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Towards More Accurate Space-Use Prediction: A Conceptual Framework of an Agent-Based Space-Use Prediction Simulation System

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Abstract: Size of building has a direct relationship with building cost, energy use and space maintenance cost. Therefore, minimizing building size during a project development is of paramount importance against such wastes. However, incautious reduction of building size may result in crowded space, and therefore harms the functionality despite the fact that building is supposed to satisfactorily support users' activity. A well-balanced design solution is, therefore, needed at an optimum level that minimizes building size in tandem with providing sufficient space to maintain functionality. For such design, architects and engineers need to be informed accurate and reliable space-use information. We present in this paper a conceptual framework of an agent-based space-use prediction simulation system that provides individual level space-use information over time in a building in consideration of project specific user information and activity schedules, space preference, ad beavioural rules. The information will accordingly assist architects and engineers to optimize space of the building as appropriate.

Keywords: space planning, spatial choice, activity-based model, agent-based modelling, space-use prediction

I. INTRODUCTION

The addition of every square metre of building space gives rise to environmental and economic costs in the increasingly urbanized built environment. Annually, (non-domestic) higher education (HE) buildings in the United Kingdom necessitate the maintenance cost of £53.40 per square metre (SMG, 2005) along with an energy consumption of 318 kWh per square metre (Environmental information 2012/2013 from Estates Management Statistics). Minimizing building space has therefore been of growing importance for several decades as people strive to achieve economic and environmental sustainability. However, sustainability and functionality in the built environment often conflict with each other. Overemphasis on sustainability may lead to impaired functionality in buildings, with the insufficient supply of space for building users even though building space is supposed to satisfactorily meet their needs and support their activities during its occupancy. Finding a well-balanced design solution is therefore important at an optimum level which minimizes building space in tandem with providing sufficient space for its functionality.

However, it is not a simple task for architects and engineers to come up with optimum design solutions for efficient space-use in a building, not only because space-use is different from one space to another but also because it is the outcome of a complex interaction process between the user, user activity, and the space itself [1]. Therefore, building space is prone in practice to be crowded or underutilized, or to alternate between these extremes over time). For this reason, in the built environment an accurate space-use prediction information during a project development is a vital requirement, by which architects and engineers can be assisted to detect potentially crowded or underutilized space in a building, to do so in a quantitative way, and accordingly to modify or eliminate not only unnecessary space but also unnecessary MEP (Mechanical, Electrical, and Plumbing) systems.

However, existing theories exhibit speed, granularity, or accuracy limitations in predicting space-use. For example, a guidelines approach does not explicitly consider user activities even though they play a critical role in understanding space-use [2]. Workplace planning [3] and user simulation [4] require architects to manually track information about where user activities will occur. Although space-use analysis [5] can generate and update such information automatically, it computes utilization by space type (e.g., meeting room, classroom) level rather than space instance (e.g., classrooms A, B) level. In addition, it cannot simulate virtual users' movements in a design over time. To address the limitations of existing theories, this study presents a conceptual framework of an agent-based space-use prediction simulation (ASUPS) system with which we envision more reliable and realistic space-use prediction in a building. This framework contributes to a long-term goal to provide architects and engineers with more accurate individual-level space-use information over time in a building, by displaying where and how long virtual users stay around building over time based on their space preference, behavioral rules, and activity schedules. The information will accordingly assist architects and engineers to optimize space of the building by modifying design or reducing unnecessary space at the level that do not harm its functionality.

II. BACKGROUND

To provide people with information on the use of space, two major research areas, namely building simulation and space planning, have led the way. In both areas, predicting space-use has become more realistic and

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accurate from occupancy modelling [6], [7] and a guideline approach [2] to user simulation [4] and space-use analysis [5], by considering more properties of, and relationships between, users, user activities, and space. However, even advanced versions of the two research areas, namely user simulation and space-use analysis respectively, do not sufficiently consider properties and relationships between users and space. Table 1 shows what features of users, user activities, and space are incorporated as predictors in the two models. A big difference between the two approaches is the metrics used in prediction. As space-use analysis focuses on space-utilization, the duration and frequency of activity are considered, whereas user simulation considers activity duration from start to finish as it is interested in occupancy schedules. However, for linking space to activity, a common feature is that the models take into account the activity's functional requirements (i.e., spatial requirements such as activity type, equipment, group size).

TABLE 1
Considered elements in space-use analysis and user simulation

	User	User activity	Space
	Important, regular user	Activity type	Space type related to activity type
Space use analysis	Job	Duration	Space size (i.e., floor area)
		Frequency	Equipment
		Equipment	Open hours
		Group size	Utilization
	Employee, guest	Activity type	Space type related to activity type
User simulation	Gender and age	start and end time	Space size (i.e., the number of seats)
	Job	Duration	Equipment
		Equipment	Location
		Group size	Occupancy

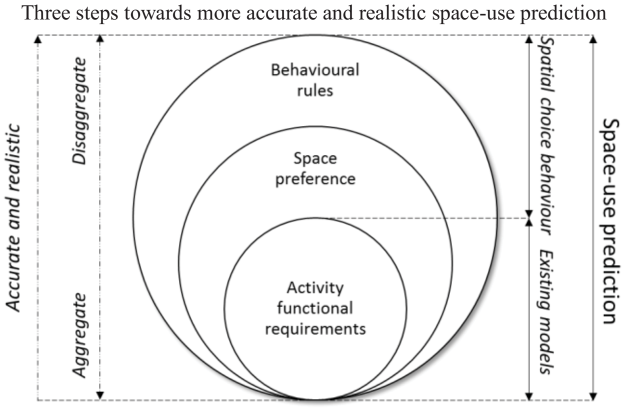
This procedure may be clear enough to display space-use in office buildings where building users have their own designated workstations, although users still need to make spatial choices for meeting activities when these take place. However, the process is not suitable in situations where many spatial choices account for space-use, such as higher education buildings and even office buildings where a 'hot-desking' system has been adopted. Indeed, when there are several spaces meeting the functional requirements of a variety of activities, space-use analysis evenly distributes the activity load across the spaces, while user simulation chooses the nearest space. Both approaches are obviously unrealistic.

The main limitations of existing models result from failure to account for the properties of, and for the relationship between, users and space. More specifically, the models do not sufficiently consider users' spatial choice behaviour, although in reality users choose spaces according to their preference. In addition, building space classifications do not reflect space attributes (e.g. noise level and the view from the windows), so that space preferences cannot be considered according to differences between spaces. Therefore, spaces that differ in their attributes are nevertheless regarded as the same type of space.

III. A CONCEPTUAL FRAMEWORK

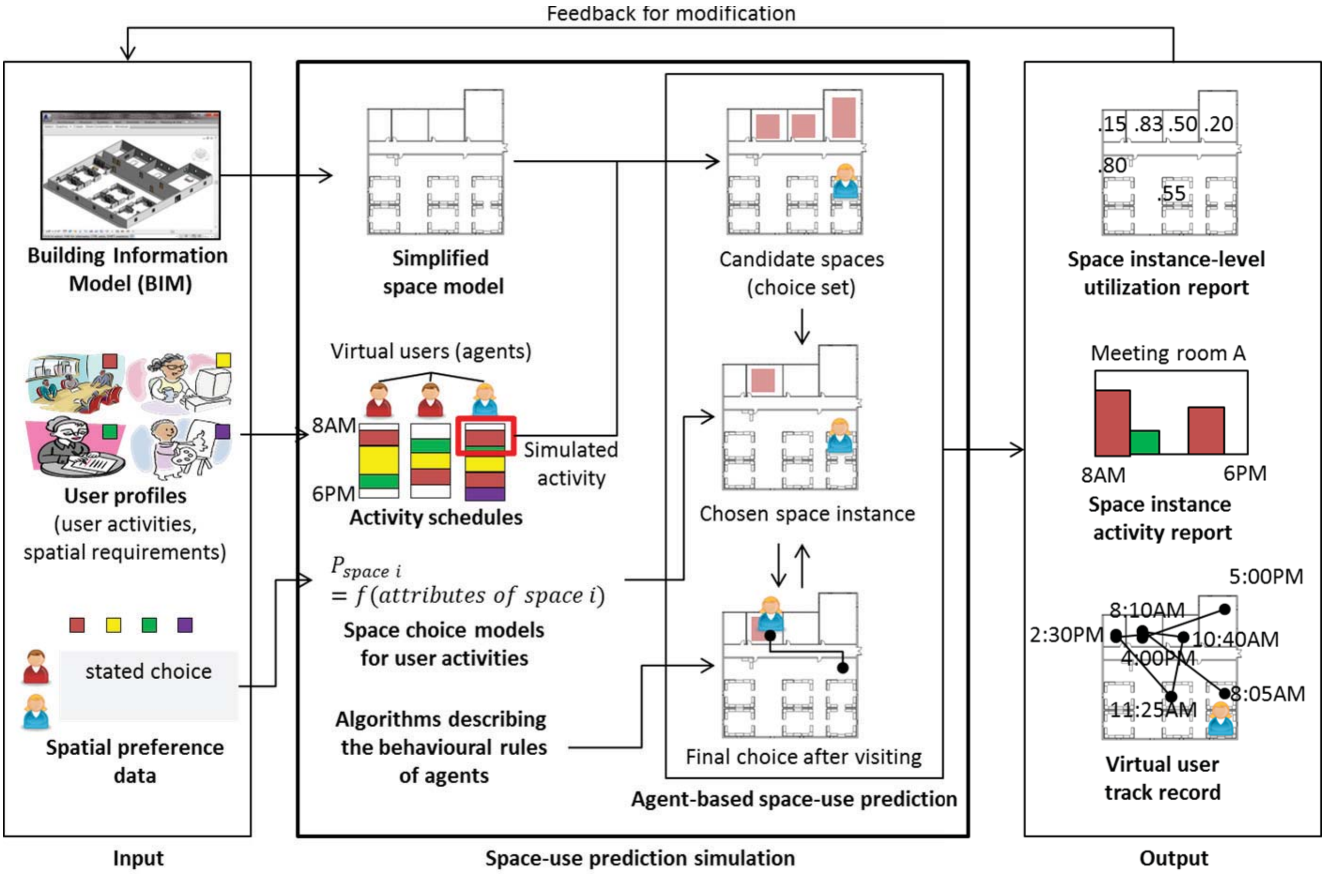
Towards more accurate and realistic space-use prediction, spatial choice behaviour should be well understood and modelled in a systematic and quantitative manner. For this, we present three steps of space-use prediction as shown in Figure 1. Existing approaches cover the first step, which links activities and spaces when an activity's functional requirements are satisfied in the spaces as mentioned earlier. In the second and third steps, spatial choice behaviour is involved in space-use prediction. In moving from the first step to the second step, the properties of users, activity and space and their relationships need to be more fully considered and modelled. That is, users, activity and space need to be more accurately classified with reference to their space preferences and space attributes, and the relationships between them need to be measured so that we can understand spatial choice behaviour. Particularly, in the third step, space-use by each user is simulated over time subject to behavioural rules (e.g., habitual behaviour and satisficing). However, such rules should be carefully approached in a systematic manner. If not, it would be easy to produce biased information because those behavioural rules are often neither systematic nor predictable. In addition, space attributes are classified into two types in response to variations of space attribute over time: they may be dynamic (time-dependent, varying over time), or static (time-independent, constant over time).

FIGURE 1
Three steps towards more accurate and realistic space-use prediction



In consideration of the three steps above, we developed a conceptual framework of the ASUPS system

FIGURE 2
Agent-based space-use prediction simulation (ASUPS) system: it integrates space choice modelling and agent-based modelling to simulate space instance-level and individual-level space-use.



as shown in Figure 2. In the ASUPS system, virtual users choose a space instance for their activities autonomously based on their space preference. Unlike user simulation, the ASUPS system maps user activities onto a space instance (e.g., meeting room A, meeting room B) in a stochastic manner according to spatial choice behaviour. ASUPS system takes a building information model (BIM), project specific user profiles, and space preference data as inputs and provides architects with a space instance-level utilization report, a user activity report for each space instance, and a track record for each virtual user as outputs.

Space-use prediction simulation necessitates the integration of choice modelling and agent-based modelling. Space choice models provide the probability of a case in which a user chooses a space instance with a set of space attributes for performing an activity. The ASUPS system must develop space choice models for each pair of user activities and user types based on space preference data, which contain information about users' space choices for performing an activity among "mutually exclusive discrete alternatives," i.e., space instances [8], [9]. Space choice models can be embedded in the system to ease architects' burden of gathering space preference data. Space-use simulation also adopts agent-based modelling to allow virtual users to choose space instances autonomously as they move around in the simplified space model according to their activity schedules. Agent-based modelling is a good fit for space-use prediction simulation because there are heterogeneous agents (i.e., users) whose behaviour is nondeterministic at a microscopic level [10] and who interact with the unique environment (i.e., a design) and update their beliefs [11]. In the ASUPS system, a user activity is simulated in the following steps: First, a virtual user identifies candidate space instances for a given activity based on space-use analysis; that is, all space instances that satisfy the activity's functional requirements are in the user's choice set. Second, the user chooses one space instance autonomously using a space choice model for the activity and user type. Third, the user moves to the chosen space instance and determines to use it. If the user determines not to use the space instance (e.g., the space is too noisy or being used by someone else), he or she might choose another space instance from the choice set. The user may also choose to wait until a space instance becomes available for his or her activity. Fourth, according to behavioural rules, users decide whether or not they come to the same space instance for the same activity at next visit.

IV. CONCLUSION

It is easily discovered that many indoor spaces are rarely used or even altogether unused for long periods of time, although the conditions of those spaces continue to be maintained for use, which in turn incurs maintenance costs and energy consumption. At the same time, there are constantly crowded spaces that have detrimental effects upon building users' work productivity. Such an imbalance of space-use substantially results from errors in space-use prediction. Accurate space-use information during a project development helps architects and engineers to find better design solutions for efficient space-use in buildings.

However, predicting space-use entails more than simply relying on the architects' expertise and experience, because building-users' space-use is the outcome of a complex process of integrating users, user activity and building space. In this regard, the ASUPS system provide architects and engineers with individual-level space-use information over time in a building, by displaying where and how long virtual users stay around building over time based on space preference, behavioral rules, and project specific activity schedules. The ASUPS system can be used in many areas not only for space efficiency because space-use is related to many building performance. For example, the information from the system would be useful for the user-presence information that constitutes essential data in building simulation tools. With help of the ASUPS, we are able to achieve better environmental and economical sustainability in the built environment.

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