Ontology-Based Representations of User Activity and Flexible Space Information: Towards an Automated Space-Use Analysis in Buildings

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Received 25 November 2018; Revised 28 January 2019; Accepted 18 February 2019; Published 1 April 2019

Academic Editor: Mohammad R. Hosseini

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Space-use analysis offers quantitative and reliable references to support architects’ decision-making regarding the planning and design of flexible spaces. To allow for automated space-use analyses of such flexible space, it is imperative to create activity and space ontologies that offer systematic and explicit forms representing user activities and the spaces in which they occur. Therefore, this study extends the current research on activity ontologies in order to capture flexible space-use patterns for user activities and develops a new space ontology by abstracting the information related to both flexible and nonflexible spaces. In addition, this study formalizes a framework for an automated space-use analysis implementation process that predicts and updates flexible space utilization by integrating user activity with flexible space. This work contributes to performance-based building design by providing a common, computer-interpretable vocabulary for representing user activities and flexible spaces and a framework for an automated space-use analysis implementation process that informs space utilization (i.e., a space efficiency measurement).

1. Introduction

In recent years, improving building space efficiency has become a primary concern in building design. It not only relates to economic considerations but also to a building’s thermal load and energy consumption level, both of which are associated with a building’s carbon footprint and overall level of sustainability. Therefore, it is critical for architects to predict space utilization during the planning phase with reliable measurements of space efficiency [1]. Architects prefer design options that use minimal space, while still satisfying the building’s functionality and allowing for various occupant activities. Flexible space is a popular choice in space planning because it promotes space efficiency, due to the ease of reconfiguration made possible by movable components. Such spaces offer a greater net usable area and increased occupant density that contribute to a building’s economy [2, 3]. However, conventional space utilization assessment methods such as workplace planning [4] and automated space-use analysis (SUA) [5] cannot yet deal with predicting the utilization of flexible space. In addition, the traditional evaluation methodology has not fully utilized integrated information models such as building information models (BIMs) to analyze space usability. As a result, architects must make such predictions on an ad hoc basis, which can be both time-consuming and inconsistent.

1.1. Motivating Cases. The Cygnaeus High School project in Finland [4] was required to reduce the school’s net spatial area from 6,926 m² to 6,508 m², without losing any function or activities space. The planner pointed out that the auditorium (270 m² in area) was only used for educational purposes approximately 2% of the time. Because the
activities it accommodated required a small time-load but large amount of space, it was suggested that the auditorium be removed and turned into three adjacent flexible classrooms (80 m² each). These flexible classrooms could then be combined into one large space by uniting the three subunits, but only for the activities previously supported by the auditorium. The Vodafone office in England [6] is a similar case. In order to improve space planning efficiency and create a multifunctional environment in a minimum amount of space, architects planned for two flexible meeting rooms that could be combined into a bigger space to support events with larger user groups. The Kentish Town Health Centre [6], a health clinic located in England, is the third example. Architects must closely engage with their customers if they are to plan spaces that meet the client’s changing needs. In the beginning, the centre was planned with eight meeting rooms, based on the client’s practical needs. As the flexible space offers a larger net usable area, five of these meeting rooms were designed to be flexible, with three subunits. However, after occupying the buildings, it was determined that some of these spaces were underutilized, which implies that manual SUA interpretation for flexible space can be error-prone. Therefore, the client required renovation so as to transform them into two counseling spaces [7, 8].

These examples illustrate that the current SUA is not yet tailored to accommodate flexible space. Architects must manually interpret on an ad hoc basis, due to the different types of flexible space-uses and activities, as well as the many properties of flexible space itself. Taking the Cygnaeus High School project as an example, if a teaching activity required a 160 m² classroom and the classroom was defined as a super-type space, given the current representations of activity and space, the spaces identified would be several nonflexible classrooms and one large flexible classroom (i.e., the 240 m² space created by combining the three subunits). Existing knowledge of SUA does not permit (1) an appropriate set of properties to be formulated for the spatial requirements of user activities, which could be applied to distinguish between flexible and nonflexible space-use or (2) a definition of a sufficient set of flexible space properties, since the properties of such a changeable space are not yet available.

1.2. Research Objectives and Scope. To fill this research gap and enable an automated SUA for flexible space, the objectives of this study are (1) to develop user activity and space ontologies that function as a common vocabulary and enable seamless performance of automated SUAs for both flexible and nonflexible space-use and (2) to extend the SUA framework [5] defining an automated SUA implementation process in flexible space, enabling architects to quickly and consistently predict its utilization based on activity and space information and update the prediction when changes occur. This will support architects’ decision-making regarding their designs. The present study focuses primarily on office and institutional buildings. User activities were determined and tested primarily by existing ontologies and SUA methods [5, 7].

2. Literature Review

The authors reviewed the concept of ontology and representations of user activity and space, which provided useful background knowledge for this study. In addition, the authors examined a number of current SUA studies, upon which this research builds.

2.1. The Concept of Ontology and Its Related Studies Using BIM Techniques. Ontology has been described as “an explicit and formal specification of a conceptualization” [9]. Theoretically, an ontology represents a shared understanding of a domain interest and provides a formalized and machine-readable model of the domain [10]. Numerous applications in information management and integration systems have been developed using ontologies that artificial intelligence applies when capturing knowledge and creating knowledge-based models [11]. Recently, many business and scientific domains have adopted ontologies for sharing, reusing, and processing domain knowledge [11]. The construction industry has also developed domain ontologies such as Industry Foundation Classes (IFC) to improve knowledge management and workflow by establishing a comprehensive data exchange set.

Recently, various studies have been conducted on representing domain knowledge in BIM models using ontologies. Jeong [12] demonstrated building information management using BIM to represent the connectivity of non-BIM data and convert those data into an ontology. Zhang et al. [11] researched a construction safety ontology for organizing, storing, and reusing construction safety knowledge. That study demonstrated the interaction between a safety ontology and BIM. In addition, researchers have employed a building energy ontology using BIM and a Modelica language for building thermal analysis. Other researchers developed the ModelicaBIM library for BIM-based energy analysis and a framework enabling BIM models to be automatically translated into building energy models [13–15].

2.2. Knowledge about Representing User Activity and Space. Text formats (i.e., natural language) are frequently used in the documentation of user activities and space details. Although such representations are convenient for professionals seeking to communicate with one another, they are not compatible with computer modeling and automatic recognition due to their inherent ambiguity [7, 16]. In contrast, ontology is a systematic and explicit method for professionals to use when representing expertise that can be stored and analyzed later through computer modelling [7, 17].

Many studies have modeled construction activities via ontologies, in areas such as automated planning [18, 19], cost estimation [20], field instruction generation [21], and the analyses of time-space conflicts [17]. Darwiche et al. [19] specified the difference between activity and action classes through ontology formalization. Other researchers added spatial requirements to represent construction activities
Many research efforts have created user simulations for building activity representation, such as modelling emergency evacuation plans [22], assessing building performance [23], and evaluating environmental effects [24]. However, these studies have focused more on individual users than the activity concept (i.e., the precursor of the user concept). Therefore, the direct use of these SUA methods cannot fully represent user activity. To do so in space utilization prediction [4, 7, 25, 26], the current research utilized activity properties (i.e., frequency, duration, user, activity load, sound insulation, and visual privacy). One study distinguished designated space-use from non-designated space-use, specifying that the subclasses of spatial requirements allowed for flexible space SUA [7]. However, an unstructured combination of existing knowledge cannot form an appropriate set of properties that distinguishes flexible from nonflexible space-use in SUA. Therefore, the current SUA process for flexible space still requires architects to conduct ad hoc analyses, especially when user activities change.

Many researchers have developed space representations that incorporate the dynamic nature of flexible spaces. One developed dynamic layout could be used in planning for temporary facilities on construction sites [27]. Another represented a construction site using a spreadsheet with grid units, in which space area was calculated by combining the occupied components [28]. Yet, others utilized sets of space properties such as space type, area, and number, as well as equipment number and area, to enhance space management practices [4, 26]. The changeable space representations in these earlier studies provided a useful background for the current research and inspired the idea of dividing flexible space into appropriate configurations to accommodate different activities.

2.3. Flexible Space in Current Space-Use Analysis Studies. Although studies related to SUA have provided useful theories such as architectural programming [29] and postoccupancy evaluation [30], these have been subject to a significant limitation. Utilization cannot be quickly and consistently tracked or updated when information about the users’ activities or spaces changes. To deal with this problem, in [4], the workplace planning theory was introduced, which can be applied during project development. The workplace planning theory determines space utilization on the basis of user activities that are manually linked to a set of building spaces. To automate the mapping between these user activities and spaces and the utilization analysis of the project information, Kim et al. [5] developed an automated SUA based on [4], which provides basic knowledge for computer-aided SUA. However, because a changeable configuration of space is not available in the current automated SUA, SUA for flexible spaces remains an ad hoc process.

To deal with this challenge, Chen and Kim [31] identified the characteristics of user activities by considering the space-use of flexible spaces and used these characteristics as precursors to define seven space-use type differentiators (SUTDs). The goal was to distinguish between flexible and nonflexible space-use. A mapping method was also developed based on these findings that maps user activities onto both flexible and nonflexible spaces and generates activity-space pairs with an algorithm in order to determine the number of usable units of a flexible space that are needed to support a certain activity. However, although this advance is available in automated SUA, activity and space ontologies for capturing flexible space-use and representing flexible space have not yet been defined and employed in automated SUA. Therefore, architects still cannot systematically and explicitly capture activity and flexible space information. As a result, automated SUA implementation for flexible space has still not been developed, and thus the utilization calculation of flexible space cannot be automated, nor the potential of automated SUA in the flexible space domain realized.

3. Methodology

To develop the activity and space ontologies, this study followed the ontology development guidelines proposed by Noy and McGuinness [32] and then defined the two ontologies based on a literature review, case studies, and interviews with architects. Classes and properties were defined to create an activity ontology that captures both flexible and nonflexible space-uses and a space ontology that represents both flexible and nonflexible spaces. These ontologies were further elaborated upon by defining the facets of each property (i.e., cardinality, value type, and range of value types). The validation tasks were already available in earlier research [7, 17, 20, 33] and conducted to measure real-world achievements. The validation method was adopted to test the formality and comprehensiveness of the two ontologies presented here, by representing user activities and spaces in four different cases to determine whether they accommodated seven SUTDs defined in earlier work [31]. Six architects were invited to participate in this test. Since this study developed a prototype of an automated SUA in which the activity and space ontologies function as data input templates, their reproducibility was tested in an automated SUA application.

To enable implementation of the proposed ontologies, this study defined a framework for an automated SUA that would deal with flexible space based on the abovementioned seven SUTDs [31], certain ontological relationships, the developed mapping method [31], and concepts related to utilization prediction [4, 5, 29]. A charrette test was then set up to test the framework’s effectiveness via utilization prediction in two separate cases (i.e., an office building and an institutional building). The test was accomplished by comparing the innovative method (i.e., performing an SUA on trials using the prototype) to the conventional process (i.e., manually performing an SUA on the trials) [34]. Each case was predicted by three architects in three trials, including one initial prediction and two updates. The architects performed the three trials by following both processes. As in Clayton et al.’s work [34], comparison of the two processes for each case was based on the time spent and consistency of the results of the utilization predictions. The
flowchart in Figure 1 shows the flow of research methodology and clarifies the relationship of each step.

4. Results and Validation

The activity ontology was extended from a previous model developed by Kim and Fischer, which developed the user activity representation as <User>, <Action>, and <Spatial requirement> [7]. The ontology for representing building space (i.e., flexible and nonflexible spaces) was newly developed in this study to provide an explicit representation of both flexible and nonflexible spaces for SUA. In addition, the implementation process for an automated SUA was also clarified with a prototype system capable of predicting the utilization of flexible space.

4.1. Ontologies Representing User Activities and Spaces. In this research, a new <Space requirement> class in the user activity ontology was defined by adding properties that derived the spatial requirements for an activity. These could then be used to distinguish flexible from nonflexible space uses. The properties’ address issues such as sound insulation, visual privacy, furniture rearrangement, and whether flexible space are allowable. <User activity> was further classified into <Typical activity> and <Atypical activity>. The ratio in <Typical activity> represents the proportion of a user group that will participate in the activity, whereas the frequency of <Typical activity> indicates the number of occurrences of a user participating in the activity per day [7].

The <User>, the driver of the activity is further classified as <Regular user> (i.e., one who needs a space that satisfies only the minimum spatial requirements of the user activity, called a constraint) or <Important user> (i.e., one who needs a space that must satisfy the spatial requirements for better performance of the user activity, called a preference). The <Action> is a short description of what the user will do in the space. The extended area, <Spatial requirement>, indicates what a user activity requires in order to occupy the space. The spatial requirement is further classified into <Whole room use requirement> (i.e., what a user activity requires to occupy the whole room) and <Equipment use requirement> (i.e., what a user activity requires to occupy only a part of the room, such as a cubicle within an office).

The newly developed space ontology includes properties that describe various features and attributes of a space, as well as restrictions on those properties (i.e., cardinalities, value types, and ranges). In this study, the space ontology abstracted the nonflexible and flexible space descriptions and associated them with their use. To be specific, space was further classified into <Flexible space>, which can quickly be changed via movable components (e.g., walls and partitions), and <Nonflexible space>, which cannot [31]. In addition, a space has one or both of the following space uses: <Whole room use>, which supports a user activity that requires an entire room, and <Equipment use>, which supports a user activity that requires only a part of a room (e.g., a cubicle in an office).

In this research, a survey of 12 architects from Hong Kong and mainland China, with an average of five years of experience in the construction industry and just over four years in SUA, was conducted to select the newly identified properties (i.e., properties in the user activity ontology related to sound insulation, visual privacy, furniture rearrangement, and whether flexible space is allowable). The architects were asked to rate their level of agreement with these properties on a 5-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree). All properties received average scores greater than 4.0, suggesting that all properties were accepted and should be dealt with as spatial requirements in the SUA. Note that the consideration of flexible space in the SUA multiplies the number of possible space-use types by roughly four (i.e., increasing the total from 288 to 1,088), as discussed by [31].

As shown in Figure 2, all properties (including the cardinalities, value types, and ranges of value types) of the user activities, users, and action classes followed the definitions provided in [7], which will not be detailed in this research. There were 13 common properties used in the space ontology and spatial requirement class of user activity ontology as summarized in Table 1.

(i) Space Type. In the user activity ontology, this property represents the specific type of space that an activity occupies (e.g., a small classroom). According to [7, 35], this differs from the space instance (e.g., classroom Y4302) in the design model. In the space ontology, this function to identify a space class (e.g., a small classroom). A space type should be unique to distinguish it from others [36].

(ii) Space Super-Type. In both the user activity and space ontologies, this property represents the super-type of a space type (e.g., a classroom) that includes one or more space types.

(iii) Designation. In the user activity ontology, this property indicates whether or not an activity requires a designated space. In the space ontology, this property characterizes whether the space is already designated for a user activity. If the space is designated for an activity, it is not available for other activities.

(iv) Sound Insulation Degree. In the user activity ontology, this property characterizes the degree of sound insulation required by a user activity, based on the user’s needs and wants. For this property, the authors interviewed 12 experienced architects. From their opinions, it was clear that sound insulation of 55 dB or more is more expensive than regular insulation. Therefore, only activities sensitive to noise and that require a high degree of conversational privacy should require spaces designed above this threshold, such as meeting rooms in law chambers, hedge fund companies, and banks. Sound insulation of 50 to 54 dB is usually sufficient for
**Figure 1:** Flowchart of the research methodology.

**Figure 2:** Ontologies representing user activities and space in space-use analysis.

| Property | Cardinality | Value type | Range |
|----------|-------------|------------|-------|
| Requirements name | [1:1] | String |   |
| Space type | [0:∗] | Instance | Space type |
| Space super-type | [0:∗] | Instance | Space super type |
| Designation | [1:1] | Boolean | True, false |
| Sound insulation degree | [1:1] | Interval | ≤39 dB, 40–44 dB, 45–49 dB, 50–54 dB, ≥55 dB |
| Allowing flexible space | [1:1] | Boolean | True, false |
teaching activities and speeches, to prevent these kinds of activities from affecting those occurring in adjacent spaces. Sound insulation of 45 to 49 dB is required for activities that do not require conversational privacy. In such environment, voices can be heard but not understood in adjacent spaces. Sound insulation of 40 to 44 dB is sufficient for activities such as normal staff training, but sound insulation of 39 dB or less is inadequate for activities such as self-study. Based on the experts’ feedback, “Guidance on sound insulation and noise reduction for buildings” [37] and “Acoustic design of schools: Performance standards” [38], five scales of sound insulation were applied in this research, as shown in Table 1. In the space ontology, this property signifies the degree of sound insulation used in a space (e.g., 44 dB).

(v) Space Number. In the user activity ontology, this property represents the amount of space that a user activity requires. In the space ontology, this property signifies the amount of a particular space type.

(vi) Visual Privacy. In the user activity ontology, this property denotes whether an activity requires a space that can guarantee visual privacy. In the space ontology, this property indicates whether or not a space can guarantee visual privacy.

(vii) Furniture Rearrangement. In the user activity ontology, this property represents whether an activity requires a space that provides rearrangeable furniture. In the space ontology, this property denotes whether a space provides rearrangeable furniture.

(viii) Other Space Features. In the user activity ontology, this property signifies the features of a space required for an activity, such as multimedia facilities. In the space ontology, this property represents the features of a space.

(ix) Equipment Name. In the user activity ontology, this property represents the specific name of the equipment required for an activity, such as workstation or cubicle. In the space ontology, this property signifies the specific name of the equipment that a space provides.

(x) Equipment Number. In the user activity ontology, this property indicates the amount of equipment that a user activity requires. In the space ontology, this property shows the amount of equipment that a space provides.

(xi) Equipment Visual Privacy. In the user activity ontology, this property indicates whether an activity requires a piece of equipment (e.g., a cubicle with partitions installed) to guarantee visual privacy. In the space ontology, this property specifies whether the equipment can guarantee visual privacy.

(xii) Equipment Rearrangement. In the user activity ontology, this property represents whether an activity requires a piece of rearrangeable equipment. In the space ontology, this property signifies whether the equipment provided can be rearranged.

(xiii) Other Equipment Features. In the user activity ontology, this property denotes the features the activity requires of a piece of equipment. In the space ontology, this property denotes the features of a piece of equipment.

The other properties related to the spatial requirements of the user activity ontology are defined as follows. The properties and facets of the <Spatial requirement>, <Whole room use requirement>, and <Equipment use requirement> classes are summarized in Table 1.

(i) Requirement Name. This functions as an identification of the requirement class (e.g., Constraint 1 or Preference 1). An user activity’s requirement name should be unique to distinguish it from others [36].

(ii) Flexible Space Allowed. This property indicates whether a user activity is allowed in a flexible space. When the value is “true,” the activity can be accommodated by a flexible space, and when the value is “false,” it cannot.

(iii) Space Minimum Area. This property signifies the minimum space area that an activity requires. When the space’s minimum area is not specified in the spatial requirement (i.e., <Whole room use requirement>), the automated SUA will use the values
for space criteria (under the <Action> class) and
group size (under the <Action> class) to au-
tomatically estimate the minimum space area needed
(i.e., space criteria * group size).

(iv) Equipment Minimum Area. This property signifies
the minimum area required for a piece of equipment
needed for an activity. When the equipment’s min-
imum area is not specified in the spatial requirement
(i.e., <Equipment use requirement>), the automated
SUA will use the value of the space criteria (under the
<Action> class) and group size (under the <Action>
class) to automatically estimate the minimum area
necessary (i.e., space criteria * group size).

The other properties in the space ontology are defined as
follows. The properties and facets of the <Space>, <Whole
room use>, and <Equipment use> classes are summarized in
Table 2.

(i) Open hour: This property indicates the number of
hours per day that a space is available for use.
(ii) Subunit number: This property represents the
number of subunits that form a flexible space. In a
nonflexible space, only one subunit is available.
(iii) Subunit area. This property indicates the area of
each subunit of a space.
(iv) Inaccessible user: This property denotes user
groups that are not allowed to access the space.
(v) Connected HT (i.e., connected head and tail
subunits): This property represents a type of
flexible space in which the head subunit either
shares a movable component with the tail subunit
(i.e., value: true) or does not (i.e., value: false). Both
types were described by [31].

(vi) Whole room use name: This functions as an
identification of the whole room use class
(e.g., S1W). It should be unique to distinguish it
from others [36].

(vii) Equipment use name: This functions as an iden-
tification of the equipment use class (e.g., S1E). It
should be unique to distinguish it from others [36].

(viii) Equipment area: This property denotes the area
taken up by a piece of equipment.

4.2. Implementation Process of the Automated Space-Use
Analysis for Flexible Space. This implementation process
enables the (1) automatic generation of activity-space
pairs by mapping user activities onto appropriate
spaces and (2) automatic calculation of utilization based
on the pairs available and certain operation prediction
theories [4, 5, 29]. This framework was developed based
on (1) SUA concepts [4, 5, 29], (2) seven SUTDs that
distinguish space-use types for SUA [31], (3) a method
for mapping user activities onto both flexible and nonflexible
spaces [31], and (4) activity and space ontologies that
capture the necessary flexible and nonflexible space-uses
of user activity and the information necessary for both

flexible and nonflexible spaces, respectively. A prototype
system (see Figure 3 represented as a unified modelling
language activity diagram) was created and used in the
validation of this research, in order to examine the re-
producibility of the developed ontologies and test the
effectiveness of the automated SUA. The prototype system
was developed in power builder, an integrated application
development environment. The implementation process
for the automated SUA had three steps (Figure 4): “en-
tering project data (input),” “mapping user activities onto
space (analysis),” and “computing utilization (output).”

Step 1. Entering project data (input)
The architect enters the data based on the user profiles
and space information. The two ontologies described in this
research function as data input templates. The architect can
enter the necessary data based on the ontologies, even
without background knowledge of them. The computer
gathers and stores these data and feeds them into Steps 2 and
3 (i.e., mapping and computing utilization) after the ar-
chitect finishes entering the data.

Step 2. Mapping user activities onto spaces (analysis)
When the input (i.e., activity and space information) is
available, the computer uses it to analyze (i.e., map user

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**Table 2: Properties and Facets of the <Space>, <Whole room use>,
and <Equipment use> classes.**

| Property                        | Cardinality | Value type | Range       |
|---------------------------------|-------------|------------|-------------|
| **Properties in <Space> class** |             |            |             |
| Space type                      | [1:1]       | Instance   | Space type  |
| Space super type                | [1:1]       | Instance   | Space super type |
| Open hour                       | [1:1]       | Float      | Positive    |
| Space number                    | [1:1]       | Integer    | Positive    |
| Subunit number                  | [1:1]       | Integer    | Positive    |
| Subunit area                    | [1:1]       | Float      | Positive    |
| Sound insulation degree         | [1:1]       | Integer    | Positive    |
| Designation                     | [1:1]       | Boolean    | True, false |
| Inaccessible user               | [0:*]       | Instance   | User        |
| **Properties in Flexible space**|             |            |             |
| Connected HT                    | [1:1]       | Boolean    | True, false |
| Whole room use name             | [1:1]       | String     | 
| Visual privacy                  | [1:1]       | Boolean    | True, false |
| Furniture rearrangement         | [1:1]       | Boolean    | True, false |
| Other space features            | [0:*]       | Instance   | Feature     |
| **Properties in <Equipment use> class** |     |            |             |
| Equipment use name              | [1:1]       | String     | 
| Equipment name                  | [1:1]       | String     | 
| Equipment number                | [1:1]       | Integer    | Positive    |
| Equipment area                  | [1:1]       | Float      | Positive    |
| Equipment visual privacy        | [1:1]       | Boolean    | True, false |
| Equipment rearrangement         | [1:1]       | Boolean    | True, false |
| Equipment other features        | [0:*]       | Instance   | Feature     |
Click “import user profile” bottom to enter the interface;
2. Click “choose” bottom to select the file to be imported;
3. Click “save” bottom to store the imported activity data in the prototype system.

1. Click “import space” bottom to enter the interface;
2. Click “choose” bottom to select the file to be imported;
3. Click “save” bottom to store the imported space data in the prototype system.

1. Click “analyzing” bottom to enter the interface;
2. Click “mapping” bottom to process the mapping and generate the activity-space pairs;
3. Click “counting” bottom to calculate the utilization;
4. Click “mapping save” bottom to export the mapping results*
4. Click “utilization save” bottom to export the utilization results*;
* The formats of the exported file include: excel, PDF, text, etc.

Figure 3: Prototype system for an automated SUA. (a) Import activity information. (b) Import space information. (c) Mapping and computing utilization.
Figure 4: Implementation process for the automated SUA.
activities onto appropriate flexible or nonflexible spaces) and generate activity-space pairs. This activity-space mapping proceeds without human interpretation and includes choosing spatial requirements, finding appropriate space, computing usable units for flexible space, and mapping activities onto the available space [31].

Step 3. Computing utilization (output)
When the input from Step 1 and activity-space pairs from Step 2 are available, the computer can prepare its output (i.e., calculate the utilization based on utilization prediction theories [4, 5, 29]). The process for this step is as follows:

Step 3.1. Processing analysis related to user activity

\[
\text{event quantity} = \frac{(\text{the number of users of an activity} \times \text{the ratio of an activity})}{\text{the group size of the action of an activity}}
\]

Step 3.1.1. Compute the load demanded by an activity, which indicates the number of hours that an activity requires from its mapped spaces. The event quantity must be calculated before computing the load demanded. The event quantity refers to the number of user groups for a given user activity. For activities that require a designated space, the computer will read the value of the event quantity from Step 2 because it is calculated before the activity is mapped onto its designated spaces. For activities that do not require a designated space, the computer will calculate the event quantity. The formulas used are as follows [4]:

\[
\text{load demanded by an activity} = \text{event quantity of an activity} \times \text{the frequency of an activity} \times \text{the duration of an activity}.
\]

Step 3.1.2. Sum and record the number of mapped spaces (or equipment) for an activity.

Step 3.1.3. Evenly distribute the load demanded for an activity to each of its mapped spaces (or equipment) by dividing “the load demanded for an activity” by “the number of mapped spaces (or pieces of equipment).”

Step 3.1.4. Move to the next activity and repeat Phases 1.1 to 1.4 if more activities are available.

Step 3.2. Processing analysis related to spaces and predictions:

Step 3.2.1. Sum and record the total space load: for nonflexible spaces, the total space load is computed by summing the loads of all mapped activities, including activities mapped onto the space and those mapped onto pieces of equipment that belong to that space. For flexible spaces, the total load is computed by separately considering each subunit. That is, the total load of each subunit of a flexible space is computed by summing the loads of all mapped activities, including activities mapped onto the subunit and those mapped onto pieces of equipment belonging to that subunit.

Step 3.2.2. Compute the utilization of space: for nonflexible space, the utilization is computed by dividing the “total space load” by the “open hours.” For flexible space, utilization also separately considers each subunit (i.e., the utilization of each subunit of a flexible space is computed by dividing the “total load of each subunit of a flexible space” by the “open hours”).

Step 3.2.3. Move to the next space and repeat Phases 2.1 and 2.2 if more spaces are available.

Step 3.3. Export and save the utilization results (including the generated activity-space pairs).

4.3. Validation. The activity and space ontologies defined in this study were tested on four cases to determine their formality and comprehensiveness [7, 17, 20]. In addition, a prototype automated SUA was developed, and the reproducibility of the two ontologies tested on two cases via the automated SUA [33]. A charrette test was also conducted to validate the effectiveness of the context of the automated SUA [34].

4.3.1. Formality of the Ontologies. Four case studies were conducted to validate the formality of the activity and space ontologies. Two were office projects (Cases 1 and 2) in Shenzhen, China. Confidentiality constraints prevent the disclosure of their names. The other two cases were institutional buildings: Cygnaeus High School (Case 3), based on [4], and an Integrated Teaching (AIT) building (Case 4) at the Chinese University of Hong Kong, developed via observation. The user activities, flexible spaces, and nonflexible spaces identified from these four cases were represented using the proposed activity and space ontologies (Table 3). The authors invited six architects with an average of fifteen years of industry experience to participate. Three were involved in the two institutional cases, and the other three participated in the two office cases. The results of these four case studies show the formality of the activity and space ontologies because 20 user activities, 10 non-flexible spaces, and four flexible spaces were all successfully represented. The 20 user activities represented nine types of space-use, four of which captured flexible space-use. Two types of flexible space were formally represented using the space ontology.

4.3.2. Comprehensiveness of the Ontologies. The activity and space ontologies were proven to be sufficiently comprehensive because the proposed activity ontology captured
seven SUTDs and the proposed space ontology captured information related to both flexible and nonflexible spaces, corresponding to four of the seven SUTDs (i.e., those related to the spatial requirements of user activity). Specifically, the <User activity> class of the activity ontology was further classified into <Typical activity> and <Atypical activity>, which considered SUTD 1 (i.e., typical activity vs. atypical activity). The <User> class of the activity ontology was further classified into <Important user> and <Regular user>, which considered SUTD 2 (i.e., important user vs. regular user). The properties of constraint and preference were available for instances of <Spatial requirements> in the activity ontology, which considered SUTD 3 (i.e., situations in which the space preference and constraints are the same vs. those in which they differ). The property of designation was available in the <Spatial requirement> class of the activity ontology, and the property representing the designation status was available in the <Space> class of the space ontology, both of which considered SUTD 4 (i.e., situations in which an activity requires a designated space vs. those in which it does not).

The <Spatial requirement> class of the activity ontology was further classified into <Whole room use requirement> and <Equipment use requirement>, and the <Space> class of the space ontology had space-uses—<Whole room use> and <Equipment use>—that considered SUTD 5 (i.e., situations in which an activity requires a whole room vs. those in which only a part of a room is necessary). The space super-type property and properties that represent the space’s features were available in the <Spatial requirement> of the activity and space ontologies, both of which considered SUTD 6 (i.e., situations in which an activity requires a specific type of space vs. those in which only the required features of the appropriate space are specified). The property that indicates whether a user activity can be accommodated by a flexible space was available in the <Spatial requirement> of the activity ontology, and the <Space> class was further classified into <Flexible space> and <Nonflexible space>, both of which considered SUTD 7 (i.e., situations in which an activity allows for the use of a flexible space vs. those in which it does not).

### 4.3.3. Reproducibility of the Ontologies

To test the reproducibility of the developed ontologies, it was necessary to determine if different architects could obtain consistent results from the automated SUA, using the proposed ontologies to represent the same case as input. Thus, the activity and space ontologies were implemented in a prototype of the automated SUA via the innovative process of the charrette test introduced in the next section. As a result, it was determined that the utilization data from the architects using the innovative process for Cases 2 and 3 were consistent with one another, which was demonstrated via the successful use of the proposed activity ontology to represent the user activities and proposed space ontology, with both flexible and nonflexible spaces used as input for the prototype automated SUA. This implies the reproducibility of the activity and space ontologies such that different architects should be able to use them to model the same activities and spaces (both flexible and nonflexible) and obtain consistent results.

#### 4.3.4. Effectiveness of the Automated SUA

To validate the effectiveness of the automated SUA’s framework, a charrette test (Figure 5) was conducted, following the definition provided in [34]. A prototype system was developed to automatically predict and update the utilization of both flexible and nonflexible spaces. Case 2 (i.e., the office case) and Case 3 (i.e., the institutional case of Cygnaeus High School) were used in this test. Three architects (i.e., Group 1, with an average of 16.3 years of work experience) were invited to test Case 2, and another three (i.e., Group 2, with an average of 13.7 years of work experience) were invited to test Case 3. There were three user activities, one flexible space and two nonflexible spaces in each. Two flexible space types [31] were included in each case.

Based on the intent of the charrette test, the testing of each case included three trials. The first predicted the space utilization based on three user activities and three nonflexible spaces. The second trial updated the space utilization based on changes in the space information (i.e., the spaces were updated to have one flexible space and two nonflexible spaces). The third trial updated the space utilization based on changes in the activity information (i.e., the spatial requirements of the user activities were updated). The architects from Groups 1 and 2 performed three trials, first via the conventional method (i.e., manually performing SUAs of the trials) and then using the innovative method (i.e., using the prototype to perform SUAs of the trials). In both cases, the propositions (i.e., the time spent and consistency of the results) necessitated specific measurements of each architect’s performance using the two processes.

The charrette results suggested that the automated SUA (i.e., the innovative method), for which no human interpretation was needed in the utilization prediction, was more effective. Tables 4 and 5 show the time spent on the three trials for Cases 2 and 3. The average time spent using the innovative method for Case 2 (i.e., 11.08 minutes = 9.05 minutes + 1.08 minutes + 0.95 minutes) was much less...
than the average time spent using the conventional method (i.e., 30.29 minutes = 17.64 minutes + 8.93 minutes + 3.72 minutes). Thus, the innovative process for Case 2 was 2.7 times faster. The average time spent for Case 3 using the innovative method (i.e., 10.76 minutes = 9.33 minutes + 0.8 minutes + 0.63 minutes) was much less than the average time spent using the conventional method (i.e., 42.34 minutes = 18.13 minutes + 14.24 minutes + 9.97 minutes). Thus, the innovative process for Case 3 was 3.9 times faster. The reasons why the innovative process was faster were that the architects did not need to manually distinguish different flexible and nonflexible space-use types, map activities onto nonflexible and flexible spaces with the appropriate configurations, and calculate the data needed (e.g., activity load, and space load) to predict the utilization.

To show that the charrette test reduces the effects of learning that can occur when subjects repeat tasks of the same case (i.e., perform an SUA first with the conventional and then with the innovative methods), the time spent by each architect during each trial was measured in each of two separate parts. For the conventional process, these two parts were comprised of the time needed to comprehend the material regarding the activities and spaces (i.e., the three architects in Case 2 averaged 10.11 minutes in total for the three trials, while the three architects in Case 3 averaged a total of 9.85 minutes for the same) and the time needed for the utilization calculation via the prototype. Neither Case 2 nor 3 saw significant reduction compared to the time needed to comprehend the material by those entering the data. In terms of generality, the charrette test included the utilization use predictions for three trials of one institutional case and three trials of one office case.

In terms of measuring the consistency of the results, the mean absolute deviation (MAD) [39] was used. The MAD of a group of utilization results for a certain space is obtained by measuring the averaged distance between each architect’s utilization value and the mean. The MAD analysis of Cases 2 and 3, shown in Tables 6 and 7, suggests that the innovative process with the automated SUA was relatively consistent among all trials. The reasons why the innovative process would be more consistent are that the architects did not need to manually analyze the flexible spaces with appropriate configurations, calculate the activity load, assign the activity load to the mapped space, and calculate the utilization. Thus, this innovative process with standardized activity and space representations will reduce the probability of manual errors and contribute to a consistent result. Therefore, the automated SUA can be considered more reliable as the ontologies help analysts accurately capture a project’s important information (i.e., activity and space) and therefore consistently predict and update the uses of both flexible and nonflexible spaces.

| Participants | Experience (years) | Time for conventional process (min) | Time for innovative process (min) |
|--------------|-------------------|-----------------------------------|----------------------------------|
|               |                   | Initial prediction | First update | Second update | Initial prediction | First update | Second update |
| Architect 1  | 6                 | 18.72               | 9.27         | 3.85          | 8.37               | 1.05         | 0.92          |
| Architect 2  | 13                | 17.02               | 9.4          | 4.05          | 9.8                | 0.93         | 0.96          |
| Architect 3  | 30                | 17.2                | 8.11         | 3.25          | 8.97               | 1.28         | 0.95          |
| Average      | 16.3              | 17.64               | 8.93         | 3.72          | 9.05               | 1.08         | 0.95          |

| Participants | Experience (years) | Time for conventional process (min) | Time for innovative process (min) |
|--------------|-------------------|-----------------------------------|----------------------------------|
|               |                   | Initial prediction | First update | Second update | Initial prediction | First update | Second update |
| Architect 4  | 8                 | 21.95               | 14.88        | 10            | 11.2               | 0.87         | 0.6           |
| Architect 5  | 5                 | 17.55               | 14.67        | 12.05         | 8.3                | 0.74         | 0.59          |
| Architect 6  | 28                | 14.88               | 13.17        | 7.86          | 8.5                | 0.8          | 0.7           |
| Average      | 13.7              | 18.13               | 14.24        | 9.97          | 9.33               | 0.8          | 0.63          |

Figure 5: Charrette test design.
Conclusions

Researchers have been made to extend the current SUA method in order to more quickly and consistently examine the performances of different design options in terms of flexible-space utilization. In a previous study [31], researchers developed a method for mapping user activities onto flexible spaces. However, current activity and space representations are not available to provide architects with a common vocabulary for capturing flexible space-use and abstracting the information accompanying the use of flexible space. In addition, a framework for the implementation process for an automated flexible-space SUA had not yet been developed. To make use of the previously developed mapping method [31] and achieve a potential automated SUA for the flexible space domain, this study defined (1) an activity ontology containing 10 classes and 32 properties and a space ontology containing five classes and 22 properties, and (2) a framework for formalizing an automated SUA implementation process to deal with utilization predictions for flexible space.

The activity and space ontologies are novel because they allow a computer to gather the information necessary to distinguish among different flexible and nonflexible space-use types and predict the utilization of both flexible and nonflexible spaces based on the developed implementation framework of an automated SUA. These are not available in current theories of user activity and space representation, which require architects to track the information manually for later utilization calculations. The proposed activity and space ontologies have been validated and are considered formal, as 20 user activities, 10 nonflexible spaces, and four flexible spaces from four different office and institutional cases were all successfully represented. To validate this method as comprehensive, seven SUTDs of user activities and information related to both flexible and nonflexible space (corresponding to four of the seven SUTDs that were related to spatial requirements) were

### Table 6: MADs of the three Case 2 trials.

| Space       | MAD of conventional process (%) | MAD of innovative process |
|-------------|---------------------------------|----------------------------|
| **Initial prediction** |                                 |                            |
| Space 1     | 0.53                            | 0                          |
| Space 2     | 4.84                            | 0                          |
| Space 3     | 7.90                            | 0                          |
| **First update** |                                |                            |
| Space 1     | Subunit 1                        | 2.58                       | 0                          |
|             | Subunit 2                        | 2.95                       | 0                          |
| Space 2     |                                | 2.56                       | 0                          |
| Space 3     |                                | 7.90                       | 0                          |
| **Second update** |                               |                            |
| Space 1     | Subunit 1                        | 2.58                       | 0                          |
|             | Subunit 2                        | 2.95                       | 0                          |
| Space 2     |                                | 0.92                       | 0                          |
| Space 3     |                                | 26.76                      | 0                          |

1 A flexible space whose head subunit does not share a movable component with the tail subunit.

### Table 7: MADs of the three Case 3 trials.

| Space       | MAD of conventional process (%) | MAD of innovative process |
|-------------|---------------------------------|----------------------------|
| **Initial prediction** |                                 |                            |
| Space 1     | 10.12                           | 0                          |
| Space 2     | 0.72                            | 0                          |
| Space 3     | 0.85                            | 0                          |
| **First update** |                                |                            |
| Space 1     | Subunit 1                        | 17.13                      | 0                          |
|             | Subunit 2                        | 0.43                       | 0                          |
| Space 2     | Subunit 3                        | 0.43                       | 0                          |
|             | Subunit 4                        | 0.43                       | 0                          |
| Space 3     |                                | 6.42                       | 0                          |
| **Second update** |                               |                            |
| Space 1     | Subunit 1                        | 14.94                      | 0                          |
|             | Subunit 2                        | 0.32                       | 0                          |
| Space 2     | Subunit 3                        | 0.32                       | 0                          |
|             | Subunit 4                        | 0.32                       | 0                          |
| Space 3     |                                | 20.50                      | 0                          |

1 A flexible space whose head subunit shares a movable component with the tail subunit.

5. Conclusions

Research efforts have been made to extend the current SUA method in order to more quickly and consistently examine the performances of different design options in terms of flexible-space utilization. In a previous study [31], researchers developed a method for mapping user activities onto flexible spaces. However, current activity and space representations are not available to provide architects with a common vocabulary for capturing flexible space-use and abstracting the information accompanying the use of flexible space. In addition, a framework for the implementation process for an automated flexible-space SUA had not yet been developed. To make use of the previously developed mapping method [31] and achieve a potential automated SUA for the flexible space domain, this study defined (1) an activity ontology containing 10 classes and 32 properties and a space ontology containing five classes and 22 properties, and (2) a framework for
captured. Finally, to deem the process as reproducible, the utilizations predicted by three architects in office or institutional cases who used these two ontologies as input for the automated SUA application were found to be consistent with one another. The proposed framework for this automated SUA implementation process for flexible space is novel because with the assistance of computer and it provides architects with a quick and consistent means of utilization prediction with regards to flexible space. This framework is embedded with (1) SUA concepts [4, 5, 29], (2) seven SU’Ts that distinguish the different space-use types that must be analyzed in an SUA [31], (3) a method for mapping user activities onto both flexible and nonflexible spaces [31], and (4) activity and space ontologies that capture the necessary flexible space-uses of user activities and the information necessary for flexible space. The three steps include “entering project data (input),” “mapping user activities onto space (analysis),” and “computing utilization (output).” The authors demonstrated its effectiveness by developing a prototype and conducting a charrette test. As the results of the charrette test show, the speed and consistency of utilization prediction are improved with the automated SUA. In terms of generality, the charrette test was conducted on one institutional case (including one initial prediction and two updates) and one office case (including one initial prediction and two updates), with six trials in total. Three architects participated in each case’s predictions.

Architects equipped with such an automated SUA will be able to quickly and consistently monitor the space efficiency of building designs and determine the effects of their decisions, such as by adding flexible space to a design, changing the number of subunits of flexible space, and refining the spatial requirements of user activity. The authors plan to extend the representations and SUA to include (1) activities containing a stochastic number of users that affect dividing flexible space into appropriate usable units and (2) flexible spaces that contain different sizes of subunits and a variety of types of movable components to support sustainable building design. In future work, the authors will link the automated SUA with BIM models to develop and visualize flexible space and its movable components and determine how these can be processed to the automated SUA. This research will contribute to performance-based designs by providing an automated method for architects to predict and update the utilization of both flexible and nonflexible spaces during project development, which will improve designs by reducing underutilized or overutilized spaces without losing the planned functions of a building facility.

Data Availability

The data used to support the findings of this research work are available from the authors including the corresponding author based on requests.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (Nos. 2016R1C1B2014542 and 2017R1C1B5075654). This work was supported by the research grant of the Chungbuk National University in 2017.

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