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Original research article

The systematic identification and organization of the context of energy-relevant human interaction with buildings—a pilot study in Germany

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ABSTRACT

Thermal building simulations serve to optimize the energy consumption of a building during its design phase. Because modern building design offers occupants increasing opportunities to interact with the building in order to adjust internal conditions according to their individual needs, the prediction of these interactions needs to be included in optimization calculations. The way to an adequate consideration of human interaction in building simulations requires that two questions be addressed: First, which contextual factors are impactful to this process, and how are they related to each other? Second, which methods are best suited to predicting energy-relevant interaction based on the knowledge of these contextual factors? This article addresses the first question through the development of a data acquisition and analysis method. The technique is based on “protocol analysis,” which is a method originally developed to generate knowledge about the cognitive processes of humans during task implementation. The proposed method is applied in a pilot-study, which produced valuable, qualitative insights into the nature of the interaction and its relation to context. The results serve to address the second question in that they point to psychological theories that may prove significant for the future conceptualization of a cognitive theory of energy-relevant interaction.

1. Introduction

Since the 1990s, building occupants have been offered increased opportunity by the actual building design to individually interact with the building and adjust the internal environment according to their multiple, individual needs. For example, individually controlled window ventilation has become more popular to save the energy required for operating mechanical ventilation systems, on the one hand, and to take advantage of the relaxed comfort requirements that seem to accompany window ventilation (e.g. [1–4]) and the establishment of personal control (e.g. [5]) on the other. Thus, in modern buildings, the occupant is less a passive recipient than he or she is an interactive ‘agent.’

Thermal simulations are often used to predict the effectiveness of energy-saving measures for buildings. For such predictions, the interactive role of the occupant has to be taken into account, because interacting with a building (such as operating windows or heating systems) will largely influence the building’s energy consumption up to a factor of two (see for example [6–12]). It makes sense to term the type of behavior that influences the building’s energy balance ‘energy-relevant human interaction.’ Other human behavior in buildings is of no relevance for the energy balance.

The use of thermal simulations for energy consumption predictions can be traced back to the 1970s (TRNSYS, for example, one of the most popular simulation systems, has now been developed for over 35 years [13]). Then, performing a thermal simulation mostly meant simulating a purely technical system, e.g. the building and its technical equipment, or the performance of solar collectors, etc. However, nowadays, with the increasing importance of energy-relevant human interaction as a factor in the prediction process, one cannot talk about purely technical systems anymore. This presents entirely new challenges as to the development of thermal simulation algorithms. For the prediction of a building’s performance to be in line with reality, methods have to be advanced in order to include a prediction of human behavior.

In technical systems, cause and effect are linked by the laws of physics. To predict the reaction of a technical system (for example the rise in room temperature) to a particular cause (such as a certain amount of solar radiation penetrating into the room), these laws have to be known and applied. Undoubtedly, the majority

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of the physical laws that affect the energy balance of a building are well-known and considered in the major building simulation packages. To predict energy-relevant human interaction, it generally makes sense to also think of cause and effect. What causes a building's occupant to act in a particular manner, such as to close the sun screen? A potential answer might be that the solar radiation is too intense. A follow-up question could then be: at what intensity does the probability of closing the sun screen increase or decrease? This relationship between solar radiation, its intensity, and the occupant's motivation to operate the sun screen is rather intuitive.

Currently, the most popular approaches used to predict human interaction are mainly based on a mathematical analysis of these simple intuitive relations. Such an approach aims to establish a mathematical relation between a particular variable – solar intensity, for example – and a particular behavior, such as operating the sun screen. These correlations usually result from a statistical analysis of externally observed behaviors, and are transferred into stochastic prediction models that can be integrated into thermal building simulations. For example, such models would attempt to predict the probability of the operation of sun screens based on predictors such as 'sunshine index,' 'illuminance' or 'solar radiation intensity' (e.g. [14–16]), or consider the operation of windows based on predictors such as 'time of year,' 'indoor and outdoor temperature' or 'external humidity' (e.g. [17,18]).

However, there are a number of problems related to *stochastic* models that are based on *external observation* of behavior. Consider the example of a building occupant that operates a particular sun screen. Operation might be motivated by a number of entirely different reasons. For example, closing this sun screen might be motivated by an attempt to mitigate solar radiation that is too intense, transmitting light that causes veiling reflections on the monitor and impairing work progress; by the occupant's wish to enhance his or her privacy; or because of a desire to limit any external distraction. On the other hand, a multitude of reasons could motivate the occupant to open the screen: the room may be too dark; the screen could have been endangered by external wind; the occupant needed external orientation in terms of potential future weather conditions; or he or she was about to leave the room, prompting him or her to open the device. Such examples demonstrate that no information will be generated about the related motives of this behavior merely from externally observing the behavior. Therefore, this example demonstrates the ambiguity of a single action if it is considered in isolation of its context. This ambiguity can only be eliminated if the context of the action is adequately taken into account. But what does 'adequate consideration of context' mean? There are two sides to this issue [19].

The first aspect concerns the question: what contextual factors have to be considered for the prediction of human interaction, and how are they related to each other? So far, the literature has not addressed a systematic approach that would answer this question. Additionally, it is striking that the contextual factors usually considered in current prediction models largely refer to technical aspects (for example, temperature, solar radiation or air quality), and to a much lesser extent to social or psychological dimensions (such as feelings of privacy or security, or the influence of the social system the individual is a part of, or individual attitudes, beliefs, or knowledge). This tendency may be influenced by the traditional engineering view of simulation, which emphasizes technical aspects. However, an incomplete consideration of contextual factors and their interrelations contribute significantly to an unsatisfactory prediction of interaction.

The second aspect of an 'adequate consideration' of context concerns the methods that are used to predict energy-relevant interaction on the basis of the relevant contextual factors. Current prediction models resort almost exclusively to statistical and stochastic methods that link predictors (i.e., contextual factors) to the probability of the execution of a particular human behavior. However, it is questionable whether standard stochastic methods are capable of adequately reflecting the complexity of the relevant context and its relation to behavior. When individuals act, they usually formulate a plan of action that is based at least on both his or her former experiences with that action, in addition to an anticipation of future events. The decision to implement night ventilation during absences from the office, for example, depends on recent experience with the effect of such an action and a prediction of the weather conditions at night and during the following day. These are complex cognitive processes that cannot be easily captured by statistical analysis and stochastic prediction algorithms. Rather, it is plausible that theories and models from disciplines that traditionally deal with the analysis of human behavior – namely, psychology and sociology – are better suited.

Although this introduction focuses specifically on the numerical prediction of energy-relevant interaction for the integration into thermal simulations, a deeper understanding of this behavior is also fundamental to answering some of the more general questions raised by Sovacool [20]: which factors, including, for example, the information available to the actor, the actor's attitudes and history, most influence individual energy consumption? How do people make decisions about energy-relevant actions in buildings, and by what means can these decisions be influenced? In light of these considerations, this paper will propose a set of steps considered essential to better understanding energy-relevant human interaction with buildings.

The first step of this process is the systematic, data-based identification of the contextual factors and their interrelations that influence energy-relevant interaction. This step should not only show externally observable factors, but also establish the relevant inner processes, including the motivations, plans, and knowledge of the actor. Once these contextual factors have been identified, they have to be brought into a meaningful order since context includes an enormous variety of different factors related to each other. Transferring them into a particular order will improve manageability and add meaning to the data.

The second step, which is explored further in future publications, focuses on the transfer of these pre-theoretical, qualitative concepts into scientific conceptualizations of pertinent disciplines, mainly psychology. For example, the above-described process of planning night ventilation – which includes retrieval of knowledge from memory and anticipating future events – can theoretically be conceptualized through system-theoretical action theories, a well-established subdiscipline of Psychology. The benefit of linking the problem-specific, pre-theoretical knowledge regarding energy-relevant behavior in buildings to established scientific disciplines that conceptualize human behavior in general is enormous, since it facilitates taking recourse to empirical data, models, and methods of these disciplines and applying these models and methods to specific problems. Models and methods of disciplines that traditionally deal with human behavior are likely to better conceptualize the influence of a complex context than stochastic models derived from engineering methods. They can "bring more of the phenomena of energy use into the light," and help remove the "blind spot" that is created by a reliance on disciplinary concepts [21,22].

The third step and long-term aim – also beyond the scope of this publication – comprises the development of a numerical cognitive model of human energy-relevant behavior in buildings. Such a model can be integrated into thermal building simulations not only to more reliably predict energy consumption of newly planned buildings, but also to forecast the effects of specific policies on energy use.

This article summarizes the results of the first step; i.e., the development and exemplary application of a data acquisition