An Analysis of Pedestrian Movement in Multilevel Complex by Space Syntax Theory - In the Case of Shibuya Station-

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Abstract
In recent years, the major Japanese railway stations have been rebuilt into building complex with deep underground and high-rise floors by the redevelopment projects. These projects probably raise the attractiveness of stations and increase the numbers of users, but on the other hand, it is expected that its complexity will make it hard for the users to get to their destinations. In this study, spaces to own such a configuration are defined as complicated multilayered space.

There are former researches, which analyses the space around stations and their outskirts, done by Parvin, A. But, there are few studies which analyses pedestrian flow of spaces inside the station and its surrounding areas.

The purpose of this paper is to handle a large station which contains many lines as a model case of complicated multilayered space and understand how pedestrians choose their route in such a large multilevel complex based on Space Syntax theory (SS theory).

As an example, this analysis is applied to Shibuya station, Tokyo, Japan, before the redevelopment. Shibuya station has 4 railway companies and 8 routes, has complicated multilayered space; from the second floor above the ground to the third floor in the basement, and is used by more than 2 million passengers per day in 2007. Moreover, Shibuya station will have new route and have more complicated multilayered space; to fifth floor in the basement in 2008 after the redevelopment.
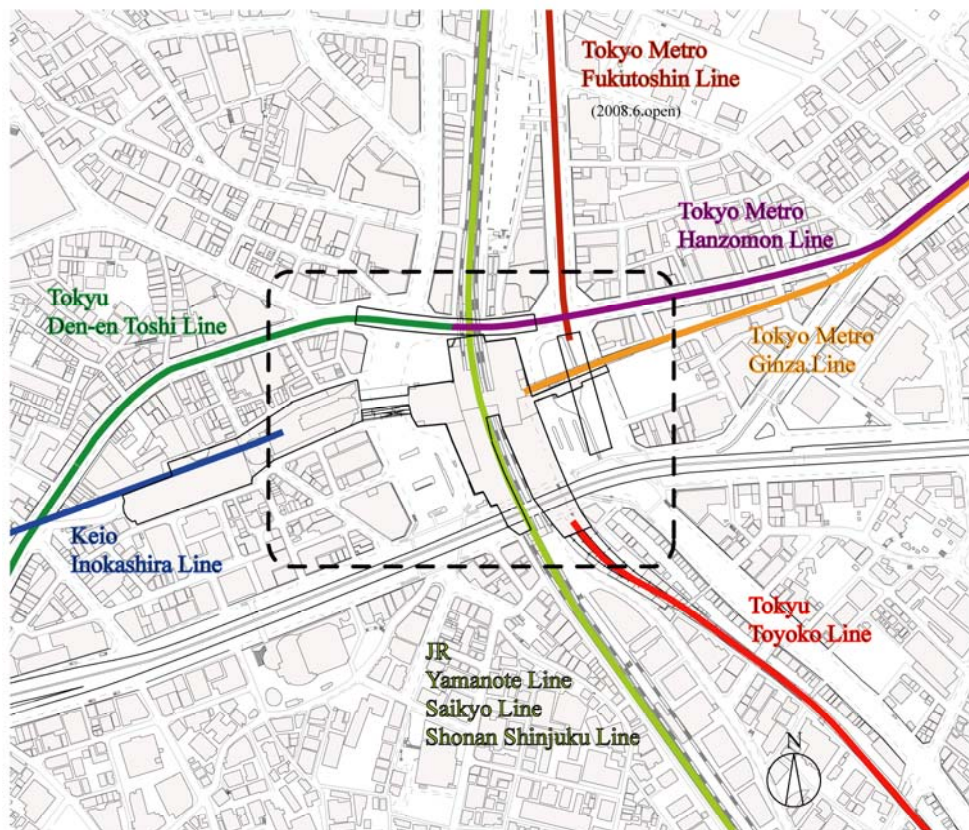
There are two features in this study. First, relations between pedestrian flow and various indexes of SS theory (especially, Visibility Graph Analysis) within the complicated multilayered space are investigated. Second, an integrated model which estimates the number of pedestrian flow within the target space according to the SS indexes is developed and compared with the actual measurement to verify the effectiveness of each indexes.

As a result, it became clear quantitatively that the choice of routes is influenced by three causes: one¦s visual range, the number of turns, and the shortest distance.

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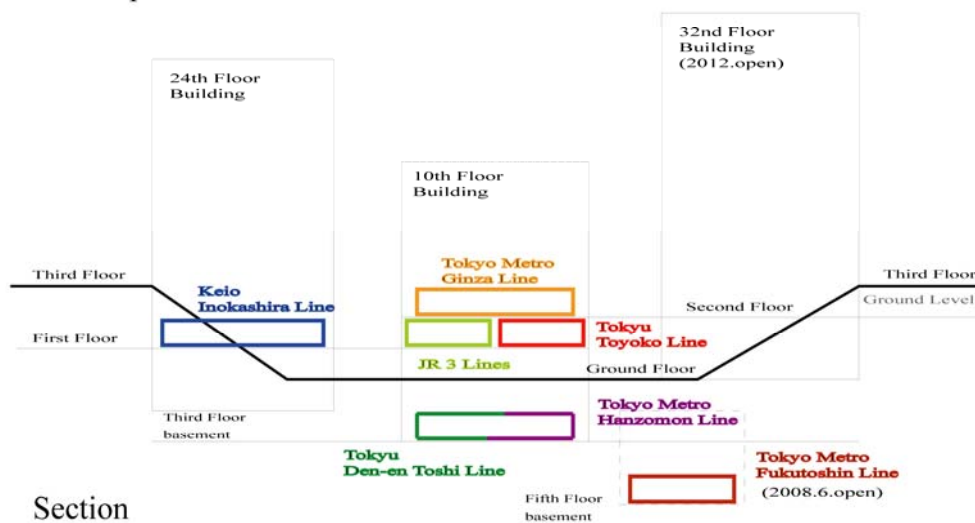
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1. Introduction

1.1. Background

In recent years, major Japanese railway stations have been rebuilt and expanded by the redevelopment projects. In Tokyo, large terminals and junctions such as Shinjuku or Shibuya station and their surrounding areas were designated as emergency redevelopment areas by government's urban rejuvenation headquarters, and accordingly railway stations and their vicinities are getting more and more developed. A railway station is a node of passenger traffic as well as a key junction of logistics; therefore redevelopment projects of these areas will also affect human flow of larger regional area.

Site map

Section

Figure 1
Site map and section of Shibuya station

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At Shibuya station, the fourth biggest station in Japan, eight lines by four different railway companies are connected, as of April 2008. There are *four stopping stations and four terminal stations*; two stopping station of Yamanote and Shonan Shinjuku Line by East JR Company, one terminal station of Toyoko Line and one stopping mutual entry station of Den-en Toshi and Hanzomon Line by Tokyu Corp. and Tokyo Metro Corp., one terminal station of Ginza Line of Tokyo Metro Corp., and one terminal station of Inokashira Line by Keio Corp. (see Figure 1). In addition, Tokyo Metro Fukutoshin Line (subway Route 13) which links from Ikebukuro to Shibuya has opened in June 2008. With the opening of the new line, the platform of Tokyu Toyoko Line now on the second floor, is to be moved to the fifth basement for the direct connection to Toyoko and Fukutoshin Line, in 2012. It can be easily predicted that it will possibly cause big changes in the pedestrian flow in the station.

As is the case of Shibuya station, terminal buildings are becoming more and more complicated and multilayered through the redevelopment projects. Redevelopment projects raise the attractiveness of stations and increase the numbers of users, but on the other hand, its complexity will make it hard for the users to get to their destinations. In this study, spaces with such configurations are called as "complicated multilayered spaces".

1.2. Purpose and features
The purpose of this paper is to handle a large station which contains many lines and commercial shopping arcades and department stores as a model case of complicated multilayered space and to estimate how pedestrians choose their route in such a large multilevel complex based on SS theory.

This study has three features. First, it investigates correlations between pedestrian flow in a complicated multilayered space and various indexes of SS theory. Second, it handles building as a complex of two-dimensional spaces instead of axial lines, and quantifies spatial characteristics based on their forms. Finally, it examines and clarifies the characteristics or preferences of pedestrian flow in multi-layered complicated space.

1.3. Related studies
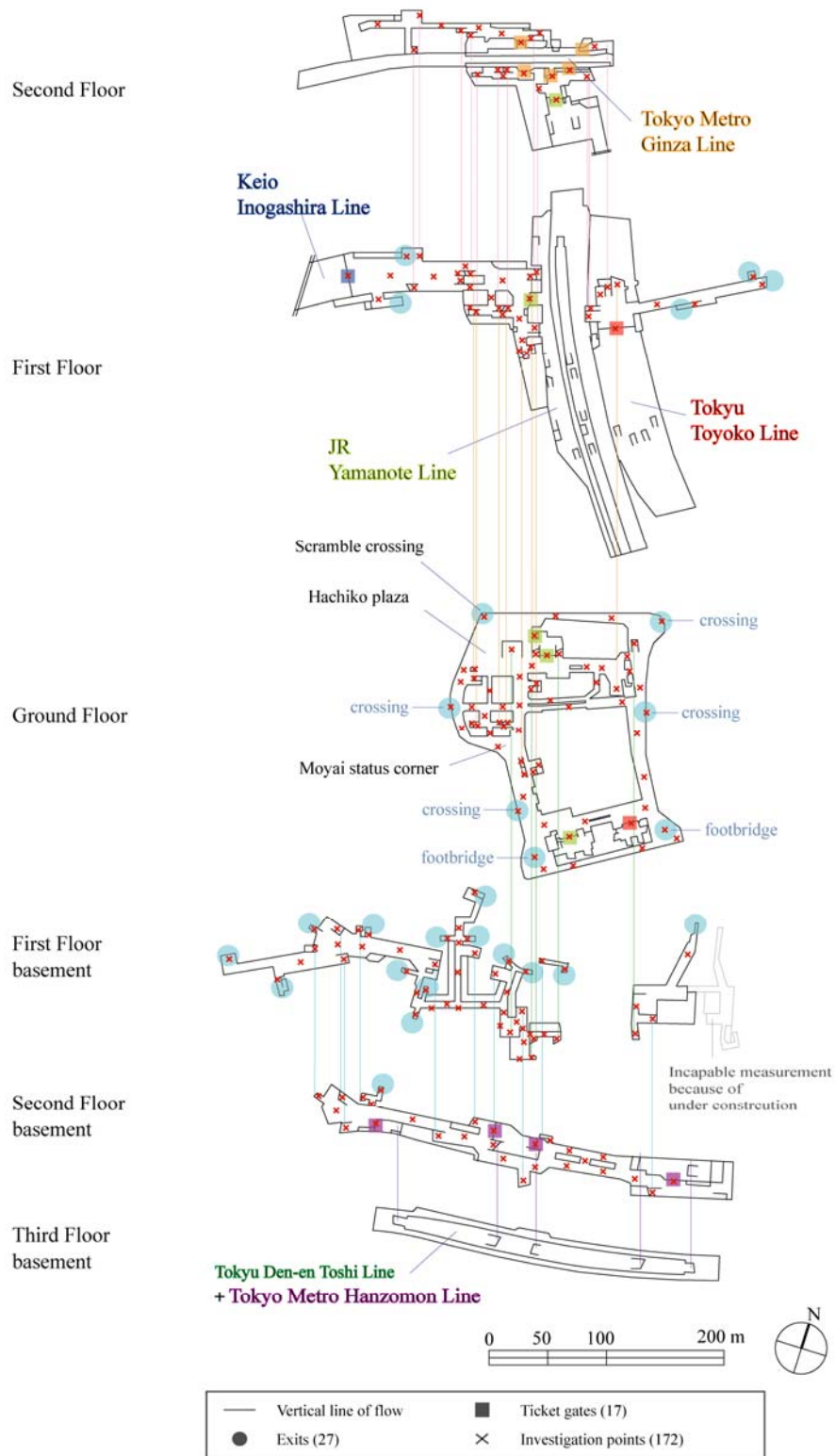The past researches related to this study are below.

- A study about the pedestrian flow using a station
  Ogiya, K., et al (2004) studied about it. The purpose of this research is to predict what kinds of influence the redeveloping train stations and its surrounding area have on the pedestrian flow. They estimated pedestrian flow by Dijkstra method considering with the present building distribution and road shape. The result showed a relationship with survey data and their estimation. The research was done around east vicinity of Shibuya station.
- A study about the action of the pedestrians in complicated space
  Penn, A., et al (1997) analyzed pedestrian movement rate and route choice in relatively unintelligible multi-level development, the Barbican and the South Bank complex, both in central London and made a model to predict these. Factors other than spatial configuration were incorporated in the model, including local visual factors, major generators and attractors of movement, and effects of grade separation. As a result, in unintelligible systems it turned out to be necessary to take a range of factors into consideration in order to model pedestrian movement behaviour.

Parvin, A., et al (2007) analyzed relations of pedestrian flow and visual accessibility in a public area and its circumstances in a complex facility by applying space syntax theory (henceforth, SS theory). They focused on Telford Gardens /Plazas in Hong Kong, which included one railroad station, a residential section, and commercial land. The quantity of pedestrian flow was analyzed mainly by the index of Visual and Spatial Integration Value. As a result, it came to be clear that "visibility" in a multi-layer space had an important influence on the pedestrian flow.

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2. Method

2.1. Study area
The study area of Shibuya station came to be the shapes as seen in Figure 2.

Figure 2
Study area

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Shibuya station was selected as a study area and the floor plans were created in reference to the map of 1/2500 scale published by Pia MOOK. The plans do not include the three ticket gates ¨C JR new south exit, Keio avenue exit, and Keio west exit. This is because they are physically far away, and possibly have little influence from the change after the redevelopment project.

Passages of two commercial facilities within the enclosure of the station are also not included because people are not likely to recognize these passages as the paths in the station because of doors. Therefore "the passage" in this study limits the definition to the space in which people can come and go freely without partitions.

The plans of all floors are different from one another. Especially as for the ground floor, a part of exterior spaces are included in the investigation area. This is because main waiting places such as Hachiko plaza and Moyai statue corner are in the exterior spaces. The exterior space was framed by the main roads. From above, study area of the ground floor is defined as an island which includes not only the interior but also a part of the exterior. The other floors have no exterior part and only connected with another floors by vertical paths.

It is confirmed that Shibuya station is complicated multilayered space from the second basement to the third floor on the ground.

In this study, we deal with a total of 17 ticket gates excluding the three ¨C JR new south exit, Keio avenue exit, and Keio west exit ¨C as previously mentioned. 27 exits to town are shown in Figure 2. As for the ground floor, exits to town are defined as "the pedestrian bridge" and "the pedestrian crossing" which link the island to the outside. As for the other floors, it is the vertical paths to the exits which have a signboard of Shibuya Station.

2.2. Visibility Graph Analysis

SS theory has three basic concepts; Convex space, Axial line, and Isovist. Among these, we adopted Visibility Graph Analysis (VGA) which has developed out of Isovist. We then interpret definitions of Visual Connectivity, Metric Shortest Path Length (MSP), and Visual Step Depth (VSD) among VGA's indexes.

- Visual Connectivity
  Visual Connectivity is "the number of apexes within the graph which can be connected directly from an apex" and means visual range from a point in the space. The value is higher if the view is wider or is open to more directions.
- MSP
  MSP is "metric distance to each apex within the graph" and is calculated by shortest Euclidean distance on the graph. Closer apex has lower MSP value.
- VSD
  VSD is "the least number of direction changes to each apex within the graph". Lower VSD value means less directional change to the destination space and the space will be leached more easily.

2.3. Summary of investigation and analysis method

The actual amount of pedestrian flow in Shibuya station was investigated in November and December, 2007. The investigations were carried out on Saturdays and Sundays, and 172 points in Shibuya station were surveyed twice for five minutes each. Therefore, we measured the amount of pedestrian flow for ten minutes in total per each point. The amount of pedestrians from 15:00 till 18:00 was surveyed, although the period of time differs a little day to day.
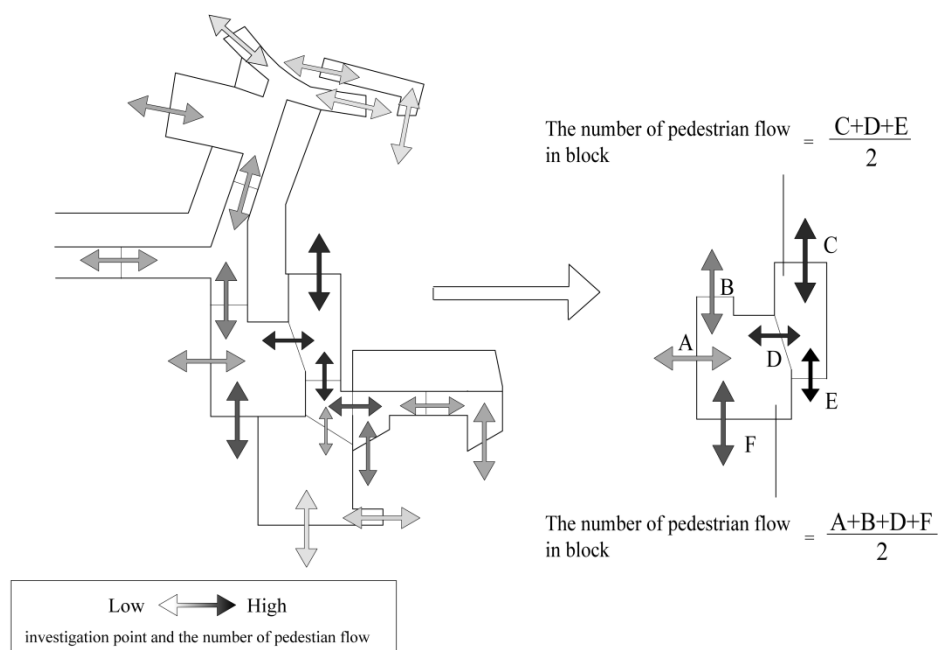
In analyzing the data with the plans by Depthmap, each index is discussed. In Depthmap, vertical paths such as stairs and escalators are represented as single point. Cells are basically connected to each other only on the plain, but if a vertical path is connected there, it links vertically to the cell on another floor.

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When it comes to straight stairs etc., it should be added one step through connected point. And it should be added two steps in the case of bending stairs. The measurement points of MSP and VSD are on 17 ticket gates shown in Figure 2, and we analyze in two ways: measuring the depth from each ticket gate, and that from all ticket gates.

After that, the strength of each index explaining the pedestrian flow can be evaluated with multiple regression analysis, and the bases on which the pedestrians find their routes in complicated multilayered space are analyzed. In a multiple regression, the purpose variable is the number of pedestrian flow obtained by investigation, and the explaining variable is each index used by VGA.

3. Actual Pedestrian flow

In pedestrian flow investigation, pedestrian movement gate count method was used. Numbers of people who pass through certain sections in a certain period of time were counted. The gate count survey were done at the main exits to the stations, at crossing points of the paths, at the ends of large convex spaces, and etc. in Shibuya station.
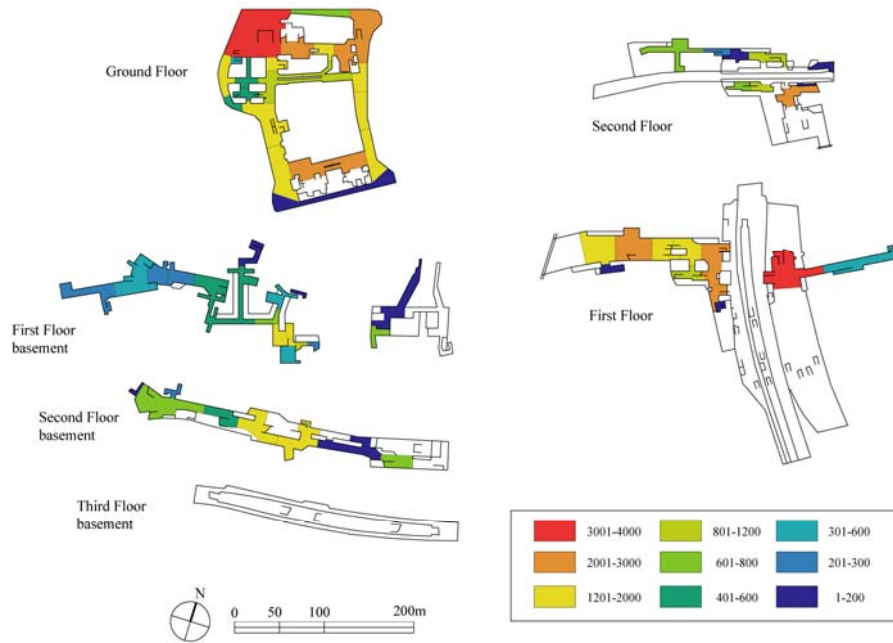
The number of pedestrian flow in block $= \dfrac{C+D+E}{2}$

The number of pedestrian flow in block $= \dfrac{A+B+D+F}{2}$

Low ⟵⟶ High
investigation point and the number of pedestian flow

Figure 3
Calculation method of the number of pedestrian flow in block

Totally 172 counting sections were chosen in the area. Then whole area of the station was divided into 75 zones by these counting sections. Pedestrian flow at the section was allocated to its adjacent zone, and flow through each zone was calculated by summing up those allocations. Figure 3 shows the calculation method of flow as an example, and Figure 4 shows the calculation result of the entire Shibuya station.
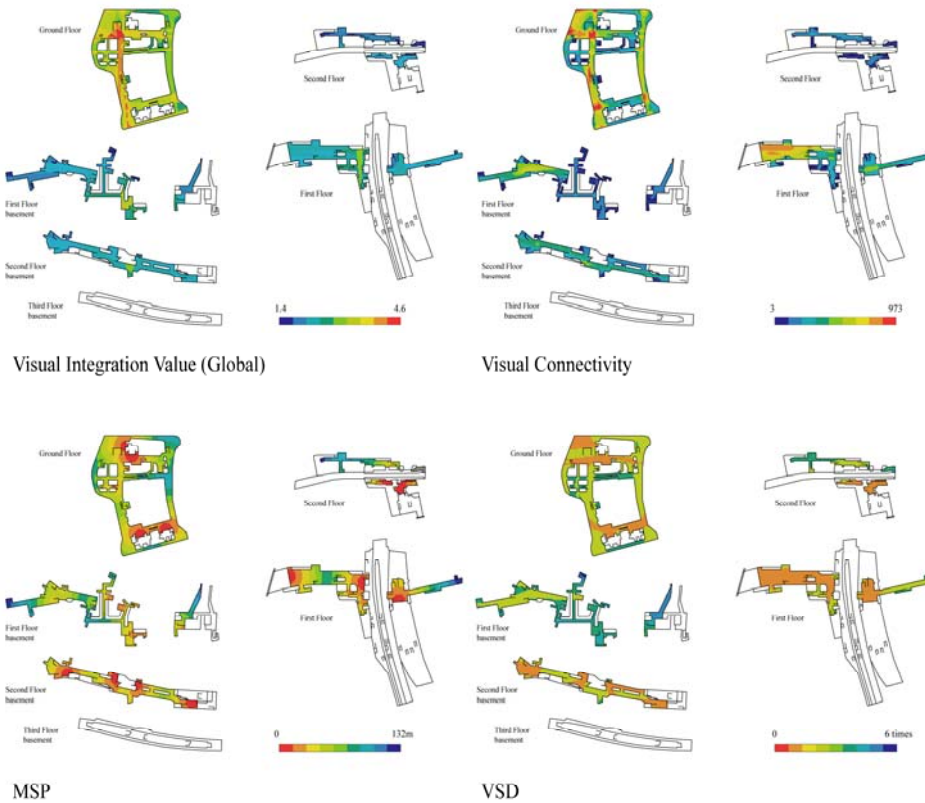
On the ground, the first, and the second floor, there were many zones with large pedestrian flow (see Figure 3). Such zones had common features, that is, "being adjacent to ticket gate", "large zone size", and "being accessible from many directions". In addition, on the first basement, which was the only floor with no ticket gates at Shibuya Station, a great amount of flow was observed in blocks including a connection with ticket gate of the second basement or Hachiko plaza of the ground floor. On the contrary, there was little pedestrian flow in other blocks. Further, the result of pedestrian flow investigation turned out two things: first was that there was less flow on the under the ground floors than on the ground floors, and second was that there was a large amount of flow on the walk-through which connected certain ticket gate to another.

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Figure 4

The number of pedestrian flow in block per ten minutes

4. Spatial analysis

Spatial configurations of Shibuya station were analyzed by Visual Graph Analysis of DepthMap. In order to make the visibility graph, the whole space was divided into grid cells by the interval of 1m. The results of Visual Integration Value, Visual Connectivity, VSD, and MSP were shown respectively (see Figure 5).

Figure 5

The results of Visibility Graph Analysis

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Next, single correlation of pedestrian flow amounts which took the logarithm of the bottom two and the value analyzed with each index of VGA were examined. It was done with two models. One case was the model including all 172 investigation points, and the other was the model including only 44 ticket gates and exits to town (see Table1). Table 1 shows that the value of each VGA index has correlation a little with the number of pedestrian flow in case of all 172 investigation points (r2 = -0.14 ~ 0.39), and the value of each VGA index has correlation considerably with the one in case of 44 ticket gates and exits (r2 = -0.81 ~ 0.69). At the same time, it turned out that it was difficult to catch the pedestrian flow by only one index.

	All	Ticket gates / Exits
Visual Int.V-Global	.387	.658
Visual Int. V-Local3	.299	.692
Visual Connectivity	.347	.688
mean MSP	-.393	-.551
min. MSP	-.313	-.614
mean VSD	-.467	-.752
min. VSD	-.340	-.809

Sig.（two-tailed） .000 in all points

Table 1
Single correlation between the number of pedestrian flow and the value of each VGA index

Based on this result shown in Table 1, the results of VGA shown in Figure 5 were examined.

- Visual Integration Value (Global)
  It means the zone is easier to reach from any networked spaces if Visual Integration Value is higher. It is because pedestrians choose a route where integration value is higher. Figure5 shows that linear space which connected Hachiko plaza and Moyai statue corner on the ground floor had the highest value in Shibuya station. This was because the ground floor was the mid-floor of the station and the vertical paths such as stairs and escalators part were mainly on the west side. On the other hand, Visual Integration Value was relatively low at periphery of the graph. The value had a slight correlation with pedestrian flow (r2 = 0.39 in case of all). However, there seemed unign orable mismatch between the results of analysis and survey because the locations of ticket gates were not taken into account.

- Visual Connectivity
  Figure 5 shows that many of large spaces which have wide range of view or crossings of passages have high Visual Connectivity. The former is to be a waiting place and the latter is a junction of pedestrian flow. Such spaces were seen mainly on the ground floor and the west side of the first floor in figure 5 for example surroundings of the statue of Hachiko and Moyai, and they were actually used as waiting places. On the contrary, low Visual Connectivity was seen mainly in vertical flow lines such as escalators or stairs, and in the second basement, the first basement and the second floor, which had complicated configuration. Narrow view gives pedestrians negative effect in channel selection and reduces staying behavior in the space. This shows that pedestrians tend to gather in large space and visible range largely affects how pedestrians act.

- MSP
  Figure 5 shows that MSP was low near the ticket gates and get higher as it goes far away from them. This was naturally because the measurement spots were set at the ticket gates. (MSP represents the shortest distance from the ticket gate.) Table 1 shows that

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there was a negative correlation between the pedestrian flow and MSP (r2 = -0.39 in case of mean MSP, r2 = -0.31 in case of min. MSP). The result of the exit far from a ticket gate generally conformed to Figure 4. It can be said that even though the designer made exit far away from the ticket gates with deep consideration to enable people contact with the city easily, few pedestrians use them. On the contrary, it can be seen continuous pedestrians on a route which connect one ticket gate to another. It differs from the result of the analysis. For example, the route which connects Keio ticket gate with JR on the first floor is the one. Even though many pedestrians come and go continuously actually, the value of MSP is lowest at ticket gate and highest at median point between two ticket gates. So, it is necessary to consider the fact in adopting MSP, and there is room for improvement in order to make better use of MSP.

- VSD
  Figure 5 shows the floors with ticket gates had low VSD and turned out to be accessible with a few turns. Much pedestrian flow was surveyed in such spaces. Conversely, it turned out that the spaces of high VSD were concentrated on the first basement, which had no ticket gates and whose shapes were complex. This meant a lot of turns were required to reach such spaces. The actual pedestrian flow there was also fewer than the other floors. The number of turns had a negative correlation with the measured number of pedestrian flow (r2 = -0.47 in case of mean VSD, r2 = -0.34 in case of min. VSD). Therefore, it can be said that the number of turns is an important index in describing a pedestrian flow. Pedestrians tend to choose their routes in which they need fewer turn because it becomes difficult for them to understand correlation between where they are and where they will be. However, there was a possibility of some mismatches between the results of analysis and the survey of actual flow, because pedestrians are coming and going from and to the excepted gates.

5. Multiple regression analysis

The strength of each index explaining the pedestrian flow could be evaluated through multiple regression analysis, and the bases on which the pedestrians made channel selection in complicated multilayered space were analyzed. In a multiple regression, the objective variable was the number of pedestrian flow obtained by investigation, and the explanatory variables were each index used in VGA.

First of all, both the minimum value and the mean value of each ticket gate were added to MSP and VSD among indices analyzed with VGA, "min" of minimum and "mean" of mean were applied as initials, and they were assumed min. MSP, mean MSP, min. VSD, and mean VSD.

Furthermore, five dummy variables (*B2F, B1F, GF, 1F* and *2F*) to show the number of floors were added to the explanatory variables, because it was thought that the number of floors on which the pedestrian flow was investigated could also affect the pedestrian flow. After all, two models were made with such variables. One is the model including all 172 investigation places, and the other is the model including only 44 ticket gates and exits to town. SPSS was used to build the models, and Step Wise method was adopted. The model formulas are below. The former is the model with all investigation points and the latter is the model with points limited to the ticket gates and exits.

$\log_2 P$ = 0.003[Visual Connectivity] - 0.017[mean MSP] - 0.495[min. VSD] + 0.899[*B1F*] + 10.831
$\log_2 P$ = 0.004[Visual Connectivity] - 0.006[mean MSP] - 0.625[min. VSD] + 9.990

(P = the number of pedestrian flow, *B1F* = the first basement)

The results of analyzing each model are shown in Table 2.

Table 2 shows that actual pedestrian flow has some correlation to the model with all points (r = 0.59, r2 = 0.35). As for the model with limited points, there is a strong correlation between the actual data and the model (r = 0.91, r2 = 0.83). Both models have higher correlation than any

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single index in Table 1. This shows that it is useful to incorporate various indexes in the model in order to predict pedestrian movement in complicated multilayered space.

	R	R^2	F Value
All	.591	.350	26.74***
Ticket gates / Exits	.909	.827	63.65***

In case of all the investigation points

	USC	SC	T value	VIF
Visual Connectivity	.003	.334	5.437**	1.152
mean MSP	-.017	-.440	-7.193**	1.145
min. VSD	-.495	-.287	-4.108**	1.490
B1F	.899	.211	2.930**	1.590

In case of ticket gates and exits

	USC	SC	T value	VIF
Visual Connectivity	.004	.412	5.675**	1.216
mean MSP	-.006	-.169	-2.233*	1.321
min. VSD	-.625	-.557	-6.957**	1.478

***. Sig. .000   **. Sig. 1% （two-tailed）   *. Sig. 5% （two-tailed）

(R: Multiple correlation coefficient, R^2: Contribution rate)

(USC: Unstandardized Coefficients, SC: Standardized Coefficients)

Table 2
The analysis results of multiple regressions

The T values in Table 2 show that these models are statistically significant and the values VIF in the same table show that there is no multicolinearity among the explanatory variables. In addition, standardized coefficients in Table 2 make it clear that three indicators (Visual Connectivity, min. VSD, and mean MSP) are significant to estimate the pedestrian flow in complicated multilayered space. Visual Connectivity is the visibility from given point. VSD is the number of times pedestrians should turn direction to move from each ticket gate to given spot, and the ticket gate which has least VSD provides min.VSD. Mean MSP is the mean value of distances of the shortest route from each ticket gate to given spot.

Below are discussions about the indexes applied to neither models, and about the dummy variable *B1F* which is adapted to the model of ticket gates and exits.

- Visual Integration Value
  Visual Integration Value is known to be one of the important indices in SS theory, because the correlation between Visual Integration Value and pedestrian flow was high enough in past researches. However, it was applied to neither of the models in this study. There are three possible reasons. First, most pedestrians in the station should have particular purposes and move to their destinations; second, the pedestrian flow depends much on "distance from ticket gates" or "the vision range from given point"; and third, it is such a synthetic index that the multicolinearity problem arises between Visual Integration Value and other indexes.

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- The other indexes that were not adopted
  Min. MSP and mean VSD fall under this category. It could be seen especially that mean VSD correlated with the pedestrian flow more strongly than any other indices given in the single correlative list of Table 1. Mean VSD, however, was rejected from the models because the T-value was high enough to exceed the 5% standard in the process of combining indices by Step Wise procedure. Min.MSP was never adopted even in the process of combining.

- Dummy variable *B1F*
  Dummy variable *B1F* was adapted to the model of ticket gates and exits. It was possibly attributed to the fact that the first basement was the only floor that had no ticket gate in Shibuya station. It seemed that the first basement had a negative influence on the amount of pedestrian flow, because closing space underground gave the impression of stifled or anxiety to people. In the first basement, however, the amount of pedestrian flow of the center block was extremely larger than the any other blocks (see Figure 4). This gave positive effects the first basement to pedestrian flow as a whole. Therefore, this factor effected the model with all the investigation points to lower the multiple correlation coefficients and the contribution rate.

6. Conclusion

In recent years, the major Japanese railway stations have been rebuilt into high-rise building with deep underground floors by the redevelopment projects. These projects aim to raise the attractiveness of stations and increase the numbers of users. But on the other hand, the complexity of the station building makes it hard for the users to get to their destinations. In this study, such buildings are defined as "complicated multilayered space".

The purpose of this study was to estimate how pedestrians choose their routes in a complicated multilayered space on the basis of SS theory. Shibuya station, a huge multilevel complex with many lines, was dealt with as a model case study.

In this study, we measured the amount of pedestrian flow, analyzed the spatial configuration with VGA, and did a multiple regression analysis with various indexes. In a multiple regression analysis, the objective variable was the number of pedestrian flow obtained by observed traffic count, and the explanatory variables were each index computed in VGA. We then could make a model to estimate pedestrian movement in complicated multilayered space and the model could be used to quantify the relative significance of each index on pedestrian movement. The multiple correlation coefficient and contribution rate of each model show that these models are valid to predict pedestrian movement in complicated multilayered space. As a result, it was shown that three indices; Visual Connectivity, min. VSD, and mean MSP were quantitatively accountable for pedestrian flow. From above, it came to be clear that the choice of routes in a complicated multilayered space was influenced greatly by three factors: one's visual range, the number of turns, and the shortest distance. First, pedestrian movement can be estimated by adopting the model at the planning phase. Second, ideal space for pedestrian passing in complicated multilayered space can be designed by considering these three indexes.

In addition, this study provided various findings about each index of VGA through the space form analysis. The place of high visibility had two features: as a waiting space, and as a traffic junction for pedestrians. This shows that "visibility" makes a significant role in pedestrian route choice and it is important to create spaces with high visibility at the planning phase. Visual Integration Value suggested that much pedestrian flow occurred in strong spatial connection between spaces. However, it was difficult to grasp whole pedestrian flow only with one index because pedestrians move irregularly with their own purposes or destinations. Therefore it became clear that to combine some indices in order to achieve a significant model is necessary.

As cities expand, urban populations will grow and complicated multilayered building will increase. This is because we need to use not only ground space but also underground and aerial space as

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long as we permit city's development within limited space. Based on such a situation, if we can estimate how pedestrians choose their routes in a complicated multilayered space we then will be able to create attractive city space while maintaining city's development.

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