An Approach to the BIM-enabled Assessment of Building Circulation using Quantitative Data and its Weight

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ABSTRACT

This paper describes an approach to the assessment of building circulation by using quantitative data and applying its weight. People have considered building circulation because of various requirements as well as design decision making. This is why assessment of building circulation plays an important role before construction stage. BIM (Building Information Modeling) and its applications enable us to examine various kinds of building design review tasks using rich building information. Within a scope of building circulation review, this paper is mainly dealing with qualitative issues. In fact, they have been ignored due to their implicit definitions such as 'comfortable circulation' in circulation requirements. We described how it could be expressed quantitatively in a certain approach. Quantitative data and its weight are key aspects to convert implicit descriptions into explicit regulations. As an example, there are several useful quantitative data derived from BIM model such as metric distance, spatial depth, number of turns, window area, spatial volume and so on. This paper aims to study an approach to quantification of circulation data for objective evaluation. We also suggested a framework using weighted data of circulation properties such as 1) vertical distance and horizontal distance 2) the number of spaces to pass 3) the number of turn 4) space of windows area, etc.

Keywords
Building Circulation; Quantitative data; Weight; Qualitative design; Assessment

1 Introduction

Analysis of building circulation issue is one of the crucial factors in the building design process [1]. Not only for making a decision but also for achieving requirements, assessment of building circulation plays an important role before construction [2,3]. They are officially defined in building design guides, building codes, Fire Codes, etc. in quantitative or qualitative descriptions [2,4,10]. For instance,

(1) "Attorney/witness rooms must be directly accessible from public circulation." [US Court Design Guide, by Department of Justice, US] [4]
(2) "Judge's chambers are accessed from restricted circulation with convenient access to the courtrooms." [US Court Design Guide, by Department of Justice, US]

Conventionally, design review tasks have been performed manually based on predefined rules by multiple domain-specific experts. They have been time consuming, expensive and arbitrary [5,6]. Now supported by BIM (Building Information Modeling) technologies, various kinds of BIM application have been developed for spatial analysis as well as circulation analysis using quantitative data from BIM models [3,5,7,8]. Especially, regarding issues of building circulation, Hyunsoo Lee et al. (2014) [5,16] introduced meaningful numeric data more than metric distance and defined them as NDBC (Numeric Data of Building Circulation). In addition, they demonstrated that NDBC applied on actual remodelling project. For further research of BIM-enabled assessment of building circulation, we have developed the former research [5,16] focusing on quantitative approach. In this research, we consider qualitative circulation issues such as 'convenient access to a specific space'. For this, we classify quantitative data applicable to quantitative or qualitative factors. And we introduce one of a framework using weighted quantitative data for supporting circulation assessment.

2 Background and Objective

This paper aims to describe BIM-enabled quantitative approach using circulation numeric data derived from BIM models. Figure 1 shows an overview of this paper as an extension of the former research (Hyunsoo Lee et al., 2014) [5,16].

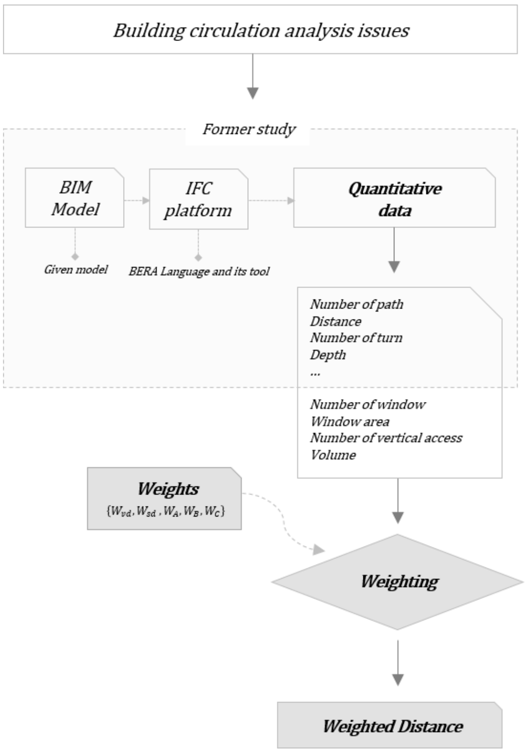


Figure 1. Overview of the paper and research scope

We have focused on quantitative circulation-related data such as metric distance, the number of turn and spatial depth as well as space of windows area and spatial volume. Based on the circulation property data, weighting function is proposed to quantify comprehensive quality of building circulation. Quantitative data and the weighting framework are the main issues to define a new concept 'WD (Weighted Distance)'. WD is the returned value from suggested weighting framework. It is compared relatively with several alternatives. WD can be expected to work as one of the indicators which support assessment of building circulation and design decision making.

3 BIM-enabled Circulation Representation and Analysis

Building circulation is regarded as one of the significant subjects because of its diverse purposes including metric distance, security and performance issues. In design stage, designing a short, simple, visible and comfortable path is desirable in general. And it is necessary to be checked to fulfil related regulations and guides for the building use [2,3,9]. Analysing circulation path has depended on experts' knowledge or empirical skills, however, it is fairly subjective and arbitrary. For computing area, most of qualitative issues regarding building circulation have been ignored. Circulation representation is primary issue for analysis of building circulation. Graph-based representation is one of approaches with computational methods [2,11]. In BIM-based application domain, Jin-kook Lee et al. (2010) defined UCN (Universal Circulation Network) as a computational method to measure and visualize walking distance on top of building models. They applied spatial data such as geometry and topological relations and introduced implementation principles with the concept of buffer distance, concave point, etc [2]. As a computer programming languages, the Building Environment Rule and Analysis (BERA) Language (Jin-kook Lee, 2011) is a BIM domain-specific programming language for design review and analysis. It is dealing with the spatial program and building circulation analysis [5,7,12]. BERA language and its applications enable users to define rules in intuitive and flexible way and to evaluate them on their given building models. In the case of circulation analysis using BERA (Hyunsoo Lee et al., 2014), NDBC (Numeric Data of Building Circulation) was designed as meaningful quantitative data of building circulation. They utilized BERA language and its program in order to derive the circulation properties data [5,16]. The research demonstrated that quantitative data from BIM models could be useful to apply for building circulation analysis in quantitative way. With the same approach, this paper discusses quantitative analysis method based on circulation-related data. Furthermore, weighting function is introduced so as to handle qualitative circulation issues such as 'simple and comfortable path'.

4 Quantitative Dataset from the Circulation Path and Property

In this part, we describe returned properties of circulation path which are derived from a BIM model. The returned properties are factors influencing building circulation from a quantitative or qualitative perspective. In order to extract circulation-related properties, BERA language is used in the same way as the former study [12]. Figure 2 shows an example of returned data properties by using BERA program code.

Among the returned properties data, we focus on 'distance', 'number of turn', 'spatial depth', 'window area' and 'volume'. They are classified into three types; 1) distance of circulation, 2) complexity of circulation, 3) amenity of circulation. Each property has an impact on building circulation with variety of weights in practice.

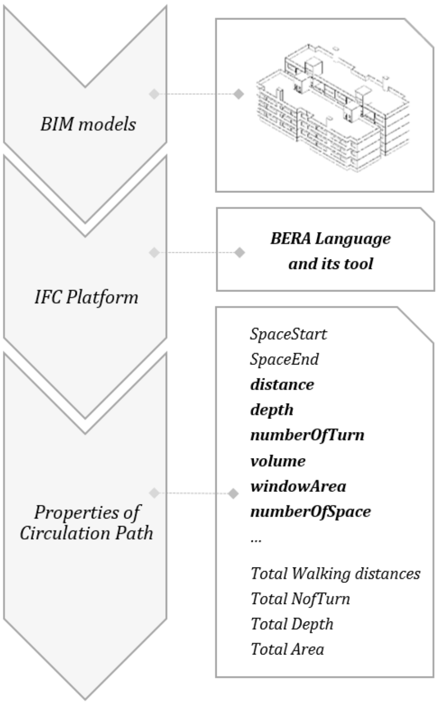


Figure 2. Example dataset from a circulation path example, retrieved by BERA language and its tool

4.1 Metric Distance of Circulation

When considering circulation path in the building, metric distance is one of the fundamental factors. It consists of two types of distance. One is a horizontal distance which comes from paths on the same floor. The other is a vertical distance which is generated by vertical access objects such as stairs, ramp, elevator, etc. connecting multiple stories [2]. Therefore, metric distance could be described as follows.

$$MD = VD + HD \tag{1}$$

Where MD (Metric distance) is a total length of circulation, VD is a vertical distance and HD is a horizontal distance.

If there are two different paths with same distance and one contains a vertical distance while the other does not, path having vertical distance may require more strength to reach a destination compared to the path without vertical moving. For this reason, whether vertical paths exist or not is reflected on our weighting framework. Although there exist differences in efficiency among vertical access objects (stairs, elevator, ramp, etc.) in reality, here is based upon a premise that all of vertical access objects have same weight.

4.2 Complexity of Circulation

A pedestrian path can be described in spatial relations with a sequence of spaces [2,9,14]. For instance, walking distance between the start and end point could be measured through 'depth' based on the number of turns in the matter of human perception [13]. In this paper, the number of turns and the number of passing spaces, namely, spatial depth are categorized into a same factor influencing complexity of and they are assigned different weight.

4.2.1 Number of Turn

Number of turn generated from BIM models is a property data of circulation path. It defines how many turns the path has while moving from a start space to a target space. As shown in figure 3 which is noted as a taxicab geometry, one can easily guess both path X and Y have same walking distance. However, path X with seven turns gives more burden to pedestrians than the other with just one turn. It is interpreted to have less connectivity between A and B [14]. Here, number of turn is grounds for a factor of circulation assessment.

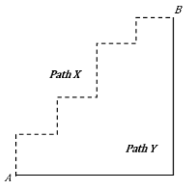


Figure 3. An example of taxicab geometry regarding number of turns [15]

4.2.2 Spatial Depth

Spatial depth represents the number of spaces traversed between the start and the target space based on well-known concept of spatial syntax. It can be counted mathematically [14,16]. The number of intermediate spaces with their conditions is involved to determine the circulation types [9]. Jin-Kook Lee et al. (2014) attempted to structure intermediate spaces taking account of the number of intermediate spaces and their topological relationships. That was conducted with BIM-based approach for building circulation representation focusing on the conceptual modelling.

4.3 Amenity of Circulation

Qualitative factors regarding pedestrian paths such as comfortability and efficiency have been estimated by empirical, inductive and intuitive reasons in many cases

[1,17,18]. Such human behavioural matters are difficult to be interpreted quantitatively. There have not been acknowledged analysis reports about qualitative issues of building circulation using quantitative approach [5]. In this paper, we include window area and spatial volume as qualitative factors for circulation review. In addition, the numeric data of circulation-related properties are given appropriate weights in a weighting process described in the next section.

4.3.1 Window Area

In general, several benefits of windows and daylight have been reported focusing on various psychological and physiological effects for humans [19,20]. They are also underlined for indoor circulation planning as useful tools for way-finding [21]. Based on the literature, an average of window area can be considered as one of the factors to affect quality of indoor paths.

4.3.2 Volume

It is generally accepted that a large-scale space with a high ceiling and a wide floor enables pedestrians to walk more easily with less interference rather than a small-scale space. Furthermore, relations between height and length or width of a space are related to spatial quality that has an impact on human cognition. For a simple example, people often feel comfortable or uncomfortable in proportion to the length of a space [1,17]. In this paper, we treat volume of passing interspaces as a qualitative factor apart from the other conditions as in case of how well-proportioned spaces are.

5 Definition of Weighted Distance

5.1 Overview

The purpose of this paper is to suggest an analysis-oriented circulation formula using circulation data and its weight. Circulation paths can be assessed in a quantitative way by comparing results from the weighting formula. Figure 4 shows an operation concept of the weighting framework. In this paper, we deal with individual paths in instance level in contrast with the former research that handled groups of paths in building level. In the former study, average values such like an average of total walking spaces from all paths were used for circulation analysis.

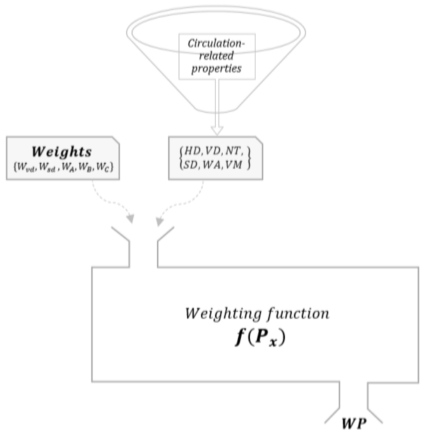


Figure 4. Concept of the weighting framework

5.2 Weighting Framework

5.2.1 Weighting on Factors of Circulation within Each Types

We define weighted distance (WD) through calculating properties value of distance, complexity and amenity with each weight. The weighted distance value can be one of the indicators for deciding which path is most appropriate. Calculations employed to derive a method of grading circulation is as follows.

$$\mathrm{P} = \{P_i | 1 \leq \mathrm{i} \leq \mathrm{n}; \mathrm{n} = \text{number of paths}\}$$

P denotes a set of building circulation paths and P_x is one of the paths included in the set P.

$$A_x = HD_x + W_{vd} \cdot VD_x \tag{2}$$

$$B_x = NT_x + W_{sd} \cdot SD_x \tag{3}$$

$$C_x = WA_x + VM_x \tag{4}$$

A_x is a weighted length of circulation. It is defined as a sum of horizontal distance (HD) and weighted vertical distance (VD) having weight as much W_{vd}. B_x is a weighted result regarding complexity of a path and it represents a sum of number of turn (NT) and spatial depth (SD). SD has a relative weight as much W_{sd} compared to NT. W_{vd} and W_{sd} assigned to VD and SD are the variables determined by performers. The values of weights would be given in accordance with each design intention. However, C_x regarding amenity of a path is a sum of two sorts of factors, which is the window area per unit area (WA) and the spatial volume (VM). Because WA and VM act on a path independently, they do not need to be weighted.

5.2.2 Converting Weighted Factors into Proportion

Based on the weighted factors A_x, B_x, C_x , we calculate them in proportion. They are $S_{A,x}, S_{B,x}, S_{C,x}$($S_{A,x}$; distance, $S_{B,x}$; complexity, $S_{C,x}$; amenity) and describes how much they account for within each type. As represented in proportion, it is able to calculate among them including addition, subtraction and multiplication regardless of units such as mm, m^2, m^3 and n (the number).

Where $S_{A,x}$ connotes proportion of weighted length in regard of P_x to total weighted length of circulation

$$S_{A,x} = \frac{A_x}{\sum A_i} = \frac{HD_x + W_{vd} \cdot VD_x}{\sum_{i=1}^{n} HD_i + W_{vd} \cdot VD_i} \tag{5}$$

Using the same approach, $S_{B,x}$ and $S_{C,x}$ are defined as following below.

$$S_{B,x} = \frac{B_x}{\sum B_i} = \frac{NT_x + W_{sd} \cdot SD_x}{\sum_{i=1}^{n} NT_x + W_{sd} \cdot SD_x} \tag{6}$$

$$S_{C,x} = \frac{WA_x}{\sum_{i=1}^{n} WA_i} + \frac{VM_x}{\sum_{i=1}^{n} VM_i} \tag{7}$$

5.2.3 Weighting on Factor Types

Where W_i (i = A, B, C) connotes percentages of weight within three types of factors on P_x ($S_{A,x}, S_{B,x}, S_{C,x}$). $W_A + W_B + W_C = 100$ (%) implies that the sum of all types is always 100(%). W_i is also variables determined by performers in accordance with design intentions, building types or design guides.

$$S_{A,x} \cdot \frac{W_A(\%)}{100} = \frac{HD_x + W_{vd} \cdot VD_x}{\sum_{i=1}^{n} HD_i + W_{vd} \cdot VD_i} \cdot \frac{W_A(\%)}{100} \tag{8}$$

$$S_{B,x} \cdot \frac{W_B(\%)}{100} = \frac{NT_x + W_{sd} \cdot SD_x}{\sum_{i=1}^{n} NT_x + W_{sd} \cdot SD_x} \cdot \frac{W_B(\%)}{100} \tag{9}$$

$$S_{C,x} \cdot \frac{W_C(\%)}{100} = \left\{\frac{WA_x}{\sum_{i=1}^{n} WA_i} + \frac{VM_x}{\sum_{i=1}^{n} VM_i}\right\} \times \frac{W_C(\%)}{100} \tag{10}$$

5.3 Definition

At last the weighting framework of circulation path can be drawn using the calculated formulas (8), (9) and (10) above.

$$WD_x = \left[\left(S_{A,x} \cdot \frac{W_A}{100}\right) + \left(S_{B,x} \cdot \frac{W_B}{100}\right) + \left\{2 - \left(S_{C,x} \cdot \frac{W_C}{100}\right)\right\}\right] \times 100 \tag{11}$$

WD is the weighted distance that denotes higher the result values more strengths a path requires. Considering relationships between S_i (i = A, B, C) and WD, S_A and S_B are positive elements while S_C is a negative element of WD. For this reason, (8) and (9) involved in S_A and S_B are added and (10) related with S_C is subtracted in the calculation process. In addition, we intend to add 2 in order to make WD ≥ 0 at all times and multiply the last formula by 100 to make the results into bigger number. The calculation would make it easier to compare the results than before.

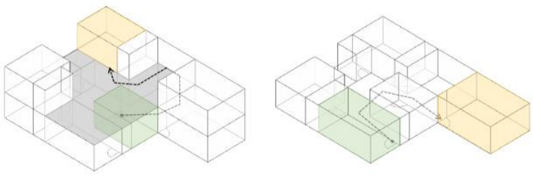
This framework aims at instances of paths for circulation analysis. Output values or WD values of varied instances can be measured to compare under the condition of same set of weights. Although it cannot be an absolute criterion, the quantitative-defined weighting framework is expected to be one of the methods that assist to assess which circulation instance is efficient among alternatives.

6 A Test Case of Circulation Analysis Using Weighting Framework

In this section, we make conceptual BIM models for the application of the proposed weighting framework to them. The test models compose a start and a target space and some of inter-spaces involved in specific circulation path as shown in the Figure 5. Table 1 represents the circulation properties and their numeric data of each path 1 (P_1) and path 2 (P_2). In this test case, weighting framework and returned data, namely WD are main issues. Thus the process to derive properties data using BERA code is not tackled in the paper.

6 factors of circulation properties data and 5 types of weights are needed as input data for applying the framework. With properties data of path instances distance, complexity and amenity factors are settled as shown in the table 1. Weights of distance, complexity and amenity are 70, 20, 10 in order and W_{vd}, W_{sd} are 2, 1 respectively. Under given conditions, calculation process and results are depicted in table 2. P_1 and P_2 get 242 and 228 marks each as the WD_i value. The figure of P_1 is higher than P_2 and it denotes that P_1 requires more

strength to reach a destination than P_2 despite same metric distance in total. In this way, weighted distance values makes feasible to review which building circulation is the most desirable among several alternatives within the specific evaluation factors.



P_1 P_2

Figure 5. Examples of conceptual models for application of circulation analysis using weighting framework

Table 1. An example of two path instances with circulation-related properties data and their weights

W (%)		**70**		**20**		**10**	
Propert-ies data		***Distance***		***Complexity***		***Amenity***	
		HD	***VD***	***NT***	***SD***	***WA***	***VM***
path	P_1	*10*	*10*	*5*	*3*	*10*	*50*
	P_2	*20*	*0*	*3*	*5*	*20*	*25*

Table 2. Application of weighting framework and calculated values of two path instances

Weight-ed Value	A_i	B_i	$S_{A,i}W_A$	$S_{B,i}W_B$	$S_{C,i}W_C$	WD_i
	$HD_i + 2VD_i$	$NT_i + SD_i$	$70\ S_{A,i}$	$20\ S_{B,i}$	$10\ S_{C,i}$	
P_1	*30*	*8*	*42*	*10*	*10*	*242*
P_2	*20*	*8*	*28*	*10*	*10*	*228*

7 Conclusion

In this paper, we attempted to describe a quantitative approach to the assessment of building circulation by using quantitative data and applying its weight. In the first place, we derived various circulation-related data from BIM models which have rich quantitative data by using BERA language and its tool. Among lots of circulation-related data, metric distance consisting of horizontal and vertical distance, number of turn, spatial depth, window area and volume are applied as factors for circulation analysis. They influence quality of circulation path but with different weights among them. Therefore, we categorized three types of factors of circulation and set up weights in two steps. The first phase is weighting within the factors in each category. The second one is weighting within three categories relatively in a range of 100(%). As a result value, WD (Weighted Distance) stands for a relative distance reflecting levels of weights of each factor. The more value of WD is interpreted the more strength is required to reach destination. In addition to the introduction of the weighting framework, we applied the framework to test models conceptually and compared design alternatives. The suggested method could not be an absolute standard for building circulation assessment. However, there might be a significance implying availability for circulation analysis and assessment in objective and quantitative way. This approach takes into consideration both quantitative and qualitative aspects of circulation. Based on the research, extended studies will be developed in view of lateral and vertical extensibility. As the former extensibility, it is available to elaborate weighting processes. It includes weighting among vertical access objects or among height, width and depth of interspaces instead of spatial volume. The latter extensibility can be practiced by adding the factors such as angle of turns.

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