Automated Mapping of User Activities onto Flexible Space in Space-Use Analysis

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Abstract: Flexible space is an adaptable space that is increasingly used in many types of buildings because it increases space efficiency and contributes to sustainable development. However, the construction industry lacks a formalized method for dealing with the changeable configuration of flexible space and mapping activities onto flexible space automatically, such that this mapping information can be used in the computation of space utilization in space-use analysis during project development. To address this problem, this study builds on the existing activity-space mapping method and expands it to include the following four phases: choosing spatial requirements, finding available spaces, computing the number of usable units of flexible space, and mapping the activity onto the available space. By incorporating this expansion into current space-use analysis, architects will be able to predict the space utilization of their designs more comprehensively and consequently plan the use of building space toward sustainable building development. **DOI: 10.1061/(ASCE)CO.1943-7862.0001328.** *© 2017 American Society of Civil Engineers.*

Author keywords: Flexible space; Space-use analysis; Space utilization; Space efficiency; Project planning and design.

Introduction

Improving the efficiency of building space by reducing underutilized space can contribute to global efforts to curtail carbon dioxide emissions and energy use, which are strongly correlated with a building's floor area (Dell'Isola 2002; Pérez-Lombard et al. 2008; Sharp 1996). Unfortunately, building-space utilization (a measure of space efficiency) is often reported to be less than 50% (Beyrouthy et al. 2009). Therefore, as a way to help architects increase utilization without harming the functionality of buildings, space-use analysis (SUA) automatically maps user activities onto available spaces given user and space information, and computes the utilization of each space based on workplace planning theory (Kim and Fischer 2014a, b; Kim et al. 2013). Using the results of SUA, architects can plan and monitor building-space efficiency quickly and consistently during project development so as to reduce improperly used space.

Flexible space is an adaptable space that can either be used as one single unit to support an activity for a large group of users, or be divided into multiple units to simultaneously accommodate different activities for several small groups of users—for example, a meeting room with movable partitions (Woodman 2011). It is different from open space, where building users change the layout of voluminous space according to their purposes and activities, because flexible space is not simply a space in which desks or chairs can be rearranged; rather, it relates to a change in the space configuration made possible by components such as movable walls and partitions (Brennan et al. 2002; Kim and de Dear 2012; Oldham and Brass 1979). Because flexible space brings economic benefits to a facility, such as more available net usable area, increased occupant density, and ease of reconfiguration (Hassanain 2006; Voordt 2004), it has become "the trend and driving force" in space planning (Bell and Joroff 2001; Greden 2005; Israelsson and Hansson 2009). For example, Schmidt III and Austin (2016) found that flexible space was present in 137 (47.2%) of 290 designs that they studied in relation to adaptable facilities. It is used in commercial, educational, and governmental buildings, among others, worldwide (Chan 2009; Greden 2005; Pearce et al. 1992; Pennanen 2004).

However, although flexible space has gained much popularity because of its potential for improving space efficiency and flexibility, current SUA theory is not tailored to it because it lacks an algorithm to deal with the following challenges: (1) flexible space can be divided into different numbers of usable units (i.e., a combination of adjacent subunits in one flexible space) according to the activity it accommodates; and (2) a single flexible space can simultaneously accommodate multiple activities in different usable units with different sizes. These challenges require architects to manually generate activity-space pairs for use in utilization calculation, which makes SUA inconsistent and time consuming (Kim and Fischer 2014b).

Moreover, because of such challenges, the relationships among flexible space, user, and user activity are more complex than when there are only nonflexible spaces. In an experiment, the authors divided 20 graduate students majoring in construction management into two groups (10 students per group) and asked them to generate activity-space pairs given five user activities and three spaces (three nonflexible spaces for Group 1 and two nonflexible spaces and one flexible space that could be divided into three subunits for Group 2). The results showed that, even with only one flexible space, Group 2 (20.7 min) took approximately 1.6 times longer than Group 1 (13.0 min) to complete the task. This clearly shows that the changeable configuration of flexible space makes mapping between activities and spaces much more complex. In this

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Note. This manuscript was submitted on August 30, 2016; approved on January 11, 2017; published online on March 22, 2017. Discussion period open until August 22, 2017; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

experiment, for example, Group 2 had to assess 45 possible activity-space pairs $[45 = 5 \times (C_3^1 + C_3^2 + C_3^3 + 2)]$ whereas Group 1 had to assess only 15 ($15 = 5 \times 3$). Without automated generation of activity-space pairs, it is difficult for architects to test different design options containing flexible space and make a sound decision about a design promptly and effectively.

Research Objectives and Scope

This study aims to formalize a mapping method that enables the generation of activity-space pairs without the human effort of speculating all possible relationships between activities and spaces, either flexible or nonflexible. The proposed method must conform to architects' knowledge about how to distinguish between flexible and nonflexible space use and how to divide a flexible space into an appropriate configuration to support an activity during mapping. The buildings considered in this study are educational and office types, for which user activities are primarily determined and tested in the current SUA theory (Kim and Fischer 2014b).

The authors first investigated 89 project cases involving flexible space in Hong Kong (18 projects from 3 regions) and in the United Kingdom (71 projects from 25 cities). These cases comprised 54 office projects, 27 educational projects, and 8 others. Of these cases, 82 (92.1%) adopted the same size of subunit for flexible space. Because the same type of movable component was installed in the flexible space in all 89 observed cases, it was assumed that the size of the subunits was the same for a certain flexible space and that the movable components in a certain flexible space were the same. The authors also observed that two types of flexible space exist: one in which the head subunit does not share a movable component with the tail subunit (Type 1; 96.6%) and one in which it does (Type 2; 3.4%) (Fig. 1). Therefore, this study considered both types of flexible space in developing the mapping method.

Methods

To formalize a mapping method for automatically generating the activity-space pairs of a flexible space, the authors first identified the characteristics of the user activities that are accommodated by it based on observations, literature reviews, and case studies. The authors then invited 12 architects to rate their agreement on each of the characteristics using a 5-point Likert scale. Second, the existing space-use type differentiators (SUTDs) (Kim and Fischer 2014a) were revised based on the identified characteristics. This task was critical to achieve the overall goal of this study, because there are already 288 different types of space use defined by user activity even without considering flexible space (Kim and Fischer 2014a). The number of space-use types increases significantly when flexible space is considered, and it is almost impossible to define how to process each space-use type individually in the mapping process. Therefore, by first identifying the SUTDs and defining a single type of space use as a combination of choices for each SUTD, mapping can be performed comprehensively and efficiently without missing any of the space-use types during SUA. Third, based on the previous two findings, the mapping method was developed and represented as a unified modeling language (UML) activity diagram. Finally, to validate the conformity and acceptability of the developed method, the authors asked 5 architects to generate the activity-space pairs given the user activities and spaces. The conformity was then measured by dividing the number of conforming pairs by the total number of pairs generated by the architects or the proposed method. Any cases in which the pairs did not conform were investigated in collaboration with the architects to determine whether the discrepancy could be attributed to the developed method. The architects were then asked to rate the proposed method.

Points of Departure

The authors reviewed the current body of knowledge related to space use and its prediction. The following three sections provide useful background for this study: prior research on SUA, activity-space mapping methods, and SUTDs.

Prior Research on Space-Use Analysis

Several attempts have been made to determine space use based on a building's design and to use the resulting information to iteratively update the design or to compare different design options.

Architectural programming (Cherry 1999) first introduced space utilization formulas for educational building projects to determine the spaces needed to accommodate user activities. Given predictable schedules and numbers of users, these formulas can calculate utilization as a measure of space efficiency during project development. However, because the quantitative relationship among space, user, and user activity is not captured in these formulas, predicting space utilization through this method can cause inconstancy across different architects. To address this inconsistency, workplace planning (Pennanen 2004) links user activities and spaces explicitly and

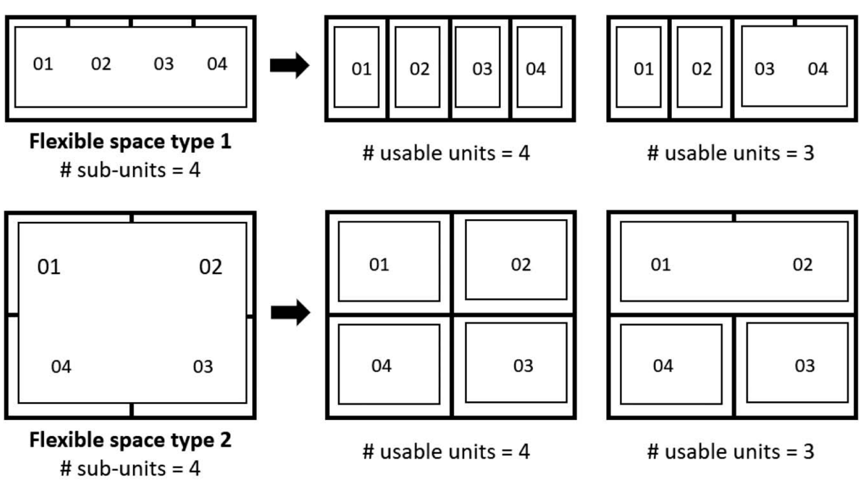

Fig. 1. Two types of flexible space considered in this study

provides a means of calculating utilization based on certain characteristics of user activities and spaces.

Because workplace planning does not offer an algorithm for mapping activities onto spaces at a sufficient level to support SUA automation, the mapping process in SUA remains slow and error prone. Based on previous research efforts, Kim et al. (2013) automated SUA so that it can automatically generate activity-space pairs and calculate space utilization given user profiles and spaces. Kim and Fischer (2014b) showed by experiment that automated SUA can significantly improve the consistency and the speed of prediction. However, because space configuration is defined in a fixed way (i.e., nonflexible space) in the current automated SUA, the utilization of flexible space must be calculated on an ad hoc basis.

In summary, the construction industry lacks a formalized method to help architects automatically generate the activity-space pairs of flexible spaces before predicting utilization during project development.

Activity-Space Mapping Methods

In addition to SUA, a user activity often needs to be mapped onto an appropriate space to move a virtual user from one space to another when simulating building usage (Goldstein et al. 2011; Shen et al. 2012; Tabak et al. 2010; Zimmermann 2007). For this purpose, some researchers (e.g., Zimmermann 2007; Shen et al. 2012) add the <Location > component in the definition of an activity and require architects to specify a space instance for each activity to be mapped. Because it is very difficult for architects to map activities onto space instances and track and update the mapping information whenever the design or user information changes, Tabak (2010) used the activity location choice algorithm, which enables architects to map activities onto space types (rather than space instances) and onto the space instance that is closest to the virtual user. Similarly, Goldstein et al. (2011) suggested the use of a function that maps activities stochastically onto space instances based on distance cost. Cha (2015) formalized the space-preference models for individual and group work activities, which can be used to map activities onto space instances, considering more factors than merely the distance, including noise, window access, and desk size. These theories provide the valuable background knowledge needed to achieve activity-space mapping in the user-simulation domain, but they cannot be used directly in this study because SUA does not deal with individual users and their activities as a time-varying factor. Moreover, none of these theories consider flexible space explicitly when mapping activities onto appropriate space instances. There is currently no established method for dividing a flexible space (with multiple movable components) into different numbers of usable units according to activity and then mapping activities onto these divided usable units simultaneously.

SUTDs

In SUA SUTDs distinguish between different space-use types. A user activity can be characterized as a combination of choices of SUTD (Kim and Fischer 2014a).The SUA checks the choices to determine their spatial requirements, find satisfactory spaces, and maps user activities onto those spaces (Kim and Fischer 2014b).

Currently, SUA considers six SUTDs: (1) atypical activities versus typical activities; (2) important users versus regular users; (3) situations in which space preferences and the minimum requirements are the same versus those in which they are different; (4) situations in which an activity requires a designated space versus those in which it does not; (5) situations in which an activity requires an whole room versus those in which it requires only part of a room; and (6) situations in which an activity requires a specific type of space versus those in which only the features of the required space are specified. These SUTDs do not encompass the use of flexible space—that is, whether the activity allows it. This necessitates the extension of the current SUTDs for the development of an activity-flexible space mapping method.

Extended SUTDs

Because the characteristics of user activities regarding space use can serve as precursors to the SUTDs, the authors first extended the five characteristics identified by Kim and Fischer (2014a) to include a new characteristic derived from literature reviews and case observations. Based on the new characteristic, the differentiator SUTD 7, which distinguishes between flexible and nonflexible space use, was newly defined. The six characteristics are as follows:

- C1: some atypical activities are not conducted regularly but require appropriate space when they are conducted (e.g., a graduation ceremony); these activities are predictable and are also considered during project development, but they are not considered in utilization prediction because they do not occur on a daily basis; this characteristic derives SUTD 1;
- C2: some activities impose stringent spatial rather than minimum requirements—for example, a department head will expect a larger private office than the minimum requirements for his or her work (e.g., a workstation in a shared office); this characteristic derives SUTDs 2 and 3;
- C3: a designated space (e.g., a professor's private office) is needed for some activities; it cannot be used by other users even when vacant; this characteristic derives SUTD 4;
- C4: an whole unit of space is needed for some activities, whereas a single piece of equipment is enough for others—for example, a lecture needs an entire lecture hall and other activities cannot occur in this space during the lecture even if some seats are empty; in contrast, the regular work of a staff requires only one workstation in a shared office; this characteristic derives SUTD 5;
- C5: for some activities, a space is specified by name (e.g., an auditorium), whereas for others certain conditions are specified (e.g., a meeting room with a table); this characteristic derives SUTD 6; and
- C6: some activities do not require a designated space but do require a space that is not flexible—for example, detention rooms in police stations, which cannot be flexible because detainees may break a movable wall and escape (a safety issue); also, some laboratory work requires a strict streamlined process that begins when one enters and ends when one leaves and which the changeable configuration of flexible space might disrupt; this characteristic derives SUTD 7.

To confirm the characteristics, 12 architects from Hong Kong and Mainland China were surveyed. Their average experience in the construction industry was 5 years, and their average experience in SUA was 4.3 years. In this survey, the architects were asked to rate their level of agreement on a 5-point Likert scale (1 = strongly disagree; 2 = disagree; 3 = neither agree nor disagree; 4 = agree; 5 = strongly agree) for these characteristics. They were also asked to name other characteristics that are necessary in SUA. In the survey results, all characteristics received average scores of more than 4.0, suggesting that they were all accepted by the architects. Although there are some characteristics of flexible space that architects might

Table 1. Seven SUTDs in Space-Use Analysis

SUTD	Distinguished space-use types
1	Typical activities
	Atypical activities
2	Important users
	Regular users
3	Constraints = preferences
	Constraints ≠ preferences
4	Requiring designated spaces
	Not requiring designated spaces
5	Requiring piece of equipment
	Requiring entire unit of space
6	Requiring specifically named space
	Requiring space with certain features
7	Allowing use of flexible space
	Not allowing use of flexible space

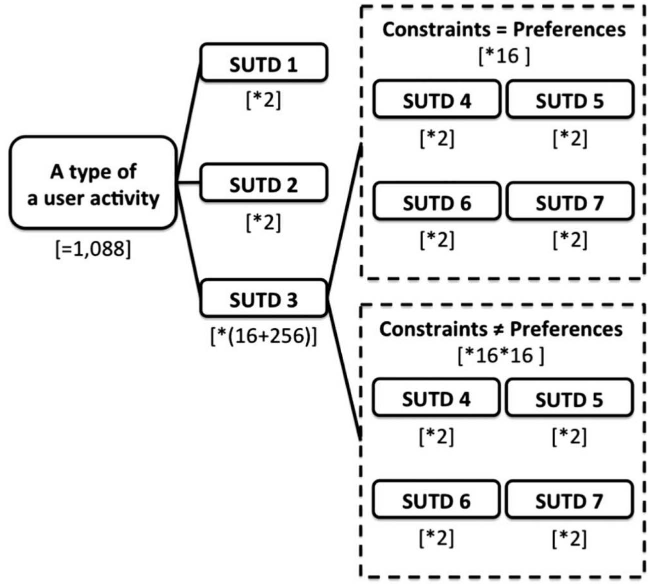

Fig. 2. Differentiation of user activities in terms of space use and its calculation

need to consider when deciding on its installation (e.g., sound insulation, visual privacy, and whether the furniture can be rearranged for an activity), these must be dealt with as spatial requirements in SUA and thus cannot be distinguished by any SUA steps. Table 1 summarizes the extended SUTDs, which distinguish space-use types that need to be considered by automated SUA.

The space-use type of a certain user activity is represented as a set of choices for each SUTD. These SUTDs consider three perspectives (i.e., activity, user, and spatial requirements) to support the proposed method for deciding on the space-use type. In addition, when the constraints of an activity are different from the preferences for it (SUTD 3), SUTDs 4–7 need to be determined separately for both constraints and preferences. Therefore, the number of possible combination of SUTDs 4–7 is 16 ($= 2^4$) for the situation where the preferences are identical to the constraints; it is 256 ($= 2^4 \times 2^4$) for the situation where the preferences are different from the constraints. Hence, when the preferences are identical to the constraints (one case of SUTD 3), the number of possible space-use types is 64 [$= 2(\text{SUTD}\,1) \times 2(\text{SUTD}\,2) \times 16$ (possible combination of SUTDs 4–7)]. When the preferences are different from the constraints (the other case of SUTD 3), the number of possible space-use types is 1,024 [$= 2(\text{SUTD}\,1) \times 2(\text{SUTD}\,2) \times 256$ (possible combination of SUTDs 4–7)]. Consequently, the proposed mapping method must deal with 1,088 ($= 64 + 1{,}024$) types of space use (Fig. 2).

Significantly, adding just one more SUTD to the existing list (Kim and Fischer 2014a) multiplied the number of possible space-use types by roughly 4 compared with the original. This clearly shows the importance of defining and keeping track of the SUTD list in SUA.

Method for Mapping User Activities onto Spaces

This section describes a novel method for mapping user activities onto both flexible and nonflexible spaces and generating activity-space pairs given the user profiles and the space program. Each activity must go through the following four phases to be mapped onto spaces in SUA: (1) choosing spatial requirements; (2) finding available spaces; (3) computing the number of usable units for flexible space; and (4) mapping the activity onto the available spaces. In the first phase, the computer selects the appropriate requirements (either constraints or preferences) for proceeding to the subsequent phases. In the second phase, the computer searches for the nondesignated spaces that meet the selected spatial requirements (i.e., "available spaces"). In the third phase, the computer calculates the number of usable units if the available space is flexible. In the fourth phase, the computer maps the activity onto the available spaces to generate activity-space pairs, which are the basis for computing utilization in automated SUA (Kim et al. 2013). Although this method uses brute-force search, its use is not limited by computational complexity because it is a typical polynomial time problem (P-problem), where computations in every phase are bounded by a polynomial expression (Sipser 2006). Also, the SUTDs defined in the previous section are used in the description of the mapping method (Table 2).

Fig. 3 is an overview of the proposed method as a UML activity diagram. This method is an extension of the activity-space pairing algorithm of Kim and Fischer (2014b) in that the second phase is modified to classify different types of available space for use in the next steps; the third phase is added to deal with the changing space configurations of flexible space according to different activities; and the fourth phase is modified to assign spaces to activities based on the available space type, as classified in the second phase.

Phase 1: Choose Spatial Requirements

Once an activity has been selected for treatment, the computer reads the user type of the activity (SUTD 2) and chooses the corresponding spatial requirements (SUTD 3) for the next phases. The method takes the following situations into account (Kim and Fischer 2014b):

- IF the constraints are different from the preferences, AND the users are regular ones, THEN the computer selects the constraints as the spatial requirements for application in the next phases;
- IF the constraints are different from the preferences, AND the users are important ones, THEN the computer selects the preferences as the spatial requirements for application in the next phases; and
- IF the constraints are the same as the preferences, THEN the computer selects the constraints as the spatial requirements for application in the next phases.

Table 2. Phases of the Proposed Mapping Method

Phase	Function	Input	Output	Related SUTDs
1	Choose spatial requirements for an activity	User activity information	Choice of spatial requirements (constraints or preferences)	2; 3
2	Find available space from space program and classify available space into different types	User activity information; space program; choice of spatial requirements	Identified available space and its type	5; 6; 7
3	Compute number of usable units if available space is flexible space	User activity information; space program; flexible space type	Number of usable units for flexible space	3
4	Assign designated space to activity (if necessary) and map activity onto available spaces	User activity information; space program; classified available space type; number of usable units	List of activity-space pairs	4; 5

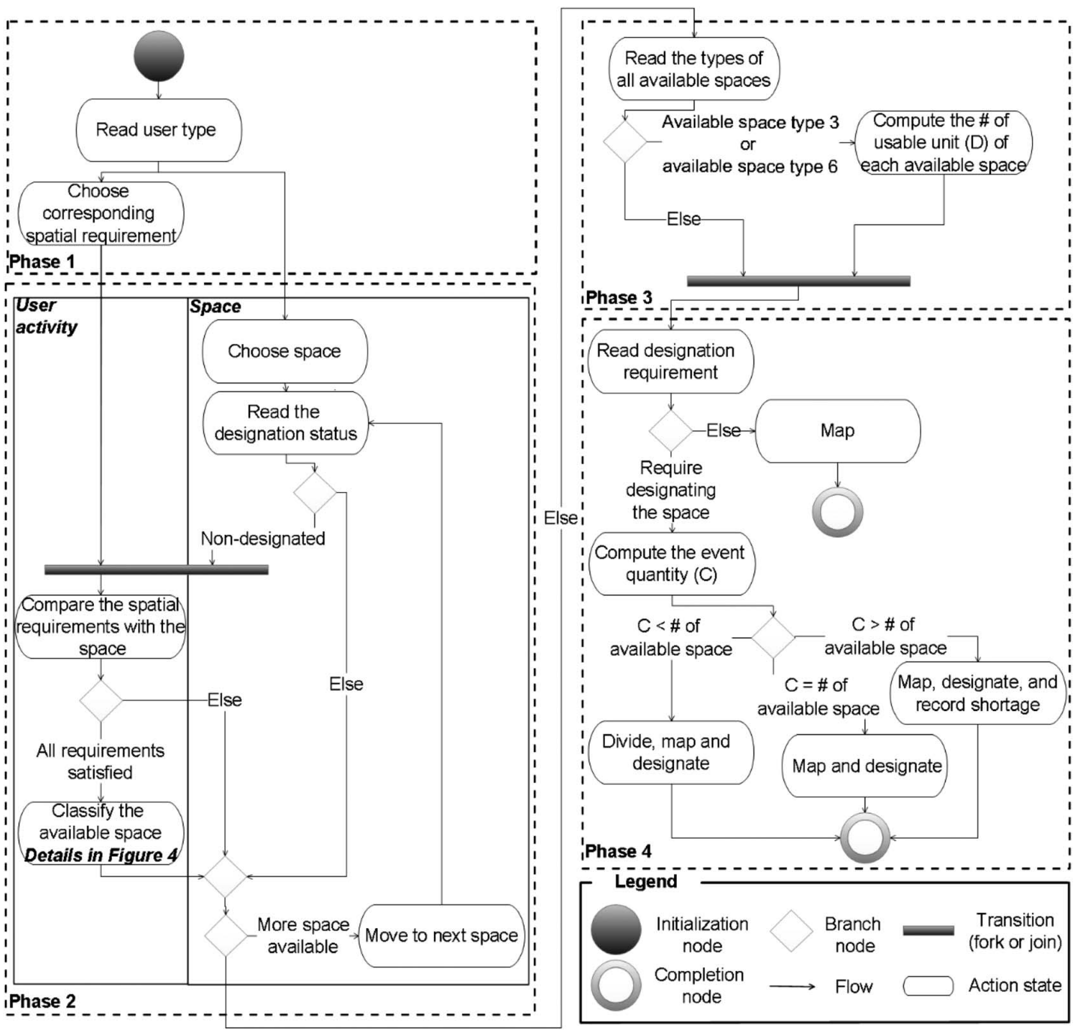

Fig. 3. Formalized method for mapping user activities onto spaces in space-use analysis

Phase 2: Find Available Spaces

Once the spatial requirements to be applied have been determined, the computer reads the values of the requirements and finds all non-designated spaces that satisfy the activity's requirements, such as space type, space name (SUTD 6), number of spaces, and minimum area of the spaces. These "available spaces" are classified into six types according to space-use type as differentiated by SUTDs 5 and 7 and according to whether or not the space is flexible for use in the next phases (Fig. 4). When all spaces have been checked and flagged with a certain available space type, the computer proceeds with the next phase of the method:

- IF an activity requires an whole unit of space (SUTD 5) and does not allow the use of flexible space (SUTD 7), THEN the computer finds all nondesignated spaces that meet the spatial requirements AND flags them as "available space type 1";
- IF an activity requires a whole unit of space (SUTD 5) and allows the use of flexible space (SUTD 7), THEN the computer finds all non-designated spaces that meet the spatial requirements

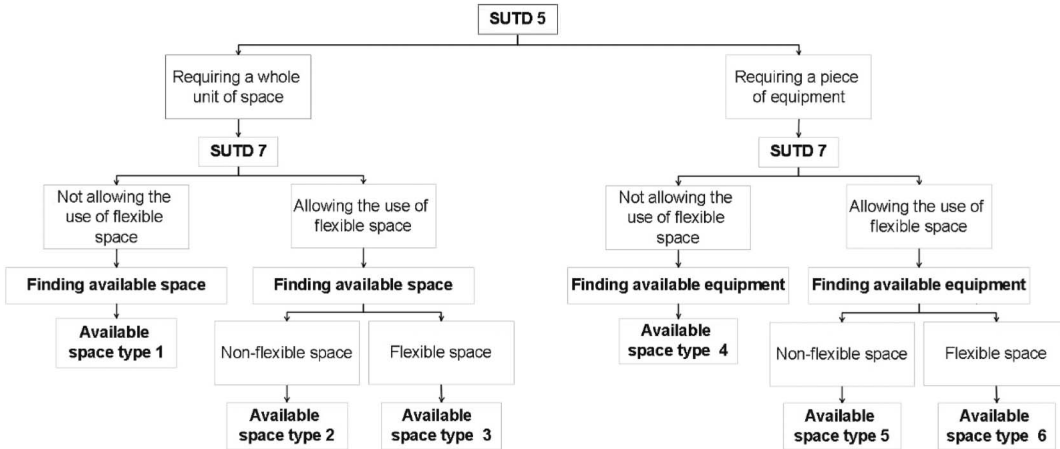

Fig. 4. Classification of the available space types in the "find available spaces" phase

and flags them as "available space type 2" for non-flexible spaces and "available space type 3" for flexible spaces;

- IF an activity requires a piece of equipment (SUTD 5) and does not allow the use of flexible space (SUTD 7), THEN the computer finds all non-designated pieces of equipment that meets the spatial requirements and flags them as "available space type 4"; and
- IF an activity requires a piece of equipment (SUTD 5) and allows the use of flexible space (SUTD 7), THEN the computer finds all non-designated pieces of equipment that meet the spatial requirements and flags them as "available space type 5" for non-flexible spaces and "available space type 6" for flexible spaces.

Phase 3: Compute the Number of Usable Units for Flexible Space

One objective of this study was to formalize a method of dividing a flexible space into an appropriate configuration to support an activity during the activity-space mapping process. To address this objective with consideration of both types of flexible space (i.e., whether the head subunit of the space shares a movable component with the tail subunit), an algorithm was developed for determining how many usable units a flexible space can have to support a certain activity. Specifically, when an available space is a flexible one (i.e., Type 3 or 6, the computer first extracts the number of subunits of the flexible space (T) from the space program. When the computer has determined the minimum number of subunits that can together satisfy the spatial requirements of the user activity (N), it calculates the number of usable units (D) that can be formed in the flexible space considering the different flexible space types according to the permutations and combinations theorem (Kinney 2009). Based on this theorem, when the order of the subunits is of no importance, all the possibilities (i.e., usable units) can be counted without repetition and omission using the combinations method. Therefore, the computer proceeds with the following algorithm steps:

- Step 1: let T be the number of subunits of the flexible space;
- Step 2: let N be the number of subunits combined into a usable unit (initially $N = 1$, which means that one subunit alone can accommodate the activity); and
- Step 3: if ($N \times$ area of the sub-unit) $\geq$ (the minimum area required by the activity), then divide the available space into D usable units per the following calculation and *stop*; otherwise, go to Step 4:
  a. $D = (T/N)$ (when $N = 1$ or $N = T$);
  b. $D = [(T - N + 1)!/(T - N)!] = T - N + 1$ (when $1 < N < T$ and the head unit does not share a movable component with the tail unit—i.e., flexible space type 1); and
  c. $D = T$ (when $1 < N < T$ and the head unit shares a movable component with the tail unit—i.e., flexible space type 2).
- Step 4: if ($N \times$ area of the subunit) < (the minimum area required by the activity), then increase N by 1 ($N = N + 1$) and go to Step 3.

Phase 4: Map the Activity onto the Available Spaces

The computer reads SUTDs 4 and 5 and maps the activity onto the available spaces (usable units in the case of flexible space) to generate activity-space pairs. Once a pair is generated, the available space type determined in Phase 2 must be recorded as a property of the pair for use in the SUA utilization calculation. If the activity does not require a designated space (SUTD 4), the computer deals with the following situations in mapping the activity onto the available spaces:

- IF an activity requires a whole unit of space (SUTD 5), THEN the computer maps the activity onto the available spaces (available space types 1, 2, and 3); and
- IF an activity requires a piece of equipment (SUTD 5), THEN the computer maps the activity onto both the available pieces of equipment and the spaces that contain the equipment (available space types 4, 5, and 6);

If the activity requires a designated space (SUTD 4), the computer deals with the following situations in mapping the activity onto the available spaces:

- IF an activity requires a whole unit of space (SUTD 5), AND the number of available spaces (available space types 1 and 2) is larger than the event quantity (i.e., the number of users divided by the group size of the activity), THEN the computer divides the available spaces into two groups (i.e., one group whose number equals the event quantity and another group whose number equals the remaining amount), maps the activity onto the former group of spaces and flags them as "designated," and leaves the latter group for accommodating other activities;
- IF an activity requires a whole unit of space (SUTD 5), AND the number of available spaces (available space types 1 and 2) is equal to the event quantity, THEN the computer maps the activity onto the available spaces and flags them as "designated"; and

- IF an activity requires a whole unit of space (SUTD 5), AND the number of available spaces (available space types 1 and 2) is smaller than the event quantity, THEN the computer maps the activity onto the available spaces, flags them as "designated," and records the number of lacking spaces (i.e., the event quantity less the number of available spaces) to inform architects about the shortage.

For an activity that requires a designated space (SUTD 4) and a piece of equipment (SUTD 5), the processes are similar to those just described. The only difference is that they must be mapped both to the available pieces of equipment and to the spaces to which the equipment belongs (available space types 4 and 5).

Validation

This section describes how the authors validated the developed method for the automatic generation of activity-space pairs encompassing both flexible and nonflexible spaces for use in SUA. Taking the objectives of this study into account, the authors defined and measured the following two metrics to represent the power of the method—conformity and acceptability—which have been applied in many computer modeling studies (Akinci et al. 2002; Kim and Fischer 2014b; Clayton et al. 1998). Here conformity is the extent to which the activity-space pairs generated conform to the pairs generated by architects. Acceptability refers to the extent to which experienced architects agree with the method's principle. The method's generality is also discussed.

Conformity of the Mapping Method

To validate the conformity of the proposed method, an experiment was conducted in which 5 architects (average 11.2 years of experience) were asked to generate activity-space pairs given 20 user activities (representing 10 space-use types) and 12 spaces (identified from two office and two educational building cases) (Table 3; see Supplemental Data A for more details). The two office cases were collected from Shenzhen, China. One educational building case, Cygnaeus High School in Finland, was developed based on Pennanen's work (2004). The other educational building case was developed by observing the use of flexible space in an integrated teaching (AIT) building at the Chinese University of Hong Kong. Because of confidentiality constraints, the names of the two office projects cannot be disclosed.

Before the experiment, the authors briefly introduced the purpose of this study and its procedures to the architects. Once the architects had conducted the mapping process manually, given the descriptions of the user activities and spaces, conformity was measured by dividing the number of conforming activity-space pairs by the number of activity-space pairs generated by the architects or the proposed method (the larger of the two numbers was taken for the calculation).

Table 3. Summary of Cases for the Validation Study

Case	Building type	Number of activities	Number of spaces	Flexible space included[a]
1	Office	5	3	Type 1 with two subunits
2	Office	5	3	Type 1 with two subunits
3	Educational	5	3	Type 2 with four subunits
4	Educational	5	3	Type 1 with six subunits

[a]Type 1 represents the situation where the head subunit does not share a movable component with the tail subunit; Type 2 represents the situation where the head subunit does share a movable component with the tail subunit (Fig. 1).

The results showed that the architects took approximately 1.5 h (minimum 1.3 h; maximum 1.7 h; standard deviation 0.14 h) to map the activities onto the spaces. The conformity of the proposed method was 98%, with only two mismatches between the architects and the method identified (Table 4; see Supplemental Data B). When asked about the reasons for the nonconforming pairs, Architect 1 said he thought that one activity could be held only in a meeting room, whereas the activity did not in fact require any specific space type. Architect 3 misinterpreted one activity's visual privacy requirement and so mapped it onto an inappropriate space. After discussion with the authors, the architects confirmed that the mismatches occurred because of their mistakes in interpretation.

Acceptability of the Mapping Method

The acceptability of the proposed method was also measured to confirm that such a high conformity was not random. After the mapping experiment described in the previous section, the authors explained the proposed method to the architects and asked them to rate its acceptability from their professional prospective on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). All of the participating architects agreed that this method was acceptable, with an average score of 4.8 (a 5 from 4 participants; a 4 from 1 participant). Comments from the architects are listed as follows:

- "The automated SUA based on this mapping method would be a good way to communicate with clients, with direct and specific data to show clients the impact of changes in any use of flexible space in the building planning."
- "The proposed mapping method can highlight the improvement in space efficiency by the use of flexible space, which is also beneficial to clients in saving money on electricity and maintenance fees."
- "The automated SUA incorporating the mapping method would save much time in analyzing the [space-use] of flexible space, which would allow us (architects) to focus more on creative things."
- "It would be better if more [user importance levels] were available in the method. For example, in some government authorities, users are classified into more than two levels, which would need different quality of space for their work."
- "It would be better if the activity-space pairs and the utilization prediction results could be shown within the 3D drawing of flexible space [e.g., building information model (BIM)] in the later design phase. This could offer a good visualization that directly shows the clients about the space-use information during building planning and design."

Generality of the Mapping Method

The developed mapping method demonstrated its generality by successfully generating activity-space pairs from four different cases (two educational and two office buildings) covering both types of flexible space as well as different numbers of subunits. The generated pairs represent all six of the "available-space types," meaning that all of the available-space types defined in this paper were tested and validated in the experiment. In addition, the activities identified and tested in the experiment represented 10 space-use types, achieved by choosing different sets of SUTDs. To determine the acceptability of the method, five architects were invited to offer their opinions after becoming familiar with the

Table 4. Conformity Test Result of the Proposed Mapping Method

Participating architect	Experience (years)	Number of pairs generated by architects	Number of pairs generated by proposed method	Number of conforming pairs	Conformity
1	8	20	21	20	0.952
2	7	21	21	21	1.000
3	14	21	21	20	0.952
4	16	21	21	21	1.000
5	11	21	21	21	1.000
Average	11.2	—	—	—	0.981

requirements of the mapping task (i.e., by manual mapping, which took them approximately 1.5 h) and learning how the proposed method automates this task.

Conclusions

Current utilization prediction methods cannot deal with building designs that include flexible space because they do not take flexible space into account when finding available spaces for certain activities and mapping those activities onto available spaces. Current theories lack an algorithm to deal with the challenges posed by the ability of flexible space to change its space configurations according to the characteristics of an activity and simultaneously accommodate multiple activities. These challenges require architects to generate activity-space pairs manually for use in utilization calculation, which makes SUA inconsistent and time consuming.

This paper described a novel method for mapping user activities onto both flexible and nonflexible space and generating activity-space pairs automatically. The method consists of the following four phases, through which each activity specified in user profiles must proceed: (1) choosing spatial requirements; (2) finding available spaces; (3) computing the number of usable units when the available space is flexible space; and (4) mapping the activity onto the available spaces. This method is novel because current theories, including workplace planning, SUA, and user simulation, do not distinguish between the use of flexible and nonflexible spaces or offer a method that computes the number of usable units of flexible space with consideration of its changing configurations and the activities it accommodates.

The conformity of the mapping method was validated by the finding that 98% of the activity-space pairs that it generates conform to the pairs generated by expert architects. The two nonconforming pairs occurred because of the architects' mistakes in interpretation, which further supports the automation of the mapping process. The acceptability of the method from the perspective of experienced architects was also measured; all agreed that it is acceptable, with an average Likert score of 4.8 out of 5.0.

Incorporation of the proposed mapping method into an automated SUA will allow architects to use SUA without ad hoc adjustments when their building designs include flexible space. Thus, equipped with a more efficient and accurate SUA tool, they will be able to check the space efficiency of their designs immediately and consistently and improve on them by reducing underutilized spaces without harming building functionality. To realize the potential of this work, the findings of this study must be embedded in an SUA tool consisting of two main components: the automated generation of activity-space pairs and the automated calculation of space utilization based on them. For this reason, the existing ontologies in SUA (Kim and Fischer 2014a) must be extended to capture the necessary properties of flexible space and then feed them to both the mapping and the utilization calculation process in SUA. In addition, to enable seamless communication between SUA and building information modeling (BIM) as a representation of the design, a process model must be developed to regulate how space and other physical elements in BIM are to be processed and translated into the corresponding elements in the mapping method. The mapping method can also be extended to deal with flexible spaces containing different sizes of subunit and different types of movable component to promote the more widespread use of flexible space in support of sustainable design and construction.

This study and the extensions just mentioned are expected to contribute to performance-based building theory by providing a means of predicting the utilization (a performance requirement) of both flexible and nonflexible spaces during project development.

Supplemental Data

Appendixes S1 and S2, including Tables S1 and S2 and Figs. S1–S6 contain details of the cases and mapping results in the validation study, and are available online in the ASCE Library (www.ascelibrary.org).

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