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Modeling space preferences for accurate occupancy prediction during the design phase

Seung Hyun Cha[a], Koen Steemers[b], Tae Wan Kim[c,*]

[a] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong
[b] The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge, 1–5 Scroope Terrace, Cambridge CB2 1PX, UK
[c] Division of Architecture and Urban Design, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea

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ABSTRACT

The accurate prediction of occupancy during the design phase of a building helps architects to improve space efficiency by eliminating the possible under-utilization and over-crowding of space during the design use phase. However, existing models exhibit limited accuracy in occupancy prediction. A major reason for this limitation is that spatial-choice behavior is ignored or oversimplified. We therefore developed a space-preference model to explain spatial-choice behavior, with a particular focus on individual work-related activities. For this purpose, we conducted a discrete-choice experiment: 2048 observations of spatial choices were collected, and a conditional logit model was used to model space preferences. The application of the space-preference model was illustrated by two case examples, with which the merits of the model were highlighted. It was then validated in a predictive success test and a case study. The model will help architects to assess potential over-crowding and under-utilization of space according to different design options.

1. Introduction

Sustainability is a key issue in the architectural, engineering, and construction (AEC) projects, as buildings have a large carbon footprint throughout their life-cycle from design to use [45]. Occupancy information can help architects and engineers to achieve sustainable design by finding an optimal design solution [19]. It is not a simple task to predict occupancy, owing to various occupancy patterns and many-to-many relations between user activities and spaces [32]. Although experts' empirical experience or guidelines generated on the basis of similar previous projects still play an important role in predicting occupancy [32], they are prone to mislead architects and engineers about occupancy because many aspects of user activities are not considered systematically.

Thus, attempts have been made to provide more systematic and reliable occupancy information for use in building design. In the domain of building simulation, the presence of occupants is modeled on the basis of parameter-based modeling [65] or multi-agent models [47]. User-simulation models [23,24,60] also display different occupancy schedules based on building users' activity schedules. In the domain of space planning, on the other hand, both workplace planning [50] and space-use analysis [30,31] predict occupancy by taking into account the integration between users, user activities, and spaces. These models compute the utilization rate of each space by mapping the load of user activities onto space types that meet the requirements of those activities (in terms, for example, of equipment or size).

However, the accuracy of existing occupancy prediction models is limited. A major reason for this inaccuracy is that, despite its importance in achieving realistic and accurate occupancy prediction, the influence of space preference on spatial-choice behavior is either ignored or oversimplified. Although Goldstein et al. [24] have modeled spatial choice by considering a distance-cost function, it is evident that the distance between the user and the space is not the only factor governing spatial-choice behavior. This is the consequence of a much more complicated decision-making process. In reality, building-users select a space from among space alternatives (e.g. room A or room B) meeting the requirements of their activities according to space preferences [9]. In addition, users can follow different preferences, even for the same activity. A preferred space is determined largely on the basis of its characteristics. The principal determinants of the characteristics of each space are found in the architect's building design; they include space location, size, furniture, and space-use policy planning. Sometimes, however, even space preferences can be partly or completely ignored in making spatial choices because of aspects of human behavior.

For this reason, Cha and Kim [10] proposed three steps to predict

* Corresponding author.
E-mail addresses: seung-hyun.cha@polyu.edu.hk (S.H. Cha), kas11@cam.ac.uk (K. Steemers), taewkim@inu.ac.kr (T.W. Kim).

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space-use in a systematic and realistic manner during the design phase. Existing strategies [30,31,50,60] cover the first step in connecting activities and spaces when those spaces meet the activity requirements. The second step entails modeling space preferences that might differ, both between activities (e.g. group work-related activity or socializing activity) and between users. At the third step, occupancy by each user is simulated over time so as to take into account both time and behaviors (e.g. individual memory, habitual behavior, satisficing, and variety-seeking).

As a contribution to the second step in the direction of more accurate and realistic occupancy prediction, this study aims to develop a model of user space preferences in spatial-choice behavior with a particular focus on individual work-related activities (hereafter 'individual work'). Occupancy simulations for each building-user over time will be the next step in taking both time and behavior into account. Discrete-choice modeling (DCM) theory is drawn on, as it is an efficient platform for displaying choice probability according to elicited preferences through mathematical equations [63]. Based on DCM theory, occupancy probability can be determined systematically by integrating information about space preferences and space attributes. Accordingly, a discrete-choice experiment (DCE) was first designed and conducted. The data were then analyzed and modeled in a conditional logit model [26]. The application of the space-preference model, once developed, was illustrated by two simple case examples, with which the model's merits were highlighted.

Finally, the model's power was tested in two kinds of validation study: (1) a predictive success test to compare the spatial choices predicted by the models with spatial choices in hypothetical cases, which is an appropriate goodness-of-fit measure to explain predictive power [38]; and (2) a case study in which spatial choices predicted by the model were compared with actual occupancy data from the Metaforum building at the Eindhoven University of Technology in the Netherlands. The scope of the exercise was limited to individual work in higher education buildings because the study mainly involved individual work by university students. Nevertheless, the modeling approach can be applied to other types of user activity, building, or location on a project-by-project basis.

2. Background

2.1. Utilization- and schedule-based approaches to occupancy prediction

Multiple approaches have been developed to explore occupancy prediction. Fig. 1 summarizes the development of utilization-based and schedule-based occupancy prediction in two research domains (i.e. building simulation and space planning). As shown in this figure, their common element is a move towards more comprehensive consideration of users, user activity and space. In the field of building simulation, occupancy schedules are predicted as a basic component of building simulation tools in order to understand energy use in buildings [33,44,56]. On the other hand, space planning focuses on computing space utilization, i.e. the percentages of frequency multiplied by the percentages of occupancy [14,50]. Although these studies employ different occupancy prediction metrics, their goal is to predict occupancy in a building as accurately and realistically as possible. No studies were included of occupants' indoor movements focusing mainly on occupant flow efficiency in a building, rather than on occupancy itself, whether in emergency situations [37,48] or in non-emergency situations [34,42].

In the field of space planning, experts' empirical expertise—(a) in Fig. 1—still plays an important role in small projects or in those when there is no guideline to which reference can be made. In practice, however, a guideline approach—(b) in Fig. 1—is commonly employed because the empirical approach has no specific metric. Guidelines are generated on the basis of results from similar previous projects, from post-occupancy evaluations, from surveys, and from the architect's cumulative expertise [32]. Consequently, for similar projects, architects consult guidelines in order to determine the number and size of certain types of space under consideration for the user's requirements [20]. Although this approach is preferred to the empirical approach because it provides metrics by which architects can be guided, aspects of activities such as activity types are not considered systematically.

As an advanced version of office space planning, Pennanen [50] proposed a well-structured workplace planning model—(c) in Fig. 1—based on a generalized theory of space utilization. To adopt this process entails consideration of activity and space properties such as activity load, group size, space type and space size, which are set up by planners. In spite of the advanced formula applied to occupancy prediction the relationship between activity and space is not described clearly enough, as a consequence of the lack of activity definition. In this sense, Kim and Fischer [30,31] proposed space-use analysis—(d) in Fig. 1—which automatically maps each activity onto a space type based on ontological relationships between users, user activity and space. In the space-use analysis, the concepts of users, user activities, space, spatial requirements, and equipment are well defined.

In the field of building simulation, the diversity factor—(e) in Fig. 1 [1]—is an approach mostly used in practice for entering occupancy schedules into building simulation tools. The advantage of this approach lies in its simplicity, since occupancy schedules at the level of the entire building can be predicted by only a few values. Nevertheless, this advantage gives rise to a limitation, in that occupancy schedules at the 'space' level in a building cannot be explained. The unreality of diversity factors has led to the development of more realistic occupancy models using parameter-based modeling—(f-1) in Fig. 2. Newsham et al. [43] developed a simple field-based stochastic model, called the Lightswitch model, in which a time-varying individual occupancy schedule is generated. An enhanced Lightswitch model was proposed by Reinhart [52] for a more realistic assessment of occupants' time-use in a building, taking into account first arrival, last departure, and temporary absence.

Wang et al. [65] suggested a probabilistic model to predict occupancy schedules in single-person offices. A Poisson process with two different exponential distributions was employed for the estimation of, respectively, an occupant's intermediate presence and absence in a room. As a result, it was found that the absence interval is exponentially distributed. Stoppel and Leite [57] also presented a probabilistic occupancy model to identify the characteristics of long vacancy states such as frequency and duration. Sun et al. [59] developed a stochastic model, using a binomial distribution to estimate the total number of office employees working extra hours. In this model (f-1), time-varying day-to-day occupancy schedules were generated; it performs better than a 'diversity factor' approach for displaying occupancy schedules. Moreover, unlike the 'diversity factor' approach, it tackles individual users' occupancy schedules at the 'space' level. In addition, a few physiological activities such as lunch and coffee breaks are taken into account. Although this approach represents some progress towards a realistic occupancy prediction, the greater part of the occupancy profile is fixed and repeated for all weekdays. It is thus an incomplete reflection of the complexity of real occupancy schedules.

For a more realistic occupancy prediction, multi-agent models—(f-2) in Fig. 1—have been used, in which decision-making rules can be encoded either individually or en bloc. Yamaguchi et al. [68] used a Markov chain to exhibit transitions between working states for each individual, thereby approximating the users' presence or absence. Page et al. [47] utilized an inhomogeneous Markov chain to propose a comprehensive model, which represents the time series of each user's presence or absence. Liao et al. [36] suggested an advanced version of Page's model, which is scalable to multiple users and spaces in a building to resolve the Page model's limitation in being applicable only to a single-person office. Wang et al. [64] proposed a model of occupancy simulation that is usable regardless of constraints in terms of the number of spaces and users. The study reduced the amount of input