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AN APPLICATION OF SPACE SYNTAX TO CRITICAL WORKING SPACE ANALYSIS: THE CASE OF BUILDING CONSTRUCTION

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Key words: space syntax, fuzzy theory, critical space analysis, building construction

ABSTRACT

The definition of critical space used in this paper is identical to the critical path definition employed in the critical path method (CPM). This definition implies that there is no extra floating space; thus, any conflict is expected to result in productivity loss. Space syntax is a theory developed to reveal the hidden interrelationships between spaces using architectural diagrams. Existing studies have indicated the potential for space syntax to identify critical spaces and to assist in reducing conflicts leading to productivity loss. However, there is not yet quantitative evidence demonstrating whether the quantitative parameters of relative convenience and relative control are suitable for analyses of dynamic construction spaces. This study is based on fuzzy theory and uses field observations, engineering personnel interviews, and questionnaires designed to utilize "fuzzy syntax". Moreover, this study further develops a method for critical space index analysis, which could be useful for the continued analysis of critical space.

I. INTRODUCTION

1. Research Motives

The construction industry often faces time pressure when projects fall behind schedule. To meet deadlines, construction companies often perform several work items at the same time. However, space can become a limited resource in construction sites when two or more crews are working in the same area, and the availability of material storage spaces may also impinge on construction efficiency. Space conflict is the main issue in construction productivity losses. Sanders *et al*. [6] found that up to 65% of efficiency losses are due to congested workspaces and that up to 58% of losses are due to path blockages. Howell *et al*. [3] suggested that reducing resource sharing (such as work areas) is the first step for performance improvement at construction sites. The identification of conflicts and critical path points at construction sites can facilitate control of the construction sequence, scheduling and can minimize delays; even when conflicts cannot be eliminated, delays can be minimized by controlling productivity losses.

Space syntax was developed by Professor Bill Hiller at London University. This concept explains the hidden relationships between spaces using architectural diagrams. Spaces are seen as limited resources in construction sites when two or more crews are working in the same area. According to the theoretical basis of space syntax, the convenience and connectivity of different spaces vary; thus space syntax may help identify the most important work spaces. Although qualitative studies have indicated that space syntax has the potential to identify critical spaces in construction and to reduce conflict leading to productivity losses, quantitative evidence on the output of critical spaces is still lacking.

2. Research Purpose

The three main purposes of this study are as follows:

This study uses space syntax analysis to explore the spatial characteristics of construction areas. This study further uses space syntax to identify critical spaces in construction areas (i.e., areas in which conflict must be prevented to avoid significant productivity losses) and thereby assist decision-makers in executing sound judgments regarding construction planning, design, control, and management.

This study employs surveys and analyses of interviews and observations to verify the accuracy of the usage of space syntax in construction areas. Specifically the two quantitative parameters typically used in the analysis of static architecture spaces, i.e. the relative convenience *Rn* and the relative control value *Cv*, are reviewed for their suitability in the analysis of dynamic construction spaces. The current literature only provides conceptual discussions; validated conclusions have not yet been presented. A comparison between the space syntax

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calculations and the results of the questionnaire survey allow us to determine whether the quantitative measures from space syntax are an accurate reflection of dynamic construction spaces.

Finally, this study develops a critical space index (CSI) to increase the efficiency of critical space analysis. This study proposes computational principles for determining the CSI to enhance analysis efficiency and to contribute to the analysis of critical space. This contribution is based on the results of space syntax calculations, with the use of fuzzy questionnaire results for verification.

3. Research Scope

The construction site in this study was analyzed using space syntax, in particular axial line analysis. The analysis focused on the building construction space; the regional space was not evaluated in this study.

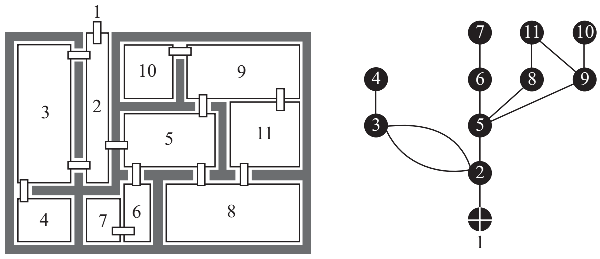


Fig. 1. A graph of a building.

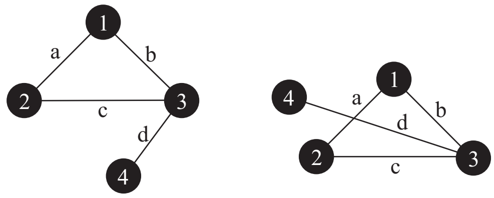


Fig. 2. Two identical graphs.

II. LITERATURE REVIEW

1. Site Layout Planning

Site layout planning deals mainly with the layout of temporary facilities on the job site. Various approaches to identifying the most appropriate layout of temporary facilities, such as geographic information system (GIS), artificial intelligence (AI), and genetic algorithm (GA) methods, have been used in previous studies to determine the optimal layout, according to the shortest traveling distance or minimum travel cost between temporary facilities. However, it has been argued that a minimum traveling distance or cost applies only to transportation optimization, while such optimization is not directly applicable to optimization of the work itself or to the shortest working period.

2. Path Planning

Path planning studies focus on the shortest route for construction equipment and operations. Based on work requirements and the initial and final locations, the shortest collision-free path can be identified by various algorithms. Typical applications include the routing of large vehicles or heavy-lift operations on construction sites, as well as proximity of autonomous landfill determined by global positioning system (GPS) techniques. However, as path planning studies are primarily concerned with equipment, workers and material storage are generally excluded. Moreover, there is no consideration of the actual space variations occurring during construction. These limitations constrain the significance of path planning studies for improving construction productivity and resolving space conflicts.

3. Graph Theory

Graph theory is a branch of mathematics concerned with encoding networks and measuring their properties. In transport geography, most networks have an obvious spatial foundation, namely road, transit, and rail networks, which tend to be defined more by their links than by their nodes. A building can also be represented as a network; its spatial expression thus can be easily represented, as shown in Fig. 1. A simple graph can be thought of as G = (V, E), where V represents disjoint finite sets of vertices, nodes, and points and E represents disjoint finite sets of edges, arcs, and lines. Here, V is the vertex set and E the edge set of G. Although such graphs may appear to be different, they are actually the same when the number of points and the distribution of the lines are identical, as shown in Fig. 2.

4. Space Scheduling

Space scheduling combines all of the working elements (workers, equipment, materials, paths, temporary facilities, and physical layouts) subject to variations in time frames or schedules and then eliminates or minimizes space conflicts between these working elements. Tommelein *et al.* [9] developed MovePlan to determine temporary facility locations according to the Critical Path Method (CPM) schedule. Thabet and Beliveau [7] defined workspace demand and availability for high-rise building construction and proposed a space capacity factor (SCF) to describe productivity loss due to space constraints. A space-constrained resource-constrained scheduling system (SCaRC) has also been developed [8]. Riley and Sanvido [5] defined construction-space use patterns in multi-story buildings and presented a space planning method based on various use patterns.

5. Critical Space Analysis

Critical space analysis in construction is correlated with the complexity of a project [11, 12]. During task implementation, in addition to the overall worksite, numerous temporary spaces are also needed to complete tasks and require an analysis of space availability over time. These temporary

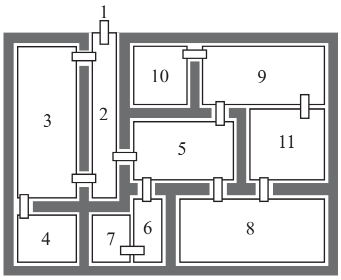


Fig. 3. Convex break-up.

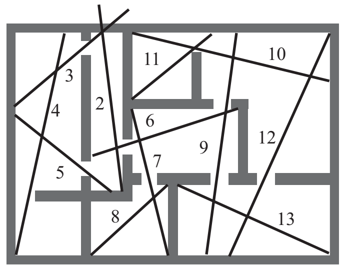


Fig. 4. Axial map.

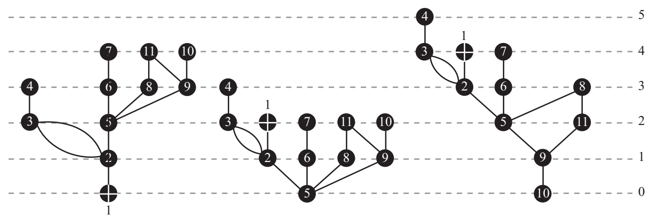


Fig. 5. Graph of axial lines 1, 5, and 10.

spaces can lead to a basic planning problem during critical space analysis, when effective spaces required by various tasks change dynamically over time. Different crews may be working in the same area, causing spatial conflicts. In addition, construction spaces constantly change. For example, the floor area for construction work will increase as the construction progresses, while the wall area will decrease with progress. Experienced project planners generally consider the effective space required based on long-term experience and intuition only, without logical deductions.

Graham [10] defined critical space as any space with a bearing capacity factor total space divided by effective space equal to 1; namely, space that has no free space. This logical deduction is similar to that of CPM, which finds that the critical path is the most commonly used path of the overall diagram and has no temporal slack.

III. SPACE SYNTAX

Space syntax provides a set of techniques for analyzing spatial configurations; this syntax was developed by Professor Bill Hillier in the 1980s as a tool to help architects predict the potential effects of their designs. This methodology has become an application tool in a variety of research and practice endeavors around the world. Space syntax has been extensively applied in the fields of architecture, urban design, planning, transportation, and interior design. Over the past decade, space syntax techniques have also been used for research in fields as diverse as archaeology, information technology, urban and human geography, and anthropology [2]. Space syntax encompasses a set of theories and tools for simulating the spatial structure of actual scenarios, as reflected in the following steps.

1. Decomposition of Spatial Structure

Spatial structure can be divided into the two decomposition elements of convex spaces and axial lines. Each convex space is a convex polygon. A concave polygon must be transformed into the minimum number of convex polygons. For instance, an L-shaped space should be decomposed into two entirely different convex spaces. In convex space, each element is visible to all of the other elements to satisfy the interaction function. As shown in Fig. 3, components 9 and 11 are decomposed from an L-shaped space. The axial line is the longest straight line that passes through the convex polygons. Axial lines are also linked to the notion of visibility. Sets of convex spaces or axial lines that cover all of the constituent elements of a setting are called convex maps or axial maps, respectively. Convex break-up discloses the minimum number of links between convex polygon spaces and concave polygon spaces, as shown in Fig. 3. An axial map describes the minimum number of links between connected lines, as shown in Fig. 4.

2. Justified Graphs of Spatial Structure

After the decomposition step, the spatial structure can be presented in graph form [4]. The graph of a spatial structure represents the permeable connections of all convex spaces and axial lines. In this graph, the joints represent convex spaces, and the lines represent the connections between spaces. Either of these two elements can be used as the basis for exploring the relative depths of the other element and for depicting the depths on a graph. Thus, the graph reflects the structure of the space.

The component used to explore the relative depths is called the root component. In a tree-shaped graph, most components are far from the root and the mean value of the relative depths is larger in comparison to other graph types. This graph can be called a deep-structure graph. Conversely, a bush-shaped graph can be called a shallow-seated structure graph. In Fig. 5, different root-based graphs are illustrated. Component 5 is shown to be in a convenient position because the graph reflects a shallow-seated structure. In contrast to component 5, the graphs of components 1 and 10 reflect a deep structure.

3. Quantitative Analysis of Spatial Structure

In terms of the intersections between lines, various morphological parameters can be derived for the analysis of a spatial structure. These parameters include values for connectivity (C*i*), control (C*v*), and depth (D*i*) as well as the connectivity index (CN). These are defined as follows (Jiang):

− The connectivity value is the number of immediate neighbors of the nodes (1).

$$C_i = k \tag{1}$$

where C*i* is the connectivity of the *i*th node and *k* is the number of immediate neighbors.

− The control value of a node expresses the degree to which the node controls access to its immediate neighbors, taking into account the number of alternative connections for these neighbors (2).

$$ctrl_i = \sum_{j=1}^{k} \frac{1}{C_j} \tag{2}$$

where ctrl*i* is the control value of the *i*th node, *k* is the number of nodes connected to the *i*th node, and C*j* is the connectivity of the *j*th node.

− The depth value represents the smallest number of steps connecting one node to the others. It is defined as the total depth and the mean depth (3).

$$D_i = \sum_{j=1}^{n} d_{ij}$$

$$MD_i = D_i/(n-1) \tag{3}$$

where D*i* is the total depth value of the *i*th node, d*ij* is the shortest path between the *i*th and *j*th nodes, *n* is the number of nodes, and MD*i* is the mean depth value of the *i*th node.

− The integration value gives the degree to which a node is integrated or segregated from the system. A node is said to be more integrated if all of the other nodes can be reached after traversing a small number of intervening nodes and less integrated if the necessary number of intermediate nodes is large. The integration of a node is measured as the average depth of the node to all other nodes, similar to the measurement of relative asymmetry (4).

$$RA_i = 2(MD_i - 1)/(n-2) \tag{4}$$

where RA_i is the relative asymmetry value of the *i*th node.

The integration value (in contrast to *RA*) is high when a node is highly integrated. The integration value is found by inverting the *RA* value.

− The local depth value gives the number of nodes located less than two steps from a given node. The local integration value is the degree to which a node is integrated or segregated with respect to other nodes at a distance of less than two steps.

Table 1. Calculation of the integrated value.

Parameters	Description
Di	$Di = \sum_{j=1}^{n} d_{ij}$ Di = Depth Value n = total components
MDi	$MD_i = \frac{\sum_{j=1}^{n} d_{ij}}{(n-1)}$ MDi = Mean depth value
RAi *RAAi*	$RA_i = \frac{2(MD_i - 1)}{(n-2)},\ RRA_i = \frac{RA_i}{D}$ RA = relative asymmetry RRA = real relative asymmetry
Rn	$D = \frac{2(n(\log_2((n+2)/3)-1+1}{(n-1)(n-2)}$ D = coefficient related to the number of lines given by Hillier & Hanson (1984) Rn = 1 / RRA

From the differences in spatial structure, two main quantitative values can be found – the integration value (*Rn*) and the control value (*Cv*). These two quantitative values are not derived from a single component, but from the relative position of each component in a system based on its connections.

The integration value is derived from the concept of relative depth and is calculated from the mean of the minimum relative depth from the root component, as shown in Table 1. Thus, the integration value can be viewed as conveying the comparative level of accessibility for all components in the system.

The control value describes the comparative level of control over the connected components. Generally, a component's control value is inversely related to its number of connected components. As the number of connected components increases, the control value grows, as shown in Fig. 6 for components 2 and 9. The connectivity index (CN) measures the number of lines that directly intersect a given axial line. This index also denotes the number of immediate neighbors of an axial line. This quantitative analysis is illustrated in Fig. 6.

4. Space Syntax and Critical Space Analysis

Based on a literature review [1] on space conflict, most conflict factors are related to the characteristics of the construction items, while the factors related to the overall construction project are neglected. The conflict analysis process flow focuses on the working items, while spatial configuration and space conflicts account for spatial characteristics. To resolve conflicts, there are no available foundations or criteria for achieving sound solutions.

Space syntax is a set of spatial analysis tools. After the three steps of spatial structure decomposition, quantitative expression, and spatial structure analysis, each integral space

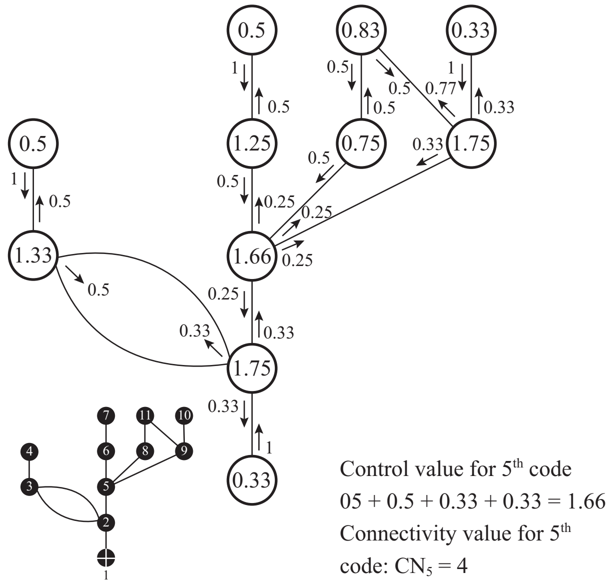


Fig. 6. Graph and calculation of the control value of the 5th node.

or dynamic axial line can be found. The two major analysis factors in this process are *Rn* and *Cv*. *Rn* denotes the level of convenience; higher convenience means that it is easier to arrive at the position or on the dynamic axial line; *Cv* denotes the level of control over adjacent units; higher control means that it is easier for adjacent units to be controlled by the unit being evaluated.

There are two methods of spatial structure decomposition. The first type is the space unit method, and the second type is the longest dynamic axial line method. The spatial unit method uses wall partitions or obstacles to divide the integral space into several space units. The longest dynamic axial line method uses the longest and fewest axial lines to cover the integral space and to connect all of the space units. Graph theory concepts are used to treat the spatial units (or dynamic axial lines) as points and the connection relations as lines. The space diagram is then converted into a topological structure for further quantitative analysis.

Quantitative analysis of *Rn* and *Cv* can be applied to individual cases. For different structure systems, values can be converted into the same benchmark for comparison through a standardized program. Thus, for construction space analysis, this method can be used to compare different spatial structures in different time phases.

The definition of critical space is not wholly accurate because in CSM, the relations among all of the construction tasks are reflected in the diagrams. However, according to Graham [10], the definition of critical space can be obtained from the information of the working items; the relation between one construction space and another is not considered. Therefore, this study does not use this critical space definition, which states that the needed space should be larger than the effective space. If there is sufficient temporal slack for the working items during construction, the crowding effect may not be significant and may not cause a significant productivity loss. Thus, this study defines critical space as a space causing significant productivity loss when disrupted by conflicts.

IV. CASE STUDY AND ANALYSIS

1. Project Profile

This study evaluated and verified the second proposal of the National Taipei University of Technology's Technology and Research Building.

The Technology and Research Building at the National Taipei University of Technology extends from Jianguo South Road (including the entrance to the basement parking lot) in the east to Xinsheng South Road in the west and from the pedestrian path in the south to Bade Road in the north. Dynamic axial lines of the construction foundation were drawn using the gate to the east of Jianguo South Road as the material entrance and with Xinsheng South Road as the material exit. The main part of the building is a concrete and steel structure, and the cut and cover method (CCM) was used. The project started with underground construction, from the basement parking lot underneath Jianguo South Road to Xinsheng South Road in the west. When the underground work reached the research building, basement excavation started. The waste soil was transported to the exit on Xinsheng South Road. Construction of the upper floors began after completion of the underground works. This project has little impact on campus ground transport or on the campus environment in general.

The project content included classrooms, research rooms, international conference centers, an underground parking lot, and auxiliary facilities. The basic dynamic axial line map consists of Jianguo South Road as the entrance and Xinsheng South Road as the exit. Level B4 to level B1 contain a machine room, a parking lot, a shopping area and a food court, and an international conference center, respectively. The first to eighth floors contain classrooms, research rooms, laboratories, and teacher offices. As this study focused on dynamic environment, it mainly investigated the three floors shown in Fig. 7, namely B1, the first floor, and the second floor. The construction included buildings A and B, with few interconnected floors. In the design of the underground buildings, the dynamic axial line of level B1 was the most complicated. From a space syntax perspective, this level is very complex and experiences a great deal of change along the dynamic axial line. Level B1 is located between buildings A and B, where the road height varies. The dynamic axial line design was chosen for investigation due to its features. The second floor varied slightly and included classrooms, large laboratories, and small laboratories. The second floor connected the two buildings and was therefore representative of the ground building.

2. Engineering Analysis Criteria

The procedures for using space syntax to analyze spatial characteristics are as follows:

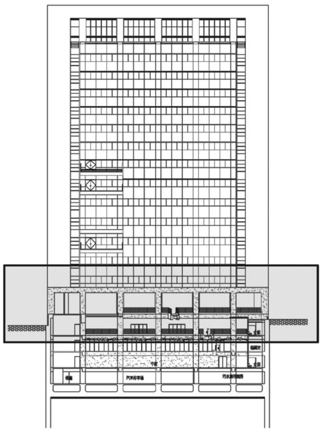


Fig. 7. A floor plan and elevation of the case study.

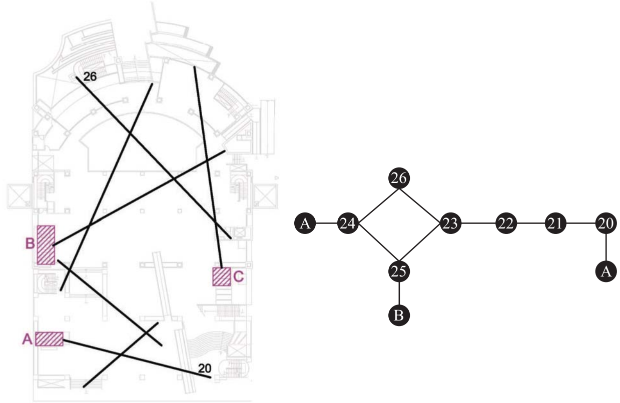


Fig. 9. 1F plan diagram and 1F topological diagram.

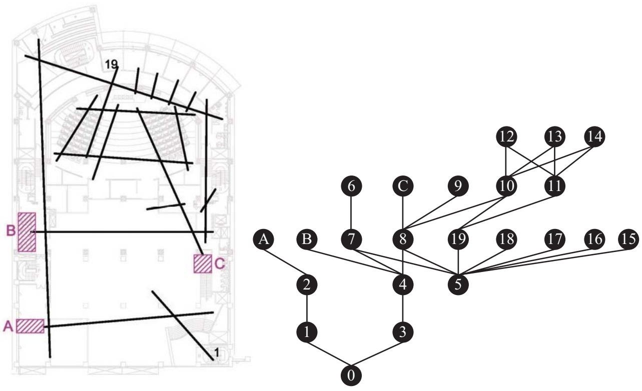


Fig. 8. B1 plan diagram and B1 topological diagram.

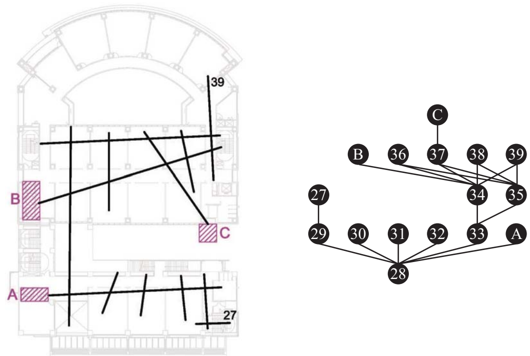


Fig. 10. 2F plan diagram and 2F topological diagram.

1. Decompose the space structure (the space is decomposed into several space units; for this research, the longest dynamic axial line method is used for decomposition).
2. Use the topological structure to produce a diagram of the longest dynamic axial line structure.
3. Use space syntax to calculate the longest axial line structure and to obtain *Rn* and *Cv*.

3. Demonstration of Spatial Characteristics

The CAD of level B1 was converted into a simple plan sketch, as shown in Fig. 8. There were three vertical entrances for the transport of personnel and materials. Following the space syntax conventions for dynamic axial line maps, a plane diagram of the 19 critical dynamic axial lines was plotted. The 19 critical dynamic axial lines and three vertical dynamic axial lines (A, B, and C) were used to achieve the transportation of personnel and materials in B1.

The dynamic axial lines for the simple plane diagram were used to transform the topological diagram. For example, dynamic axial line 0 was used as the only entrance, as shown in Fig. 8, and the transformation of the topological diagram facilitated the observation and calculation of *Rn* and *Cv*. Structural analysis of the topological diagram revealed that the important dynamic axial line could be found rapidly through observation, and after comparison with the calculated data, the main dynamic axial line could be determined. The CAD of level 1F and the topological diagram of 1F are shown in Fig. 9. Diagrams of 2F are shown in Fig. 10.

Based on the analysis criteria of the engineering characteristics, *Rn* and *Cv* were calculated. Then, the quantitative priority, correlation coefficient, and linear distribution diagram were used to find the correlation between *Rn* and *Cv*.

From the topological structure depth values, the mean depth values, integration values and control values for different components were obtained. Differences in the parameter values were used to identify and analyze spatial attributes.

A set of spatial analysis parameters was calculated. As shown in Table 2, the relative depth, integrated value, control value, and connectivity value were calculated.

In the field of space syntax, the path with the lowest mean relative depth value and the highest integrated value is frequently used. The magnitude of the control value reflects the control level over connected areas. If paths with high control values conflict, the accessibility of resources will be reduced and the project process will be delayed.

The correlation coefficient for *Rn* and *Cv* is 0.3267, as shown in Fig. 11. This result reveals that correlation is low, as verified by the *t*-test result. This finding indicates that

Table 2. Special analysis parameters.

No.	Connectivity value	Control value	Integrated value	No.	Connectivity value	Control value	Integrated value
1	2.00	**0.75**	**1.19**	**22**	2.00	**1.00**	**0.92**
2	2.00	**0.83**	**1.06**	**23**	2.00	**0.83**	**0.93**
3	3.00	**1.08**	**1.46**	**24**	3.00	**1.33**	**1.05**
4	4.00	**1.21**	**1.71**	**25**	3.00	**1.16**	**1.26**
5	4.00	**1.08**	**1.81**	**26**	3.00	**0.99**	**1.33**
6	8.00	**5.08**	**1.27**	**27**	2.00	**0.66**	**1.00**
7	1.00	**1.00**	**1.00**	**28**	1.00	**0.50**	**0.77**
8	3.00	**1.38**	**1.37**	**29**	2.00	**1.17**	**0.97**
9	6.00	**2.11**	**1.67**	**30**	1.00	**0.17**	**0.96**
10	1.00	**0.17**	**1.15**	**31**	1.00	**0.17**	**0.95**
11	5.00	**2.00**	**1.23**	**32**	1.00	**0.17**	**0.97**
12	5.00	**2.00**	**1.23**	**33**	3.00	**0.54**	**1.32**
13	2.00	**0.40**	**0.93**	**34**	6.00	**2.49**	**1.31**
14	2.00	**0.40**	**0.93**	**35**	5.00	**2.16**	**1.55**
15	2.00	**0.40**	**0.93**	**36**	2.00	**0.37**	**1.11**
16	1.00	**0.13**	**0.96**	**37**	3.00	**0.70**	**1.45**
17	1.00	**0.13**	**1.14**	**38**	2.00	**0.37**	**1.11**
18	1.00	**0.13**	**1.14**	**39**	2.00	**0.37**	**1.11**
19	1.00	**0.13**	**1.14**	**A**	3.00	**1.00**	**1.40**
20	3.00	**0.53**	**1.24**	**B**	3.00	**0.75**	**1.75**
21	2.00	**0.83**	**1.10**	**C**	3.00	**0.83**	**1.62**

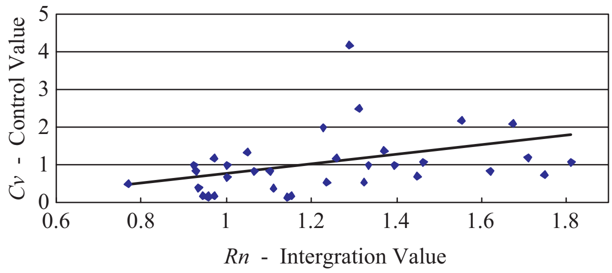


Fig. 11. A floor plan and elevation of the case study.

intelligibility is low; intelligibility, as defined in space syntax, is a good indicator of people's understanding of the built environment. A dynamic construction site may be less intelligible by pedestrians than a static, built environment. Thus, to improve people's understanding of the construction environment, it is key to find critical spaces in the dynamic construction site. As *Rn* and *Cv* are lowly correlated, it is proposed that only one of the two parameters will be highly correlated to the critical space.

4. Summary

The *Rn* and *Cv* values calculated in the simple plane diagram showed a high correlation for the dynamic construction space. The *Rn* and *Cv* values calculated for the plane diagram (including the vertical dynamic axial line) of buildings with high complexity had a low correlation for the dynamic construction space. The two values were correlated due to a false appearance caused by environmental factors.

Regardless of whether we consider only a plane or both plane and vertical lines, *Rn* can identify the convenience of each unit; however, based on the results, *Rn* cannot effectively reflect the importance of the position of stairs or exits/entrances (these may be critical spaces and space positions). In addition, for multi-story buildings, the units with the highest convenience are the middle floors, which is not useful for finding critical spaces. *Cv* can only reflect the unconnected units among the adjacent units of a building and cannot effectively reflect the spatial characteristics. Thus, this study suggests that *Cv* and *Rn* cannot effectively reflect spatial importance and cannot identify whether a space is a critical space. To allow space syntax to more effectively analyze spatial characteristics, this study proposes a new model for applying the CSI.

V. QUESTIONNAIRE DESIGN AND STATISTIC ANALYSIS

1. Fuzzy Questionnaire Design

The main aim of the fuzzy questionnaire design in this study was to use fuzzy syntax variables, which use natural words or word groups in complicated or difficult-to-define situations, so as to provide rational definitions and descriptions that compose an alternative response to traditional quantification. The salient feature of fuzzy syntax variables is their fuzziness. For example, the different levels of impact of

Table 3. Degree of congestion.

Construction site space	Description of degree of congestion
Spacious	There are no materials or scraps on the ground that could affect working, walking, or material transporting.
Uncongested	There are some materials or scraps on the ground that could affect working, walking, and material transporting.
Congested	Execution and handling are affected.
Fairly congested	Execution and handling are greatly affected.
Very congested	There is almost no available access or space for working.

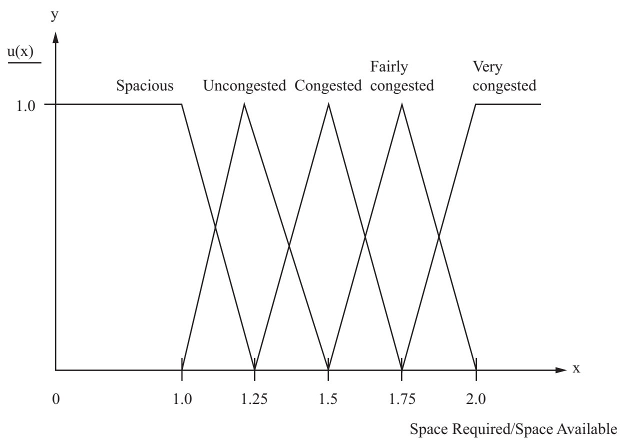
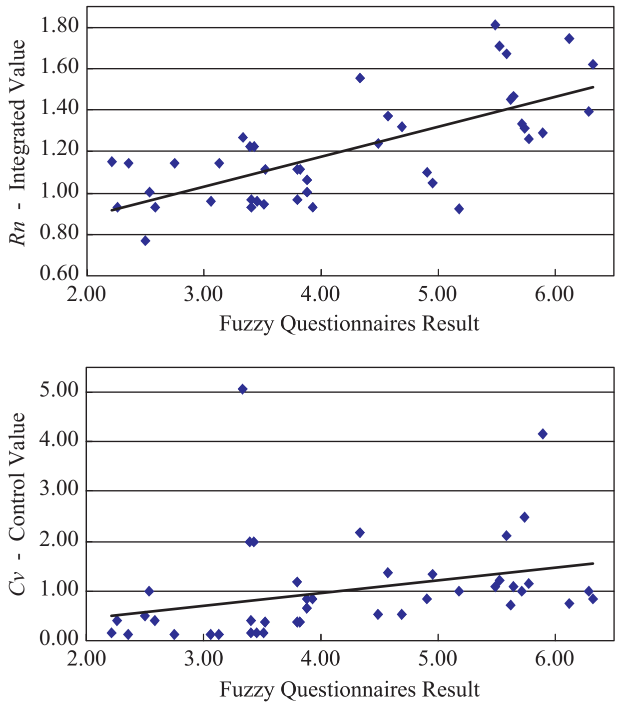


Fig. 12. Membership Function of the Degree of Congestion.



Correlation	Fuzzy Questionnaires	
	Correlation coefficient	Pearson (R^2)
Integration value	0.6993	0.4890
Control Value	0.3127	0.0978

Fig. 13. Correlation of *Rn* and *Cv* to fuzzy questionnaires results.

workplace congestion can be described using natural language: spacious, uncongested, congested, fairly congested, and very congested, as shown in Table 3. When faced with qualitative evaluation values, experts can use more natural language to efficiently express their feelings toward the evaluation value.

This study employed fuzzy intervals to design fuzzy questionnaires. The membership function of the degree of congestion is shown in Fig. 12. The longest dynamic axial line method in space syntax was used to plan a simple diagram and to calculate the impact of the importance of *Rn*. The fuzzy syntax variables were defined, and the membership functions of the dynamic axial lines in the workspace were measured.

2. Analysis of Questionnaire Results

After the questionnaires were retrieved, the results were analyzed. This study prioritized and compared the fuzzy statistical value of the *Rn* and *Cv* values, which were calculated using the longest dynamic axial line method. The fuzzy statistical value was used as a benchmark to verify and evaluate whether the *Rn* or *Cv* values were suitable for the dynamic axial line of the actual construction space. The top 15 dynamic axial lines of the 3 values were compared. The results show that the *Rn* and *Cv* values had 11 overlapping dynamic axial lines, showing a small level of error. The *Cv* and fuzzy statistical values had only 7 overlapping dynamic axial lines, which showed a greater level of error. Furthermore, for the *Cv*, all of the dynamic axial lines were connected to the vertical dynamic axial lines. In practice, the number of overlapping axial lines could be used to predict, when compared to the *Cv*, whether the *Rn* was more likely to approach the importance of the dynamic axial line of the actual construction evaluated by the fuzzy questionnaires.

Based on the fuzzy questionnaire results and the integration value distribution, a positive correlation and similarity were confirmed, as shown in Fig. 13. The fuzzy questionnaire results and integration values are shown in Table 4, and axial maps of the study case are shown in Fig. 14. In Fig. 14, the axial lines 8, A, B, and C are among the longest axial lines in the axial maps, and they are also the top four critical lines as evaluated by the fuzzy questionnaires.

VI. CRITICAL SPACE ANALYSIS

1. Establish CSI

The *Rn* values and the order ratio of the 15 lines obtained by the fuzzy questionnaires had 11 overlapping dynamic spatial lines, while the other four spatial dynamic lines did not overlap. This study found that the space syntax concept does not

Table 4. Fuzzy questionnaire results and integration value for each axial line.

	Fuzzy Result	Integrated Value		Fuzzy Result	Integrated Value
Axial line 1	3.88	1.06	Axial line 22	3.93	0.93
Axial line 2	5.64	1.46	Axial line 23	4.95	1.05
Axial line 3	5.52	1.71	Axial line 24	5.78	1.26
Axial line 4	5.49	1.81	Axial line 25	5.72	1.33
Axial line 5	3.33	1.27	Axial line 26	3.88	1.00
Axial line 6	2.53	1.00	Axial line 27	2.50	0.77
Axial line 7	4.57	1.37	Axial line 28	5.89	1.29
Axial line 8	5.58	1.67	Axial line 29	3.79	0.97
Axial line 9	2.22	1.15	Axial line 30	3.45	0.96
Axial line 10	3.39	1.23	Axial line 31	3.52	0.95
Axial line 11	3.42	1.23	Axial line 32	3.41	0.97
Axial line 12	2.58	0.93	Axial line 33	4.69	1.32
Axial line 13	2.26	0.93	Axial line 34	5.74	1.31
Axial line 14	3.41	0.93	Axial line 35	4.34	1.55
Axial line 15	3.05	0.96	Axial line 36	3.82	1.11
Axial line 16	2.75	1.14	Axial line 37	5.62	1.45
Axial line 17	2.36	1.14	Axial line 38	3.52	1.11
Axial line 18	3.13	1.14	Axial line 39	3.79	1.11
Axial line 19	4.49	1.24	Axial line A	6.28	1.40
Axial line 20	4.91	1.10	Axial line B	6.12	1.75
Axial line 21	5.18	0.92	Axial line C	6.32	1.62

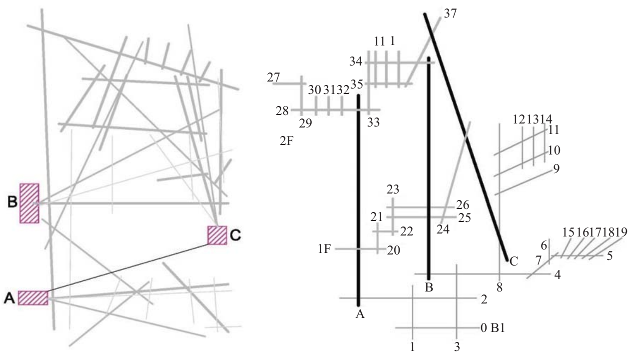


Fig. 14. Axial maps of the study case.

require the vertical dynamic line concept, so the vertical dynamic line was neglected. The vertical dynamic axial line primarily connected the main axial lines of the entrance, the exit, and the upper and lower spaces. If the building space exceeded the first floor, the importance of the vertical line would have to be considered. The analysis framework for space syntax only focuses on the plane analysis and ignores the concept of upper and lower spaces. In this study, the space index was calculated by increasing the weights of the vertical dynamic axial lines and the adjacent dynamic axial lines to construct the CSI.

2. The Concept of Standard Deviation

The standard deviation in probability statistics is often used to measure statistical dispersion. The standard deviation is defined as the square root of the variance and reflects the degree of intra-group individual dispersion; thus, the standard deviation is a measurement concept of the dispersion of a set of data from its mean. The standard deviation can be regarded as a measurement of uncertainty. For example, when a repeated measurement is conducted in physics, the standard deviation of the measured value set represents the measurement accuracy. The standard deviation of the measured values plays an important role in determining whether the measured value meets the predictive value. If the mean of the measured values and the predictive value are highly divergent (in comparison with the standard deviation), it can be stated that there is a discrepancy between the measured value and the predictive value.

After comparing the mean value of the fuzzy questionnaires with one, two, and three standard deviations of the *Rn*, the spatial dynamic axial line (including the vertical dynamic axial lines) after one standard deviation was overlapped with the 12 lines of the fuzzy questionnaires out of the 13 spatial dynamic axial lines. The value of the spatial dynamic axial lines after two standard deviations increased greatly, but the ranking did not change. Both the use of one standard deviation and the use of more than two standard deviations led to 12 overlapped lines. This study established the CSI when there were no extreme values; thus, one standard deviation was selected as the increased weight of the CSI.

3. Critical Space Analysis

In this study, critical space was defined as the space in

Table 5. The CSI ranking of each dynamic axial line.

Rank	Axial Line	CSI	Rank	Axial Line	CSI	Rank	Axial Line	CSI
1	4	2.06	15	20	1.35	29	23	1.05
2	B	2.00	16	33	1.32	30	6	1.00
3	8	1.92	17	5	1.27	31	26	1.00
4	C	1.87	18	19	1.24	32	29	0.97
5	2	1.71	19	10	1.23	33	32	0.97
6	3	1.71	20	11	1.23	34	15	0.96
7	37	1.70	21	9	1.15	35	30	0.96
8	A	1.65	22	16	1.14	36	31	0.95
9	25	1.58	23	17	1.14	37	12	0.93
10	34	1.56	24	18	1.14	38	13	0.93
11	35	1.55	25	36	1.11	39	14	0.93
12	28	1.54	26	38	1.11	40	22	0.93
13	24	1.51	27	39	1.11	41	21	0.92
14	7	1.37	28	1	1.06	42	27	0.77

which conflict must be prevented as it would cause enormous productivity losses. The judgment criteria were as follows:

1. Conflict occurs at the only exit/entrance. This case had no exits/entrances where absolute depth was zero.
2. Conflict occurs at the only vertical entrance. This case had more than three vertical dynamic axial lines.
3. CSI. The CSI ranking is shown in Table 5.

After verification, the CSI and the correlation coefficient obtained from the fuzzy questionnaires were 12.7% higher than the *Rn* and the correlation coefficient obtained from the fuzzy questionnaires, and their coefficient of determination was 19.3% greater than that obtained by the *Rn* and the fuzzy questionnaires. The CSI model is therefore rational, and its application to other building spaces is also feasible. The equation for the CSI is as follows:

$$\mathrm{CSI} = Rn + Rd \qquad (6)$$

where *Rn* is the integrated value and *Rd* is the standard deviation of the average *Rn*.

VII. CONCLUSION AND SUGGESTIONS

Based on the space syntax operation and the results of fuzzy questionnaires, this study analyzed whether the quantitative parameters of the syntax are suitable for the analysis of dynamic construction spaces. This study could encourage the development of the CSI concept to increase efficiency of critical space analysis.

1. Conclusion

The findings of this study are as follows.

1. Space syntax was used to analyze spatial characteristics, in particular, the spatial characteristics of construction sites. The definition of critical space was used to explain how control of the critical spaces can effectively reduce productivity losses and minimize unnecessary consumption through efficient management.
2. A questionnaire and analysis based on fuzzy theory were used to verify the accuracy of space syntax in construction sites. Regarding the quantitative parameters of the fuzzy questionnaires (*Rn* and *Cv*), the correlation coefficient between the results of the fuzzy questionnaires and the *Cv* was 0.70. The significant characteristic value was greater than +1.9, indicating that the *Rn* and the critical space in the questionnaire survey were consistent. The correlation coefficient and importance of the *Cv* and the fuzzy questionnaires did not reach statistical significance.
3. The CSI was established. After comparing the *Rn* and the fuzzy questionnaire results, the critical dynamic axial lines that were inconsistent with the *Rn* were correlated with the vertical dynamic axial lines. This step aimed to increase the weights of the dynamic axial lines correlated with the vertical dynamic axial lines to reconstruct the CSI and to allow it to model actual construction situations.

The equation for the CSI and the standard deviation is given as

$$\mathrm{CSI} = Rn + Rd$$

where *Rn* is the integrated value and *Rd* is the standard deviation of the average *Rn*.

Upon comparing the results calculated from the CSI with the top 13 important dynamic lines calculated from the fuzzy questionnaires, it was found that the two approaches yielded different but similar rankings. The correlation coefficient was 0.83311, which was 9% higher than the *Rn* coefficient. This finding demonstrates that the CSI model is rational.

2. Suggestions

Due to time limitations, this study only investigated building construction and the spaces associated with dynamic axial lines. Suggestions for future studies are proposed as follows:

1. The CSI model should be applied to other situations. This study only evaluated building construction and the spaces associated with dynamic axial lines. However, other spaces, such as tunnels and bays, are also limited due to the presence of large permanent machines and the spaces used for personnel, machines, and materials. The regional spaces used for large permanent machines should be studied.
2. The calculation of critical spaces in construction sites can be achieved by computer simulations. Software exists for large urban planning or automatic analysis systems of the spatial dynamic axial lines used in traffic route planning. However, automatic analyses for building construction

spaces are rare. Existing automatic simulations of construction sites focus on the time intervals of the structures, but software has not been used to analyze construction space conflicts. Future studies can use 4D-CAD construction space schedule simulation systems together with the findings presented in this paper to examine critical spaces and construction schedules before conflicts lead to productivity losses.

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