-specific information about entities. In the case of the Architecture, Engineering & Construction (AEC) industry, technological progress has been severely constrained by the limited intelligence of such applications in representing buildings and being able to extract relevant information from the representation that is needed for design, analysis, construction management, operation, and other purposes. To overcome the limitations of general-purpose geometric representations, researchers have been developing and using object-based data models that are specific to their domain. This translates to a data model that is built around building entities and their relationships (Fig. 2(b)). Such a data model is rich in information about the building that can be extracted and used for various purposes, be it documentation, visualization, or analysis [17]. Thus, information about building components and spatial relationships can be easily obtained from an application using a building information model (building data model), whereas several complex calculations are required to derive the same information from an application using a geometric data model.

2.3. Graph theory and Space Syntax

Methods for spatial analysis are often based upon graph theory. In 1736, Leonhard Euler solved the problem referred to as the Seven Bridges of Koenigsberg [18]. At the time, the seven bridges were built on the Pregel River in the city of Koenigsberg (now Kaliningrad, Russia) in Prussia. The problem is whether it is possible to walk a route that crosses each bridge exactly once. Euler simplified the city map into a graph by regarding the land areas as vertices and the bridges as edges, as shown in Fig. 3, and proved that it was impossible. The reason for this is that each vertex has an odd number of edges. For example, vertex *A* is of degree 3 and vertex *B* is of degree 5. As all vertices have odd number of edges, it is impossible to re-enter any vertex after leaving it and then using each edge only once, and this makes starting and ending at the same point impossible.

The resolution by Euler presaged the idea of topology and laid the foundations of graph theory. Topology begins with a consideration of the nature of space, investigating both its local structure and its global structure. Topology is a branch of mathematics that is an extension of geometry and includes many subfields. Steadman [19] explored the relationship between graph and geometry and discussed a systematic way in which plans satisfying size constraints can be developed from a given graph.

Space Syntax is based on topology and graph theory, and it has been used mainly for the analysis of spatial configurations. The methodology is the theory and analysis technique introduced by Hillier and Hanson [2,3]. The justified graph (J-graph) is a picture of the "depth" of all spaces in a pattern from a particular point in it. Fig. 4 shows J-graphs for the corresponding spatial structures, drawn using the exterior space as root. We immediately see that the first is a "deep tree" form, and the second is a "shallow tree" form. All trees, even two as different as in the two in the figure, share the characteristic that there is only one route from each space to each other space. However, where "rings" are found, the J-graph makes them as clear as the "depth" properties, showing them in a very simple and clear manner as what they are, that is, alternative route choices from one part of the pattern to another [3].

Total depth (*TD*) can be acquired from the J-graph. *TD* is the sum of 'depth' from a node to the other nodes in the spatial