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Abstract

Space-use can only be effectively determined when space, user, and activity perspectives are taken into account simultaneously. We develop a knowledge-based framework for automated space-use analysis to enable analyzers to predict and update space utilization simultaneously considering these three perspectives with computational assistance. The framework includes the formalization of the concepts for space-use analysis such as users, user activities, spaces, equipment, and space utilization, the ontological relationships among the concepts, and the automated space-use analysis process. We demonstrate the effectiveness of the proposed framework through a trial run on select areas in an academic building at Stanford University. Our results show that the proposed framework can support iterative refinement of the architectural design and its usage by predicting the utilization and visualizing the results automatically. This automation in space-use analysis contributes a consistent, clear, and efficient means of analyzing space-use in support of architects' and clients' decision-making about the design.

Keywords

Framework; Space utilization; Space-use analysis; User activity; Design

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1. Introduction

Space-use analysis is defined as the prediction of how much each space in a facility will be used by users and their activities. It is currently gaining more significance because many companies or public agencies are disposing of or condensing their workspace in response to a challenging economy. Clients question the space-use of a facility from three different perspectives: (1) space perspective; is there too much space? (2) user perspective; can all users work as they expect? and (3) activity perspective; does the facility support the activities the company needs to do for its business? These three perspectives are interrelated, and changes in one perspective (e.g., change in the size of a space, change in the number of a user group, change in the frequency of an activity) introduce changes in other two perspectives. Therefore, these three perspectives should be integrated in space-use analysis for planning space-use of a facility in the programming phase, for monitoring space-use as a design evolves in the design phase, and for improving space-use as information about actual use becomes available in the occupancy phase.

Along with this multiplicity of perspectives of space-use, the multiplicity of design options, each of which has a variety of spaces, and the complex relationships between activities and spaces necessitate automated space-use analysis. However, the construction industry currently lacks a framework that formalizes the relationships among different perspectives and steers the implementation of automated space-use analysis that is based on that formalization. Consequently, current methods of space-use analysis are unable to predict, document, and communicate space-use in facilities with sufficient consistency, transparency, and efficiency to allow clients to select the design or to allow architects to refine the design for a new facility that best meets users' needs. Even state-of-the-art space planning tools, such as dRofus [1] and Onuma Planning System [2], do not predict space-use by simultaneously taking into account these three perspectives and update space-use automatically when there are changes in user and activity perspectives. These tools lack the formalized framework to relate user and activity perspectives with space perspective. When the design is iteratively refined, the predicted space-use becomes increasingly ambiguous, and clients or architects cannot rely on these predictions when making decisions about the design.

1.1. Motivating cases

We examined two space-use analysis practices used to solve issues in two building projects in Korea and one space-use analysis practice used in the US [3]. We show how, despite the different project sizes and analyzer (i.e., a professional who conducts space-use analysis) types, space-use analysis was conducted in all three cases in an intuitive and experience-based way because of the lack of a framework that formalizes the relationships among space, user, and activity perspectives. The space-use analysis in each case failed to provide a solid ground for decision-making about the design.

1.1.1. Case 1: The size of the gym in a construction company

In 2007, a Korean construction company decided to move its headquarters from Seoul to a provincial town. The gross area (6,060 m^2) and the number of floors (4 floors and 1 basement) were determined to maximize the use of the site according to building regulations. An in-house architectural team (the analyzer) was in charge of developing the space program and the design for the new building. During the design phase, one of the company's vice-presidents reviewed the design and thought that the size of the gym should be increased for the 200 employees who worked at headquarters (user perspective). The analyzer adjusted the size in accordance with the vice-president's opinion, but when the president reviewed the design, he thought that the size of the gym was too large (space perspective) for the employees' expected exercise activities (activity perspective) and wanted a reduction in size. This incident shows that conflicting opinions can arise when a client organization has multiple decision-makers. In an interview with one member of the in-house architectural team, he recalled that because the analyzer did not have a formal and consistent method of informing the decision-makers (here, the vice-president and the president) about the employees' space-use, the analyzer "simply followed" the opinion of the most powerful person, in this case, the president.

1.1.2. Case 2: Storage vs. meeting rooms in a publishing company

In 2010, a publishing company in Korea consulted with an architectural firm (the analyzer) about the company's desire to build a new building to provide more space for 20 employees and to provide the president with an art room for her paintings. The determined gross area was 660 m^2. During the planning phase, the company wanted to increase the size of the storage room to hold an additional 10,000 books (from 20,000 to 30,000 books) (activity perspective). However, because the project had already exceeded its budget, the company had to reduce the size of other spaces to increase the size of the storage. The analyzer had several options to address this trade-off, including reducing the size of the art room or the workstation area. However, without an analytical tool that integrates the space (e.g., meeting rooms, the art room, storage for books), user (e.g., employees, editors, the president), and activity (e.g., having a meeting, editing a book) perspectives, the impact of these options on space-use could not be analyzed and compared in detail.

1.1.3. Case 3: Shared labs vs. independent labs in a university facility

Whelton [3] describes the Hearst Memorial Mining Building Seismic and Program Improvement Project on the University of California, Berkeley campus. The gross area of the building was 130,000 ft^2 (12,077 m^2). An architectural firm (the analyzer) conducted an architectural programming study, which included developing the space program. After developing the space program, the analyzer found that the project exceeded the original budget determined by the "project planning guide" and re-examined the space program to find appropriate ways to reduce the cost (space perspective). After investigating various options, the analyzer and client decided to provide shared laboratories instead of separate and independent laboratories, which could affect students' laboratory activity. However, these options were analyzed and explained by an intuition-based discussion among the project committee members rather than by a systematic means of integrating the space (e.g., research laboratories, faculty and graduate student offices, classrooms), user (e.g., students, faculty, staff), and activity (e.g., having a class, conducting an experiment) perspectives.

1.2. Research objectives

Frameworks have been developed and used in the construction industry either to view domain knowledge in an organized way [4,5,6] or to implement a novel method and facilitate its use [7,8,9]. We have developed a framework for the latter purpose with a focus on predicting space utilization in the programming and the design phase, where space utilization is a performance metric for space-use analysis that shows the usage rate of a space [10,11]. Specifically, we propose a framework that formalizes the concepts that are related to three perspectives of space-use and the relationships among them. Moreover, we extend this framework by formalizing the implementation process and its relationship to the concepts so that analyzers can predict, document, and visualize space utilization automatically. Using the proposed framework, analyzers can predict the utilization of each space based on space, user, and activity information and update the prediction when this information changes in a consistent, clear, and efficient way to support decision-making about the design.

1.3. Research methodology and scope

We applied knowledge representation and reasoning [12] to this research because it allows us to represent the necessary concepts in a computer-interpretable form and to reason about the representation to predict space-use. We limited our scope to office and educational buildings because their spaces are determined primarily by user activities and they have clearer user profiles than other facility types. First, we identified characteristics of user activities in facilities by investigating observed cases and the literature on user activities. Second, we defined the concepts for space-use analysis based on the identified characteristics of user activities and formalized the ontological relationships among the concepts, building on existing activity representations. Third, we defined the implementation process of automated space-use analysis using Integrated Definition for Functional Modeling (IDEF0) and related functions of the process to the concepts for space-use analysis. Fourth, we applied the proposed framework to select areas in the Jerry Yang and Akiko Yamazaki Environment and Energy (Y2E2) Building, Stanford University, to demonstrate its use in automated space-use analysis. In our framework, “user information” refers to the user profiles that include the types of users, the number of expected users, their activities, and their functional needs, preferences and priorities [10]. “Space information” refers to the space program that lists the number and the size of each space type. Although space location, geometry, or aesthetics information also affects the space-use, this research considers only aforementioned parameters, which are more dominant in space-use analysis.

2. Points of departure

We reviewed prior work concerning space-use analysis to examine existing frameworks and assistive iterative refinement model in spatial design computing on which we build our framework for automated space-use analysis. We also reviewed activity representations in the Architecture, Engineering, and Construction (AEC) industry and user activity models to build a representation of user activities, which is a key concept necessary for space-use analysis.

2.1. Prior work

The prior work, which provides useful theoretical concepts, consists of the following four domains: (1) architectural programming, (2) post-occupancy evaluation, (3) workplace planning, and (4) operations research for space assignment. Although the importance of space-use analysis has been recognized widely [13,14], previous research efforts provide only limited frameworks for automated space-use analysis. Architectural programming [10,15,16] does not formalize quantitative relationships among user, space, and space utilization and therefore predicts the utilization inconsistently and explains its prediction unclearly. Post-occupancy evaluation [17,18,19] does not adequately incorporate project specificity into space-use analysis, meaning that detailed properties of spaces, users, and activities are ignored, and therefore utilization is not tracked and updated when this information changes. Workplace planning [11] does not represent properties of spaces, users, and activities and the relationships among them at a sufficient level of detail to map activities onto spaces automatically. Operations research [20,21] focuses on optimizing the decision variables such as space types and numbers rather than representing the space-use of current design options in support of clients' decision-making.

Cherry [10] introduces space utilization as a formula for predicting the number of spaces needed for classes in educational facilities. According to Cherry, 100% utilization implies that it is unacceptable to users due to scheduling inflexibility and long queues for activities in the space. In contrast, 0% utilization implies that it is unacceptable to clients due to building costs. Space utilization is similar to capacity utilization in the manufacturing industry, which is a ratio of the actual output to a sustainable maximum output, i.e., capacity [22]. The biggest difference is that capacity utilization is targeted at the point where marginal costs are equal to average costs in manufacturing [22], while it is difficult to define and measure both costs in facilities. Therefore, Cherry [10] emphasizes the need for a policy on the planned utilization to use the utilization as a measure of the space-use. Pennanen [11] generalizes the computation of the utilization to apply it to other types of facilities, such as office buildings and hospitals. Based on work experience, he argues that if the utilization of a space is less than 50%, activities can be conducted without waiting. If the utilization is less than 75%, activities may need to be scheduled. In addition, if the utilization is larger than 80%, there seems to be a shortage of space [11]. Together, these research efforts provide us with the utilization computation method and the implication of various utilization levels for developing our framework.

2.2. Assisted iterative refinement in spatial design

Spatial computing for design is defined as "a body of work that is concerned with the use of formal methods in knowledge representation and reasoning in general, and terminological and spatial representation and reasoning in specific, for solving problems in modeling and validation in the domain of spatial design [23]." Based on the definition, Bhatt and Freksa [23] propose an iterative refinement model in spatial design that is assisted by knowledge systems. According to their model, a spatial design should be abstracted and represented in a computer-interpretable form so that knowledge systems can reason about the design to produce valuable information that was originally barely noticed. The information is then used to provide design feedback and its visualization within the conventional design workflow. We utilize this model specifically for the development of a framework for automated space-use analysis that assists iterative refinement of the design according to space utilization. To do so, the spatial design and its representation should be integrated with user and activity information because space utilization is affected not only by spatial design itself (e.g., by increasing the number of spaces), but also by users' space usage (e.g., by limiting a user group's usage of a space).

2.3. Activity representations in AEC

Many researchers in AEC have represented construction activities for various purposes, such as planning [24,25], time-space conflict analysis [26], cost estimation [27], and field instruction generation [28]. Darwiche et al. [24] represent activities as a tuple of <Objects>, <Actions>, and <Resources> on which other representations have been built to support different purposes. However, these representations directly link <Actions> to specific spaces for construction defined as <Spaces> [26] or <Work area> [28], while user activities in facilities are sometimes conducted in a space that satisfies certain requirements, e.g., any room with a table for six people. In addition, these representations differentiate the activity concept and the action concept in that activity is described by multiple concepts including action(s). We adopt that differentiation and apply it to the representation of user activities in facilities. However, we assume that single activity has only one action because some activities have no sequences [29], and sequences of user activities are sometimes vague and hard to define.

2.4. User activity models

Some researchers have modeled user behavior in facilities to simulate users' movement such as herding and separation in emergency [30] or in a normal situation [31,32]. However, these simulation models only partially represent user activities for use in space-use analysis. Two research efforts have modeled user activities to predict space utilization. Tabak [29] combines user and space information to simulate users' occupancy in a facility. He classifies activities into skeleton activities (i.e., activities that are formed in a sequence) and intermediate activities (i.e., physiological or social activities). Activity properties include frequency, duration, priority, location, and facilities. Pennanen [11] models user activities to compute the utilization of each space automatically. The properties he considers include activity driver, load (i.e., hours that an activity demands from spaces), and group size. These models provide not only background knowledge of user activities in facilities, but also a set of properties of user activities that we can use in this research. However, the models do not clarify the ontological relationships among different concepts such as spatial requirements and spaces to be used in knowledge systems, and they therefore introduce human interpretations in space-use analysis, especially when mapping user activities onto spaces in a facility.

3. Concepts for space-use analysis

There is a need for a logical framework in which analyzers can gather, represent, and use the knowledge about users and spaces in support of automated space-use analysis. This section presents our definitions of the concepts for space-use analysis and their relationships to provide ontological knowledge for the domain of space-use analysis in general and to provide the representation that automated space-use analysis uses in its reasoning process.

3.1. Characteristics of user activities

The representation of a domain depends on the application that intends to use the representation [33]. Therefore, we identified the following five characteristics of user activities in facilities that space-use analysis must consider based on observations, interviews with analyzers in practice, and review of architectural programming and workplace planning literature.

First, some users require a space with more than minimum requirements for better performance of their activities. In this paper, we call the minimum spatial requirements *constraints* and the spatial requirements for better performance *preferences*. Clients need to decide which user groups are allowed to have spaces that satisfy preferences and which users are not. We call the former *important users* and the latter *regular users*. Second, some activities require having a designated space such as a professor's office [11]. If a space is designated, the space cannot be used by other users even if the space is vacant. Therefore, the *designation* characteristic should be considered when spatial requirements of an activity are represented. Third, some activities require occupying a whole room, while others need only part of a room. For example, a meeting activity requires a whole conference room, and therefore other activities cannot occupy the space simultaneously. In contrast, the regular work of an employee requires occupation of only one workstation in the office space, and consequently other employees can use other workstations in the same space for their activities. We distinguish these two spatial requirements by calling the former *whole room use requirements* and the latter *equipment use requirements*. Fourth, some activities are conducted in a specifically named space, while others can be conducted in any space with certain requirements. This characteristic calls for the use of *spatial requirements* rather than *spaces* when representing user activities, which we already pointed out in Section 2.3. Fifth, some atypical activities also require a space. Atypical activities are activities that are not conducted on a regular basis [10]. Although atypical activities do not affect the calculation of space utilization, they should also be represented and connected to user and space information so that an analyzer can ensure that the design still accommodates atypical activities when space or user information changes. We therefore distinguish *typical activities* and *atypical activities* in space-use analysis.

3.2. Concepts for space-use analysis

Based on the characteristics of user activities in facilities, we have defined the concepts for space-use analysis and the ontological relationships among the concepts. The concepts include spaces, equipment, users, user activities, actions, spatial requirements, and space utilization.

3.2.1. Spaces and equipment

Space is defined as a physical entity that accommodates a user activity, e.g., a conference room. *Equipment* is another physical entity that accommodates user activities (e.g., a workstation, a computer), but it represents part of a room while *a space* represents a whole room. A *space* can have multiple pieces of *equipment*, in which case the whole space is not occupied by activities. Therefore, spaces are grouped into two subclasses: *occupiable space* that has no equipment and is occupied by activities and *non-occupiable space* that is not occupied and has pieces of equipment that are occupied by activities. *Occupiable spaces* and *equipment* can be designated by user activities while *non-occupiable spaces* are not allowed to be designated.

3.2.2. Users

User is defined as a subject of a user activity, e.g., students, employees. In space-use analysis, *user* and *user group* are interchangeable because space-use analysis does not consider individual users and their personal needs, e.g., Tom works well with Jane, so he wants to study near her. *User* has two subclasses: *important user* that requires satisfying the preferences of his or her activities and *regular user* that requires satisfying the constraints of his or her activities, i.e., minimum requirements.

3.2.3. User activities and actions

User activity is defined as an *action* of users that requires occupying spaces. Therefore, user activity is defined not only by its action, but also by its users and its requirements. User activity has two subclasses: *typical user activity* that occupies spaces on a regular basis and therefore should be taken into account in utilization computation and *atypical user activity* that only needs to be checked if spaces in a facility can accommodate the activity.

3.2.4. Spatial requirements

Spatial requirements are defined as properties of a space that an activity requires for occupying the space. Spatial requirements have two subclasses: *whole room use requirements* that characterize the properties of a whole room (e.g., minimum size of a room, the number of a room) and *equipment use requirements* that characterize the properties of part of a room, i.e., equipment. Since some activities require occupying any spaces that satisfy certain requirements such as size, type, and conditions of the spaces, spatial requirements can have *anySpace* value for their *space name* property.

3.2.5. Space utilization

Utilization of a space is calculated by dividing activity loads in the space by open time of the space. For example, if an activity A occurs three hours and an activity B occurs one hour in a space that has eight-hour open time, the utilization of the space is 50%. Based on the previous work that suggests the implication of the utilization [10,11], we categorized the utilization of non-designated spaces or equipment into 4 groups and the utilization of designated spaces or equipment into 2 groups, as shown in Table 1. In our framework, the categories are color-coded to visualize the implication.

Table 1. The implication of the utilization

Non-designated spaces or equipment			
Range of utilization	Implication	Description	Color-code
utilization <=50%	No wait	Activities can be done without waiting.	Green
50%< utilization <=75%	Adequate	Activities may need to be scheduled.	Yellow
75%< utilization <=100%	Inconvenient	Activities need to be relocated.	Red
100%< utilization	Infeasible	Activities cannot be physically accommodated.	Gray
Designated spaces or equipment			
Range of utilization	Implication	Description	Color-code
utilization <=100%	No wait	Activities can be done without waiting.	Green
100%< utilization	Infeasible	Activities cannot be physically accommodated.	Gray

3.3. Ontological relationships among the concepts

The ontological relationships we defined in Figure 1 answer the questions of how to describe user activities, how to relate user activities to spaces or equipment, and how to compute and evaluate the utilization based on the product (e.g., spaces, equipment) and the organization (e.g., users and their activities) information.

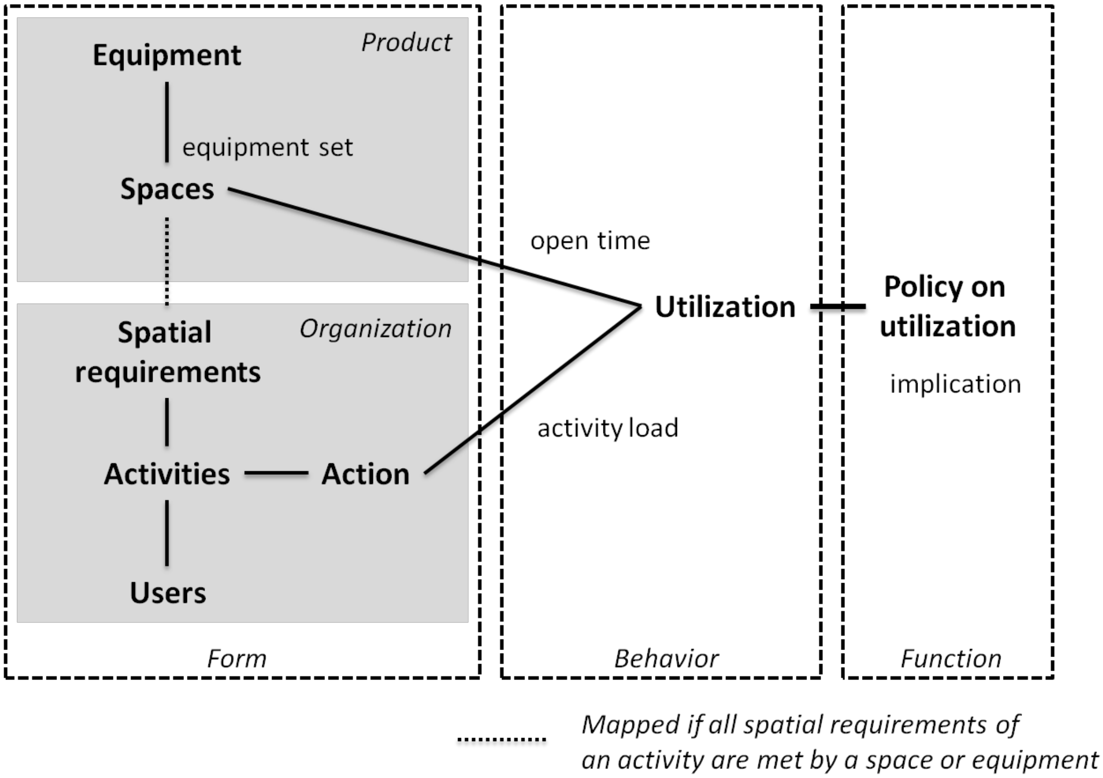

Figure 1. The ontological relationships among the concepts for space-use analysis

We suggest a tuple of <User>, <Action>, and <Spatial requirements> (i.e., <UAS> tuple) as a representation of user activities for automated space-use analysis. Examples of user activities from one case study we analyzed are (1) <Employees><Have a meeting><In a meeting room that is larger than 15m^2>, (2) <Editors><Edit a book><In any room with quiet conditions>, and (3) <A company president><Paints as her hobby><In an art room>. User activities are accommodated by spaces or equipment that satisfies spatial requirements of the activities. The concept of *equipment set* is defined to differentiate the same equipment in different spaces. Space utilization is computed in light of the pairs of a user activity and a space. Our framework provides the policy on utilization consisting of 4 categories to which the utilization of each space is compared to inform analyzers about the implication.

4. Automated space-use analysis process

Based on the concepts for space-use analysis and the relationships among them, we defined functions of the automated space-use analysis process using IDEF0 and how each concept for space-use analysis is incorporated into this process. The functions consist of “building the knowledge base,” “mapping user activities onto spaces,” “computing utilization,” and “visualizing the results.” Outputs of the last function are used by analyzers or clients to refine the architectural design or user profiles, which makes the space-use analysis process iterative. The overall process is shown in Figure 2.

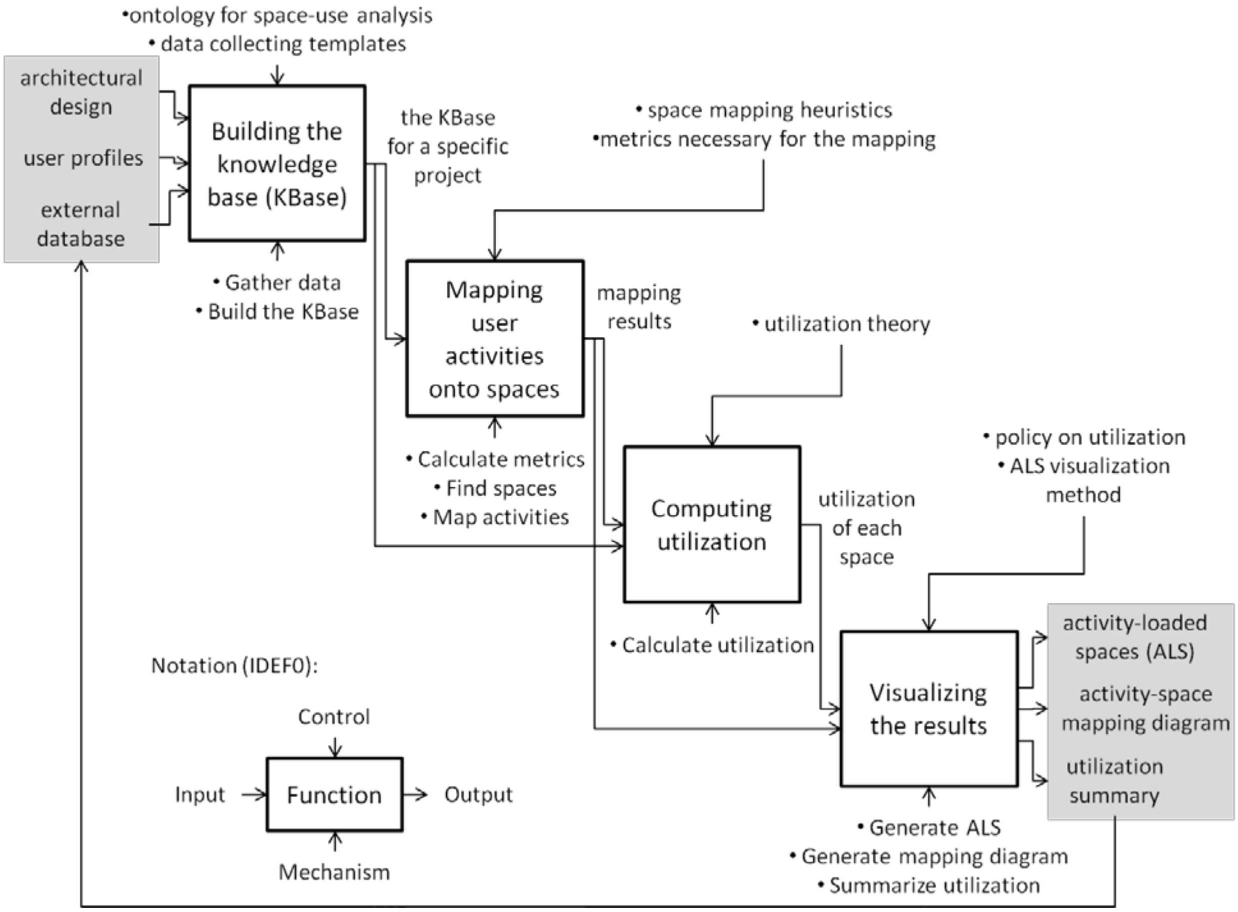

Figure 2. Automated space-use analysis process

4.1. Building the knowledge base

The “building the knowledge base” function takes input from the architectural design, user profiles, and the external database to provide the knowledge base for a specific project as an output. Table 2 explains the information that needs to be gathered for building the knowledge base. The ontology for space-use analysis is needed as a control. Data collecting templates, another control, can help analyzers input the necessary information even without knowing the ontology for space-use analysis. Gathering data and building the knowledge base are two mechanisms in this function.

Table 2. Required information for building the knowledge base for space-use analysis

Concept for space-use analysis	Required information
User	Name, The number of users, Regular users or important users
User activity	User, Action, Preferences (spatial requirements), Constraints (spatial requirements), Ratio[a], Frequency[b], Typical or atypical
Action	Group size, Duration[c], space criteria
Spatial requirements[d] (In case of whole room use requirements)	The name of space, The number of space, The minimum size of space, The type of space, Conditions of space,
Spatial requirements[d] (In case of equipment use requirements)	The name of space, The name of equipment, The number of equipment, The minimum size of equipment, The type of equipment, Conditions of equipment
Space	Size, Type, Number, Conditions, Open hour, Inaccessible user group, Equipment set if the space is non-occupiable
Equipment set	Equipment, The number of equipment, Conditions of equipment, Open hour of equipment, Inaccessible user group

Equipment	Size, Type

[a] what percentage of users are involved in this activity – 1.0 means all of the user group are involved
[b] how many times a user is involved in this activity per day
[c] how many hours an action continues per occurrence
[d] values for all the properties are not mandatory

4.2. Mapping user activities onto spaces

The "mapping user activities onto spaces" function takes the knowledge base as an input to provide the pairs of user activities and spaces or equipment sets as its output. The mapping is conducted not manually by analyzers but automatically by a set of rules. The rules consist of metrics necessary for the mapping and space mapping heuristics, which are controls of this function. Calculating the metrics, finding spaces, and mapping user activities onto the spaces are three mechanisms in this function.

We defined the following three metrics for the mapping:

- *Event quantity* refers to the number of groups for a given activity; it is calculated by dividing the number of users by the size that the activity requires to have, i.e., group size

  Event quantity = (the number of users of the activity × the ratio of the activity) ÷ the group size of the action of the activity
- *Load* refers to hours that an activity demands from spaces

  Load = event quantity of the activity × the frequency of the activity × the duration of the action of the activity
- *Space-use area* refers to the area that a group of users requires for an activity

  Space-use area = the group size of the action of the activity × space criteria of the action of the activity

We divided space mapping heuristics into two groups: "mapping activities requiring designated spaces" and "mapping activities not requiring designated spaces." As for "mapping activities requiring designated spaces," there should be rules to find spaces. Activities of important users should satisfy their preferences, while activities of regular users should satisfy their constraints. If the preferences or constraints are whole room use requirements, then the activities should be mapped onto occupiable spaces. If the preferences or constraints are equipment use requirements, then the activities should be mapped onto equipment sets and non-occupiable spaces that contain the equipment sets. Then, (1) if the number of spaces that occupy the activity is larger than the event quantity of the activity, the spaces should be divided into two entities; the number of the first entity is equal to the event quantity, and the number of the second entity is the remaining number. The first entity should be mapped with the activity and flagged as "designated", while the second entity is not. (2) If the number of spaces is equal to the event quantity, the spaces should be mapped with the activity and be flagged as "designated". (3) If the number of spaces is less than the event quantity, the spaces should be mapped with the activity, be flagged as "designated", and store the number of lacking spaces (the event quantity minus the number of spaces) in the *lack* property of the spaces. In terms of "mapping activities not requiring designated spaces," knowledge systems do not need to calculate the difference between the number of spaces and the event quantity. These systems only need to find spaces that are not designated and satisfy the spatial requirements of an activity and map the activity onto the spaces (Figure 3).

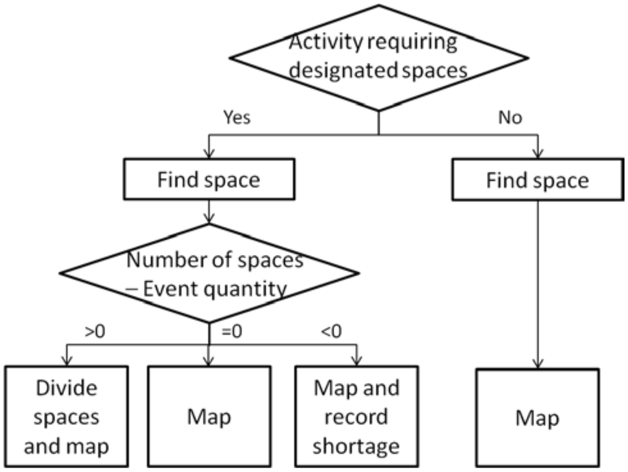

Figure 3. Space mapping heuristics

4.3. Computing utilization

The “computing utilization” function takes the knowledge base (i.e., output of the first function) and the mapping results (i.e., output of the second function) to compute the utilization based on the utilization theory [10,11]. Computing the utilization is a mechanism of this function, which has the following four steps:

- Step 1: For all user activities, sum up the number of spaces or equipment that occupy the activity and record the value in the activity.
- Step 2: For all user activities, compute the load per space or equipment by dividing the load of the activity by the recorded value in Step 1.
- Step 3: For all spaces or equipment sets, compute the total loads by summing up all the loads per space or equipment of activities that occupy the space or the equipment set.
- Step 4: For all spaces or equipment sets, compute the utilization by dividing the total loads by open time.

4.4. Visualizing the results

The “visualizing the results” function takes outputs of “mapping user activities onto spaces” and “computing utilization” functions to provide visualized results of space-use analysis. The policy on utilization, one of the controls in this function, was defined in Section 3.2.5. We propose the visualization method of activity-loaded spaces, which is another control of this function, as shown in Figure 4. This visualization shows which activities occupy a space (by black area and the name of the activities), how long the activities occupy the space (by loads per space in the x-axis), how much of the space the activities occupy (by space-use area in the y-axis), and how many area-hours of the space cannot be used even if the space is vacant (by gray area).

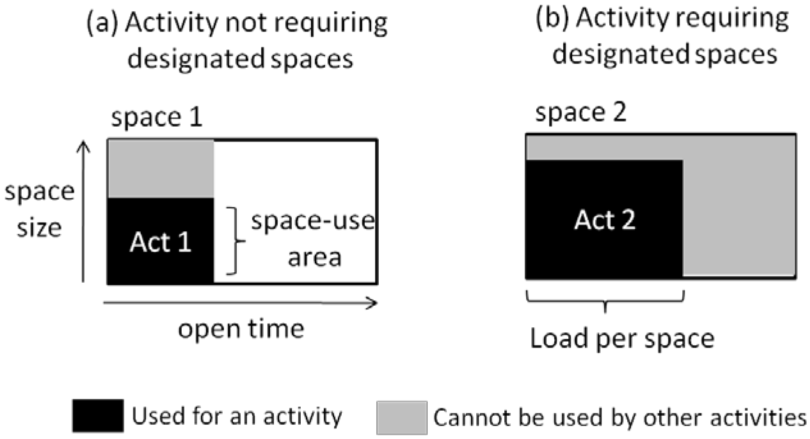

Figure 4. Visualization method of activity-loaded spaces: (a) activity-loaded space where activity 1 does not require designated spaces, (b) activity-loaded space where activity 2 requires designated spaces

This function has three outputs: activity-loaded spaces, the activity-space mapping diagram, and the utilization summary. Since automated space-use analysis makes spaces in the architectural design "activity-loaded," analyzers can see the visualization of an activity-loaded space easily by selecting the space in the design. The activity-space mapping diagram illustrates the links between user activities and spaces so that analyzers can see the automated mapping results at a glance. The utilization summary allows analyzers to see and document the utilization of each space by providing color-coded spaces in the architectural design based on the policy on utilization and by providing a table that lists spaces, their utilizations and the implications thereof.

5. Prototypical implementation

We conducted a trial run on select areas in the Y2E2 Building, Stanford University (Figure 5) to show the effectiveness of the proposed framework in terms of enhancing consistency, transparency, and efficiency of space-use analysis. We gathered and defined user and space information based on observation, hourly measurement of space-use, interviews with users, the architectural design of the Y2E2 Building, and Stanford University Space and Furniture Planning Guidelines [34]. We then observed how the framework helps analyzers predict, document, and communicate space utilization and respond to changes in space and user information. We used F-Logic [35], a knowledge representation and reasoning language, to represent the knowledge base for this building, to reason about that base to map user activities onto spaces, and to compute the utilization of each space. Although we manually represented the results for this paper, we specify the data we used that were drawn from the previous functions to show that the visualization can also be automated.

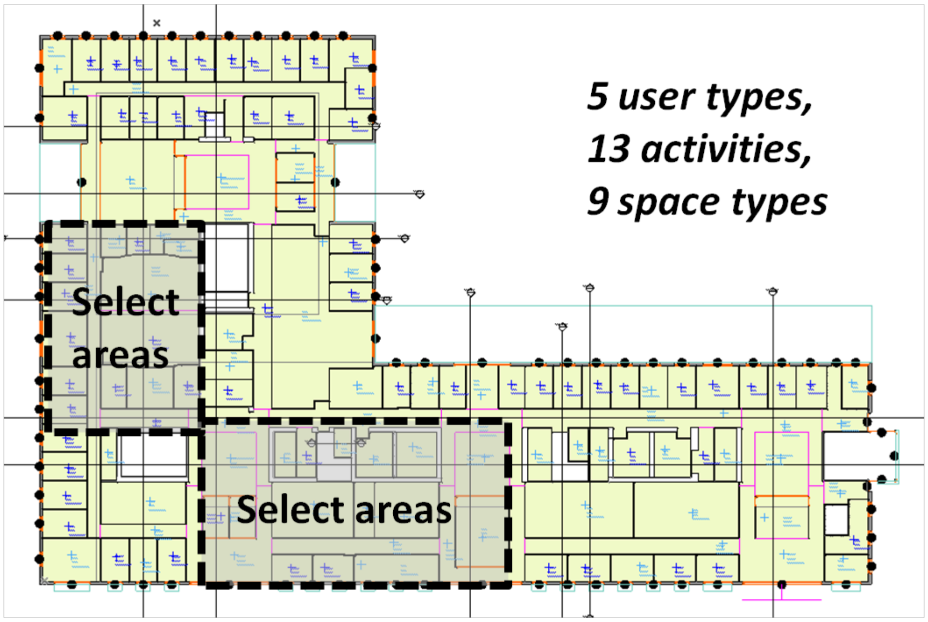

Figure 5. Select areas in the Y2E2 Building, Stanford University

5.1. Building the knowledge base

We defined the knowledge base that is specific for select areas in the Y2E2 Building. The knowledge base includes 5 user types, 13 user activities, and 9 space types, as shown in Table 3. We scaled down the number of undergraduate students and graduate students proportionate to their enrollment in the Department of Civil and Environmental Engineering, the department that is located in and uses this building. In terms of faculty, researchers, and staff, we counted the number of them in the select areas. We identified user activities by observation of those areas and also interviewed users to gather information on the spatial requirements of each activity. We also referenced Stanford University Space and Furniture Planning Guidelines to identify the spatial requirements of user activities, e.g., minimum size of a private office for faculty.

Table 3. Users, user activities, and spaces of the Y2E2 Building

User types	User activities	Space types
1. 25 undergraduate students 2. 122 graduate students 3. 5 faculty 4. 12 non-faculty scholars (e.g., visiting scholars and research associates) 5. 6 staff	1-1. Graduates having classes 1-2. Undergraduates having classes 2-1. Graduates meeting for coursework (computer work) 2-2. Undergraduates meeting for coursework (computer work) 3-1. Graduates meeting for coursework (no computer work) 3-2. Undergraduates meeting for coursework (no computer work) 4. Graduates meeting for research 5-1. Graduates studying individually 5-2. Undergraduates studying individually 6. Faculty working 7. Staff working 8. Non-faculty scholars working 9. Faculty meeting	1. A computer cluster containing 25 computers (792 ft^2) 2. A classroom (792 ft^2) 3. Three small conference rooms with a computer (100 ft^2) 4. A conference room with a computer (286 ft^2) 5. Five private offices (180 ft^2) 6. Three shared offices containing 2 workstations (160 ft^2) 7. Two cubicle spaces containing 6 workstations (358 ft^2) 8. Two small conference rooms (157 ft^2) 9. A large conference room (546 ft^2)

The knowledge base consists of 64 facts about this trial run in F-Logic. Here are some examples of the knowledge base:

- User activities:

  gradsMeetingForResearch:TypicalActivity[user -> grads, action -> haveResearchMeeting, ratio -> 1.0, frequency -> 0.1, constraints -> cons4, preferences -> pref4].

- Spaces:

  smallConferenceRoom:OccupiableSpace[spaceType -> conferenceRoom, size -> 157, number -> 2, openTime -> 8.0, conditions -> quiet, designated -> False, inaccessible -> noOne].

5.2. Rules for automated space-use analysis

Once analyzers build the knowledge base, knowledge systems can reason about it using rules for automated space-use analysis. In this run, we developed 33 rules that represent metrics necessary for the mapping, space mapping heuristics (controls of “mapping user activities onto spaces” function), utilization computation method (a control of “computing utilization” function), and policy on utilization (a control of “visualizing the results” function) in F-Logic. Here are some examples of the rules:

- Metrics necessary for the mapping (Computing load of an activity):

  *?ACT002[load -> ?V002] :- ?ACT002:Activity[evtQty -> ?_EQ002, frequency -> ?_FR002, action -> ?AC002], ?AC002:Action[duration -> ?_DUR002], ?V002 is (?_EQ002 * ?_FR002 * ?_DUR002).*

- Utilization computation:

  ?SP309[utilization -> ?UTIL309] :- ?SP309:OccupiableSpace[loadInSpace -> ?_VAL309, openTime -> ?_OPEN309], ?UTIL309 is (?_VAL309 / ?_OPEN309).

For visualizing activity-loaded spaces, we acquired the following values, which were specified in Section 4.4:

- Open time: Since this is a property of spaces and equipment sets, we can query the values from spaces and equipment sets (See Section 4.1).
- Load per space or equipment: The computation of the load is described in Section 4.3 (Step 2).
- Space size: This is also a property of spaces and equipment; we can therefore query the values from spaces and equipment (See Section 4.1).
- Space-use area: The computation of the area is described in Section 4.2.

5.3. Analysis results

Our knowledge system mapped 13 activities onto 9 spaces automatically, generating 26 links between activities and spaces. The automated mapping of user activities onto spaces and utilization computation based on this mapping contribute to the consistency of space-use analysis. That is, utilization is always the same given the same space and user information because our framework formalizes the concepts that are related to three space-use perspectives (space, user, and activity) and their relationships. Figure 6 shows the activity-space mapping diagram of this building. The relationships between activities and spaces are complex, meaning that each activity occurs in at least 1 space and at most 4 different spaces, and each space also accommodates at least 1 activity and at most 6 different activities. The activity-space mapping diagram visualizes those relationships and the utilization implication of spaces in one figure.

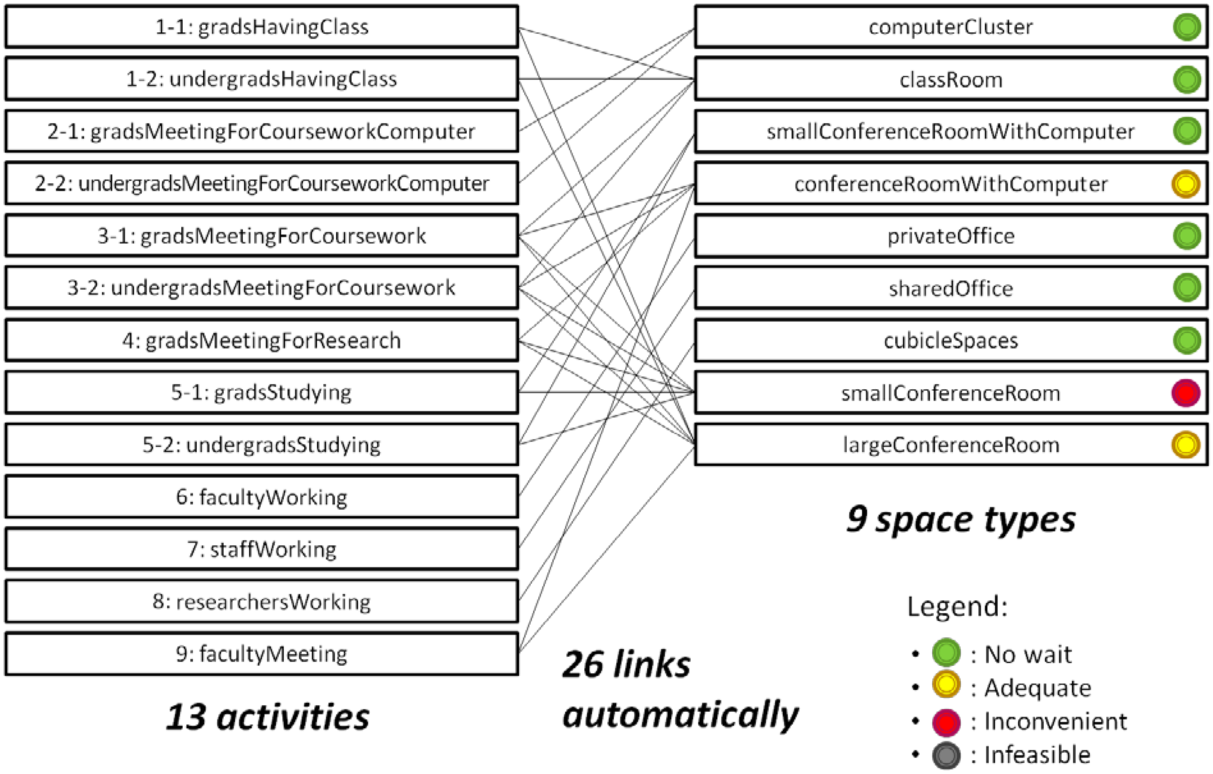

Figure 6. Activity-space mapping diagram of the Y2E2 Building (initial setting)

Analyzers can populate an activity-loaded space by selecting a space in the activity-space mapping diagram or in the architectural design to see the use of the space in detail. For example, Figure 7 represents the activity-loaded space of a conference room with a computer. As shown in the figure, the space accommodates 4 activities, i.e., faculty meeting for 0.23 hours, graduates meeting for coursework for 1.48 hours, graduates meeting for research for 2.03 hours, and undergraduates meeting for coursework for 0.87 hours. The utilization of this space is 58%, which implies that those activities may need to be scheduled in this space. The space-use areas those activities require are much less than the size of this space (286 ft^2), which means that the size of the space can be reduced without affecting the space-use of those activities.

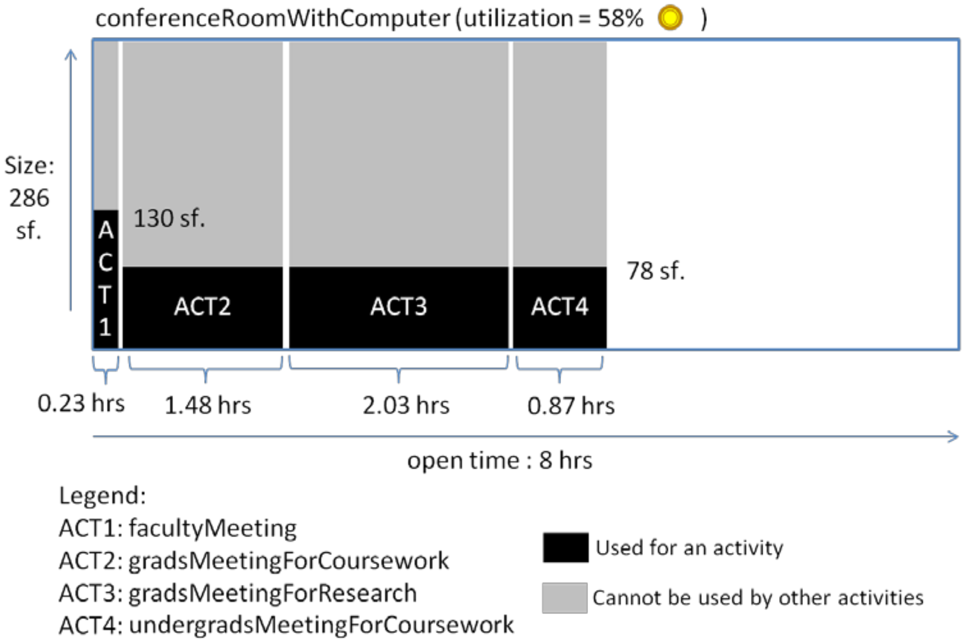

Figure 7. Activity-loaded space of the conference room with a computer

Utilization of each space is summarized in Table 4. The implication of utilization is visualized in the architectural design, as shown in Figure 8. Thus, our framework displays the activity-space mapping diagram, activity-loaded spaces, and the summarized utilization in the architectural design visually, which enhances the transparency of space-use analysis. Since the utilization of small conference rooms is 99% (i.e., its status is classified as "inconvenient"), the spatial design and/or the space usage of the Y2E2 Building should be modified by iterative refinement with the assistance of automated space-use analysis.

Table 4. Utilization summary table of the Y2E2 Building

Space	Utilization	Implication
Computer cluster	20%	No wait
Classroom	46%	No wait
Small conference room with a computer	44%	No wait
Conference room with a computer	58%	Adequate
Private office	40%	No wait
Shared office	50%	No wait
Cubicle space	50%	No wait
Small conference room	99%	Inconvenient

Large conference room	74%	Adequate

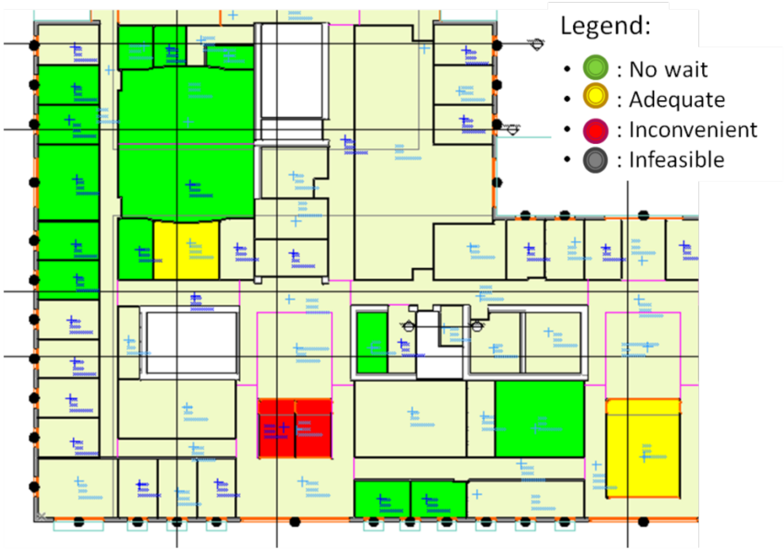

Figure 8. Utilization summary in the architectural design of the Y2E2 Building (initial setting)

5.4. Iterative refinement in spatial design and space usage

In this trial run, we developed two options to respond to the unacceptably high utilization of small conference rooms in the initial setting. The first option is to increase the number of small conference rooms from 2 to 3 while maintaining the gross area of this building by reducing the size of a large conference room (546 ft^2 to 389 ft^2). If the first option does not reduce the utilization of small conference rooms to an acceptable level (i.e., "no wait" or "adequate" status), then the second option would be to maintain the first option but to prevent undergraduate students from using small conference rooms and require them to find other conference rooms for their individual study. Please note that the first option is a change in the spatial design (i.e., space information), and the second option is a change in the space usage (i.e., user information). Automated space-use analysis must be able to update the utilization according to changes in both spaces and users.

To test these options, we first changed the knowledge base according to the first option. Our knowledge system then mapped activities onto spaces and computed the utilization of spaces automatically. Figure 9 is the activity-space mapping diagram of this scenario that applies the first option to the initial setting. The system deleted 2 links (the links between graduates having classes and a large conference room and between undergraduates having classes and a large conference room) from the initial setting because those activities require any space that is larger than 400 ft^2. These changes in mapping and the increased number of small conference rooms resulted in changes in utilizations of spaces: (1) the utilization of a classroom changed from “no wait (46%)” to “adequate (58%),” (2) the utilization of a large conference room changed from “adequate (74%)” to “no wait (48%),” and (3) the utilization of a conference room with a computer changed from “adequate (58%)” to “no wait (48%).” Although the utilization of small conference rooms dropped by 17%, it remained under “inconvenient” status at 82%.

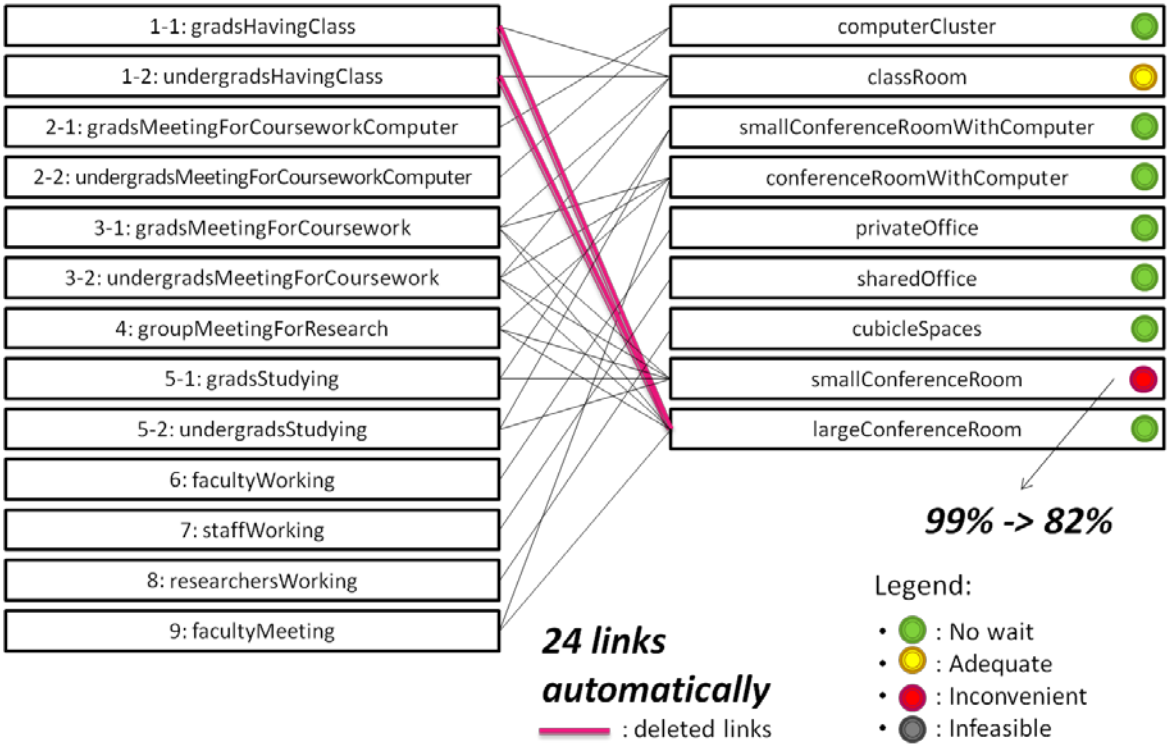

Figure 9. Activity-space mapping diagram of the Y2E2 Building (the first option)

Since with the first option alone the utilization of small conference rooms is still unacceptable, we changed the knowledge base according to the second option. As a result, our knowledge system deleted 2 links (the links between undergraduates meeting for coursework and small conference rooms and between undergraduates studying individually and small conference rooms) and added 2 links (the links between undergraduates studying individually and conference rooms with a computer and between undergraduates studying individually and a large conference room), as shown in Figure 10. As a result, the utilization of small conference rooms changed from "inconvenient (82%)" to "adequate (68%)" while maintaining utilizations of all other spaces at an acceptable level. The summary of the iterative refinement and its impact on the space-use is shown in Table 5. The iterative refinement process described in this section demonstrates the efficiency of our system: when clients or architects change any space and user information that affects space-use, our system can immediately track the changes and update space-use because it has a formalized space-use analysis process.

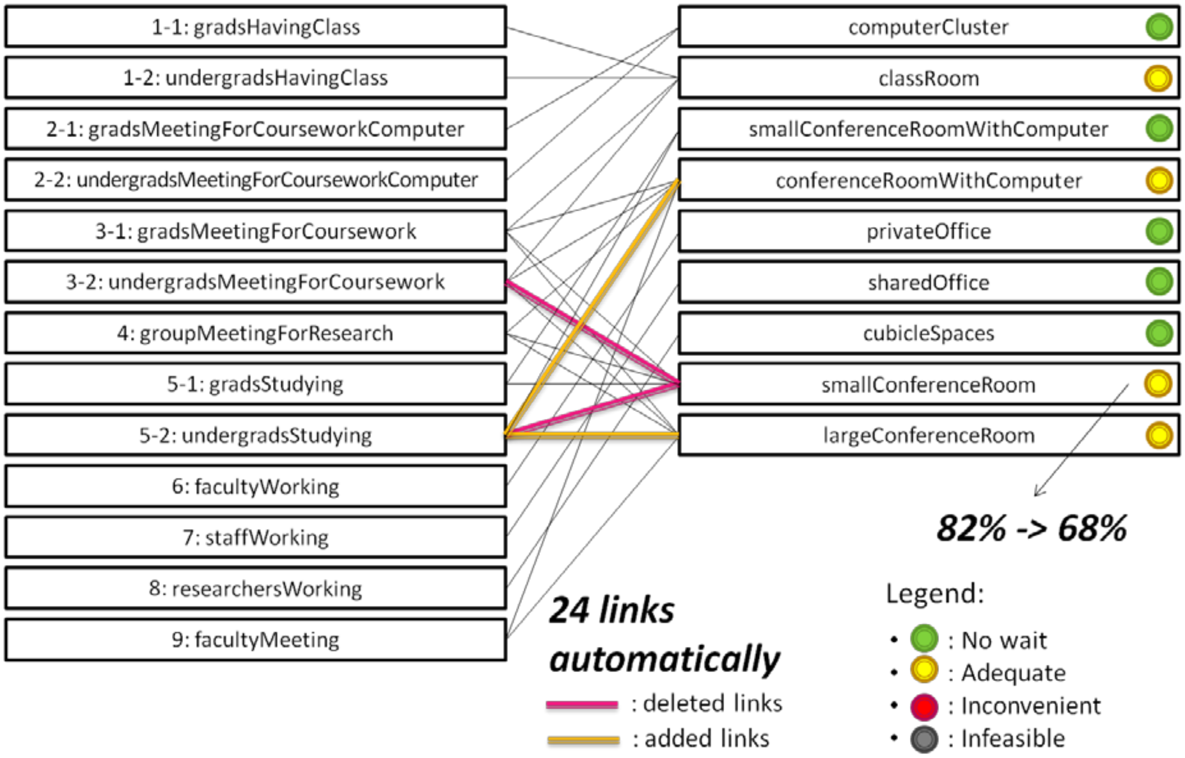

Figure 10. Activity-space mapping diagram of the Y2E2 Building (the second option)

Table 5. Summary of the iterative refinement and its impact on the space-use in the trial run

Refinement	Initial setting	First option	Second option
Description	N/A	Increasing the number of small conference rooms by reducing the size of a large conference room	Not allowing undergraduate students to use small conference rooms
Impact on the activity-space mapping	N/A (26 links between activities and spaces)	2 links are deleted	2 links are deleted / 2 links are added
Space	Utilization	Utilization	Utilization
Computer cluster	20%	20%	20%
Classroom	46%	58%	67%
Small conference room with a computer	44%	37%	38%
Conference room with a computer	58%	48%	63%
Private office	40%	40%	40%
Shared office	50%	50%	50%
Cubicle space	50%	50%	50%
Small conference room	99%	82%	68%
Large conference room	74%	48%	63%

6. Discussion and conclusion

Decisions about space-use will always be subjective and heavily dependent on the architects' holistic approach to a facility. However, having a formal model that incorporates related information into space-use analysis process is important because this model provides analyzers with a consistent means of assessing and comparing architects' decisions about space-use. In addition, due to its consistency, this formal model can be calibrated from real usage data and therefore strengthened to complement its reductive approach.

In this paper, we have proposed a knowledge-based framework for automated space-use analysis to enable analyzers to predict and update the utilization simultaneously considering these three perspectives with computational assistance to support clients' and architects' decision-making about design. This framework includes the formalization of the concepts for space-use analysis (i.e., spaces, equipment, users, user activities, actions, spatial requirements, and space utilization), the ontological relationships among the concepts, and the automated space-use analysis process using the concepts. We have suggested a new tuple of <User>, <Action>, and <Spatial requirements> as a representation of user activities, which are accommodated by spaces or equipment that satisfies spatial requirements of the activities. The automated space-use analysis process has the following four functions: “building the knowledge base,” “mapping user activities onto spaces,” “computing utilization,” and “visualizing the results.” We have demonstrated the effectiveness of the proposed framework through a trial run on select areas in the Y2E2 Building at Stanford University. Our results show that, compared to conventional methods, the proposed framework leads to greater consistency, transparency, and efficiency in space-use analysis. In addition, our proposed framework has been developed based on knowledge representation and reasoning which has generality as one of its innate strengths, because it aims to develop the right degree of abstraction of domain knowledge (in this research, concepts for space-use analysis and their relationships) and use the abstraction recursively within the defined world (in this research, office and educational buildings) [12].

Since this framework formalizes semantic relationships among different perspectives, connecting this framework to other computational models can reduce analyzers’ efforts to build a project-specific knowledge base. A Building Information Model (BIM), for example, provides a computational representation of an architectural design, and consequently, space information that is stored in BIM as properties (e.g., space size, space type, open time) can seamlessly feed into this framework. A declarative spatial reasoning framework (CLP(QS)) that allows qualitative spatial reasoning to interface with declarative programming languages [36] and a three-level formalization (conceptual, qualitative, and quantitative) for design artifacts and specification of design requirements based on the formalization [37] will allow analyzers to formalize spatial knowledge (equipment, space, and spatial requirements) as a high-level abstraction and will allow computers to reason about the spatial knowledge on a quantitative level that is connected to BIM. Having a database of the knowledge base that is sortable by various factors, such as project types and regions where the project are conducted, can also reduce analyzers’ effort to build the project-specific knowledge base. Such a database would be more useful when analyzers intend to apply space-use analysis in early design phases, where information about users, user activities, and spaces are often insufficient for building a project-specific knowledge base.

Our work provides a foundation for automated space-use analysis that assists iterative refinement of the design. To achieve the full potential of our work, the functions of the space-use analysis process should be defined in detail to facilitate its use in practice. For example, space mapping heuristics need to be elaborated because this paper assumes that spatial requirements of a user activity should be entirely satisfied by a space to trigger the mapping between the activity and the space. In addition, the concepts for space-use analysis should also be further elaborated to include stochastic features (e.g., fluctuating numbers of users), more properties that affect space-use (e.g., the location, the geometry of spaces), and start/end time of user activities.

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