OCCUPANTS' SPACE HEATING BEHAVIOUR IN A SIMULATION-INTERVENTION LOOP

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ABSTRACT

eViz is a large UK research project, which aims to reduce building energy demand through visualizations. In eViz, building performance simulation is adopted to visualise the impact of occupants' behavioural change on the energy consumption of their buildings. In this project, occupants' space heating behaviour is considered to have significant energy saving potential, due to its great impact on the house energy consumption during the wintertime.

This paper presents some initial results from the eViz project. Firstly, a simulation-intervention loop is established, which drives behavioural change of building occupants to save energy. In this loop, building performance simulation is used to visualise the impact. Secondly, the result from a thorough review of relevant literatures supports that occupants' operation of space heating in actual buildings is a complex behaviour, as 27 factors could possibly influence this behaviour. However, in traditional building performance simulation, most of these factors have not been seriously considered, when modelling occupants' space heating behaviour. Therefore, lastly, to handle this issue in eViz, a preference-based simulation approach is chosen and the use of this approach in building performance simulation is demonstrated in this paper, using an example room.

INTRODUCTION: THE EVIZ PROJECT

Reducing the energy used for space heating is a challenge as it is not only related to the technical performance of the building and its heating systems and indoor and outdoor environmental conditions, but also strongly relates to the behaviour of occupants (Meier & Rehdanz, 2010; Yao & Steemers, 2005). The representation of the latter in building performance simulation presents a significant challenge.

The work described in this paper is part of the interdisciplinary eViz project (eViz, 2013). eViz (Energy Visualization for Carbon Reduction) will use energy visualizations in order to achieve changes in occupant behaviour which then should lead to energy demand reductions in buildings. eViz anticipates to deliver visualizations to building occupants through APPs running on mobile devices.

In order to deliver energy visualizations that steer building occupants towards a different, energy saving behaviour, eViz will need to assess the various courses of action that are available. To this end, eViz will need to: 1) capture the actual energy use behaviour that is displayed by an occupant; 2) predict the effect of any changes to this energy use behaviour which will be provided through building performance simulation; 3) provide visualizations to the building occupants; 4) observe whether the suggested changes in behaviour are actually implemented in the occupants' real life, and 5) discern whether energy savings are achieved (Figure 1).

This paper presents a pilot study that investigates the complexity of occupants' space heating behaviour in actual buildings, and how this behaviour is traditionally modelled in current building performance simulation. As a first stage towards setting up the observe-simulate-visualize-verify loop of eViz it first reviews the current state-of-the-art in occupant behaviour in residential buildings, focussing specifically on the factors influencing the frequency, area and magnitude of space heating behaviour. Secondly, the current approaches to the representation of these factors influencing occupants' space heating behaviour in building simulation tools are discussed. Lastly, a preference-based simulation approach is introduced to make the modelling of occupants' heating behaviour more realistic in the simulation, with a demonstration of its implementation for an example room. The current contribution reports an initial phase of the eViz project that will ultimately guide the research direction.

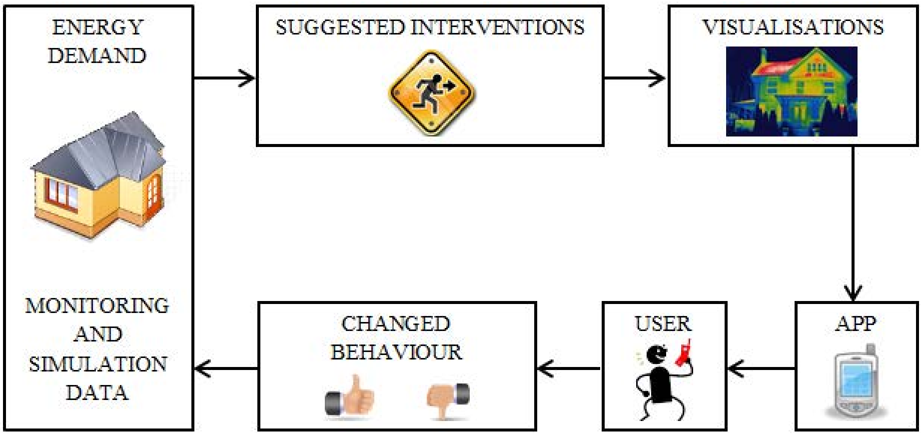

Figure 1 eViz loop

METHODOLOGY

To achieve the aim of capturing occupants' space heating behaviour through simulation, a thorough literature search of the potential factors influencing occupants' space heating behaviour in residential buildings is completed. The amalgamated results of previous studies, either confirming or rejecting a causal relationship between the factor and space heating behaviour, are used to establish a series of important 'factors', which need to be incorporated in building performance simulation. In addition, the paper reviews how these factors are currently implemented in traditional building simulations. In each section, the findings as well relevant discussions are presented simultaneously.

BACKGROUND: THE ROLE OF OCCUPANT BEHAVIOUR IN BUILDING ENERGY USAGE

Occupants affect the performance of buildings in two ways: "passively" and "actively" (Mahdavi, 2011). Passive effects describe occupants' presence in a building as a source of heat, water vapour, carbon dioxide etc., and active effects describe occupants' manipulation of control devices such as windows, shades, radiators and fans to bring about desirable indoor conditions.

While building simulation tools represent all key heat and mass transfer processes in buildings, it has been noted that there is often a discrepancy between simulated and measured energy use (Bordass, Cohen & Field, 2004; Bordass et al., 2001; Demanuele, Tweddell & Davies, 2010; Menezes et al., 2011).

The reasons for this discrepancy are currently under further investigation. Apart from consequences of assumptions, simplifications and numerical processes, it has been suggested that it is also strongly related to the role of occupant behaviour (Fabi et al., 2011). In order to investigate the role of occupant behaviour on the energy performance of buildings, a number of studies (Branco et al., 2004; Emery & Kippenhan, 2006; Marchio & Rabl, 1991; Norford et al., 1994; Seligman & Darley, 1977; Seligman, Darley & Becker, 1978) have focused their attention on the energy consumption of identical buildings. The results show that the variation between actual and predicted energy use is mainly related to the final build quality, the building systems installed and the manipulation of these systems by the building occupants.

As the focus of eViz is on changing occupants' behaviour in buildings in order to achieve energy demand reductions, the passive effects of occupants, which are hard to control, are currently outside the scope and instead the emphasis is placed on the modification of the active behavioural effects.

While many factors contribute to the energy demand of a dwelling, this paper only focuses on the energy used by the space heating system, due to its great contribution during the wintertime. Generally, this part of energy is related to control settings (the operation of the space heating system with respect to frequency, area and magnitude), physical factors (efficiency of the building fabric/heating system), and environmental conditions (outdoor climate). However, the deciding factor is the human occupant of the indoor space, who judges the thermal comfort conditions and changes control settings to achieve desired indoor environmental conditions. In this paper, this active behaviour is named as 'space heating behaviour', which leads to the definition of three interrelated variables: setpoint temperature, number of rooms heated and heating period. Even so, currently not enough is understood about how space heating behaviours relate to other underlying factors (e.g. gender of occupants, dwelling types, occupancy etc.) to incorporate these explicitly in performance simulation applications in order to achieve realistic simulation-based building performance predictions.

At present, the traditional way of modelling occupants' space heating behaviour in simulation tools is based on assumptions directly applied to the building energy balance. In the following sections, an investigation is carried out on what factors can possibly influence occupants' space heating behaviour in actual residential buildings, and how those factors, if at all, are currently being handled in building performance simulation.

REVIEW OF FACTORS INFLUENCING SPACE HEATING BEHAVIOUR

Table 1 presents the findings of a thorough literature search of the potential factors influencing occupants' space heating behaviour in residential buildings. In total, 38 papers related to this behaviour have been found. Based on the results from these papers, a discussion is made in this paper, with respect to the influence of potential factors on occupants' space heating behaviour.

Table 1
Literatures evaluating the factors influencing occupants' space heating behaviour

Potential influencing factors	Does the factor influence occupants' space heating behaviour?		
	Total No. of papers	**No. of 'Yes' papers**	**No. of 'No' papers**
01. Outdoor climate	5	5	0
02. Room type	8	8	0
03. Dwelling type	6	6	0
04. Dwelling age	4	3	1
05. Dwelling size	1	0	1
06. House insulation	5	5	0
07. Previous dwelling type	1	1	0
08. Type of heating systems	4	4	0
09. Type of temperature control	7	7	0
10. Energy use recording	4	3	1
11. Occupant age	10	9	1
12. Occupant Gender	1	1	0
13. Occupant Cultural/Race	2	2	0
14. Occupant Education level	2	1	1
15. Ownership	2	1	1
16. Household size	8	4	4
17. Family income	7	3	4
18. Thermal sensation	3	2	1
19. Time of day	7	7	0
20. Occupancy	6	6	0
21. Time of week	2	1	1
22. Type of heating fuel	1	0	1
23. Perceived IAQ and noise	1	1	0
24. Social grade	1	1	0
25. Health	1	1	0
26. Year/Season	1	0	1
27. Heating price	1	0	1

In Table 1, Columns 2 to 4 provide a series of numbers that establish the current research on each factor. Column 2 lists the total number of collected literatures with a suitable discussion on the influence of each factor. Column 3 provides the number of literatures that confirm the influence of the factor on occupants' space heating behaviour, and Column 4 indicates the number of studies that reject the influence of that factor.

From Table 1, it can be seen that within these papers, 27 possible factors have been considered in existing studies to have influence on occupants' space heating behaviour, but with varying conclusions regarding their casual effect. Within these potential factors, some have been investigated more frequently than others. For individual factors, not all of the previous studies agree on whether they have an influence on space heating behaviour or not. Although the number of previous studies for each factor varies, the following factors could be considered to be unambiguously influential on occupants' space heating behaviour in residential buildings, namely *outdoor climate*, *room type*, *dwelling type*, *house insulation*, *type of heating system*, *type of temperature control*, *occupant age*, *time of day*, and *occupancy*, as the number of studies confirming the influence is much higher (more than 3 studies) than the number of studies rejecting the influence. The remaining factors could be classified into three categories: 1) the influence of that factor had been confirmed in a small number of existing studies and without papers rejecting the influence, and this category includes *previous dwelling type*, *occupant gender*, *occupant cultural/race*, *perceived IAQ and noise*, *social grade*, and *healthy*; 2) the influence of that factor had been rejected in a small number of existing studies and without papers confirming the influence, and this category includes *dwelling size*, *type of heating fuel*, *year/season*, and *heating price*; 3) the influence of that factor had been confirmed and rejected in nearly equal numbers of existing studies, and this category includes *dwelling age*, *energy use recording*, *occupant education level*, *ownership*, *household size*, *family income*, *thermal sensation*, and *time of week*. The factors in these three categories still need further studies to identify their influence. Therefore, at this time, it is not possible to exclude any of the 27 possible factors of occupants' space heating behaviour, based on the results from existing studies.

REPRESENTATION OF OCCUPANT BEHAVIOUR IN SIMULATION TOOLS

In the last section, 27 possible factors have been identified to have influence on occupants' space heating behaviour in residential buildings, based on a thorough review of relevant literatures. In this section, a discussion is made on how these factors are currently used in building performance simulation.

Figure 2 links the 27 factors to a schematic process for building performance simulations, which consists of the definition of a virtual experiment, the production of simulation output in terms of observable states, and finally postprocessing or aggregation of these observable states into performance indicator values, following the structure presented by Augenbroe in (Hensen & Lamberts, 2011).

Figure 2 mainly shows three levels of information. The core level, which is enclosed by the red dotted line box, shows the process of building performance simulations. Therefore, this level is called the simulation procedure level in this study. Normally, there are three sequential steps in this level. Firstly, Step 1 prepares two parts of information for the simulation: information on building representation and information on operational conditions. Occupants' space heating behaviour, which is the behaviour investigated in this paper, belongs to the second part of information, as highlighted in Figure 2. Based on the information prepared in Step 1, building performance simulation tools will then generate some observable states in Step 2, such as heating load, humidity load, environmental factors indoors and pollutant emissions. In the last step, Step 3, the observable states will be aggregated to higher level information (performance indicators), for example, energy consumption per annum, overheating hours, peak load or others.

In the second level, which is outside the red dotted line box but enclosed by the blue dash line box, many traditionally included inputs for the building performance simulation are defined. Therefore, this level is called simulation inputs level. From the above figure, it can be seen that some factors discussed in this paper have been used in traditional building performance simulation, as they are connected with one or more information boxes inside the simulation procedure level. However, only a few of them, such as room type, occupancy etc., are currently connected with the modelling of occupants' space heating behaviour.

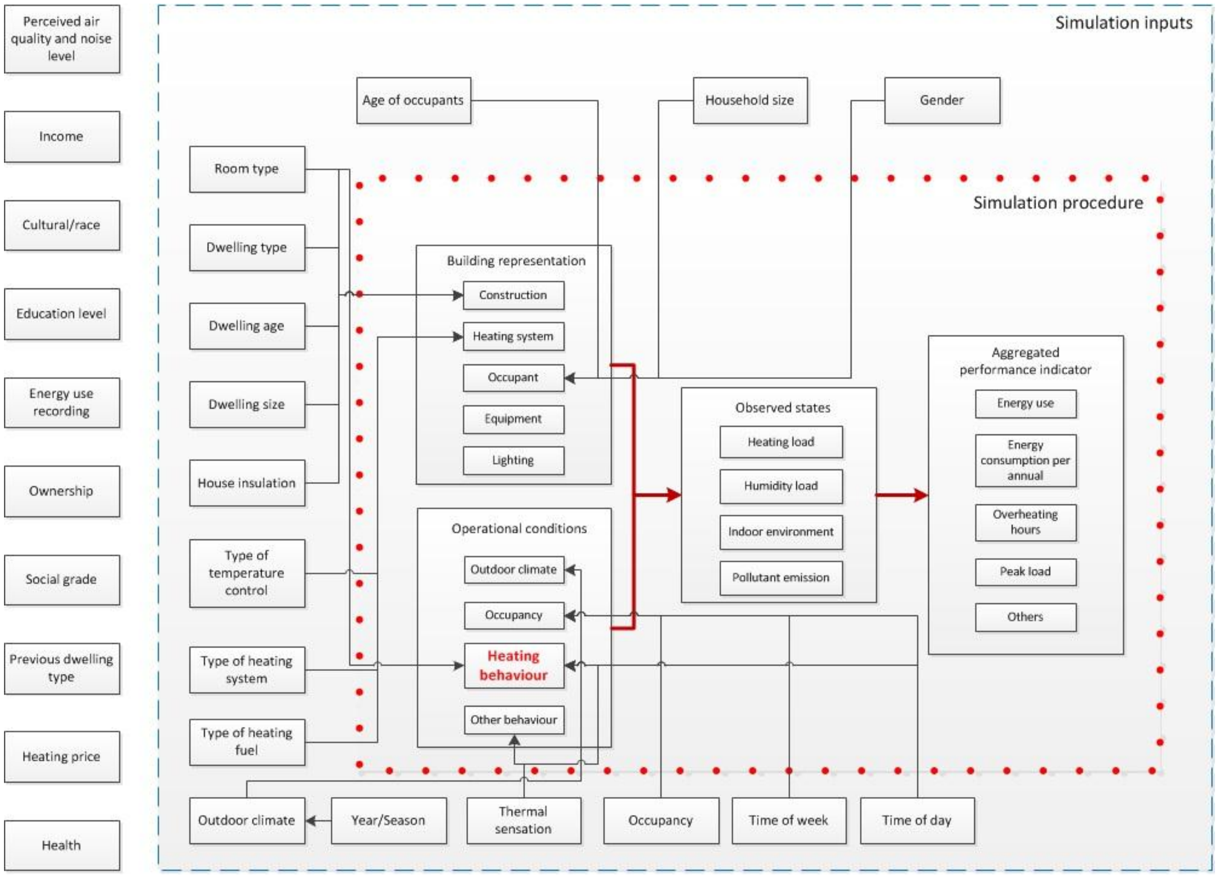

Figure 2 Implementation of factors in traditional building performance simulation

The last level information is that outside the blue dash line box. It is the information that is currently ignored in the building performance simulation process. Figure 2 highlights which factors discussed in this study are included in this level, as listed on the left side of the diagram.

From the information provided in this section, it can be identified that occupants' actual space heating behaviour is much more complex than the traditional behavioural patterns defined in recent building performance simulation. Building simulation experts typically focus on the building performance within a context of uncertainty. Typically they have precious little information about how actual building occupants use the building; in many cases users are unknown, let alone that complex relations with non-engineering, non-building contextual factors can be established. Under this condition, the experts have to model a standard occupant behaviour, then applying safety factors to deal with potential deviation. As a consequence many of the intricate relationships depicted in Figure 2 are not available for simulation efforts unless new models are established.

PREFERENCE-BASED SIMULATION

Based on the above discussions, it could be found that occupants' space heating behaviour is very complex in actual buildings, but this complexity is not well treated in current building performance simulation. There are 27 possible factors are proposed in exiting studies, to have possible influence on occupants' space heating behaviour, and it is a challenge to consider all of them in building performance simulation. In eViz, the simulation results will be shown to each building occupant, in order to visualise the impact of changing behaviour on the energy consumption of their buildings. In such cases, a realistic modelling of their space heating operation in the simulation process is essential, as this could affect occupants' acceptance of our suggestions. To handle this issue, a preference-based simulation approach, which is introduced in this section, is adopted in eViz to provide more realistic building performance simulations.

Personal behavioural preference has been demonstrated by Wei et al. (2013) as an important factor affecting occupants' use of windows in office buildings. Based on their survey results, Wei et al.

discussed that if an occupant's personal behavioural preference is considered when modelling his/her window behaviour, other factors that can classify building occupants into common sub-groups could be ignored, as these factors only affect *"the distribution of types of window users"* in each sub-group. In their study, these factors included occupant gender, which classifies building occupants into males and females, and floor level, which classifies building occupants into those working on the ground floor and those on upper floors. Within the 27 factors discussed in this paper, there are a great number of factors that have this characteristic, such as type of dwelling, type of temperature control etc. Therefore, if the simulation is carried out based on occupants' preference of space heating operation, the complexity of modelling their space heating behaviour in simulation could be significantly reduced, and this approach is called preference-based simulation in this study.

The factor personal behavioural preference generally classifies building occupants into several behavioural levels according to how actively they undertake a particular behaviour. For occupants' space heating behaviour, this could be referred to different preferred levels of space heating setpoint in their buildings. Normally, when modelling occupants' behaviour in buildings, a three-level hierarchy of behavioural preference is adopted (Bourgeois, Reinhart & Macdonald, 2006; Haldi & Robinson, 2009; Yun, Tuohy & Steemers, 2009): 'active', 'medium' and 'passive'. Therefore, in this study, a three-level hierarchy has been proposed for occupants' space heating behaviour in residential buildings, i.e. 'active heating user', who prefers a high heating setpoint; 'medium heating user', who chooses an average heating setpoint; and 'passive heating user', who uses a low heating setpoint. Apparently, occupants' personal behavioural preference will directly influence the energy consumption of their buildings, an 'active heating user' uses more energy than the other two user types, due to a higher setpoint of the heating system. Therefore, a change from a higher level of heating user to a lower level could help to reduce the building energy demand, as shown in Figure 3, and this defines the behaviour change direction for space heating operation.

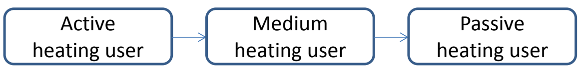

Figure 3 Behaviour change direction for space heating operation

One challenge of modelling occupants' behaviour based on the personal behavioural preference is how to allocate a particular user type for the simulated building. Generally, there are two methods that can be used: 1) generated from data collected from longitudinal monitoring of occupants' behaviour (Haldi & Robinson, 2009; Wei, Buswell & Loveday, 2013; Yun, Tuohy & Steemers, 2009), or 2) deduced by occupants' stated behavioural preferences (Rijal et al., 2007). In eViz, the latter method is adopted, as the former method is time-consuming, as well as with a high economic cost. To obtain occupants' stated preferences in the future study, a computer-based tool has been developed as shown in Figure 4, where the section relating to space heating behaviour has been highlighted.

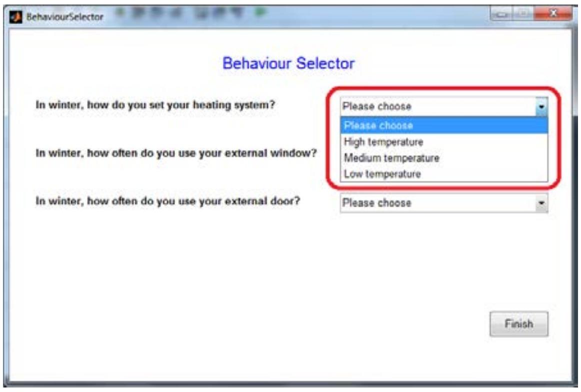

Figure 4 Behaviour selector in eViz

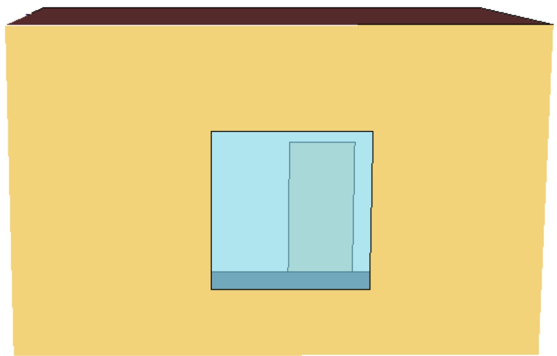

Figure 5 Example room

To demonstrate the implementation of the preference-based simulation approach, a lightweight example room is modelled in Energyplus V7.2 (DOE, 2013), which contains a window and a door, located on the south façade and the north façade respectively, as shown in Figure 5. In this model, the space heating system is manually controlled by the room occupant through setting different temperature setpoints.

To demonstrate the energy saving potential by changing behaviour from a higher space heating user type to a lower user type, corresponding heating setpoints for each type of space heating users are defined as: 21°C for the 'active heating user', 19.5°C for the 'medium heating user' and 18°C for the 'passive heating user', based on the range of comfort temperature defined for living spaces in BS EN 15251 (BSI, 2008). Figure 6 shows the simulation results for the winter period (1st October to 31st March), using the outdoor weather data collected from the Gatwick, London, UK.

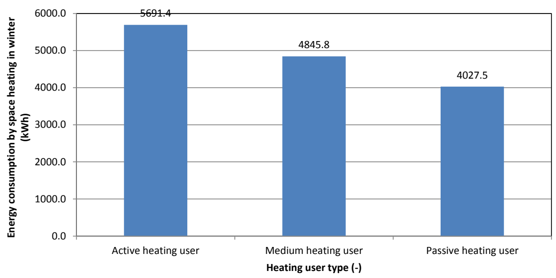

Figure 6 Space heating energy consumption in winter, for different space heating users

The simulation results depicted in Figure 6 reflect that changing heating behaviour has a significant contribution on reducing the building energy demand: for an 'active heating user', if he/she changes to a 'medium heating user', the total energy saving during the winter period could be up to 845.6 kWh, and a further reduction of 818.3 kWh could be achieved if he/she changes to a 'passive heating user'.

The above example is based on engineering temperature values recommended in building design standards. To realistically classify the three types of space heating users, occupants' actual behaviour in real buildings is still needed to be captured, and this task is currently being conducted in the eViz project. However, the above example indeed demonstrates that the preference-based simulation approach can be used to drive behaviour change in buildings.

CONCLUSION

This paper describes some initial work from an interdisciplinary project, eViz, which is aiming to achieve changes in occupant behaviour for energy saving, using energy visualizations. As a first stage, this paper reviews the potential influential factors on occupants' space heating behaviour in residential buildings, which is one of the two important types of active behaviour considered in eViz. The other active behaviour considered in this project is window opening behaviour. From this work, a set of 27 factors has been defined that contains all the factors considered by researchers in previous studies to have influence on occupants' space heating behaviour in residential buildings, and this reflects that occupants' space heating behaviour in actual buildings is a very complex process.

As building performance simulation is the main approach adopted in eViz to visualize the influence of changing behaviour upon building energy demand, the representation of those 27 factors in present building performance simulation is discussed as well. It is found that current modelling of space heating behaviour in building performance simulation only considers a small number of influential factors discussed in this study. Therefore, further studies are needed to provide more realistic behaviour modelling in simulation.

To address the complexity of occupants' space heating behaviour in real buildings, a preference-based simulation approach is introduced in this paper. It can not only reduce the number of influential factors that are needed for realistic behaviour modelling, but also drive behaviour change in buildings. The latter one has been demonstrated in this paper using a lightweight example room modelled in Energyplus.

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http://www.eviz.org.uk/

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