

BIM-enabled Definition of a Path Object and its Properties to Evaluate Building Circulation using Numerical Data

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Abstract

In this paper, we seek to define the path object and its properties as an instance level of a circulation path between two spaces. We further suggest the practical application of path objects in design review issues using numeric data on building circulation (NDBC) as a complete collection of circulation paths from a given Building Information Modeling (BIM) model. As the use of BIM is increasingly being implemented in architecture, engineering, and construction industries, rich data related to building objects and useful digital representations have been developed for specific circulation review tasks. Among the several benefits observed from such applications, this paper focuses on the BIM-enabled formal definition of the path object and its properties. We further demonstrate the use of several analysis applications using the NDBC. Due to the rich spatial information defined in a BIM model, path objects can be instantiated dynamically, and a specific data model for building circulation paths can be defined with a series of numeric data sets. In this paper, the formal definition of a path object and its properties are explored, and one of its NDBC applications is clarified and demonstrated for further circulation analysis tasks using a software tool developed by us.

Keywords: path object; Numeric Data of Building Circulation; Building Information Modeling; design review

1. Background and Motivation

Building circulation refers to the way people move through and interact with spaces or zones within a building. A reasonable and effective building design is critical as it affects building usability, economic issues, and circulation (Chan-Ju, 2005). Circulation affects building design, spatial program, and design validation in various design regulations such as RFPs, design guides and legal standards. Design evaluations that specifically focus on the issue of circulation are mostly conducted qualitatively with the exception of legal issues that define exact numeric values of the circulation distance (Jin-Kyoung, *et al.*, 2013). Although previous research efforts have tried to quantify circulation indicators (Hillier, *et al.*, 1983), various methods of representing and calculating circulation are still utilized (Mee-Young, *et al.*, 1999). Moreover, several types of digital building models in the form of 3D CAD have been used for path

planning; however, these methods typically support only geometric information rather than semantic information related to building components (Ya-Hong, *et al.*, 2013).

In contrast to generalized computational software in architecture, Building Information Modeling (BIM) supports digital representations of physical and functional characteristics of building objects in architecture, engineering, and construction. BIM serves as a shared knowledge resource for information during its life-cycle. BIM is founded on open standards for interoperability including the Industry Foundation Classes (IFC) schema and BIM authoring tool data structure (buildingSMART, 2015, Kristen and Kenneth, 2012). It is possible to query specific information in BIM. Moreover, BIM enables dynamic generation of spatial topology based on building objects and spatial properties (YoungZhi, *et al.*, 2009). Using BIM applications, computational representations of building circulation (Jin-Kook, *et al.*, 2010, 2011, 2014) and validation studies have been conducted (GSA, 2007, Charles 2009, JaeMin, 2010) with circulation analysis in a more quantitative way.

Here, we describe the information dataset of a path object within an IFC schema structure. Rather than focusing on a design knowledge-like domain, we focus on path objects and their raw numeric data from

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given building instances for addressing design-related issues. We pursued the following three objectives in this paper: 1) definition of a path object and its related properties, 2) definition of Numeric Data for Building Circulation (NDBC) as expanded criteria of a derived path and its properties, and 3) demonstration of NDBC with an external database for design review applications.

2. Research Scope and Approach

Our goal in this work was to define a path object and properties of building circulation and to build an external database of NDBC for use in dealing with building circulation analysis issues. "Dynamic" path objects are derived from "static" space objects. Therefore, the properties of path objects are influenced by the properties of space objects including the type, properties, relationships, and so on.

Building circulation data can be applied during design review for various purposes. The path object and its defined properties can be referenced for objective assessments rather than for qualitative design reviews. All path objects and related properties of a building model can be represented as numeric data (which we refer to here as NDBC). NDBC can be derived from static objects with the operator concept that queries or extracts required objects. In addition, we show the extension of NDBC applications to design review, where both the external database and its authoring interface are employed.

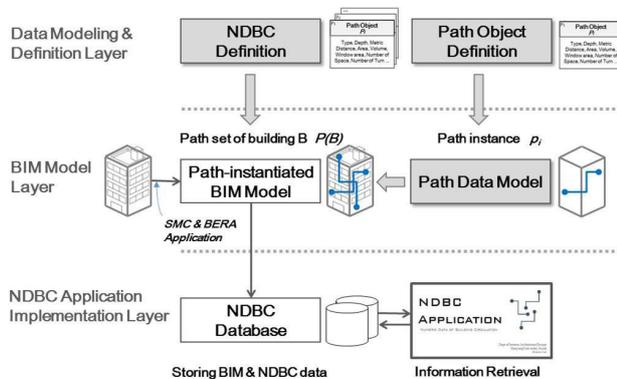


Fig.1. Research Overview

The concept of NDBC is presented in its entirety in Fig.1., which also reflects the research sequence described in this paper: 1) retrieving building circulation-related data from an IFC model using Building Environment Rule and Analysis (BERA) language in a Solibri Model Checker (SMC) environment (Solibri, 2015), 2) defining the NDBC, including path objects and properties, 3) establishing an external NDBC database, and 4) applying NDBC to design review issues.

3. Building Circulation-Related Design Review

3.1 Circulation Planning

With the development of IT capability, design planning or quantity takeoffs using computational programs are regularly conducted for architectural designs. In particular, BIM allows quantification of design quality and enables computational evaluation by providing geometric and semantic information associated with building objects and the relationships between them. Thus, in this section, we review the conventional approach to circulation analysis and its BIM-enabled methodologies and applications.

3.2 BIM-Enabled Circulation Representation and Its Applications

BIM is capable of storing both geometric and rich semantic information associated with building components and their relationships for the purpose of lifecycle data sharing (Ya-Hong, *et al.*, 2013). Circulation involves all the information related to objects including spaces, walls, doors, and stairs. Several studies have focused on computational building circulation-related issues using BIM.

In order to perform design reviews based on the circulation analysis, Yong Zhi *et al.* introduced a framework to enable space syntax analysis using building information modeling to automatically retrieve space topology. They compared design outcomes based on changes in circulation flow (YoungZhi, *et al.*, 2009). There have been several studies on approaches to represent circulation for indoor environments. Jin-Kook *et al.* described circulation within buildings and surveyed how circulation representation can be applied to analysis of building circulation-related issues (Jin-Kook, *et al.*, 2010, Charles, *et al.*, 2009, Jin-Kook, *et al.*, 2014, Bin, *et al.*, 2014, YunGil, *et al.*, 2011, Hermann, *et al.*, 2014, Barbara, *et al.*, 2013).

Eastman *et al.* presented a rule checking system for circulation and security validation of automated code checking for a courthouse building in the United States. Circulation rules were parameterized into four high-level conditions (start space, intermediate space, destination, and transition), which were able to be computationally processed in an SMC plug-in (Charles, *et al.*, 2009 b). In a continuation of the GSA court house automation project, Lee suggested a logical foundation upon which one can build an automated checking module for circulation rule-checking that is capable of independently outlining the rule-validation process (JaeMin, 2011).

In this section, we reviewed cases of research and development that focused on the representation of BIM-enabled circulation and its application for various types of design review. Previous literature on BIM-enabled circulation analysis has dealt with several different representational methodologies and means of validating them. The present paper focuses on the path object used in building circulation analysis within the BIM environment with a quantitative data-set of related path properties.

4. Definition of Path Objects and Related Properties

Each path has its own start space, target space, and intermediate spaces defined by pedestrian movement in the building environment. Therefore, each path can be considered as a sequence of consecutive spaces. As described in Section 3, circulation analysis is an important component of the design phase and the assessment of a design; however, path objects do not exist in formal standards such as the IFC.

This section describes the definition of path objects and their properties as they relate to space objects for use in circulation-related design regulations or codes rather than for checking specific rules. General path objects and properties are defined and organized. We then classified the computable numeric data associated with the properties. The defined type of path property was then applied and various design assessments were made.

4.1 Definition of Path Object

The definition process begins with a building and its components.

[Def. 1] $B = \{F, V\}$

Here, B denotes the Building, F denotes the Floor, and V denotes the vertical penetration object in B . If the operator 'getPath()' that generates building circulation is given to B , the path object, P , can be instantiated:

[Def. 2] $getPath(B) \rightarrow P(B)$

$P(B) = \{p_1, p_2, p_3, \dots, p_n\}$

$P(B)$ denotes path object instantiated by the operator in a given building model B , as a set of path instances.

[Def. 3] $P(B) = \{PR(P), G(P)\}$

$PR(P)$ denotes properties of the path object and $G(P)$ is a graph that represents path instances $P(B)$ for calculation and analysis (measurement of distance, depth, etc.).

[Def. 4] $S(P) = \{SS(P), TS(P), IS(P)\}$

Here, SS , TS , and IS are sets of start, target, and intermediate spaces, respectively. Each circulation path related to a space object can be expressed as follows.

$SS(P) = \{ss_j | ss_j \in SS\}$, where ss_j is a set of start space of $P(B)$

$TS(P) = \{ts_k | ts_k \in TS\}$, where ts_k is a set of target space of $P(B)$

$IS(P) = \{is_l | is_l \in IS\}$, where is_l is a set of intermediate space of $P(B)$

All space objects in a building model can be SS , IS , and TS based on the goals of the building user.

Circulation path objects are derived from space objects and related conditions. The path generation operator previously mentioned, $getPath()$, can encompass not only building model B , but also the diverse space objects and their related conditions. Space objects with conditions can be located in the parameter position $getPath()$.

$$getPath(SS_{cond}, TS_{cond}) \rightarrow P(SS_{cond}, TS_{cond}) \\ = \{PR(P(SS_{cond}, TS_{cond})), G(P(SS_{cond}, TS_{cond}))\}$$

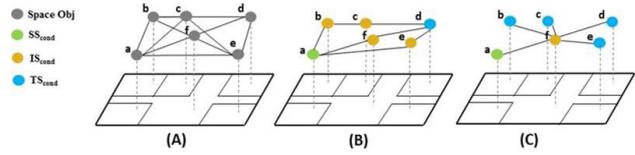


Fig.2. Path Generation According to Operator $getPath()$. (A): $getPath(B)$, (B): $getPath(SS_{cond}, TS_{cond})$, (C): $getPath(SS_{cond}, IS_{cond}, TS_{cond})$

SS_{cond} and TS_{cond} denote the condition of each start space and target space. Additionally, IS_{cond} can be included in one of the parameters in operator $getPath()$ to generate a path object as a condition. Conditions of space objects can include space name, space department, space use, egress status, vertical penetration space, and cardinality, among others. Fig.2. describes a path representation diagram within the virtual space layout of a building model using path generation operator concepts.

4.2 Path Properties

Properties are dependent on path objects and related space objects. The following path properties are computed automatically by the $getPath()$ operator with simultaneous path generation. Unique IDs for start and target space objects are given to each path. Then, each respective path property is given numeric data. In addition, path property-related regulations are described in order to determine their importance.

[Def. 5] $PR(P) = \{PR | PR(P) \text{ is a set of properties of path } P(B)\}$

1) Walking Distance $WD(p_i)$

$$WD_{p_i} = \sum_{i=1}^n E_j(p_i)$$

WD denotes the walking distance of path instance p_i . E denotes the Edge of G that represents p_i . Thus, the numeric data of the distance between two (start, target) spaces is the summation of all edge lengths in the path graph.

2) Number of Turns $NT(p_i)$

NT denotes the number of turns of path instance p_i . The numeric data for the number of turns in the path instance can be calculated by subtracting 1 from the number of edges in p_i .

3) Depth $D(p_i)$

D denotes the spatial depth of path instance p_i . Depth value is assigned according to how many spaces are away from the start space. Depth is related to the concept of spatial integration, which defines a space in relation to all other spaces in the spatial program.

4) Area $A(p_i)$

A denotes the area of path instance p_i . It is related to the qualitative amenities of the space and also takes into account the width of the space that p_i travels through.

5) Height $H(p_i)$

H denotes the height of path instance p_i .

6) Volume $VL(p_i)$

$$VL(p_i) = A(p_i) \cdot H(p_i)$$

VL denotes the volume of path instance p_i . Volume is related to area and height of the path instance.

7) Number of Windows $NW(p_i)$

NW denotes the number of windows along path instance p_i .

8) Window Area $WA(p_i)$

WA denotes the window area of path instance p_i .

9) Space sequence of $SS(p_i)$, $IS(p_i)$, $IS(p_i)$

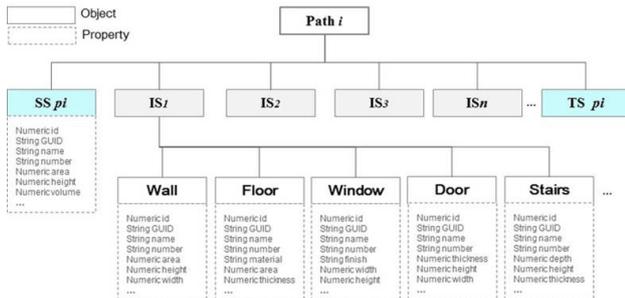


Fig.3. Intermediate Spaces and Properties Related to the Start Space and Target Space of the Path Instance

IS denotes the sequence of the intermediate space(s) of path instance p_i . There are significant regulations related to intermediate space conditions in terms of the pedestrian movement. As shown in Fig.8, p_i has related spatial information including intermediate spaces. Intermediate space properties are based on the SMC viewer in this paper. However, other IFC model viewing program can be used to obtain additional quantities of space objects.

5. Numeric Data of Building Circulation

Numeric Data of Building Circulation (NDBC) describes all possible path objects, properties, and processed values of each path property using the NDBC expanded operation. NDBC can be expressed as follows:

[Def. 6] $NDBC = \{Set\ of\ P(B),\ Operation\ OP(P)\}$

NDBC is applicable when an actual given instance model exists. This section describes visualization path generation using an expanded operator, which utilizes an example model and its computable property values for representation purposes. The target test model was designed in Autodesk Revit 2015, and its IFC format was used. Derivation of the path object was accomplished by using the BERA language and the SMC environment. The following sections describe each NDBC operator in sequential order.

5.1 Path Object Instantiation for NDBC

The example model included 24 space objects on a single floor (4 public spaces, 7 building common

spaces, 1 maintenance space, and 12 major-related space groups such as classrooms or laboratories).

$$getPath(F) \rightarrow P(F) = \{PR(P), G(P)\}$$

$$P(F) = \{p_1, p_2, p_3, \dots, p_{286}, p_{287}, p_{288}\}$$

F denotes the single floor in the target test model. $getPath(F)$ retrieves all path objects of space objects in this floor. We obtained a total of 576 path objects through the computation process. However, the instantiated path set includes overlapped path objects. For instance, the path object from space ID 34 to space ID 17 and the path object from space ID 17 to space ID 34 space were identical instances. Thus, the total number of path objects should be divided by two. Therefore, 288 path objects were derived, and examples are shown in Fig.4.

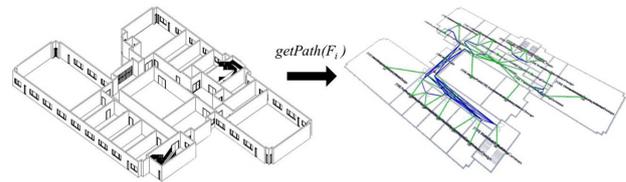


Fig.4. Test Target Model (Left) and All Path Objects with $getPath(F_i)$ Operator (Right)

In addition, $PR(p_i)$ were computed by individual path objects p_1 to p_{288} as shown below when path objects are generated within the BERA language tool environment.

```
id = p1
SS = [144] TransferRoom
TS = [128] ToiletW5_Public
WD = 7.33
D = 3
NT = 1
A = 1124.35
H = 13.12
VL = 14751.47
WA = 0.0
NW = 0
Spaces = [197] Corridor8_BuildingCommon > [127]
StairsMain5_BuildingCommon
```

5.2 NDBC Operations for NDBC-Specific Properties

This section describes the operator used for applying numeric path property data for deriving a meaningful value for design quality, $calculateValue()$. This command provides arithmetical results of NDBC including quantity, summation, and average. This operator is more meaningful when it deals with entire space groups in a given building model to evaluate overall design quality for evaluating building circulation. This operator can be represented as follows:

[Def. 7] $calculateValue(P) \rightarrow$
 $CV(P) = \{Qnt(P), S(PR(P)), A(PR(P))\}$
 1) $calculateQnt(P) \rightarrow (n)p_i = (n)SS_{cond} \cdot (n)TS_{cond}$

Here, Qnt denotes the quantity of path instances from the generated operator. $(n)p_i$ denotes the number of path instances from the given SS_{cond} and TS_{cond} . If there are sets of $SS = \{s_1, s_2\}$, then $(n)SS$ can be 2. If $TS = \{t_1, t_2, t_3\}$, then $(n)TS$ can be 3. Then, set P_i can be derived as $P(SS, TS) = \{P(s_1, t_1), P(s_1, t_2), P(s_1, t_3), P(s_2, t_1), P(s_2, t_2), P(s_2, t_3)\}$, can be 6. The number of path instances also can be estimated with the generated path ID from the generated operator:

2) $calculateSum(PR(P)) \rightarrow$
 $S(PR(P)) = \{pr(p_1) + pr(p_2) + \dots + pr(p_n)\} = \sum_{i=1}^n PR(p_i)$

Here, sum denotes the summation of $PR(P)$ values. The parameter space of $calculateSum()$ accommodates $PR(p)$ values. WD was chosen as an example, as shown below.

$$SWD(P(ss,ts)) = \{WD(p_1) + WD(p_2) + \dots + WD(p_n)\} = \sum_{i=1}^n WD(p_i)$$

In the calculation above, SWD is the summation of the total walking distances of path set $P(ss,ts)$. If the value of each SS and TS is more than 1 (especially with many relations), then the overall properties of the path set from the conditions of the space group can be calculated as the total summation value. With $calculateSum()$, we can get $S(PR(P))$, SNT , SD , SA , SH , SVL , SNW , and SWA .

3) $calculateAvg(PR(P)) \rightarrow A(PR(P)) = S(PR(P)) / (n)p_i$

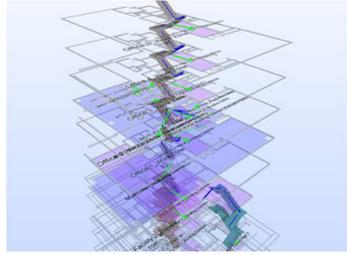
Here, Avg denotes the average $PR(P)$ values. Like the description of $S(PR(P))$ above, this average value calculation operator also utilizes $PR(P)$ as an input parameter.

$$AWD(P(ss,ts)) = \{WD(p_1) + WD(p_2) + \dots + WD(p_n)\} / (n)P(ss,ts)$$

The average value of each path property is meaningful when comparing quantitative values of multiple path sets from SS and TS that have different conditions. According to $(n)SS_{cond}$ and $(n)TS_{cond}$, $(n)P_i$ increases or decreases according to $S(PR(p_i))$. Thus, the $calculateAvg(PR(p_i))$ aims to derive a property value of each path instance for objective comparison with other path sets. It is not conclusive whether the average value directly reflects the design quality, but this method does allow for quantitative evaluation of design issues. $CalculateAvg()$ generates $A(PR(p_i))$, ANT , AD , AA , AH , AVL , ANW , and AWA . For diverse calculation results of $PR(p_i)$, an example model is used that includes 9 evacuation-related space objects to evaluate quantitative

data for circulation in public spaces. Table 1. visualizes a path from the public space group to the evacuation space group, which is accompanied by related numeric data.

Table 1. Calculated Value of NDBC by Each Condition of Space Object Sets

Visualization of path graph	$calculateValue()$ Result
	$calculateQnt(P_i) = 108$
	$calculateSum(PR(p_i))$
	$\rightarrow SWD(P_{ss,ts}) = 3280$
	$SNT(P_{ss,ts}) = 1247$
	$SD(P_{ss,ts}) = 478$
	...
	$calculateAvg(PR(P_i))$
$\rightarrow AWD(P_{ss,ts}) = 30.37$	
$ANT(P_{ss,ts}) = 11.54$	
$AD(P_{ss,ts}) = 4.4$	

5.3 NDBC Operations for Retrieving Related Information

We mentioned that an instantiated path travels from the start space to the target space with intermediate spaces according to the condition of SS and TS . This section focuses on intermediate spaces occurring between start and target spaces and their properties. These spaces can be expressed with the $getRelObj()$ operator, which provides advanced properties beyond the simple properties expressed by $getPath()$.

[Def. 8] $getRelObj(P) \rightarrow RelObj(p_i)$
 $= \{RelComponent(p_i), RelSpace(p_i)\}$

$RelComponent$ denotes related components of specific or grouped spaces, while $RelSpace$ denotes space objects referenced by $RelComponent$. Using the related space objects and their associated properties, specific building features can be validated including: 1) rules (fire area, non-combustible material of wall, restricted space zone) and 2) qualitative issues (volume of space, color material of building elements, window area that pedestrians encounter). Moreover, with a series of IS , additional information about connected, accessible space objects and properties can be tracked. Fig.5. describes derived space objects and related properties from a specific p_i .

This diagram can be expanded according to intermediate space objects and related space objects. If the properties of a space object are predefined in detail, more information can be tracked, such as the cost of the material and the color of a building element. In order to track additional information, the external database includes NDBC and spatial information of a given building. The SS_{cond} is defined as the server room and TS_{cond} is defined as the strategic planning room. Using the $getPath()$ operator, intermediate spaces are derived as below:

Space Sequence = [11] Restricted Corridor > [17] Hall > [37] Public Lobby > [51] Front Desk > [57] Business Hall > [59] Restricted Corridor

$IS(P("server\ room", "strategic\ planning\ room"))$

$$= \{is_1, is_2, is_3, is_4, is_5, is_6\}$$

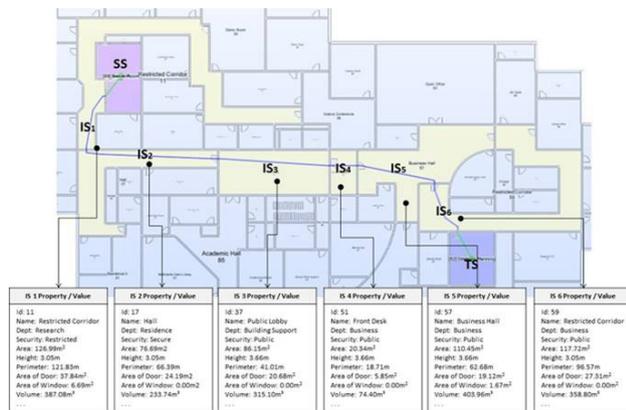


Fig.5. Plan View Visualization of a Path Object from 'Server Room' to 'Strategic Planning Room' and Its Intermediate Spaces

The derived intermediate space set implies that $is_1 = s_{11}$, $is_2 = s_{17}$, $is_3 = s_{37}$, $is_4 = s_{51}$, $is_5 = s_{57}$, $is_6 = s_{59}$. Each is_n can be matched with an ID of a space object in the given model. One of the intermediate space objects is chosen as a target tracking object to determine the expanded boundary of the instantiated path-related object.

6. Implementation and Demonstration of NDBC

This section describes an implementation of NDBC with an external database and an application that is connected to a database. The 'NDBC application' is for managing the NDBC of a given building model. With this application, users who need specific information about building circulation can 1) review the overall path objects and their related or expanded properties, and 2) reuse the NDBC to review the design for a specific purpose without the target building model (BIM model or IFC model, etc.). As shown in the demonstration of NDBC, actual building models are used for test target model comparison, code compliance checking, and design review.

6.1 External database and its application of NDBC

This section describes the NDBC external database for data viewing, retrieval, and management used for design review. Previous research on automated design checking has shown that a building model does not typically include the detailed level of information required for effective automated code checking. This is true despite the ability to attach a set of properties to objects, which means that BIM can potentially be a far more convincing means of communicating building designs to code checking authorities. While BIM is becoming an industry standard, it is not yet common for models to contain semantically rich information because IFC supports the class level of building models and related components, not additional instantiated objects such as building circulation.

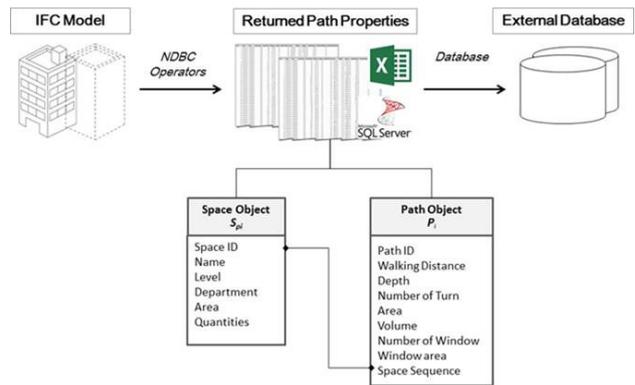


Fig.6. Process of External Database Creation for NDBC

There is a lack of knowledge-based systems using BIM in research and projects (Abhijeet, *et al.*, 2014, Shu-Hui, *et al.*, 2013, Tan, *et al.*, 2012, Bhargav, *et al.*, 2009), but the systems can be a potential data source for supporting a BIM-enabled data model.

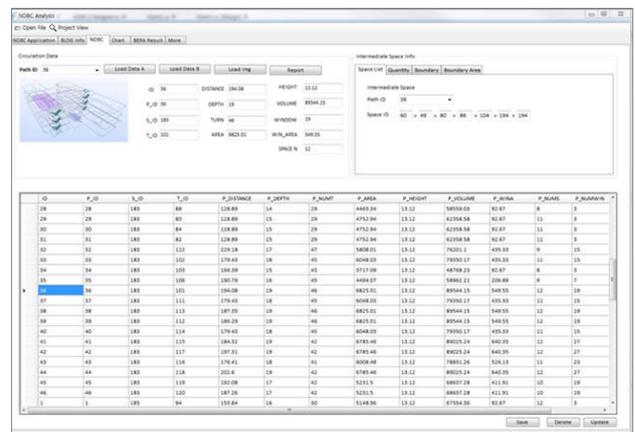


Fig.7. Screen Shot of NDBC Application that Includes an External Database

Fig.6. describes the process of designing an external database for NDBC information from a given building model.

Returned path properties consist of two data tables: 1) all space objects within a building model and their related properties and quantities, and 2) path objects and their properties. In the data table, path objects generated by specific operators are entered with their own ID and property set as one row. The space information (SS , IS , TS) of a passing path object can be tracked using the mapping relationship between the space ID in the space sequence of 'Path Object p_i ' and the 'Space Object $S(p_i)$ ' data table. The path object of each row in the table contains space sequence information for each ID of SS , TS , and IS ; different path object IDs can be combined to infer the other path sequence without the given model. Fig.7. shows a screen shot of NDBC application interface that is connected to an external database.

6.2 Case Study: An Actual Comparison between Design Alternatives

This case study focused on a comparison between design alternatives that have different spatial allocations. The comparison utilized NDBC for a remodeling project (Hyunsoo, *et al.*, 2014). The target test model is an actual building within the Hanyang University campus in Seoul, Korea. The building, which is for the College of Human Ecology, is composed of three major departments: Food & Nutrition, Clothing & Textile, and Interior Design.

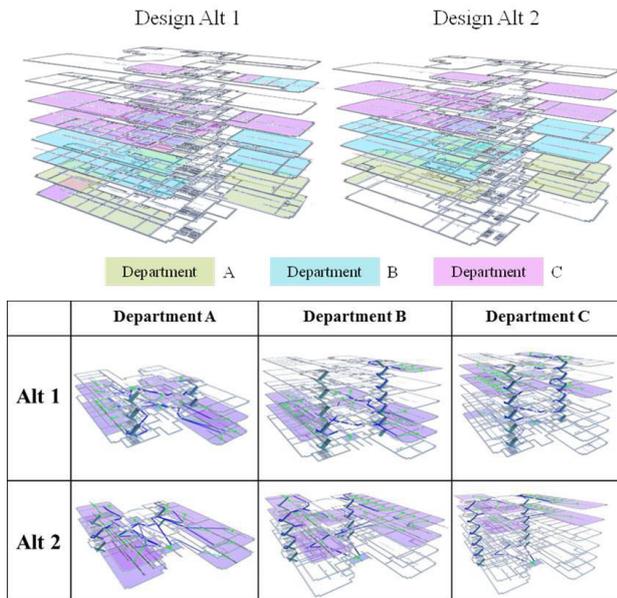


Fig.8. Visualization of *getPath("Entrance", "Department A")*; in Design Alternatives #1 and #2

To determine a reasonable, efficient, and equivalent spatial allocation, we conducted circulation analysis, and the derived NDBC *getPath()* was compared with a set of parameters with the main entrance as SS_{cond} and each department-related space as TS_{cond} . The derived circulation graph and NDBC of design alternative 1 and design alternative 2 are shown in Fig.8., which also shows the visualized path graphs from *getPath(MainEntrance, DepartmentA)*.

The plan of each design has a different number and area of department spaces according to the number of internal users within each department. Therefore, a difficulty exists in comparing design alternatives for total summation of the circulation path data. As a result, the average values of each NDBC are influential factors for comparing overall design alternatives irrespective of the number of spaces within each department. Fig.9. shows a comparison between design alternatives 1 and 2 in terms of the average value per path object using *calculateAvg(PR(p))*.

In terms of circulation efficiency, the values of *AWD*, *ANT*, and *AD* in design alternative 2 were higher than the values in design 1. This quantitative result means that building circulation from the main entrance

to spaces in three different departments have longer walking distances, more turns, and greater spatial depths in design 2 than those in design alternative 1. From a qualitative perspective, each value of *ANW* and *AWA* in design alternative 2 was higher than that in design alternative 1 except for spaces in department C. This means the quality of visibility or outside vision in design alternative 2 was generally higher than in design alternative 1. This demonstration illustrated the quantitative method used for expressing objective values related to building circulation; whether the NDBC has extended meaning is not within the scope of this paper. However, NDBC can clearly be used to support design decisions and infer path quality, as shown in this example.

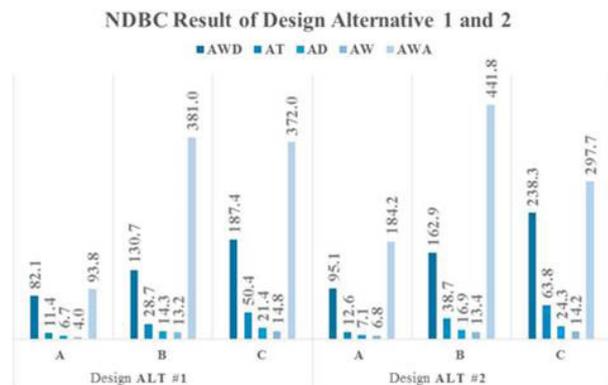


Fig.9. Comparison Chart of Average Value of NDBC Result

7. Summary

In this paper, we introduced NDBC as a complete collection of path objects, their definitions, and their expanded properties from a given BIM model. Use of NDBC enables quantitative analysis and interpretation of building circulation based on various BIM-enabled properties. This type of dynamic dataset can be stored in an external database for reuse in design review. The formal definition of a path object is provided and implemented for storing NDBC data. Thus, various NDBC data can be retrieved in order to reuse the data for design review purposes including a comparison between design alternatives. Such comparison are based on an NDBC application that supports data viewing, calculation (max, min, total summation, average value), and tracking related building components.

Building circulation has been addressed in various ways, but its definition or representation has never been formally established in the IFC schema. Therefore, we suggest a BIM-enabled path data model that focuses on quantitative data of path objects that can be populated from a given model. NDBC can be utilized as an assessment indicator of building design, and this research has the potential to be used for a broader range of design review issues pertaining to building circulation.

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References

- 1) Abhijeet D, Salman A, Shreekanth A (2014), A framework for a BIM-based knowledge management system, Creative Construction Conference, Procedia Engineering 85 (2014), pp.113-122.
- 2) Barbara S, Bogdan H-B, Maciej P, Monika R, Mateusz W, Michał K (2013), BIM Based Indoor Navigation System of Hermes Mobile Robot, Romansy 19 – Robot Design, Dynamics and Control, Volume 544 of the series CISM International Centre for Mechanical Sciences, pp.375-382.
- 3) Bhargav D, Lauri K (2009), Collaborative knowledge management—A construction case study, Automation in Construction, 18 (2009), pp.894-902.
- 4) Bin W, Haijiang L, Yacine R, Alex B, Hoang N. O (2014), Hindawi Publishing Corporation, Scientific World Journal Volume 2014, Article ID 589016, <http://dx.doi.org/10.1155/2014/589016>.
- 5) Building design guidelines of national Daegu science museum, Korea.
- 6) buildingSMART (2015), What is a BIM?, <http://www.buildingsmartalliance.org/index.php/nbims/faq/>
- 7) Chan-Ju K (2005), A study on building 'the spatial configuration graph of circulation', Journal of the Architectural Institute of Korea Planning & Design, 21 (10), pp.139-146.
- 8) Charles M E (1999), Building Product Models: Computer Environments, Supporting Design and Construction, CRC Press, ISBN 9780849302596 - CAT# 0259.
- 9) Charles M E (2009), Automated Assessment of Early Concept Designs, Architectural Design, Special issue, Closing the Gap, Volume 79, Issue 2, pp.52-57.
- 10) Charles M E, Jaemin L, Yeon-suk J, Jin-Kook L (2009), Automatic rule-based checking of building designs, Automation in Construction, 18 (8), pp.1011-1033.
- 11) Circulation: Defining and Planning (2012), U.S. GENERAL SERVICES ADMINISTRATION PUBLIC BUILDINGS SERVICE.
- 12) Code of Practice for Fire Safety in Buildings (2011), The government of the Hong Kong special administrative region, Buildings Department, http://www.bd.gov.hk/english/documents/code/e_fs2011.htm
- 13) Code on accessibility in the built environment (2013), Building and Construction Authority.
- 14) Enforcement Decree of the Building Act, 34, (1) in Korea Building Act.
- 15) GwangYa H, AgReum P, BokKyung P (2010), The Mechanism of Space Cognition of Large Mixed-use Complex - Case Studies of Coex and Central City in Seoul, Journal of the Urban Design Institute of Korea, 11 (2), pp.199-214.
- 16) Hermann M, Wolfram K, and Christian F (2014), Pedestrian simulation based on BIM data, 2014 ASHRAE/IBPSA-USA, Building Simulation Conference, pp.425-432.
- 17) Hillier B (2007), Space is the machine: A configurational theory of architecture, Space Syntax, ISBN 978-0-9556224-0-3. pp.288-314.
- 18) Hillier B, Hanson J (1984). The social logic of space, Cambridge University Press. Cambridge.
- 19) Hillier B, Hanson J, Peponis, J, Hudson (1983), Space syntax: a new urban perspective, Architects' Journal, 30th November, pp.47-63.
- 20) Hyunsoo L, Jisoo K, Minkyu S, Jin-Kook L, Inhan K (2014), A Demonstration of BIM-enabled Indoor Spatial Analysis for Design Decisions using BERA Language, ISARC 2014 : The 31st International Symposium on Automation and Robotics in Construction and Mining.
- 21) Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, INTERNATIONAL STANDARD ISO 16739:2013(E) (2013), First edition.
- 22) JaeMin L (2010), Automated checking of building requirements on circulation over a range of design phases, PhD Dissertation, College of Architecture, Georgia Institute of Technology.
- 23) Jihoon K (2009), A Study on User Circulation of Large Commercial Complex by Visibility Analysis, Journal of the Regional Association of Architectural Institute of Korea, 11(2), pp.73-83.
- 24) Jin-Kook L, Charles M E, Jaemin L, Kannala M, and Yeon-suk J (2010), Computing Walking Distances within Buildings based on the Universal Circulation Network, Environment and Planning B: Planning and Design, 37 (4), pp.628-645.
- 25) Jin-Kook L, Charles M E, Yong Cheol L (2014), Implementation of a BIM Domain-specific Language for the Building Environment Rule and Analysis, Journal of Intelligent & Robotic Systems, 24 (2012), 203-212, doi 10.1007/s10846-014-0117-7.
- 26) Jin-Kook L, Mijoeng K (2014), BIM-enabled Conceptual Modelling and Representation of Building Circulation, International Journal of Advanced Robotic Systems, 11:127, doi: 10.5772/58440.
- 27) Jin-Kyoung L, Chan-Ju K, Sang-Ho Y (2013), A Development of Quantification Indicators for Circulation System Evaluation in Mixed-Use Buildings, Journal of the Architectural Institute of Korea Planning & Design, 29 (9), pp.59-66.
- 28) Korean Building Act, National Legislation Center, <http://law.go.kr/lOrdinAstSc.do?menuId=9&p1=&subMenu=1&nwYn=1§ion=&tabNo=10&query=%EA%B1%B4%EC%B6%95%EB%B2%95&x=0&y=0#>
- 29) Kristen B, Kenneth S (2012), How to measure the benefits of BIM-A case study approach, Automation in Construction 24 (2012), pp.149-159.
- 30) Lee J-K, Lee J, Jeong Y-S, Sheward H, Sanguinetti P, Abdelmohsen S, Eastman C M (2012), Development of Space Database for Automated Building Design Review Systems, Automation in Construction, 24 (2012), pp.203-212.
- 31) Saif H, Craig Z (2003), Just down the road a piece: The development of topological knowledge of building layouts, ENVIRONMENT AND BEHAVIOR, Vol. 35 No. 1, DOI: 10.1177/0013916502238868, pp.132-160.
- 32) Shu-Hui J, Shih-Ping H, Hui-Ping T (2013), Applications of Building Information Modeling (BIM) in Knowledge Sharing and Management in Construction, World Academy of Science, Engineering and Technology International Journal of Civil, Structural, Construction and Architectural Engineering, 7 (11), pp.486-490.
- 33) Solibri, Solibri Model Checker® (SMC), an IFC-based rule checking BIM tool, <http://www.solibri.com>
- 34) Standards Australia (2009), Committee ME-064, Access for people with disabilities-Design for access and mobility, Australian Standard.
- 35) T. Liebich, Y. Adachi, J. Forester, J. Hyvarinen, K. Karstila, J. Wix (2006), Industry Foundation Classes IFC2x3, International Alliance for Interoperability.
- 36) TAN, H, CARRILLO, P, ANUMBA, C J(2012), Case study of knowledge management implementation in a medium-sized construction sector firm, Journal of Management in Engineering, 28 (3), pp.338-347.
- 37) The building regulations 2000, Secretary of State.
- 38) U.S Courts Design Guide, Judicial Conference of the United States.
- 39) Ya-Hong L, Yu-Shen L, Ge G, Xiao-Guang H, Cheng-Yuan L, Ming G (2013), The IFC-based path planning for 3D indoor spaces, Advanced Engineering Informatics 27 (2013) 189-205.
- 40) YoungZhi L, Jumphin L, SeongKi L, JinWon C (2009), Design with space syntax analysis based on building information model: Towards an interactive application of building information model in early design process, In Joining Languages, Cultures and Visions: Proceedings of the 13th International CAAD Futures Conference, pp.501-514.
- 41) YunGil L, ChangHoon P (2011), A study on the development of automatic generation system of navigation graph for dynamic user simulation using artificial intelligence for game based on BIM, Journal of the Architectural Institute of Korea Planning & Design, 27 (12), pp.63-70.