Evaluation of the occupants' exposition to the indoor environment.

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Abstract. User behaviour has a significant contribution to the final energy consumption figures of buildings. As indicated in finding from the IEA EBC Annex 66 project, proper and continuous monitoring of occupant behaviour inside buildings can support reaching of the zero energy-building standard (ZEB). The collected data, however, must be gathered via in situ methodology to avoid potential influences on data quality. Commonly used measurement techniques such as plug-load monitoring, CO2 level sensing or PIR, are sufficient to describe energy-related occupant behaviour at the zone/room level. However, this resolution of description can only be treated as an energy consumption overview as it cannot guarantee an identification of individual indoor environment quality preferences. Development of a solution that can grant access to an individual description of occupant needs requires direct monitoring of their inside building activity. Herein, access to necessary input data can be provided with the use of the depth registration camera because the suggested measuring technique can deliver information about routine occupant positioning inside each zone/room. Additionally, it provides data about the position of the observed occupants’ body limbs. If information about the distribution of the occupants is delivered, it is possible to couple such with a result matrix obtained via CFD studies. Moreover, the coordinates of occupant limb positions can be used as a data-probing device in simulation studies. With such a tool, it will be possible to monitor the exposure of each limb to the thermal properties of indoor air. Collecting data through this methodology can grant access to a more profound understanding of the occupant thermal comfort sensation and the habits that influence building energy use.

1. Introduction
Simulation of the indoor occupant behaviour (OB) has become one of the most trending subjects in building performance simulations (BPS) [1]. The increase in the popularity of the subject is directly related to the conclusions draw from past studies [2],[3],[4]. Yet, today’s BPS accuracy has only reached around 30% percent in terms of real energy consumption forecast. Hence, the lack of effective and real forecast has to be addressed and improved, especially in a sector that according to the International Energy Agency report from 2017, consumes around 25% of all globally produced energy [5].

Such low accuracy, according to the D. Yan [6] and D. Bing [7], is due to the underestimation of OB impact on total building energy consumption. Additionally, as pointed out in [7], lack of BPS accuracy comes about by the absence of comprehensive OB models capable of simulating human indoor behaviour. In previous approaches, access to such data was limited and could not allow for individual identification of building user expectations. Hence, description and understanding of this parameter should lead to incremental improvement in the quality of BPS energy use forecast, as each person holds an individual assessment of thermal comfort. As preferred indoor air conditions and acceptance range varies among users, it is understandable why studies that aimed at formulating a coherent comfort description among building users as a group have failed. Fanger [8] describes indoor environment via the use of the predicted mean vote (PMV) model, and the resulting predicted percentage of dissatisfied (PPD) model combines a subjective sensation of the indoor environment with a possibility of
recognizing dissatisfaction among space users. Herein, Fanger’s approach evaluates given space in terms of its thermal acceptance. Other commonly used models such as the adaptive thermal comfort model, also operate on variables related to indoor conditions and mean monthly outdoor air temperature. This results in an estimation of satisfactory factor [9].

Such mentioned models, now commonly used in estimating building indoor environment conditions, focus on a description of thermal comfort at a room/zone level. Indeed, at the time in which these measurement methods were discovered, this degree of recognition was considered as sufficient. More recently, however, the idea of thermal comfort and indoor well-being has been introduced [10].

OB in buildings is a complex phenomenon. Detection and proper description of simple related activity like adjustment of the thermostat, may necessitate numerous observations to take in human preference. Therefore, the ability to describe such activity involves the use of sophisticated tools that can make grand un-bias observations. Although in-situ measurements could potentially be considered as a source of data, the gathered input still requires an additional cross-check interview with the observed individuals to ensure proper interpretation.

Extension of the OB description by reaching towards higher spatial and temporal resolution seems to be the correct direction of research. Such a move is indicated in the development of BPS tools that include OB as an essential part of energy summations. These tools introduce the use of stochastic methods to describe the occupancy state inside a simulated environment. Even though such models do not treat occupants as separate individuals, such advancement could be considered as a step towards such individualization. Current BPS tools include Energy Plus [11] or DeST [12]. Development of an OB model capable of simulating individual actions requires access to data in a resolution that can capture actions of significant effect upon indoor air quality. The gathered information should help to evaluate occupant exposure to the indoor environment and enable the drawing of precise conclusions. In doing this, access to real indoor air property data by way of measurement logs has become a standard. The appropriate way of a collection of such data was previously well described, and is available in well-known guidebooks [13].

Still, besides the precise description of indoor conditions, it is necessary to ascertain occupant indoor localisation. The ability to combine the monitored information regarding indoor conditions with occupant localization and time allows for the development of personalised thermal comfort profiles. To do so, it is necessary to access information about volume air mass properties through computational fluid dynamics (CFD). Herein, indoor environment sensors can be used to ascertain boundary conditions for CFD simulations. Once the proper data are made available, it is essential to formulate a new methodology to evaluate the occupants’ exposure to indoor conditions. The main aim of this paper is, therefore, to introduce a novel methodology regarding indoor environment analysis. The combination of occupancy data with timed indoor condition information in the scope of the particular person was not found in current literature. Thus, there are no available methods to process and interpret such an output. Hence, we chose to explore the possibility of merging these data sets and to propose a new methodology to evaluate occupant thermal comfort. This study is not aimed at extensive numerical investigation. The goal is to investigate the possibility to exploit result data achievable from commercial software, to introduce a new evaluation technique. Therefore, the particular setting of the simulation software solvers was similar to other, already published studies [14],[15].

2. Methods

Investigating occupant exposure to the indoor environment requires a specific combination of data inputs. To conduct effective CFD studies of the selected room/zone, besides gaining the necessary environmental data, simultaneously, the same place has to be monitored by depth registration cameras. In this work, CFD simulations were conducted as a steady-state, but the observation of occupant activity lasted for a full twenty-four hour period.

Access to the particular data about air volume physical properties required conducting a series of measurements coupled with numerical simulations. For the investigation purposes, a test case that represents a living room was selected. Room selection was dictated by its applicability to the investigation case. It is a zone inside a home/flat, that is considered to be public, so any type of monitoring device would not disturb occupant privacy. What is more, since it is a public part of the
home/flat, there is a high chance of capturing various occupant activities during the daytime via the use of depth registration.

A geometrical representation of the room was drawn utilizing the CAD/CAM software ‘SolidWorks’. The room was filled with the same furniture and appliances as the actual. The geometrical representation of each room feature was also included in the main simulation geometry. The geometrical representation of the room air volume was then used later on to formulate a hexagonal mesh that is necessary for further simulation steps. Herein, minimum edge size designed mesh was set at a value of 0.005 [m], and maximum edge size was set at a value of 0.02 [m]. The selected parameters allowed the formulation of a mesh of less than four million elements. This quality of generated mesh was considered acceptable for the simulation statistics (average aspect ratio: 1.035, element quality: 0.995 and skewness: 3.833e-3). A simplified drawing representing room layout is shown in Figure 1

![Figure 1](image_url)

**Figure 1.** Visualisation of the room used for the numerical studies.

Once the virtual room geometry was set, it was necessary to collect the physical properties of the investigation area. To establish the simulation boundaries conditions, each wall, ceiling and roof was captured using an industry quality thermo-vision camera, Flirt E60. The obtained infra-red pictures were used to formulate thermal profiles of each surface.

The generated mesh external surfaces representing walls ceiling and floor were exported so as to be employed for the formulation of boundary condition profiles. This mesh information was represented as three-dimensional information about mesh node positions. The exported data was subsequently overlaid with the information obtained by the thermo-vision camera in order to probe the contained thermal information. After this, the collected wall, ceiling and floor temperature was exported to the Ansys Fluent software to be used to generate corresponding boundary conditions.

Information about the air velocity was collected via the use of the TSI VelociCalc multi-function ventilation meter 9565-p anemometers. Measurement devices were place in front of the window (that was later on threatened as an inlet), door and ventilation outlet (that were later on threatened as an outlet) and middle of the room (for the calibration reference).

Data about occupant activity was collected via the use of the depth registration camera Microsoft Kinect v2.0 for Windows. With the use of this measurement technique, it is possible to gather information about occupant placement and position inside the monitoring area [16]. As previously studies show [17], it is possible to formulate an occupant behaviour profile that holds information about occupant position, identification, clothing and activity level. For this study, only information about placement and behaviour was used. The data set that describes occupant body placement was sampled with a frequency of around 30 [Hz]. Each captured frame delivered information as a twenty-five point skeleton model (SM) presentation of the human body, wherein each point (joint), holds information about the three-dimensional position. The delivered position provided information about the distance of the observed joint from the location of the monitoring device. One frame can capture up to six SMs at the time. Each captured frame of the information package is connected with simultaneously obtained global clock information. This set of data allow re-creating in a virtual spectrum, body position and its
transitions, as well as occupant position within the monitored space. For this investigation case, only one measurement depth registration camera was used.

The plot of all captured points during the measurements trial can be considered as being a cloud point data set. Such a data set holds the observed volume (occupants are unable to access areas that are physically blocked by furniture, walls or devices) through time. Therefore, it has to be correctly transformed to fit into the virtual geometry model of the room used for simulation purposes. Hence, a transformation vector was set via measurement of the device placement inside the actual room and analysis of the gathered surface data. The occupants, while moving about inside the monitored space, leave a signature on how the device receives information about the flat surface. Joint points from SM that represents the spine base are usually stable in terms of distance to the floor. Therefore, the plane slope that is generated via observation of this joint point can be analysed and used in a transudation vector. Once the position data is properly fitted to the observed room, it can be further processed. To fully utilize the collected SM information inside the CFD software, it is necessary to wrap all of the points in a singular polyline. Direct import data to the Ansys environment can be done with the use of the cloud point information, but such an import method will disconnect points order and will block further processing. To import all joint positions into the Ansys software environment, it is necessary to re-arrange the position data in a matrix with a dimension of \((n \times 3)\), where \(n\) represents several points in a polyline and 3 is the three-dimensional position of each point on a polyline. Formulation of such a matrix can be obtained by re-arranging SM information.

Information about each joint position (beyond the first) has to follow the previous in the re-arranged matrix. Because SM always produces an even number of records for each joint, there is no need for sorting information about matrix composition. Of note, the produced matrix can always be divided by twenty-five (the number of SM points or joints), thus the simulation will deliver information about one SM joint matrix dimension range inside the export polyline at any one time. After the numerical simulations are finished, it is possible to import into the simulation the resulting prepared polyline and probe results.

3. Results
Successful import of the polyline allows for the export of selected variables, in this case, a set of velocity vectors for each dimension, as well as temperature information. The exported variables have to be once again re-arranged into the matrix that represents in one dimension, a number of gathered frames (the subsequent twenty-five - the number of SM points or joints representing one individual occupant). After this procedure, graphs can be plotted wherein each separated line represents the exposure of each joint to the investigated indoor air variable. Results of such procedure are displayed in Figure 2. To not blur results plot with all of the twenty-five record plots, it was decided to plot four selected joint exposition plots that represent: head, neck, left wrist and spine base.
4. Discussion
The methodology presented in this paper explains the procedure of obtaining data about occupant exposure to the indoor environment. In the proffered new methodology of evaluating indoor OB, it is necessary to take an additional step and combine a clock date from occupant monitoring with indoor air variables collected via CFD simulation results. Beyond the temporal localisation of the collected variable that mimics occupant location and position, it is then possible to generate a series of cumulative variables values that can be graphed in any temporal resolution. This will allow to evaluate occupant thermal comfort in a similar way as climate evaluation of indoor condition assessment [18].

It should be recognized that plots of this constantly growing variable can be generated in the scope of one day with a resolution of one second. This approach to indoor data analysis will highlight any slight changes in the investigated variable. Because the suggested approach holds a “memory” of previous steps, side effects of any given indoor conations can be investigated. Therefore, the approach has the potential to formulate new reaction arcs to describe building energy-related occupant behaviour. What is more, if the processed data are matched with a history of occupant actions, it will be possible to estimate if the conducted action originates from the physical properties of the indoor environment or from other effects. Of note, it is assumed that each time an occupant leaves the room, the current state is held as a cumulative value. A sample of such processed data is shown in Figure 3.

5. Conclusion
The presented paper shows a novel approach for gathering and analysing data sets related to individual occupant thermal comfort. Base on the given examples, certain advantages of the proposed methodology can be underlined. It is one of the first description methods, which focuses upon the individual perception of indoor air proprieties. Gained results should be obtained with the use of the steady-state simulation. Therefore, simulated phenomena do not change while the occupant is transmitting thru the air volume, or during the time flow. Reaching this level of accuracy requires more steps of several studies to have full control of simulated phenomena.

Next step should aim into the introduction of the same methodology into the transient CFD simulations. The general procedure of data extraction would not change. The main difference will be an amount of the extracted polylines. Each time step (inside CFD) will produce separate air volume properties. Therefore, it will produce separate export polyline dataset.

If movement polylines are generated automatically, with the use of the other, external software, introduced methodology will gain new functionality. It would allow to forecast occupant’s future exposition to various indoor air properties and test different layout setup scenarios. With such functionality, it would be possible to re-use previous experiments results.
Suggested in this paper methodology introduced a new approach for investigated occupants' exposition to the indoor environment should. In a current stage of development, it is hard to estimate the impact or usability of this method. Therefore, further investigations with the use of this technique are recommended.

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